Received: 5 July 2023 | Revised: 4 December 2023 | Accepted: 14 December 2023

DOI: 10.1002/aqc.4067

RESEARCH ARTICLE

WILEY

Novel large-scale mapping highlights poor state of sea trout populations

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Funding information

Miljødirektoratet; Norges Forskningsråd, Grant/Award Number: 160022/F40

Abstract

1. The state of sea trout in 1251 Norwegian watercourses was assessed based on a scoring system for human pressures, abundance data, and local knowledge.
2. Over 16,000 km of rivers and lakes were available to sea trout in these watercourses, spanning from the temperate to Arctic regions.
3. Sea trout were classified to be in a good or very good state in fewer than 25% of the watercourses and in a poor or very poor state in almost 40%. Twenty-nine watercourses had lost their sea trout populations.
4. Salmon lice from aquaculture salmon farms had by far the largest adverse effect on sea trout among the human impact factors, both in the number of watercourses (83%) and river area affected (60%), and the total effect on sea trout abundance.
5. Agriculture and hydropower production also had strong adverse impacts (35% and 19% of watercourses), but substantially lower than that caused by salmon lice. Culverts related to road crossings and other habitat alterations also had impacts on sea trout in many watercourses (27%).
6. Exploitation of sea trout has been reduced in Norway in recent years, both in the marine and freshwater fisheries. Yet, the exploitation pressure was moderate or high in almost 14% of the watercourses where the state of sea trout was poor or very poor, suggesting a high potential for overexploitation in these.
7. The state of sea trout was best in the northern sparsely populated areas. However, distribution of watercourses with sea trout in a poor or very poor state was more linked to aquaculture, agriculture, and hydropower production than human population density.
8. The developed approach for large-scale mapping of state and pressures, which is vital for prioritizing management measures, may inspire other nations in their conservation effort for this important species.

KEYWORDS
acidification, anthropogenic pressures, brown trout (*Salmo trutta*), culverts, exploitation, hazardous substances, salmon lice (*Lepeophtheirus salmonis*), sewage

1 | INTRODUCTION

Salmonids are well-known and culturally important migrating fish species and have historically supported commercial, sustenance, and recreational fisheries in large parts of the world (Kershner et al., 2019; Myrvold et al., 2019; Quinn, 2018). Many salmonid species are still highly prized among anglers and to some extent support commercial fisheries. Salmonids spawn in freshwater, but many species are anadromous, which means that all or some individuals perform feeding migrations to the sea (Gross et al., 1988). Such use of multiple habitats and long migrations make populations vulnerable to multiple threats from human activities (Crozier et al., 2019; Dauwalter et al., 2020; Forseth et al., 2017; Gregory & Bisson, 1997) resulting in declining abundance and extinctions (Anderson et al., 2014; Katz et al., 2013; NASCO, 2019; Rand et al., 2012).

The brown trout *Salmo trutta* is a salmonid with a worldwide distribution, after having been introduced to many areas outside their natural distribution range (Klemetsen et al., 2003; Lobón-Cerviá & Sanz, 2018). Brown trout is a partially migrating species (Chapman et al., 2012). Sea trout, which is the anadromous form, has a high social and economic value as a resource for recreational angling (Butler et al., 2009; Harris & Milner, 2006). They have considerable life history variation and occur in a variety of watercourses, from very small streams to large rivers and river systems and connected lakes (Klemetsen et al., 2003). During the marine migration, sea trout may reside in estuaries, at sea in full-salinity sea water, or they may move repeatedly between estuaries and adjacent marine areas (Thorstad et al., 2016). Time spent at sea compared with fresh water varies considerably among individuals and populations and is likely to be governed by trade-offs between the costs and benefits associated with their freshwater and marine habitat (Thorstad et al., 2016).

The state of sea trout populations and fisheries varies across the distribution range, according to the influence of local and regional factors (Harris & Milner, 2006; ICES, 2013; Milner et al., 2006). Populations are healthy in some regions, whereas major collapses are seen in other regions. Human-derived impact factors that may act on sea trout in fresh water include acidification, other pollution (e.g., from agriculture, roads and mining), hydropower development, other river regulations, migration obstacles, and habitat alterations (Thorstad et al., 2016). Threats in the marine environment include salmon lice from aquaculture and construction and deployment of harbours, piers, bridges, fish farm structures, and other industrial developments (Thorstad et al., 2016). Climate change, overexploitation, and diseases caused by viruses, bacteria, fungi, and parasites caused by fish farming can affect sea trout in both freshwater and marine habitats.

Despite the larger, global distribution area, brown trout is studied to a much lower extent than the close relative Atlantic salmon *Salmo salar* (Birnie-Gauvin et al., 2019). This is also the case in Norway, where both species occur in several watercourses. More than 1200 watercourses are registered to hold sea trout, and around 450 of these watercourses also hold Atlantic salmon. The state of Atlantic salmon is well known, but this is not the case for sea trout. The aim of this study was to classify the state of sea trout in 1251 Norwegian watercourses and for each watercourse assess the threats to sea trout from human activities. By doing so, an overview of the state and pressures can be provided as a foundation for management measures. The watercourses are located over a large geographical area, from 58°N to 71°N, spanning from the temperate to Arctic regions and from highly developed urban areas to rural areas. As such, the assessment is relevant for other parts of the world's sea trout distribution area. Moreover, the methodological approach for large-scale mapping may inspire other nations as part of their conservation effort for this important species.

2 | MATERIAL AND METHODS

This study was performed by the 13 scientists in the Norwegian Scientific Advisory Committee for Atlantic Salmon Management with assistance from a GIS expert (Vegar Bakkestuen). The committee members are appointed by the Norwegian Environment Agency, and assessments and advice for sea trout and anadromous Arctic charr (*Salvelinus alpinus*) are parts of the committee mandate. The committee has members from seven different research institutions in Norway, with at least one primary expert for all the major human pressures. Whenever expert judgements were used in this study, the primary expert(s) suggested their assessment, which was next discussed among the committee members before reaching a consensus conclusion.

A system to classify the state of sea trout on watercourse level was developed based on an assessment of human pressures, the sum of pressures, use of abundance data, and assessment of available catch statistics, reports, and local knowledge. The quality of catch statistics for sea trout is highly variable among rivers and streams, and there are many watercourses where there is no fishing for sea trout, either because the stream is too small or the abundance is reduced to the extent that fishing is closed. Other types of abundance data, such as spawner or redd counts, counting of upstream migrants, electrofishing, or gill netting in lakes, exist only for some of the rivers. However, various data sources on different human pressures are available for many rivers, and the use of local knowledge provided an additional knowledge base and quality control. Local knowledge was used by a river-by-river consultation with those responsible for the management of anadromous salmonids at The County Governor (the state's representative in the 11 counties of Norway that all have freshwater fish managers). In cases where these representatives did not have specific knowledge themselves on the watercourses, they often consulted other local people. In addition, 180 Norwegian reports (often environmental impact assessments), notes or local databases were compiled and used in the assessment (Supporting Information S1). These provided additional information on sea trout for 495 of the watercourses. The assessments were carried out based on the most recently available data for 2020 and 2021.

The state of sea trout was assessed for 1251 watercourses that were previously identified in the Norwegian Environment Agency database as holding sea trout https://lakseregisteret.statsforvalteren.no/. Each watercourse has a single outlet to the sea. The watercourses vary from small streams that flow directly into the sea to large watercourses with several tributary streams and lakes that drain off to the sea through a main river. A first step for mapping the state of sea trout was to identify and map the river stretches available to sea trout in each watercourse.

Almost all Norwegian watercourses with Atlantic salmon also hold sea trout, but many watercourses holding sea trout do not hold Atlantic salmon. The state of sea trout was compared in watercourses with and without the co-occurrence with Atlantic salmon. Watercourses with sympatric salmon and sea trout generally represent the large rivers in Norway, whereas allopatric trout are mainly found in smaller rivers and streams. Most Norwegian watercourses hold few fish species on stretches available to anadromous fish, but species such as European minnow (*Phoxinus phoxinus*), European flounder (*Platichthys flesus*), Northern pike (*Esox lucius*), sticklebacks (*Gasterosteus aculeatus*, *Pungitius pungitius*), and anadromous Arctic charr (only in northern Norway) are present in many of the assessed watercourses.

2.1 | Identification of river stretches and areas available to sea trout in each watercourse

For 448 Norwegian watercourses holding Atlantic salmon, the stretches available to anadromous salmonids in the main river and important tributaries had already been mapped, based on local knowledge (www.lakseregisteret.statsforvalteren.no). For small tributaries in these 448 watercourses, and for most other watercourses with sea trout, river or stream stretches available to sea trout had not been mapped. The stretches available to sea trout in all rivers and tributaries where this had not been done previously were mapped by identifying migration barriers for anadromous salmonids. This was done by using high-resolution LiDAR-based digital terrain models and 1:5000 maps (Norwegian Mapping Authority, www.hoydedata.no). The Google Earth Engine (Gorelick et al., 2017) was used to map potential migration barriers defined as a gradient steeper than 24° over a 2 m or longer stretch, because these are shown to be potentially the natural upstream limit to migration (Hedger et al., 2020). In many cases, man-made migration barriers such as culverts, dams, and other barriers hinder accessibility to parts of the watercourse that were originally available to sea trout, and such barriers were mapped by use of aerial photos and maps, or collected from regional databases (available for some of the counties). Information on natural and man-made migration barriers was verified for each watercourse or adjusted based on local knowledge.

When the present-day migration barriers had been identified and mapped, the length of river stretches available to sea trout was calculated along the river centreline from the river mouth to the migration barrier. Through lakes, the shortest possible swimming route was used. The accessible area was calculated for river stretches and lakes separately, using the 1:5000 map. In this map, rivers and streams wider than 1 m are drawn as polygons overlaying the water-covered area when aerial photos were taken.

2.2 | Assessment of human pressures

For each type of human pressure, an impact score from 0 to 3 was assigned based on the estimated impacts on smolt production or spawner abundance, from no effect (score 0) to more than 30% reduction in abundance (score 3) (Table 1). Pressures acting on juveniles in fresh water were assessed based on their long-term effects on smolt productivity, also considering the density-dependent compensation mechanisms (Einum & Nislow, 2011), whereas factors acting on migrating smolts and trout at sea was assessed based on adult returns. How each of the human pressures were scored is described below and in Table 1. Information on hydropower infrastructure, habitat alterations, agriculture, urbanization (an index for sewage drains), and water quality was available from data provided by the Norwegian Water Resources and Energy Directorate (NVE) and aerial photos and maps (https://norgeibilder.no, https://norgeskart.no) provided by the Norwegian Mapping Authority, the Norwegian Public Roads Administration, and the Norwegian Institute of Bioeconomy Research NIBIO. Information from NVE Atlas was also used, which is a map-based database containing data provided by NVE (https://atlas.nve.no), and Vann-Nett, which is a database containing information used to assess the status of individual water bodies under the Water Framework Directive 2000/60/EC (https://vann-nett.no, NVE and Norwegian Environment Agency). For all human pressures, any additional local information that was provided was included.

2.2.1 | Hazardous substances: copper and nickel

Pollution by metals in watercourses was assessed based on levels of copper and nickel, which are typically related to mining activities, using data reported to Vann-Nett to assess the requirements of the European Water Framework Directive. Other hazardous substances were not included because data are lacking for many watercourses. Impact scores were 0 or 1 and not higher, because these impacts are usually limited to only parts of the stretches available to sea trout within watercourses.

TABLE 1 Classification of human activities (impact factors) on sea trout in each watercourse. X indicates the range of the scale used for each impact factor. Scores reflect assessed impacts on smolt production or adult returns, where 0 = no effect, 1 = small effect (<10% reduction), 2 = medium effect (10%–30% reduction), and 3 = large effect (>30% reduction). The criteria for each of the scores are given. The citation for Vann-Nett can be found at https://vann-nett.no.

Impact factor	Scores 0	1	2	3	Criteria for scores
Hazardous substances; copper and nickel	X	X			0: threshold values of copper and nickel not exceeded. 1: threshold values of either copper, nickel, or both exceeded. In some cases, score 1 was given if presence of other known hazardous substances that have impacts on fish was listed in Vann-Nett. Threshold value used for copper was 7.8 μg L^{-1} and for nickel 4 μg L^{-1}.
Culverts	X	X	X	(X)	0: <0.25, 1: 0.25–1.3, and 2: >1.3 estimated number of culverts per km river stretch. 3: impassable culvert in river mouth, and sea trout regarded as lost from the watercourse.
Sewage and runoff pollution	X	X			0: ≤11.5 and 1: >11.5 buildings in a 250 m zone on each side of the river. Score 1 was also used where specific effluents were identified and reported in Vann-Nett.
Agriculture	X	X	X	X	0: <10%, 1: 10–20%, 2: >20–35%, and 3: >35% agricultural area in a 100 m zone on both sides of the anadromous stretch but reduced by one score if there was >50% riparian vegetation in a 10 m wide zone of the same stretch.
Acidification	X	X	X		0: no known acidification. 1: acidified, but with liming, and 2: acidified, no liming, as classified in Vann-Nett.
Hydropower production	X	X	X	X	Sum of two indices used, truncated at a maximum of 3. One index was related to water abstraction and assessed by reduction in catchment area or annual runoff: 0: <10% reduction, 1: 10–30% reduction, 2: >30%–60% reduction, and 3: >60%. The other index was related to other impacts of hydropower production and assessed by reduction in smolt production.
Water abstractions	X	X	X	X	0: none registered. 1: water abstracted and used in salmon aquaculture or other use of water. 2: large abstraction of water and migration barriers that obstruct migration to parts of the watercourse, and 3: very large abstraction that causes parts of watercourse to be dry, and/or migration barriers related to the water abstraction hinder migration to large parts of the watercourse (in some of these cases, sea trout was regarded as lost from the watercourse).
Habitat alterations	X	X	X		0: <50%, 1: 50–100%, and 2: >100% of available stretches to sea trout equipped with embankments along river shores to protect against erosion and floods (values larger than 100% were possible, because embankments along both sides of the river were summed).
Salmon lice from aquaculture	X	X	X	X	Estimated from a regression model that predicts effect from a salmon lice index and salinity (see main text).
Overexploitation	X	X	X		1: total exploitation level is high and the state of sea trout in the watercourse moderate, or total exploitation level is moderate and the state of sea trout in the watercourse poor or very poor. 2: total exploitation level is high and the state of sea trout in the watercourse poor or very poor, and 0: all other combinations of exploitation level and state of sea trout in the watercourse. For score 1 and 2, the sea trout in the watercourse is likely to be overexploited.

2.2.2 | Culverts

Road crossings over streams and associated culverts often constitute migration barriers for sea trout because of poor culvert design and reduce the stretches available to sea trout. Map data were used to record the number of road crossings minus the number of bridges as the best estimate of the number of culverts in each watercourse. As the effects of culverts on migration may range from easily passable, via partial (e.g., flow-dependent) to full barriers, the impact based on the number of culverts was scored from 0 to 2 (Table 1). However, if there was an impassable culvert in the river mouth close to the sea, documented by local information, this was regarded as sea trout being lost from the watercourse and score 3 was used. The classification was adjusted based on aerial photos. Closed streams where the water is transferred through pipes or tunnels underground for reasons other than road crossings were also included in the assessment.

2.2.3 | Sewage and runoff pollution

An urbanization index (Erikstad et al., 2023) was used as a proxy for the pollution burden of surface runoff, waste treatment, and industry effluents, assuming that highly urbanized areas have a higher probability of such pollution than less developed areas. The index is calculated from infrastructures and urban areas in 500-m-diameter circles and is available in maps (N50). It ranges from 0 in areas without mapped infrastructure to 15 in dense city areas. The mean of this index in a 250-m zone on each side of the anadromous stretch was calculated, and based on expert judgement, a limit at 11.5 was assigned as a negative effect. Where specific effluents were reported in Vann-Nett, these were also considered. Impact scores were 0 or 1 and not higher, because effluents undergo strict regulations for cleaning, and accidental releases rarely affect the entire anadromous stretch within watercourses and usually have only short-term effects.

2.2.4 | Agriculture

Agricultural activities may enhance brown trout productivity in the generally nutrient-poor stream systems in Norway if agricultural activity is minimal in the area along the watercourses but reduce abundance if a large proportion of the area is affected (Johnsen et al., 2011). Based on maps (N5; Ahlstrøm et al., 2019), an estimate was made of the proportion of the area in a 100-m-wide zone along both sides of the anadromous stretch that was registered as agricultural area. Agricultural activity along rivers and streams may involve nutrient runoff, fine sediment runoff, and deposition and often involves channelization and other habitat alterations with potential large effects on sea trout recruitment. The impact was scored from 0 to 3 (Table 1), based on the relationship between the proportion of agricultural area and the production of 0+ trout given by Jonsson et al. (2011), accounting for the difference in how the proportion of agricultural land was estimated (the whole catchment in Jonsson et al., 2011). Next, riparian vegetation was considered. It has been shown that riparian vegetation is important for biological production, particularly in small streams, and can protect the streams from the adverse effects of agricultural activities (e.g., Hoffmann et al., 2009; Popov et al., 2005; Tolkkinen et al., 2021; Zhang et al., 2010; reviewed for Norwegian watercourses by Blankenberg et al., 2017) as well as thermal stress (Dugdale et al., 2018; Hannah et al., 2004). Based on the mean canopy height model from LiDAR (obtained from hoydedata.no), the proportion of woodland was estimated in a 10-m zone on both sides of the anadromous stretch. In cases where more than 50% of this zone was classified as woodland, the agricultural score was reduced by one unit (a limit set by expert judgement).

2.2.5 | Acidification

Acid deposition produced by sulphur and nitrogen emissions from the combustion of fossil fuels in power plants, other industry, and means of transport in other European countries has resulted in acidification of watercourses and loss of Atlantic salmon and sea trout in many Norwegian watercourses in the southern part of the country (Hesthagen et al., 2016; Hesthagen & Hansen, 1991). Anadromous salmonids may be affected by low pH, or from aluminium released from the soil at low pH, that attaches to fish gills and affects osmoregulation when the fish enter the sea during migration. The assessment was based on data from Vann-Nett. Large-scale liming programmes are established to improve the water quality in many large rivers. In these limed rivers, score 1 and not 0 was used, because liming rarely protects fish completely from the damaging effects of acidification (Clair & Hindar, 2005), and liming programmes usually do not cover all tributaries used by sea trout. Score 2 was used for documented acidified watercourses that are currently not limed, but score 3 was not used in any of the watercourses because large kills of sea trout in acidified watercourses are no longer reported. In addition, sea trout are less affected by acidification than Atlantic salmon that are targeted in the liming programme (Hesthagen et al., 2016).

2.2.6 | Hydropower production

The impact of hydropower production on brown trout production may result from (i) water abstraction from parts of, or entire, watercourses, which will reduce the water-covered area and therefore the production potential for sea trout; and (ii) other effects such as dams and weirs creating migration barriers, turbine mortality, altered water discharge and temperature during the annual cycle, hydropower-induced supersaturation, and hydropeaking (reviewed by Johnsen et al., 2011). These two types of effects were evaluated separately, providing two indices that were combined into one score.

All hydropower facilities in the watercourses assessed were identified from data provided by NVE in the NVE Atlas (https://atlas.nve.no/Html5Viewer/index.html?viewer=nveatlas#). In this database, all power stations, reservoirs, tunnels, or pipes transporting water between reservoirs and to the power station are given. Water abstraction to neighbouring catchments can also be identified and the proportion of abstraction can be estimated, both in terms of the proportion of the total catchment area and annual runoff. Power stations were classified by size in terms of production capacity, as micro, mini, and small power stations (≤10 MW), or large power stations (>10 MW). Information on the maximum turbine flow rate (m^3 s^{-1}) was either obtained from the licences provided (only for some of the stations) or estimated from the hydropower head (m, provided in the database or estimated from maps), maximum power generation (in MW), and generation efficiency (set at 90% for large and 85% for small hydropower stations). The flow rate was related to the annual mean flow of the watercourse (also provided in the NVE database), which is important for the evaluation of impacts, particularly the effects of hydropeaking or accidental shutdowns at power stations and the danger of juvenile trout and invertebrates becoming stranded.

The scoring of the index that considered reduced sea trout production capacity caused by water abstraction (Table 1) was adjusted in some cases based on the size of the watercourse and the shape of the river bed (wide or narrow) as observed from aerial photos (https://norgeibilder.no/). If, for example, the abstraction was 50% in a small watercourse (mean annual flow <5 m^3 s^{-1}) and large foreshore areas were observed in aerial photos during low summer flows, a score of 3 rather than 2 was given (Table 1). In some cases, environmental impact assessment reports provided additional information on the effects of the water abstraction (Supporting Information S1). In cases where abstraction only affected parts of the anadromous stretch, the proportion of the total area affected was used in the scoring.

The scoring for the other index, which considers all adverse effects of hydropower production other than abstraction, was based on a combination of expert judgements by the committee and available environmental impact assessment reports for some of the watercourses. As Norway has developed a significant proportion of the large watercourses for hydropower, extensive studies have been performed to assess the effects, particularly for salmonid fishes. As reviewed by Johnsen et al. (2011), the links between the environmental changes associated with hydropower developments and adverse impacts is well described, and the impacts can be classified by expert judgement from an understanding of the hydropower system.

As will be shown later, Norway has experienced a period with extensive developments of small hydropower schemes. In many cases, these were constructed in high-gradient tributaries with a water outlet at the top of the accessible stretch for sea trout. In such cases, a minimum score of 1 was used, because hydropeaking restrictions given in the licences for small power stations are rarely followed, and short-term stops and starts occur frequently (L'Abée-Lund & Otero, 2018). Moreover, bypass valves (installed in some power stations) to compensate for reductions in flow during accidental turbine shutdown do not function as intended in several power stations (Vingerhagen & Vaskinn, 2017). Hydropeaking operations and accidental shutdowns cause rapid changes in water flow and water level, with high risk of stranding of juvenile sea trout and benthic fauna (Harby & Noack, 2013; Hvidsten, 1985). In many cases, however, the area affected constitutes a small part of the production area for sea trout.

2.2.7 | Water abstraction

Water abstraction to supply water to the Atlantic salmon aquaculture industry (mainly land-based hatcheries producing smolts for release in marine fish farms), other industry, agricultural irrigation, and for drinking water may have impacts on sea trout, particularly in small watercourses. Water abstractions were mapped by using data provided by NVE, maps of hatcheries used in aquaculture obtained from the Fisheries Directorate (www.fiskeridir.no), and information from Vann-Nett and the Norwegian Environment Agency database (https://lakseregisteret.statsforvalteren.no/). The extent of water abstractions (often unavailable information) and migration barriers installed to prevent anadromous fish from entering river stretches where water intakes for hatcheries are situated (mandatory for such facilities, unless recirculation aquaculture systems are used) were assessed from the data provided by NVE, reports, and aerial photos. Owing to the difficulties in finding quantitative data, the scoring was based on a qualitative description ranging from small abstractions relative to the flow and no migration barriers (score 1) to large abstractions causing periods with no, or very low flow or migration barriers strongly reducing the available area for sea trout (score 3; Table 1).

2.2.8 | Habitat alterations

Data on the length of river stretches affected by mitigation measures, such as embankments to protect river banks against erosion and floods, were obtained from NVE Atlas. Impact scores were kept to a maximum of 2 and not 3, because such measures mainly affect the river banks, and embankments are often made from large stones and not uniform concrete walls. Boulder and rock embankments may reduce habitat quality, but often provide some shelter habitat for salmonids, so the adverse impact on total population size is not expected to be large.

2.2.9 | Salmon lice from aquaculture

Salmon lice (*Lepeophtheirus salmonis*) are ectoparasites of salmonids in the sea. Salmon farming increases the abundance of salmon lice. Salmon lice feed on host mucus, skin, and muscle, and infestation may induce osmoregulatory dysfunction, physiological stress, anaemia, reduced feeding and growth, increased susceptibility to secondary infections, reduced disease resistance, and ultimately mortality of individual sea trout (Thorstad et al., 2015). For Atlantic salmon, annual estimates of smolt mortality resulting from salmon lice are available for all Norwegian populations, based on modelled infestation levels along the Norwegian coast, an individual post-smolt migration model and the established tolerance level of post-smolts (Johnsen et al., 2020). No such estimates are available for sea trout. To provide such data, a simple prediction model for salmon lice mortality was developed based on infestation pressure, salinity, and estimates of mortality of sea trout from a sampling programme at sea.

First, model estimates of infestation pressure (index values) were provided by the Norwegian Veterinary Institute (Kristoffersen et al., 2014) and given as map-based data for each week from 2012 to 2020. It has been shown that sea trout mainly use the sea areas within 20–30 km from the river mouth (Thorstad et al., 2014, 2016) and salmon lice index data from a 20 km radius from the outlet of each river were extracted. Similarly, based on studies of the duration of the marine migration of sea trout in Norway (Berg & Berg, 1989; Jonsson & Jonsson, 2009; L'Abée-Lund & Vøllestad, 2018; Thorstad et al., 2014, 2016; Ugedal et al., 2014), and with a focus on first time migrants (most susceptible to salmon lice infestation owing to their small size), data for the 8-week period from week 26 to 33 were used. For the regression model, the 75 percentile of the mean weekly salmon lice index values for those 8 weeks for each of the 9 years for each watercourse was used. The 75 percentile rather than the mean was used because it was assumed that it is periods and years with high infestation that result in mortality and reduce the abundance of sea trout. Second, the infestation pressure index does not consider salinity, and salmon lice avoid and cannot reproduce in salinities at approximately 18 ppt and lower (Johnson & Albright, 1991; Pike & Wadsworth, 1999). Therefore, salinity data from the upper 1 m of the water column were collected from the same sea area from which the salmon lice index data were extracted. These data were provided by the Institute of Marine Research, Norway, collected from the hydrodynamic NorKyst800 model (Asplin et al., 2020) for a selected period over 3 years (2018–2020).

Third, an extensive surveillance programme has been in operation since 2010, where sea trout are sampled annually in gill nets or traps at up to 44 stations (the number varies among years) along the coast of Norway and the number of salmon lice are counted on each fish (Grefsrud et al., 2018). From these observations and the established tolerance limits (Bjørn & Finstad, 1997; Wells et al., 2006), salmon lice-induced mortality has been classified (Grefsrud et al., 2018). The data on infestation pressure, salinity, and mortality were coupled by identifying rivers or streams within 20 km (along the sea) of the surveillance stations with at least 2 years of mortality estimates. Thus, in the further analysis, 36 stations representing 137 watercourses were included. For these 36 stations, the mean lice-induced mortality of sea trout was calculated for the years 2012 to 2017. Rather than using the mean directly as the response variable, the mean was classified into the mortality classes 0 (<5%), 1 (5%–10%), 2 (11%–30%), and 3 (>30%), in accordance with the classification in Grefsrud et al. (2018). This was regarded as a robust approach given the uncertainties of the mortality estimates.

Finally, in a linear regression model using salmon lice mortality class (0–3) as a continuous response variable, the salmon lice infestation index ($\beta = 0.21$) and salinity ($\beta = 0.022$) and the intercept (-0.82) were included as significant explanatory variables ($P < 0.001$ for all), with the model explaining 52% of the variation in mortality scores. As expected, mortality scores increased with increasing infestation index and with increasing salinity. This regression model was used to predict impact scores (decimal values rounded to the nearest class) for all watercourses. An alternative multinominal logistic regression with mortality classes as factors produced similar results (significant effects of lice index and salinity) and an overall correct classification at 62%. The approach taken is supported by studies showing significant relationships between predicted salmon lice infestation intensity from models and the observed infestation of sea trout sampled in the monitoring programme (Bøhn et al., 2021; Myksvoll et al., 2018).

2.2.10 | Exploitation

Conservation limits are not established for sea trout in Norway, and overexploitation cannot be estimated quantitatively. The impact of fishing was therefore assessed based on characterizing the exploitation level as low, moderate, or high based on a scoring system (Table 2). Note that exploitation only involves overexploitation if it affects the spawner abundance to the extent that recruitment is reduced (Forseth et al., 2017). Next, the exploitation level and state of the sea trout in the watercourse were combined (Table 1) based on the assumption that if the exploitation level is high and state of the

TABLE 2 Score system used to assess exploitation level for sea trout as low (score 0 or 1), medium (score 2), or high (score 3) in fresh water, recreational fisheries in the sea, bag net and bend net fisheries at sea and illegal fishing at sea and in fresh water. The scores were summed and used in the assessment as outlined in Table 1. The percentages for freshwater fishing refer to the assumed proportions of the sea trout spawner run caught by the anglers.

Exploitation level score	0 low	1 low	2 medium	3 high
Fishing in freshwater (legal)	No	Yes, low exploitation (<10%)	Yes, moderate exploitation	Yes, high exploitation (>40%)
Recreational fishing in the sea within 40 km from the river mouth (legal)	Limited	Common	Extensive	Very extensive
Bag net or bend net fishing in the sea within 40 km from the river mouth (legal)	No fishing, or not relevant owing to the small body size of sea trout in the watercourse	Bag net or bend net fishing where sea trout is caught to a limited extent	Bag net and bend net fishing where sea trout is regularly caught	Not relevant
Illegal fishing in the rivers and sea	Rare	Common	Considerable	Not relevant

sea trout poor or very poor, it is likely that the sea trout in the watercourse is overexploited. Score 3 was not used for overexploitation because of the extensive measures to reduce exploitation implemented during recent decades (see Section 4).

The extent of angling in the watercourses, and in bag net and bend net fisheries at sea, was assessed based on duration of the fishing period, fishing regulations, and reported catches. Bag nets and band nets are two gears used in salmon fisheries that also capture sea trout. For the watercourses, the feasibility of fishing was also considered because many streams are not suitable for fishing owing to their small size. For bag net and bend net fisheries in the sea, watercourses dominated by small sea trout (body size <1.5 kg) were given score 0 as the mesh size of the nets is too large to catch small sea trout. There was no system for reporting catches from recreational fishing in the sea before 2019, and the quality of the catch statistics for 2019–2021 was poor, even though this has become a popular activity in many regions. The assessment had to be made based on fishing regulations (closed or restricted seasons in part of the country), Google searches (searching for 'sea trout', 'fjord/coast', and combined with names of counties and regions), and local information. The level of illegal fishing in the watercourses was estimated from local information. The potential extent of illegal fishing in the sea was scored based on data from the Norwegian Nature Inspectorate (SNO) on sea trout caught in confiscated gear (mainly gill nets). Both the number of confiscated nets within 30 km from the watercourse outlet and the minimum distance between the net location and the outlet were considered (see Anon, 2019). The scores of exploitation level of fishing in fresh water, recreational fishing in the sea, bag net and bend net fishing at sea, and illegal fishing (rivers and sea) (Table 2) were summed. A total sum of 1–2 was classified as 'low exploitation', 3 as 'moderate exploitation', and ≥4 as 'high exploitation'.

2.3 | Assessment of the state of sea trout

The state of sea trout in each watercourse was classified in five classes, from very poor to very good, based on the total impact of the human pressures, abundance data when available, and local knowledge. The total impact of human pressures was calculated by adding the scores from the evaluation above (except scores from exploitation), where a total sum of 0–1 was classified as 'very good state', 2 as 'good state', 3–4 as 'moderate state', 5–7 as 'poor state', and >7 as 'very poor state'. The classification was thereafter compared with available abundance data, particularly catch statistics, but also data from fish counters, snorkelling surveys, and electrofishing (Supporting Information S1). Negative or positive time trends, or data showing high or low abundance compared with expectations, were used to adjust the classification up or down (where there was a clear negative trend in abundance) one class and, in some cases, more than one class. Although conservation limits are not established for sea trout, the river area and a range of likely egg densities were used to provide a rough estimate of the expected adult abundance with which abundance data could be compared. In addition, in some watercourses, sea trout was classified as 'lost' if sea trout no longer have access as a result of dams or impassable culverts in the outlet to the sea or because of heavy pollution.

The classifications based on the procedures described above, and an overview of the data that were used, were sent to The County Governors in all counties for a local evaluation and quality control. Any new information and additional data that were provided from local sources, and comments on the classification and assessment of human pressures, were used to adjust the final classification.

All technical reports and databases found through a web search or provided by local sources, which contained data on the sea trout in specific watercourses, were considered in the classification. These sources provided information on the sea trout in 495 watercourses (Supporting Information S1).

The final step in the assessment was to evaluate to what extent exploitation might be an important human pressure. This was done by combining the state of the sea trout population and the exploitation level in each watercourse, as described above.

3 | RESULTS

3.1 | Length and area of river stretches available to sea trout

More than 16,000 km of rivers and lakes were available to sea trout in the 1251 watercourses (Table 3). The total area available was more than 145,000 ha, of which lake area constituted 72%. The 448 watercourses that also held Atlantic salmon were generally larger than those without Atlantic salmon and constituted 80% and 88% of the total length and area available to sea trout, respectively. Sea trout mainly spawn in rivers, not in lakes. Considering river area only, the area available to sea trout was usually larger than 1 ha in watercourses with co-occurrence of Atlantic salmon, whereas

TABLE 3 Length of watercourses (including shortest stretches through lakes), river area, lake area, and total area available to sea trout in watercourses with and without co-occurrence of Atlantic salmon. The proportions of the total river stretch and area for the two types of watercourses are also given.

	Number of watercourses	Total length of river stretches (km)	River area (ha)	Lake area (ha)	Total area (ha)
Watercourses with Atlantic salmon	430	13,045 (80.2%)	39,438	88,364	127,802 (87.8%)
Watercourses without Atlantic salmon	821	3226 (19.8%)	2018	15,751	17,769 (12.2%)
All watercourses	1251	16,270	41,456	104,115	145,571

in watercourses without Atlantic salmon, the available area was usually less than 1 ha (Figure 1).

The largest watercourses dominate the total area available to sea trout. The Tana watercourse in northern Norway constitutes 29% of the total river area available to sea trout alone (areas of the Finnish part of the watercourse were not included in the calculation). The nine largest watercourses constituted half the total river area available to sea trout, and the 134 largest watercourses constituted 90%.

3.2 | Human pressures

Salmon lice were shown to have an adverse impact on sea trout in more than 80% of the 1251 watercourses (Figure 2a). Agriculture affected sea trout in 35% of the watercourses, culverts 27% of the watercourses, habitat alterations 25% of the watercourses, and hydropower production 19% of the watercourses. For sea trout in 170 watercourses (14%), it is likely that fishing had an adverse impact by overexploitation. The other pressures (sewage and runoff pollution, other uses of water, acidification and hazardous substances) were each assessed to affect sea trout in 2.5% to 13% of the watercourses (Figure 2a). Salmon lice were the greatest pressure in terms of affected river area (59.8%; Figure 2b). Hydropower appeared as a more important pressure when considering affected river area (40.1%) rather than the number of affected watercourses.

To compare the overall impact of the different human pressures at a national level, the scores from all assessed watercourses (Table 1) were summed for each of the pressures. Almost half (47%) of the total impact on the state of sea trout in all assessed watercourses was the result of salmon lice. Thereafter, agriculture, hydropower production, culverts, and other habitat alterations had the greatest level of impact, but the magnitude of impact was much lower (9%–15% each; Figure 3) than for salmon lice. The impact of salmon lice was not sensitive to the choice of threshold values for a negative effect (5%–10% was used to identify a small impact). Salmon lice was shown to be the greatest impact factor—even if the watercourses with low impact were removed from the analyses, it still constituted 45% of total impact, and if the impact of salmon lice was given a maximum value of 2 instead of 3 when mortality estimates exceeded 30%, it still constituted 32% of the total impact.

There were differences in the magnitude of the assessed effect of several of the human pressures between the generally larger watercourses with Atlantic salmon and the smaller watercourses without (Figure 3). It is notable that the adverse impacts of salmon lice and hydropower production were greater in watercourses with Atlantic salmon than in watercourses without them. The opposite was found for the impacts of agriculture and culverts, where the impact was greater in the smaller watercourses without salmon than in those with them.

There were geographical differences in the impacts of human pressures on sea trout (Figure 4). Salmon lice affected sea trout negatively over large parts of the country, but less so in the south-eastern and north-eastern parts (Figure 4). Salmon lice also had smaller impacts in the inner parts of large fjords, than closer to the coast due to lower salinity close to large rivers draining into the fjords. Hydropower production also impacted sea trout in watercourses spread over most parts of the country, in areas where the topography is suitable for hydropower production (i.e., south-western Norway, and to a small extent the north-eastern parts of the country). Agriculture mainly impacted sea trout in watercourses in the south-eastern part of the country and in single watercourses elsewhere except in northern Norway (Figure 4). There was no clear

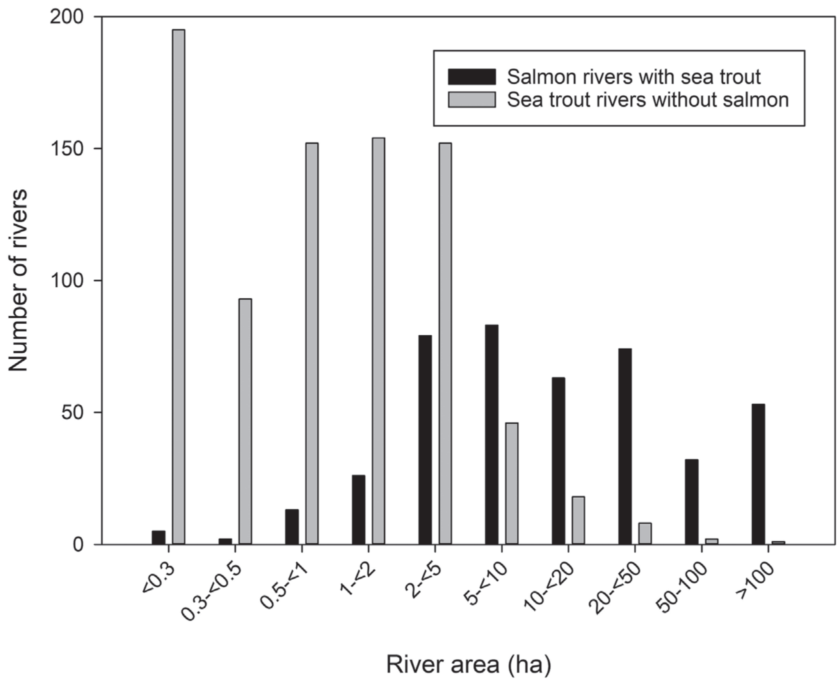

FIGURE 1 Size distribution of 1251 watercourses based on area (ha) available to sea trout (lake area not included). The distribution is given for watercourses with and without co-occurrence of Atlantic salmon (430 compared to 821 watercourses, respectively).

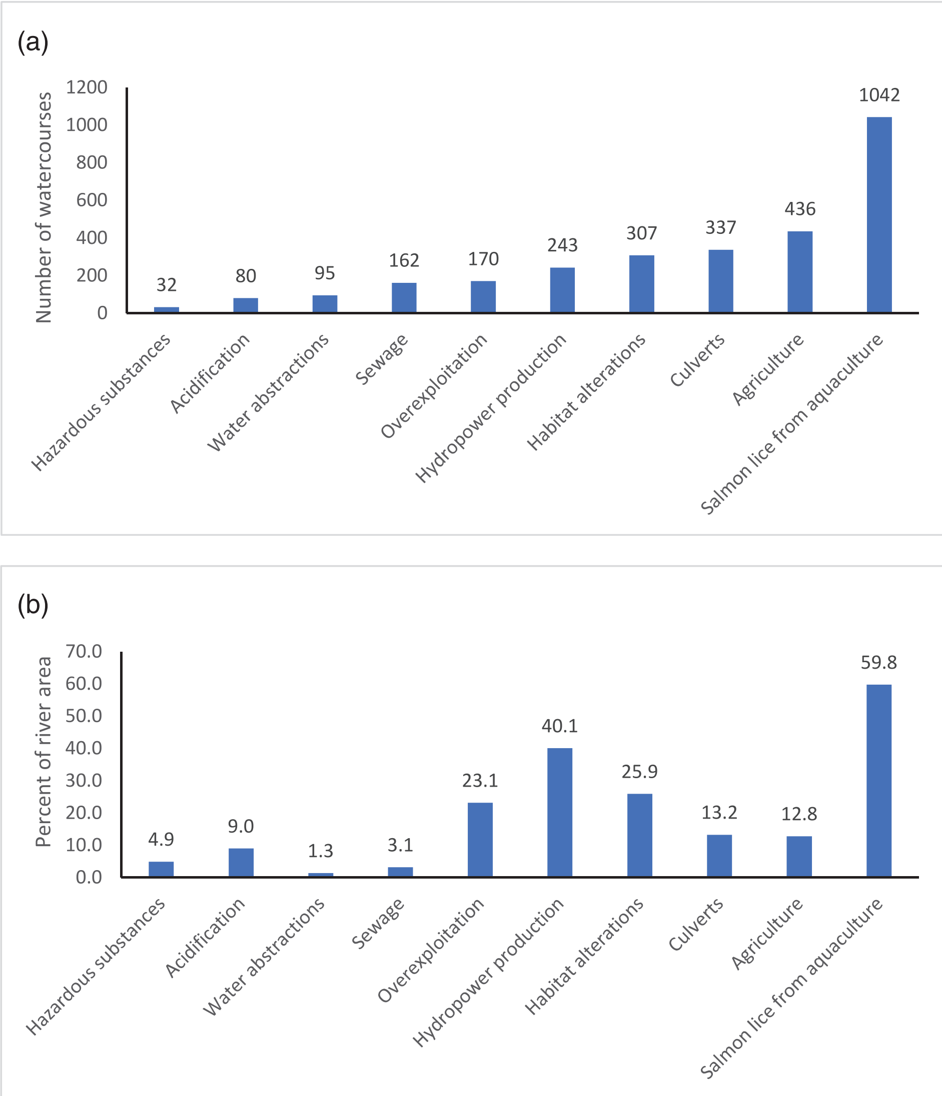

FIGURE 2 Number of watercourses (a) and proportion of the total river area (b) assessed to be adversely affected by each of the different human pressures (a total of 1251 watercourses were assessed with a total river area available for sea trout of 41,456 ha). Sea trout were affected by more than one pressure in 75% of the watercourses.

geographical pattern in the distribution of watercourses affected by culverts, but there were fewer in northern Norway than elsewhere. Other habitat alterations were shown to impair sea trout populations in watercourses along the entire coastline, but more in south-eastern Norway, and less in northern Norway (Figure 4). Watercourses with possible overexploitation, that is, those with a combination of high exploitation pressure and sea trout in a poor or very poor state, were spread over most parts of the country (Figure 4).

Hydropower production was shown to have adverse impacts on sea trout in 243 watercourses. Of these, 124 were related to small power stations (capacity <10 MW) and 119 to large power stations (>10 MW). Installation of power stations with impacts on sea trout began after 1900, and only small power stations were installed during the early years of the 20th century (Figure 5). Installation of small power stations reached a preliminary peak during the 1950s but increased again from the late 1980s until about 2015. Installation of large power stations affecting sea trout started after 1910 and peaked during the 1960s (Figure 5). Very few large power stations have been installed since 2010.

3.3 | State of sea trout

Based on the total impact of human pressures combined with abundance data and local knowledge, sea trout were classified to be in a good or very good state in only 25% of the watercourses. Nearly 40% of the watercourses fell into the categories poor or very poor state or had entirely lost their sea trout populations (29 watercourses; Figure 6). The state of the sea trout was similar in watercourses with and without the co-occurrence with Atlantic salmon, except that all watercourses where sea trout were lost were small watercourses without Atlantic salmon. The reasons for sea trout being lost from watercourses were mainly migration barriers that hindered entrance, habitat alteration, and water abstraction.

There was a clear geographical pattern in the state of sea trout, with the poorest in watercourses in south-western and middle Norway (Figure 7). Watercourses in northern, southern, and south-eastern Norway had sea trout in a better state. Many of the watercourses with sea trout in a good or very good state were situated in northern Norway. There was no correlation between the

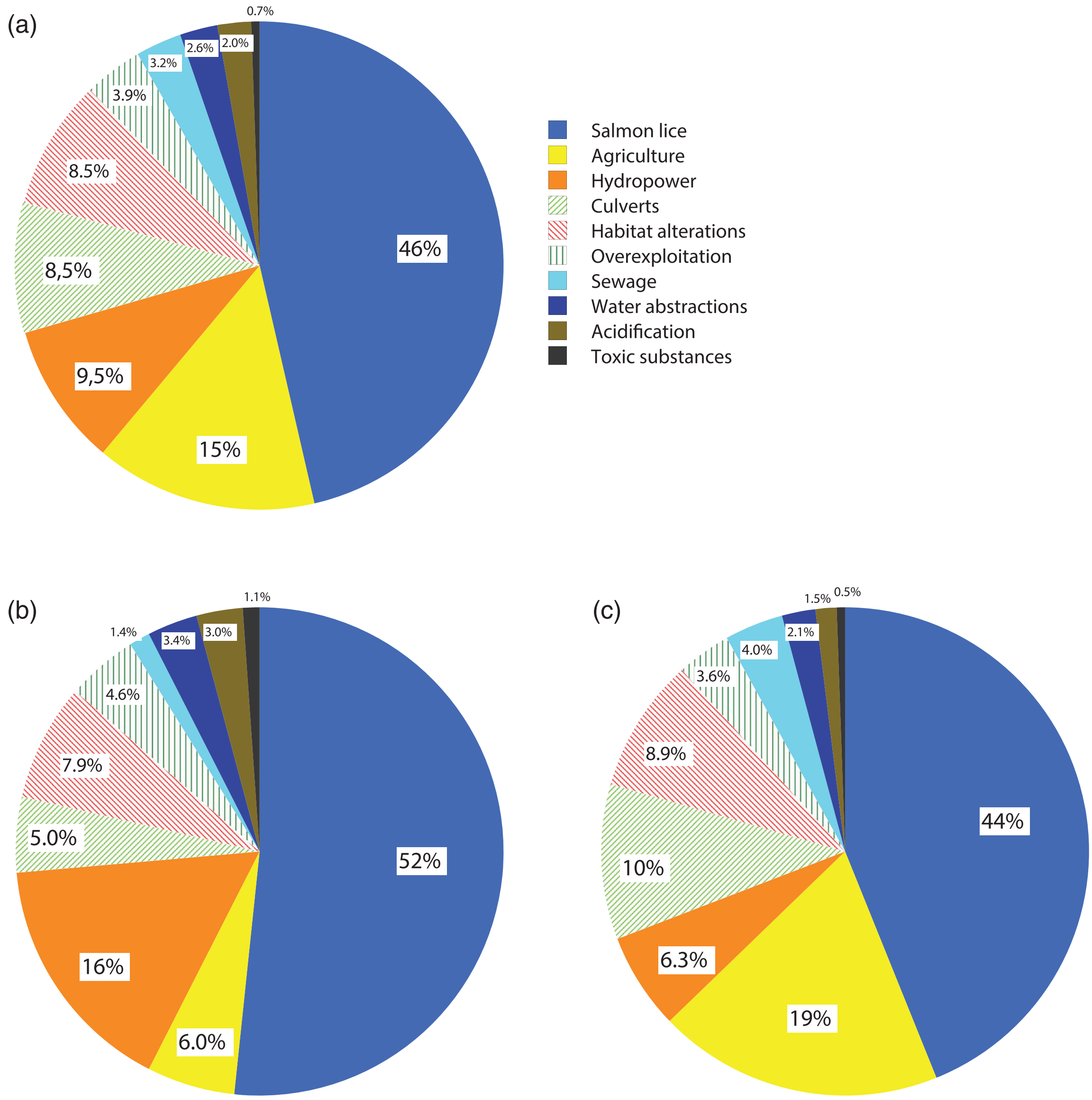

FIGURE 3 Assessment of the effects of different human pressures on the state of sea trout in all 1251 watercourses (a), separately for sea trout in 430 watercourses with Atlantic salmon (b), and separately for 821 watercourses without Atlantic salmon (c). The effect was calculated from summing the effect scores for all watercourses for each assessed human pressure (described in Table 1). Percentages shown in the figure are calculations of the proportion each pressure constituted of the total sum of the impact from all pressures.

proportion of watercourses with sea trout in a poor or very poor state in each county and human population density ($P \gg 0.05$, $N = 9$ counties, data from Statistics Norway).

4 | DISCUSSION

This comprehensive assessment of sea trout, covering 1251 watercourses, showed that sea trout was classified in a poor state in many of the Norwegian watercourses. Sea trout were in a good or very good state in only a quarter of the watercourses. Salmon lice from aquaculture was assessed to be by far the greatest impact factor, both in the number of watercourses affected and in the proportion it constituted of the total sum of adverse impacts from all pressures. Agriculture and hydropower developments also had strong adverse impacts, but far less severe than those from salmon lice. Culverts related to road crossings and other habitat alterations also affected sea trout in many watercourses. The state of the sea trout was best in the northern areas, where the human population is sparse. However, the distribution of watercourses with sea trout classified to be in a poor state was generally more linked to aquaculture and hydropower production than human population density. The system developed for classifying state and human pressures ensured that all available data for each watercourse could be used in the classification, even though different types of data were available for the different

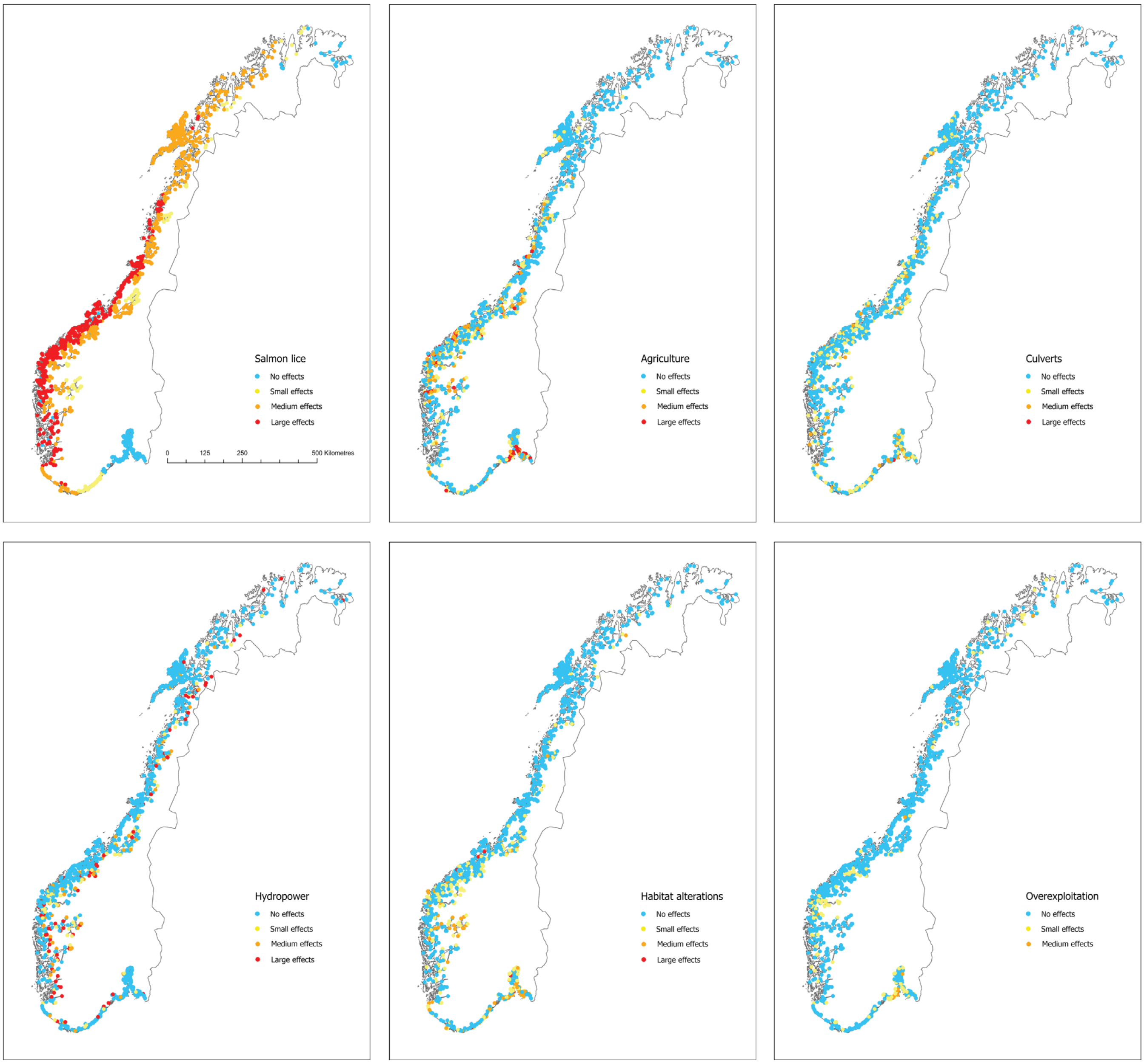

FIGURE 4 Maps of Norway showing the assessed impact of each human pressure. The assessments are based on the score system described in Table 1. Maps showing farming locations, and therefore relevant to the impact of salmon lice, can be found at https://portal.fiskeridir.no/portal/apps/webappviewer/index.html?id=87d862c458774397a8466b148e3dd147.

watercourses. The use of regional (The County Governor) and local knowledge significantly strengthened the assessment.

Salmon lice were shown to impair sea trout populations in more than 80% of the watercourses, representing 59.8% of the river area available to the species. Sea trout in intensive areas of salmon farming in Norway, Ireland, and Scotland have been adversely affected by salmon lice from Atlantic salmon farms since the late 1980s (Butler, 2002; Gargan et al., 2016; Hatton-Ellis et al., 2006; Shephard et al., 2016; Thorstad et al., 2015). Salmon lice from aquaculture can considerably increase mortality and reduce growth both in Atlantic salmon and sea trout in farm-intensive areas (Johnsen et al., 2020; Skaala et al., 2014; Vollset et al., 2016). Sea trout are likely to be more seriously affected by salmon lice than Atlantic salmon because most sea trout remain feeding and growing in coastal waters, where salmon farms are situated, during their entire marine migration (Bøhn et al., 2021; Fjørtoft et al., 2014). Atlantic salmon, in contrast, migrate through coastal areas on the way to ocean feeding grounds or during return to their native rivers and are hence exposed to salmon lice over shorter time periods than sea trout. In addition to increased mortality and reduced growth, salmon lice have been shown to influence sea trout migrations and life histories (Eldøy et al., 2020; Gargan et al., 2016; Gjelland et al., 2014; Serra-Llinares et al., 2020). Brown trout is a partially migrating species, which means that within a population there might be both sea-migrating individuals (sea trout)

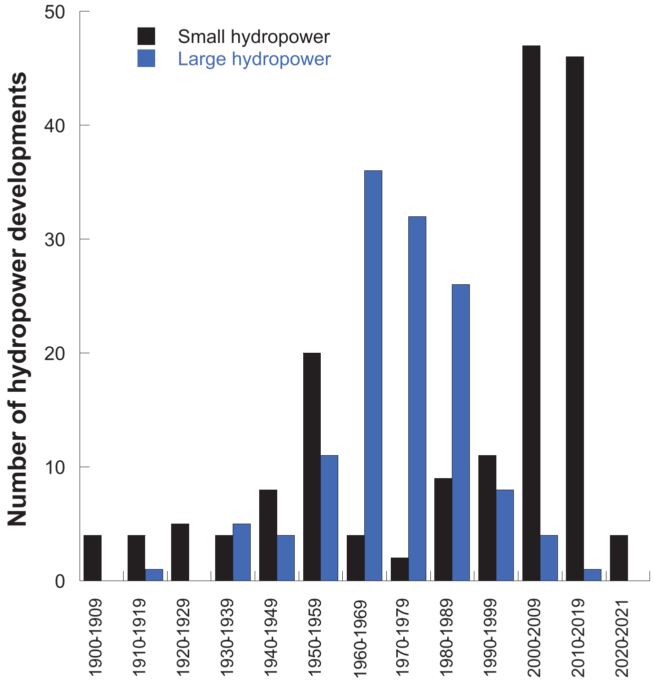

FIGURE 5 The number of small (≤10 MW) and large (>10 MW) hydropower facilities with impacts sea trout that were set in operation in different time periods. There are 296 hydropower developments included in the figure. In watercourses with power stations set in operation in different years, the power station expected to have the greatest impact on sea trout was used.

and freshwater resident individuals. Whether or not to migrate may be driven by a trade-off between the benefits of changing habitat and the associated costs of doing so (Gross, 1987; Secor, 2015). Reduced growth and increased mortality during the marine phase caused by salmon lice will reduce the benefits and increase the costs of marine migration for sea trout, and this may result in selection against anadromy in areas with high lice levels. This would be similar to the increased migratory cost for trout migration in long and steep rivers (Bohlin et al., 2001). Salmon lice-induced selective effects on sea trout may also lead to changes in genetic composition and reduced diversity, and possibly to the local loss (transient or permanent) of sea trout and establishment of exclusively freshwater-resident populations (Thorstad et al., 2015).

The impact of salmon lice was found to impair the state of sea trout in watercourses distributed over a large geographical area, including almost all watercourses along the west coast of Norway. Only sea trout in watercourses in the south-eastern and the very northern part of the country were affected to a very limited extent by salmon lice. In the south-eastern part of the country, there is little salmon farming (Statistics Norway www.ssb.no), and a minimal impact of salmon lice from farming was expected because salmon lice do not spread far from salmon farms. There is salmon farming in the northern part of the country, but salmon lice develop more slowly, are less abundant, and less infective owing to cold sea temperatures (Sandvik et al., 2021). However, with global warming, it is expected that the impact of salmon lice on sea trout and other salmonids will increase in these northern areas as a result of increasing sea temperatures (Godwin et al., 2020; Sandvik et al., 2021).

Sea trout in watercourses in the inner parts of fjords were shown to be less affected by salmon lice than sea trout in watercourses in outer parts of fjords and on the outer coast—except in the fjords most heavily developed for Atlantic salmon farming in south-western Norway, where the impact of salmon lice on sea trout were severe even in the inner parts of fjords. The more limited effect of salmon lice on sea trout in the inner parts of fjords is because there is more brackish water in these areas, which contributes to a reduced production of salmon lice larvae compared with outer areas with full-strength sea water. Salmon lice are marine parasites that are absent from sites of low salinity (Johnson & Albright, 1991; Pike & Wadsworth, 1999). However, the impact on sea trout in the inner fjords might have been underestimated because some sea trout from watercourses in these areas may have longer migrations than previously considered (Birnie-Gauvin et al., 2019; Eldøy et al., 2015) and may therefore be more exposed to salmon lice than suggested by the present assessment. The overall impact of salmon lice was even greater in the watercourses with Atlantic salmon than in those without, probably because more of these watercourses are located in areas with intensive fish farming activity and high levels of salmon lice.

Agriculture was shown to have the second highest level of impact on sea trout, but the number of watercourses affected and the magnitude of effect was far lower than for salmon lice. Agricultural land use may influence sea trout by nutrient runoff, organic pollutants, oxygen deficits, removal of riparian forest, and augmented sediment loads—and such damaging effects are shown for brown trout in a number of studies throughout large parts of their distribution range (Donadi et al., 2021; Luckenbach et al., 2003; Naden et al., 2016; Ramezani et al., 2016). One of the reasons for agriculture not having a greater impact is that farmland constitutes only 3.5% of the total area of Norway (Statistics Norway), and many watercourses with sea trout, particularly in northern Norway, are located in areas with limited or no farming. In addition, many streams in Norway are nutrient- poor, and a low level of agricultural activity may actually enhance fish production, probably because of the added nutrients (Jonsson et al., 2011). Agriculture affected sea trout to a larger extent in small watercourses without Atlantic salmon than in the large watercourses where they co-occur. This is because many small watercourses are located in areas with intensive agriculture. Moreover, the impacts of nutrients and sedimentation from agriculture may be greater in small watercourses than in large watercourses, where the dilution effect is larger.

Hydropower development was demonstrated to have the third greatest impact on sea trout, although in fewer watercourses than agriculture and with a smaller total effect on abundance. The impact of hydropower developments were greater in the large watercourses where sea trout co-occur with Atlantic salmon than in the small watercourses, probably because many large watercourses have been developed for hydropower production. Consequently, hydropower

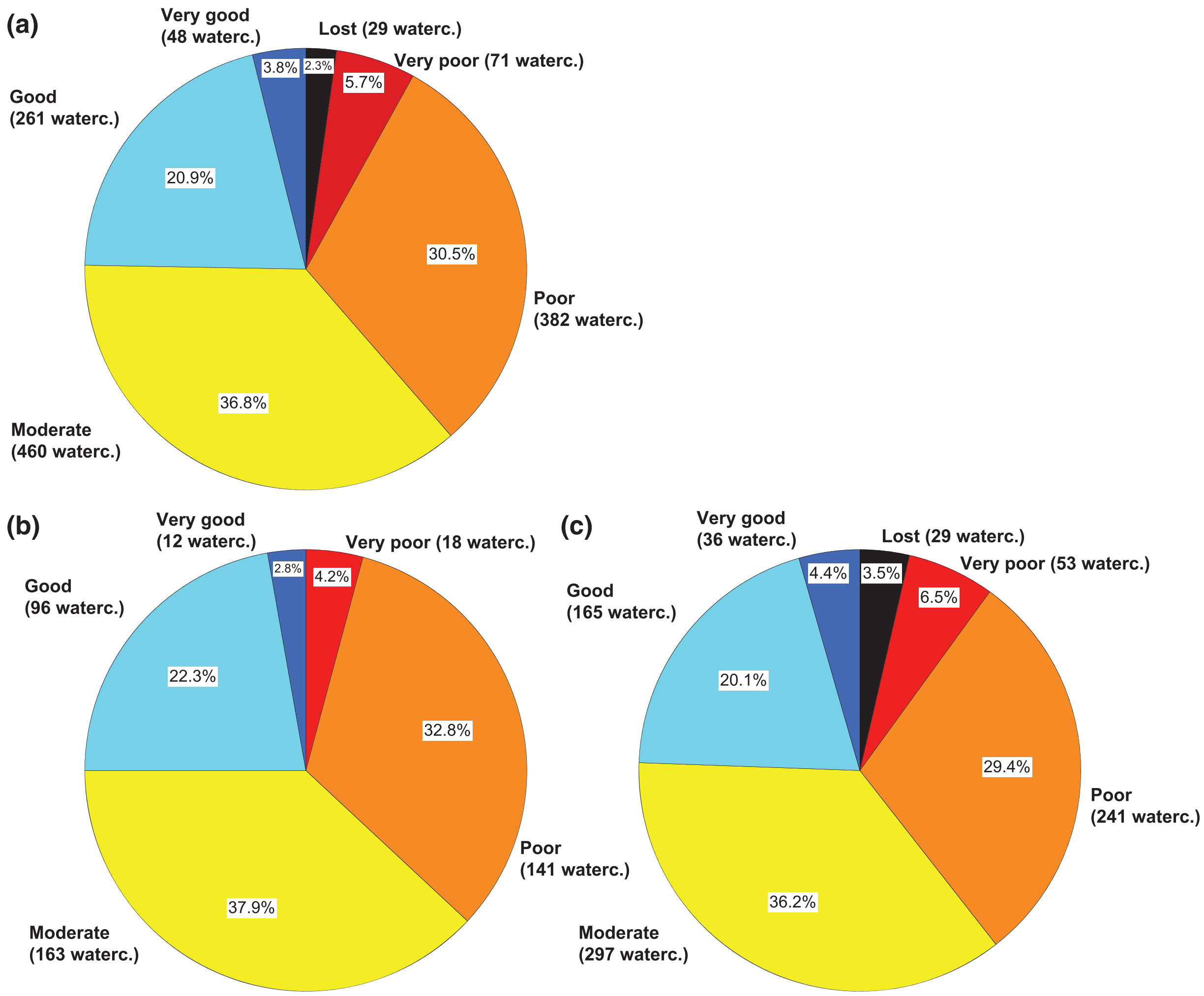

FIGURE 6 Proportion (%) of watercourses with sea trout classified to be in very good, good, moderate, poor, and very poor state for all 1251 watercourses assessed (a), separately for sea trout in 430 watercourses with Atlantic salmon (b), and separately for 821 watercourses without Atlantic salmon (c).

ranked second among the pressures in terms of affected river area. Many of the large hydropower developments affecting sea trout were installed between 1960 and 1990, and very few new, large power stations have been installed since 2000. However, between 2000 and 2019, a large number of small hydropower stations were installed in watercourses containing sea trout, followed by a reduction in installations from 2020. This caused a fresh increase in the adverse effects of hydropower developments on sea trout, mainly as a result of hydropeaking (Halleraker et al., 2022; Harby & Noack, 2013; L'Abée-Lund & Otero, 2018). The effects of hydropower developments on sea trout include mortality, injuries, migration barriers at power stations, reduced trout production capacity owing to water abstraction, altered water flow and temperature regimes during the year, and non-natural flow fluctuations, but the effects vary substantially among rivers (Birkel et al., 2014; Johnsen et al., 2011). In Norway, barrier effects and mortality brought about by turbine passage are not common for sea trout, because a high proportion of the dams and power stations are located upstream of the stretches available for anadromous salmonids. Severe impacts of hydropower developments on sea trout have been documented in many studies (Jepsen et al., 1998; Östergren & Rivinoja, 2008; Pavlov et al., 2018). There is considerable potential for improving the conditions for sea trout in many rivers regulated for hydropower production, by alterations at migration barriers and adjustments of the power production regimes to reduce the impacts on the different life stages of sea trout (Barlaup et al., 2008; Calles & Greenberg, 2009; Haraldstad et al., 2022). For small power stations in particular, there may be the potential to reduce mortality caused by fluctuating water levels and stranding of juveniles (L'Abée-Lund & Otero, 2018). For example, it has been shown that hydropeaking restrictions in the licences of small power stations are rarely followed, and the increasing solar and wind-generated energy in the grid may make peaking itself more valuable and increase the incentive for hydropeaking (L'Abée-Lund & Otero, 2018).

Culverts and other habitat alterations such as embankments also affected sea trout to a relatively large extent. Both culverts and other habitat alterations each influenced a larger number of watercourses than hydropower production, but the impact on total

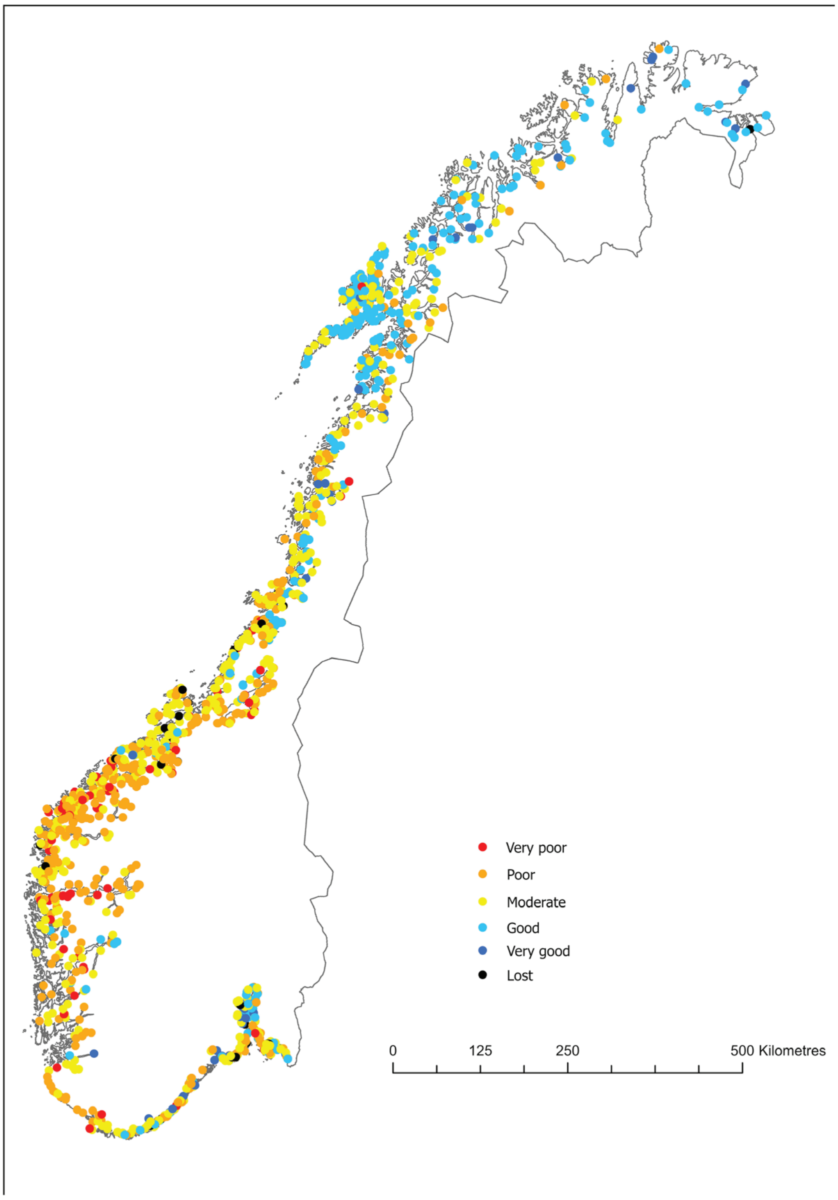

FIGURE 7 Map of Norway showing the classified state of sea trout in the 1251 watercourses assessed.

abundance was approximately the same for each of these three pressures. Culverts had a larger effect in watercourses without Atlantic salmon than with them, probably because culverts are more common in small watercourses, whereas road crossings in large watercourses are more often bridges. Many culverts have a poor design and act as migration barriers for sea trout, and there are many opportunities to redesign and improve the functionality of culverts (Larinier, 2002). In general, there is considerable scope for restoring habitat and migration routes for sea trout in rivers damaged by habitat alterations. For the other pressures assessed, such as sewage and runoff pollution, acidification, hazardous substances, and water abstraction for purposes other than hydropower production, relatively few watercourses were affected, and the total impacts were small. Nevertheless, there were severe impacts on sea trout from water abstraction for aquaculture and associated migration barriers in some of the watercourses.

Fishing can be an important mortality factor for sea trout. There were more watercourses with possible overexploitation of sea trout in some parts of southern Norway than elsewhere, reflecting areas with high exploitation in marine recreational fisheries, where there is still a bag net fishery, and where additional illegal fishing still takes place. In general, exploitation of sea trout has been reduced in recent years, through closed fisheries and reduced duration of the fishing season both in watercourses and at sea. These are why the impacts of fisheries were assessed as being fairly small compared with many of the other human pressures.

Sea trout in the large watercourses, which also hold Atlantic salmon, dominated the total production potential for sea trout in relation to the available area. Even though the production of sea trout is likely to be larger per area in watercourses without salmon than with salmon (Hesthagen et al., 2017), it is clear that the large watercourses holding Atlantic salmon are also important for the total production of sea trout. Indeed, the available area in watercourses with Atlantic salmon is almost 20 times higher than in watercourses without Atlantic salmon. Although the small watercourses with sea trout constitute a small fraction of the total production area for sea trout in Norway, they may be important for the total sea trout production in a local area. In areas with few or no large watercourses, sea trout from small watercourses may dominate the occurrence of sea trout in the marine areas. Sea trout in small watercourses may also be important to maintain genetic variation, as they do for Atlantic salmon (Hindar et al., 2004; Kuparinen et al., 2010; Tufto & Hindar, 2003), and may be important in a portfolio effect that may protect population complexes against extinction, as shown for other salmonid species (Schindler et al., 2010; Schindler et al., 2015). Genetic variation within and among sea trout populations should be studied further, particularly on how and to what extent sea trout in neighbouring watercourses exchange spawners, and how they differ genetically.

The classification system developed for this study was suitable for assessing a large number of watercourses, which had different types and quality of data available. The assessment of the most data-poor watercourses is more uncertain than of watercourses with good quality catch statistics and other abundance data available. One advantage of doing such an assessment and making the results available in an open database is an increased likelihood of receiving further information on the different watercourses, as more local people will check the status of their watercourse. The initial classification of status was based on the sum of pressure scores. There is increasing evidence that freshwater ecological status can be predicted from pressures (Arrighi & Castelli, 2023; Grizzetti et al., 2017), but the relationships between the different pressures and the abundance of trout were not explored in the present study. This could be done by linking the different pressures with independent estimates of abundance or status from a subset of data-rich rivers.

The present assessment is likely to be an underestimate of the impacts of human pressures on sea trout because there are several activities that have not been considered owing to lack of knowledge and data, such as infections from pathogens related to fish farming. There may also be nonassessed impacts from pollution events that are not monitored, habitat alterations in river mouths related to harbours and other infrastructure, invasive species, and reduced food availability in marine areas owing to altered ecosystems and prey fish communities as a result of commercial fishing for marine fish. Climate change is also likely to be adversely influencing sea trout populations, because of altered water flows and increased water temperatures during the year. The presence of climate- sensitive parasites (e.g., *Ichthyophthirius multifiliis* and *Tetracapsuloides bryosalmonae*) in these watercourses may result in disease, mortality and reduced production (Jørgensen & Buchmann, 2020; Wahli et al., 2002). In northern Norway, the increased temperatures brought about by climate change seem to have resulted in a reduced abundance of Arctic charr, but an increased abundance of sea trout in recent years (Svenning et al., 2022). In most watercourses, sea trout were affected by several human activities, and interactions among factors may cause greater effects on sea trout than inferred from the assumption of additive effects. Furthermore, it was difficult to determine the natural upstream limit to migration in watercourses where the stretches available to sea trout were reduced owing to man-made migration barriers. Thus, the extent of lost river stretches to sea trout could not be estimated. These limitations should be prioritized in future research. A future impact may be the increased abundance of invasive pink salmon (*Oncorhynchus gorbuscha*) particularly in northern areas (Lennox et al., 2023; Sandlund et al., 2019), which may compete with sea trout or alter the freshwater and marine ecosystems in ways that influence sea trout populations (Hindar et al., 2020).

The assessment and ranking of human factors enable managers to evaluate the different impacts and prioritize mitigation measures, both at a national, regional, and watercourse level. The need for measures related to salmon lice from aquaculture farms is critical, because the impacts on sea trout abundance were shown to be massive and acting over large geographical areas. Infections and diseases resulting from the spread of pathogens from Atlantic salmon and rainbow trout (*Oncorhynchus mykiss*) farms may also be detrimental to sea trout, but as is the case for wild Atlantic salmon (Forseth et al., 2017), the level of knowledge on this is low. There is also a need for mitigation measures related to agriculture, hydropower production, and other habitat alterations. Relevant efforts in this context include restoration of riparian buffer zones to help rehabilitate brown trout in catchments with high human land use and improvement of migration through culverts and other small migration barriers. In other cases, there is a need for fundamental changes in policies and management efforts, such as related to Atlantic salmon farming and large hydropower developments. For a partially migrating species such as sea trout, human impacts that shift the cost–benefit balance of migration may result in selection against migration, altered life-history traits, and reduced recruitment. Such changes in the extent of migration in a partial migration system may have cascading ecosystem effects (Peller et al., 2023). Examining how human activities influence animals during migration is necessary to assess the consequences for individuals and populations and to develop and evaluate management measures.

The methodological approach for large-scale mapping of state and pressures may be used by other nations as part of their conservation effort for this important species. The importance of such assessments for salmonid fishes can be illustrated by a similar assessment for Atlantic salmon first reported by the Norwegian Scientific Advisory Committee for Atlantic Salmon Management in 2010 (Anon., 2010) and later published internationally (Forseth et al., 2017). It firmly established salmon lice and escaped farmed salmon from salmon farming as the major threats to Atlantic salmon among authorities and management bodies in Norway, and in 2017, the Norwegian government established a new regulatory framework, the 'traffic light system', to regulate growth in the farming industry based on the effects of salmon lice on wild salmon (Vollset et al., 2018). Sea trout is currently under consideration for inclusion in this framework. Similarly, measures have been implemented to reduce escapes of salmon from farms, resulting in reduced incidents of farmed salmon in wild populations (Glover et al., 2019). The current mapping of the state and pressures for sea trout are likely to have similar management implications for conservation efforts.

AUTHOR CONTRIBUTIONS

Conceptualization and development of assessment methods was a joint effort by the Norwegian Scientific Advisory Committee for Atlantic Salmon Management (all authors except Vegar Bakkestuen). Peder Fiske, Torbjørn Forseth, and Eva B. Thorstad wrote the first draft of the manuscript. Vegar Bakkestuen developed the GIS methodology and performed all GIS analyses. All authors contributed to revision and editing of the manuscript and approved the final version.

ACKNOWLEDGEMENTS

We thank representatives at The County Governors, other local people, and Atle Kambestad at the Norwegian Environment Agency, who provided local information and quality checked the classifications based on local knowledge. In addition, we thank the Norwegian Veterinary Institute for providing data on salmon lice infestation pressure and the Institute of Marine Research, Norway, for salinity data. We thank Dr Hugo Flávio and one anonymous referee for their thorough reviews and valuable comments to the manuscript. We also acknowledge the exceptional thorough reading and editing of the Chief Editor, Professor Philip J Boon. The Norwegian Environment Agency provided funding for the mapping of state of sea trout. Preparing the manuscript was financed by The Research Council of Norway, project no. 160022/F40 NINA basic funding.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The assessment of status and anthropogenic pressures for each watercourse are available online at https://nina.maps.arcgis.com/apps/instant/basic/index.html?appid=376b94218a0f4d0b967dbc620b89313a and an API for downloading is available upon request.

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How to cite this article: Fiske, P., Forseth, T., Thorstad, E.B., Bakkestuen, V., Einum, S., Falkegård, M. et al. (2024). Novel large-scale mapping highlights poor state of sea trout populations. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 1–20. https://doi.org/10.1002/aqc.4067