Possible risk on the dispersal of *Gyrodactylus salaris* following removal of migration barriers in a river

A case study at Kungsbackaån in Halland County, Sweden

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Abstract

Gyrodactylus salaris is a salmon parasite, described for the first time in Sweden in the 1950s, occurring naturally also in Russia and Finland. During the 20th century it was broadly introduced to other countries in Europe. Reasons are for example introduction of farmed fish in natural rivers or the spread of parasites directly from fish farms into riverine systems. *G. salaris* can cause lethal diseases in entire salmon populations of a river as was seen in Norway in the 1970s.

This thesis is based on the principle of a scoping review and aims to give an idea of a possible risk of dispersal of *G. salaris* into riverine systems by creating new spawning grounds for salmon within river restoration projects. The research site Kungsbackaån in Sweden is described and importance of river restoration to create natural spawning grounds for salmon is highlighted.

In conclusion, a spread of *G. salaris* can be mitigated by precautionary actions and a removal of migration barriers is favorable for the development of natural spawning anadromous fish populations. If the parasite is once introduced into an ecosystem, eradication is difficult. Eradication methods used so far can cause significant damage to the ecosystem. It can be assumed that genetical features of salmon populations on the Swedish west coast are the main reasons for the fact that no devastating *G. salaris* outbreaks have yet been detected in that region.

Further research is needed regarding the parasite *G. salaris* and its characteristics such as transmission routes or the parasite-host interaction, as well as environmental conditions impacting the development of parasite populations. It is particularly important to investigate the role of genetic differences in the host and parasite populations in the future.

Language: English Key words: *Gyrodactylus salaris*, river restoration, *Salmo salar*, Kungsbackaån, scoping review, parasite spread

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»Culturing a fish species may result in "culturing" its ectoparasite species«

G. Malmberg (1993).

1 Introduction

Even though rivers and lakes are not covering even one percent of the Earth's surface, one fourth of the planet's vertebrates are freshwater fish. Human actions are influencing their habitats stronger than ever. Over 50 percent of the Earth's rivers have experienced an anthropogenically induced change in the biodiversity (Su et al., 2021).

In the 1970s salmon were widely infected with *Gyrodactylus salaris* in several rivers in Norway. The discovery occurred due to a massive mortality of infected salmon in watercourses. In the 1980s, a *Gyrodactylus* committee was established, and it could be proven that the parasite was introduced into the river systems by stocked fish from infected hatcheries. It is unknown how *G. salaris* first came to Norway where it can be claimed to be an invasive species. It is proposed that overcoming the geographical barrier of the Scandinavian mountains was only possible due to transports between hatcheries from Sweden to Norway. The devastating outbreak in Norwegian rivers was possible as Atlantic salmon is genetically different from Baltic salmon even though they belong to the same taxonomic class. Atlantic salmon is more sensitive to *G. salaris* than Baltic salmon (Johnsen & Jenser, 1991).

It is estimated that infections of *Gyrodactylus salaris* are responsible for economic damages of more than 5 billion United States dollar in Norway (Hansen et al., 2003). The removal of the parasite from more than 20 rivers in Norway has probably led to an irreversible loss of some traits of the original salmon strains of those rivers, as most of the salmon died due to the treatment (The Fish Site).

G. salaris was first detected at the Swedish west coast in the Säveån River in 1989. A general decline of salmon stocks in water courses of western Sweden was discovered after that and in 2001 a program to monitor the infections of *G. salaris* was put into effect (Degerman, E. et al., 2012).

The devastating impact that an infection of *Gyrodactylus salaris* can have on an entire salmon populations and river systems is calling for an investigation of the species and the problem to further establish measures to limit a dispersal or new outbreaks.

The aim of this thesis is to investigate the possible impact that a removal of migration barriers for reestablishing spawning grounds in the river Kungsbackaån can have on the spread of *G. salaris*. Potential pathways of the parasite to enter the river system will be identified. The importance of river restoration and the ability for salmon to spawn naturally will be pointed out while answering the research question.

This thesis is written in cooperation with Melica Ek, Göteborg, an environmental consultancy company that has the mandate to monitor Kungsbackaån and to implement an environmental impact assessment and propose for a removal of the migration barriers as well as a budget for this project. The investigation about the possible dispersal of *Gyrodactylus salaris* is part of this project.

2 Method

The thesis is based on a literature review. The important background information about the host, the parasite and the study area are introduced in chapter 3.

The literature review is partly focusing on the study area. Documents of previous monitoring as well as plans for the restoration measures were considered, such as data from the VISS service (Vatteninformationssystem Sverige). A complete systematic literature review was not possible to conduct in this thesis and therefore the concept of the method described by Pollock et al. (2020) for a scoping review was followed. This decision was taken, because Pollock et al. (2020) propose a scoping review when e.g., gaps in research are identified. This method is applicable in this study as no literature about impacts of river restoration measures on a possible *G. salaris* dispersal or outbreak could be found prior to this thesis. Also, the JBI (Joanna Biggs Institute) Manual for Evidence Synthesis description of scoping reviews fits the principal of the method used in this thesis (Aromataris and Munn, 2020), as I aim to give an overview of the field, while it can also lead to a systematic review in the future. For this thesis relevant research articles were searched and identified mainly in Google scholar. Other relevant literature such as newspaper articles or directives and regulations from organizations and institutions such as the EU were searched in a normal search engine as they were not always available in Google scholar.

A qualitative risk analysis was further conducted and described in chapter 4 to investigate the likelihood and possible consequences of an introduction and dispersal of *G. salaris*. The risk analysis supports the measures and recommendations that are proposed in chapter 5.

The risk analysis is inspired by the method used by Peeler and Thrush (2004). A qualitative risk analysis such as the one in Peeler and Trush (2004) (following the concept mentioned in OIE, 2003) needs to identify the hazard, assess the risk and its management and point out risk communication as well as include communication about the risk with relevant stakeholders. In this thesis, identification of the risk as well as risk assessment and its management were done following the scoping review. The risk assessment focuses on possible ways of spreading. It outlines possible impacts that the removal of the migration barriers can have as for example an extension of spawning grounds. The dispersal of the parasite can be impacted by other factors in the future such as climate change. The risk management will be assessed by identifying preventive measures and regulations already set in place in other regions as well as by describing a possible adaptation of salmon to the parasite.

3 Literature review

Decades of human use and change of surface waters have led to significant modifications of waterbodies' original conditions. This raised a deeper consciousness for the environment and ecosystem management in politics and society. River restoration has become an important topic in the field of sustainable water body management and aquatic ecology. In year 2000 the European Union established the Water Framework Directive that came into force in 2003 aiming to manage water bodies in Europe (Muhar et al., 2016; WFD, 2000**).** This directive was implemented into Swedish law within the "Miljöbalken" in chapter 11 dealing with water operations (Miljöbalk (1998:808).

3.1 River restoration

Rivers that cannot fulfil their natural ecological or socioeconomical functions anymore need river restoration. Indicators can be an incapability of furnishing potable water, alleviate floods and retaining particles or nutrients as well as lacking to be a suitable habitat for flora and fauna. Another indicator can be, if recreational activities, such as fishing or swimming, are no longer safe due to human induced alterations of the water course. The aim is a re-establishment of conditions that allow the lost functions (Palmer, 2006).

River and stream degradation is often human induced due to agricultural or industrial activity, urbanisation, damming or channelisation. In many cases it is impossible to restore the riverine system into its original state, amongst others, due to a dependence of the water resources. Yet, rivers have the ability to recover, and measures that are designed uniquely for a river can help to re-establish a state in which a river can fulfil its natural processes while being a biotope for diverse populations of flora and fauna (THERRC, 26.02.2021). It is important to account for ecological, hydrological, and geomorphological processes in different spatio-temporal scales to ensure sustainable river restoration. These aspects should be considered during all stages of a river restoration process. Furthermore, it is important to consider a multitude of stakeholders to identify the needs of a river system when designing the project plan (Clarke et al., 2003).

The goal of river restoration is to reverse the mostly human induced trend towards degradation of the aquatic system. It aims to improve the state towards the natural that represents the best compromise between the ecosystem of the river and human activities (CIRF, 12.02.2021).

The plan for the river restoration and removal of migration barriers for Kungsbackaån is currently being worked out by Melica Ek.

3.1.1 Juridical framework

The Habitats Directive ('Conservation of natural habitats and of wild fauna and flora' 92/43/EEC) and the Water Framework Directive ('Establishing a framework for community action in the field of water policy' 2000/60/EC) are the most important documents on European level setting statutory grounds for river restoration and the need to restore riverine habitats that are not anymore in suitable states. These two directives make the restoration of habitats that are no longer in a suitable state a legal requirement. While the Habitat Directive pursues the conservation and protection of species and habitats regarded as essential in Europe, the Water Framework Directive focuses on the restoration, protection and improvement of surface waters considering ecological, chemical, and morphological parameters (Clarke et al., 2003).

3.2 Parasitism

More parasitic living species have been discovered than species living a non-parasitic or symbiotic life, therefore parasitism is claimed to be the most successful way of life (Price 1980; Windsor 1998). Parasitism can be described as a presence of the parasite in or at the host organism because of morphological and/or physiological properties and the relationship between those organisms with each other (Lucius and Loos-Frank 2008; Zander 1998). Parasites can be assumed to contribute significantly to the evolution of their host as they are using the host's body to fulfil necessary mechanisms of life such as feeding or using it for reproduction. The host's organism can be negatively impacted by the parasite's lifestyle, in terms of intoxication, mechanical damage or a change of behaviour that can lead to a higher predation risk. Thus, only the individuals best adapted to the parasitism can survive (Klimpel et al., 2019).

3.3 The parasite *Gyrodactylus salaris*

In 1956, Malmberg was the first to describe *Gyrodactylus salaris* close to Idalsälv, Sweden (Hansen et al., 2003). *G. salaris* is a small (0.5 – 1 mm) organism belonging to the phylum Platyhelminthes (flatworms) and the class Monogenea. It is an obligate viviparous freshwater ectoparasite with a direct life cycle meaning that only one host species is necessary to complete its life cycle. The parasite attaches with two strong anchors that are surrounded by a characteristic wreath of hooks to the salmon’s skin or fins and can cause gyrodactylosis to Atlantic salmon (*Salmo salar*). Infected fish often try to scrape off the parasite by chafing the skin on the ground or stones. *G. salaris* has sexual and asexual reproduction and gives birth to completely developed pups that can reproduce by themselves so the parasite multiples rapidly (Fremmedartsbasen, 2018). The host organism also serves as carrier of the parasite. Dispersal often occurs by restocking or transportation of infected live fish, by not compliant cleaning of contaminated fishing gear before using in another water system or by infected fish migrating in brackish water. *G. salaris* is distributed in Europe and appears in most countries besides Ireland and Great Britain especially in fish farms. In the wilderness the parasite occurs mostly in Russia, Finland, and Sweden. It has been detected on rainbow trout and other salmonids, which can serve as hosts for survival and reproduction. *G. salaris* needs a live host and the following environmental conditions to survive. The temperature must be between 0 °C and 25 °C. There are no data available for higher temperatures, but the species is not resistant to freezing. The parasite does not survive in dry environments and needs to be enclosed by water. *G. salaris* is sensitive to low pH as a pH <5 causes death of the parasite after a few days. The survival of parasites that are unattached from their host is only possible for some days and depends on temperature, whereas lower temperatures commonly allow longer survival. On dead hosts *G. salaris* can survive for approximately 2 weeks in low temperatures. Some strains of the Baltic salmon have shown resistance to the parasite. Despite *G. salaris* being a freshwater parasite, reproduction takes place at salinity levels reaching 5–6 and survival at higher salinity depends on the temperature. However, alterations in the chemical composition can cause sensitivity in the parasite, which can be used as a factor in different treatments in for example aquaculture (OIE, 2009; gov.scot, 2019).

Gyrodactylus salaris (Fig. 1) is the only parasitic fish pathogen that is listed in the OIE (Office International des Epizooties) (Paladini et al., 2014).

Fig. 1. The parasite *Gyrodactylus salaris* attached to salmon skin. (Olstad, 2013).

3.3.1 Gyrodactylosis

Gyrodactylus salaris grows quickly on Atlantic salmon and is one of the biggest threats to non-resistant salmon stems. It can therefore have a considerable ecological impact on salmon populations. The mortality rate of infected Atlantic salmon can be as high as 100% in a water course, if no treatment is taking place (OIE, 2009; Fremmedartsbasen, 2018).

Due to the size of the parasite the diagnosis of gyrodactylosis is difficult with the naked eye and must be made by an expert, and usually requires confirmation by molecular genetic analysis of the parasite such as PCR (Polymerase Chain Reaction). If the infection is advanced, the fish occurs with a grey colour, mucus and fungal infestation (gov.scot, 2019). It is supposed that the disease of gyroactylosis is mainly expressed through secondary infections. Those can be open wounds, fungal infections or osmoregulatory problems (Olstad, 2013).

3.3.2 *Gyrodactylus salaris* in Sweden

The existence of *G. salaris* on the west coast of Sweden was first been investigated in 1989. *G. salaris* was detected in a salmon hatchery in Laholm, situated close to the River Lagan and in the River Säveån. In 1991 it was identified in Ätran. In an extensive examination of almost all salmon rivers at the Swedish west coast in 1997, *G. salaris* was determined in eight water courses. The existence of the parasite is also suspected in Lake Vänern (Olstad, 2013).

In 2018 the Norwegian database for biodiversity claimed that *Gyrodactylus salaris* has spread further on the Swedish west coast and the northern-most river infected is the Göta älv close to Kungsbackaån. Nowadays a further dispersal direction northwards is unlikely due to the higher salinity levels, but the effects of climate change and thus a change in the water composition to more brackish water can have an impact on a further spread (Fremmedartsbasen, 2018).

3.3.3 *Gyrodactylus salaris* in Kungsbackaån

In 2015 *G. salaris* was identified in River Rolfsån, which outlet is about 100 m away from the outlet of Kungsbackaån (Sportfiskarna, 2015). In 2017, the Norwegian Veterinary Institute identified the existence of the parasite also in Kungsbackaån.

3.4 The Atlantic salmon: *Salmo salar*

The Atlantic salmon, *Salmo salar*, belongs to the family of Salmonidae. The species can be found in the northern hemisphere. Salmon occurs from Portugal to Pechora in Russia, up to Iceland and the southern waters of Greenland and until the northern North American Atlantic Coast from Connecticut to the Ungava Bay in Canada. There are three main groups of salmon that are genetically distinct: The Western Atlantic salmon, the Eastern Atlantic salmon and the Baltic salmon. Salmon is an anadromous freshwater fish, that spends most of its life in marine waters, while being born and spawning in fresh water. The spawning season begins in autumn or early winter going from October until January and individuals usually spawn in the same river that they were born in. The new-born salmons (i.e., smolt) start their life in the river in late winter or early spring. A female salmon weighing between 8–10 kg lays around 10.000 eggs. To go back to their home river salmon can jump up smaller waterfalls or similar. Until a salmon reaches the state of parr, meaning that it is fully developed and leave the river, it can take several years. However, there are also stational freshwater salmons. The salmon has a long coil-shaped body with a central placed dorsal fin and a tiny fat fin without fin rays which is situated between the dorsal and the tail fin. The length of an adult is between 0.8 m and 1 m but can reach 1.4 – 1.5 m. Its weight counts 5 – 15 kg while the highest value measured was 36 kg according to Lokki et al. (1998), however Moen and Svensen (2008) state that the salmon can reach a weight up to 40 kg. The salmon is a very powerful and muscular swimmer and hunter and feeds in freshwaters mainly on water insects and in saltwater also on other fish, e.g. herring or amphipods.

Salmon prefers cold, flowing water with a stony bottom in freshwater areas, while it lives pelagically in the open seas (Malmberg, 1993; Lokki et al. 1998; Moen & Svensen 2008).

In Europe, the Atlantic salmon (Fig. 2) was distributed throughout all countries in rivers entering the Atlantic Ocean as well as the Baltic Sea. However, due to anthropogenic impact, like building of migration barriers, expansion of cities and deterioration of water courses, Atlantic salmon stocks have decreased in many rivers (Hendry et al., 2003).

Fig. 2. Juvenile *Salmo salar* catched with spider fly in river Kaitum close to Linafallet, Sweden. (Wemmer, 2013).

3.4.1 Salmon in Kungsbackaån

Hasselrot and Carlsson (1993) state (according to Bydén et al., 2000) that a large salmon stock was found in Kungsbackaån until the water was acidified and salmon stocks in Kungsbackaån declined drastically. Due to liming measures starting in 1983 the stocks could recover.

3.4.2 Ecological and socioeconomical importance of salmon

The Atlantic salmon is a not threatened species and it can be estimated that due to for example aquaculture, there might be more salmon than ever alive on the planet Earth. However, many natural spawning habitats are not available anymore for the species. As adult salmon always return to the same river area for reproduction, each river system has developed their own genetical pool, that is adapted to the special spawning area. This genetic diversity is considered a main factor for the ability of salmon to have populated extensive areas. Protection or restoration of their habitats is crucial to save the genetical pool of Atlantic salmon strains (Dodson et al., 1998).

The Atlantic salmon is listed as a species of European importance in the annexes II and V of the European Union's Habitats Directive (Hendry et al., 2003).

Kulmala et al. (2013) describe the socio-economic benefits and the ecosystem services of Baltic salmon (*Salmo salar* L.), which can be considered similar for the Atlantic salmon. It is pointed out that salmon plays an active role in maintaining food webs and ecological stability as well as in the reduction of sedimentation. Furthermore, it is claimed that the cultural value of salmon is higher than the economic, as it represents cultural heritage and identity. Additionally, the willingness to invest in habitat restoration for salmon is high, as salmon is a popular fish for angling.

Salmon is also important as a host for the freshwater pearl mussel (*Margaritifera margaritifera*). The species is an important organism for freshwater filtration and minimization of sediments in riverine systems. The mussel is listed as critically endangered in Europe and needs a salmonid species as a host in its life cycle. Thus, their population declines proportionally to the decline of migratory salmonid populations (Cosgrove and Hastie, 2001).

The Atlantic salmon is claimed to be economically and culturally one of the most valuable species (Thorstad et al., 2008). It is complex to evaluate the consequences, a *G. salaris* outbreak might have. Economic impact on for example fish farms or recreational fishing can be calculated considering the costs of eventual treatment, monitoring or other. However, it is unlikely to be able to calculate the ecological or cultural damage (Peeler and Thrush, 2004).

3.5 The study area: Kungsbackaån

The river system of Kungsbackaån (Fig. 3) is located in southwestern Sweden and extends over the counties of Västra Götaland and Halland in the communes of Härryda, Mark, Mölndal and Kungsbacka. Kungsbackaån starts in Lindome as the extension of Lindomeån starting at the outlet of Västra Ingsjön and enters in Kungsbacka into the Kungsbackafjord, Kattegat. The Kungsbackafjord is a marine nature reserve since 2005. At Lindome Lillån is flowing into the same water course as Kungsbackaån. Kungsbackaån has a catchment area of around 302 km^2 of which 6.6 % are lake areas. The area is characterized by a rural forest landscape upstreams and more and more agricultural and urban areas downstreams. (SMHI, 1995; Wemmer and Bydén, 2020; Adler, 2016) According to VISS (25.02.2021) Kungsbackaån is a natural watercourse of 9km lengths.

Fig. 3. Kungsbackaån close to its outlet into the Kattegat. (Wemmer, 2020).

3.5.1 Migration barriers in Kungsbackaån

The size of the spawning and nursery area for fish of Kungsbackaån is 32.380 m^2. There are numerous migration barriers for anadromous fish in the county of Västra Götland (Fig. 4). According to Bydén et al. (2000) Kungsbackaån has four migration barriers for salmon and trout that might also impact the movement of other fish (Fig. 5).

Figure 4. Migration Barriers for anadromous fish in the county of Västra Götland, Sweden, represented by black dots. (Bydén et al. 2000).

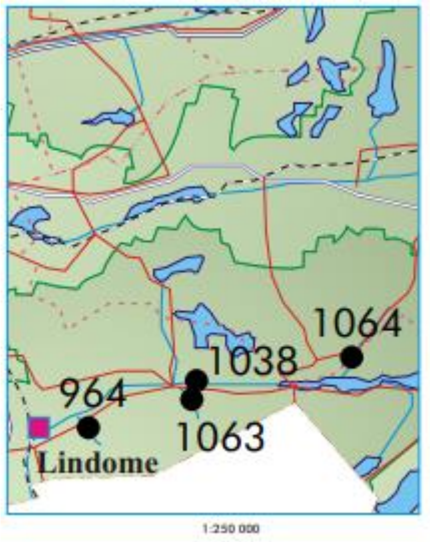

Figure 5. Migration barriers for anadromous fish in Kungsbackaån, Sweden, represented by black dots. (Bydén et al. 2000).

3.5.2 River restoration measures in Kungsbackaån

There are 30 planned restoration actions in the catchment area of Kungsbackaån. The focus is on three sectors: agriculture, community planning and hydropower. There are nine actions focusing on biotope care in lakes or watercourses. Five actions intend to re-establish routes for fishes. Three cases intend to establish new routes for fishes. Eight planned actions have the aim to change the position of bypasses or pipes. At one site it shall be ensured that there is a minimum water level for fish at the hydropower plant. An up- and downstream passage needs to be enabled in eight sites. In one position a technical downstream passage for fish is planned (VISS, 2021).

In figure 6 the sites intended for possible measures to enable up- and downstream passages for fish are marked for the catchment area of Kungsbackaån.

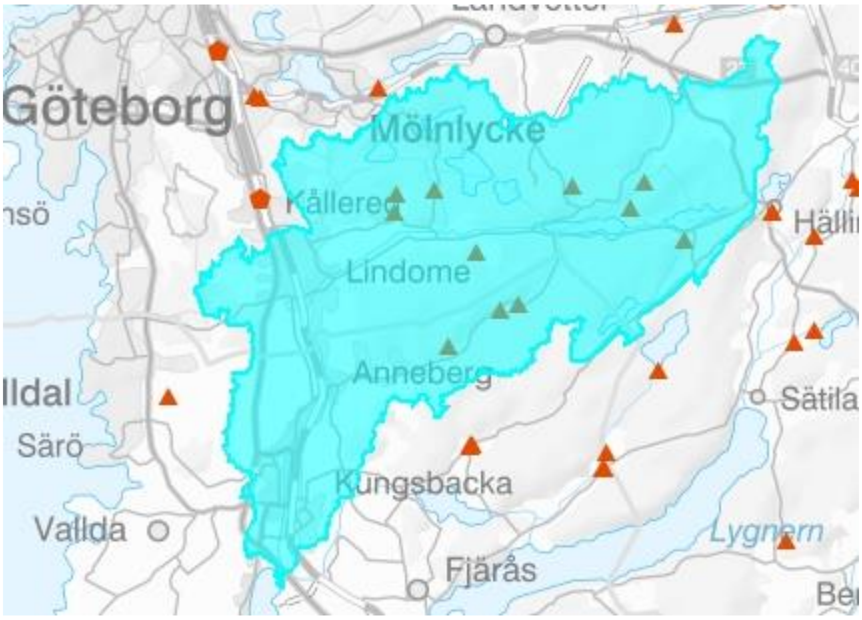

Figure 6. The catchment area of Kungsbackaån (marked in blue) showing possible sites (marked with orange triangles) to implement measures for up- and downstream passage for fish from 2021 onwards. (VISSa, 2021)

4 Assessment of risks and consequences

According to Peeler and Thrush (2004), risk analysis in aquaculture was for the first time applied in 2001. Its aim is to identify the likelihood and possible consequences of an introduction of alien species into a new environment.

Harris et al. (2010) propose to study a possible outcome of a parasite infection via the method of "*the epidemiological triangle*". This method is based on the idea that an infection can result in an endemic "*stable cycling of parasite and host, no evident episodes of host mortality*" (Harris et al., 2010), epidemic "*sudden onset of parasitic disease, death of a large proportion of the host population, often followed by disappearance of parasite*" (Harris et al., 2010) or another state between these two extremes. This is depending on the interaction between the three factors host, parasite and the environment. Furthermore, time is proposed as an additional factor to investigate the development of an infection to for example coexistence, extinction of one of the species or in a pathogenic disease.

For *G. salaris* to be able to create a stable population in a salmon river, an infected salmon must disperse the parasite at least to one other salmon individual in the river. The establishment depends on the density of the salmon population and environmental conditions, such as pH and temperature. Other factors in the chemical composition of the water, such as salinity levels, humus content or eutrophication can also affect the survival of the parasite (Peeler et al., 2006).

4.1 Transmission routes of *G. salaris*

Bakke et al. (1992) argue (according to Olstad, 2013) that there are four transmission routes of *G. salaris* in a river: via contact of live or dead hosts, when detached parasites spread through floating in the water column or by individuals attached to the substrate. The importance of the different transmission routes has not yet been finally assessed. It is suggested that spread via contact of live hosts is the most common way. Johnsen and Jensen (1991) suggested that dispersal between different rivers may take place when salmon migrate in brackish water, resulting in a possible transmission, even over long distances.

Soleng et al. (1998) studied the transmission routes of *G. salaris* and detected a correlation between temperature and rate of transmission of *G. salaris* in salmon populations. The results showed that higher temperatures in the water column lead to higher infection rates in salmon populations. It was assumed that the hatching of salmon in spring when temperatures rise favour the spread of the parasite, because the activity levels of the fish are high at that point of time. On the other hand, it was shown, that lower temperatures allow a longer survival of *G. salaris* individuals.

Moreover, Soleng et al. (1998) suggest that dispersal via contact of live hosts is the most important way of transmission. Keenleyside (1962), (Hearn 1987) and Mo (1992) pointed out, (according to Soleng et al., 1998), that salmon individuals have little direct contact with each other in the water column. Furthermore, epidemiological theory suggests that for direct spread between live individuals, a minimum number of hosts is needed for the parasite to survive; yet cases in Norwegian rivers have shown a host decline approaching 100 %. According to the studies of Soleng et al. (1998), as well as other research results (Lester 1972; Scott and Anderson 1984; Bakke et al., 1992), a transmission of detached parasites drifting in the water column has a significant importance for dispersal. Anderson and Gordon (1982) and Scott and Anderson (1984) suggest that the high mortality of Atlantic salmon populations is not favourable for the *G. salaris* development as the parasite causes almost no harm to its native range of salmon hosts (according to Olstad, 2013).

It is possible for the parasite to disperse from a coastal area to freshwater in case of anthropogenic movement of infected live fish for example for brood stocking. It can also occur when infected fish escape offshore from fish farms and migrate into river systems or if infected wild fish migrate from coastal areas to rivers (Peeler et al., 2006).

An important factor of the spread of *G. salaris* has been transportation of live fish between rivers and farms (OIE, 2019). Furthermore, a spread can occur if infected smolt are transported from fish farms for continued growing in sea water fish farms (Peeler et al., 2006). Transportation of live animals has been identified as playing a major role in the spread of diseases (Peeler and Thrush, 2004).

Further studies are needed to understand the exact transmission routes of *G. salaris* and their significance respectively.

4.1.1 Hosts for *G. salaris*

Salmon is not the only possible host for *G. salaris* and a spread of the parasite from other hosts to salmon is possible albeit unlikely in freshwater systems (Peeler and Thrush, 2004; Malmberg, 1993). The Scottish government created a table showing all possible hosts and their probability of transmitting the parasite in different environments, that can be seen in annex 1 of the contingency plan of the Scottish government (on the 15.06.2021 available at https://www.webarchive.org.uk/wayback/archive/3000/https://www.gov.scot/resource/doc/1062/0115961.pdf).

The EU lists Atlantic salmon (*Salmo salar*), rainbow trout (*Oncorhynchus mykiss*), Arctic char (*Salvelinus alpinus*), North American brook trout (*Salvelinus fontinalis*), grayling (*Thymallus thymallus*), North American lake trout (*Salvelinus namaycush*) and brown trout (*Salmo trutta*) to be susceptible farmed fish as hosts for *G. salaris* (COMMISSION REGULATION (EU) No 346/2010 of 15 April 2010).

However, Bakke et al. (1991) point out that only Atlantic salmon, rainbow trout (*O. mykiss*) (according to Peeler et al., 2006) and, as stated by Bakke et al. (1999), Atlantic salmon × brown or seatrout (*Salmo trutta*) hybrids (according to Peeler et al., 2006) are hosts on which a survival and reproduction of *G. salaris* is possible.

4.2 Extension of spawning grounds

The migration of salmon to spawning grounds can be delayed by many weeks due to human made barriers and obstacles or completely prevented. Changes of migration patterns can also be caused by other often anthropogenically induced factors such as light, poor water quality or pollution or alterations in the water temperature or velocity. The impact that those stressors and the different migration patterns have on for example spawning or entire salmon populations are still not fully known. This results in a lack of understanding of which factors or combinations of factors can favor or disfavor migration of salmon. Furthermore, migration barriers can complicate the location of a suitable spawning site for salmon (Thorstad et al., 2008).

As stated earlier, damming of streams can have a significant negative impact on the water body. Garcia de Leaniz (2008) states that damming can lead to crowding of migratory fish populations that might enhance the spread of parasites or infectious diseases. Furthermore, Peeler et al. (2006) point out that the density of salmon stocks is a crucial factor for the establishment of a *G. salaris* infection. Thus, the extension of spawning grounds and easier accessibility of such for fish could increase the salmon population in a river system.

4.3 Climate change

It is suggested that climate change will have a significant influence on parasites and the diseases they cause. Higher temperatures are not only assumed to favor parasitism and infections but also to have negative effects on the host populations as such. It is suspected that even small elevations in temperature can have significant impact on aquatic ecosystems, including fish and their parasites. It is believed that climate change will lead to faster and increased growth rate and maturation of parasites leading to an increased amount of parasite generations per year as well as a longer infection period per year. Those effects are presumable more serious in southern and northern latitudes than in tropical areas, as the parasitic life cycle and transmissions are usually dependent on seasonal changes. (Marcogliese, 2008). However, Byers (2021) points out that every organism, including parasites, have their optimal temperature range, meaning that some diseases or parasites might disappear with climate change. On the other hand, Byers (2021) argues that climate change not only has effects on temperatures but also on many other characteristics of aquatic ecosystems such as oxygen or salinity levels. Additionally, those alterations can impact the transmissions of parasites. Further it is stated that ectoparasites such as *G. salaris* often show high sensitivity to climate change induced alterations in the physico-chemical composition of the water. Thus, a change in for example salinity might impact the survival of *G. salaris*.

5 Risk Management

The World Trade Organization (WTO implemented an "Agreement on the Application of Sanitary and Phytosanitary Measures (SPS Agreement)" (WTO, 2021). This agreement obliges member states to take sanitary or phytosanitary measures "only to the extent necessary to protect human, animal or plant life or health" (WTO, 2021). Additionally, all measures taken must be based on scientific evidence and shall not discriminate trade between member states (WTO, 2021). Pharo (2003) points out (according to Peeler and Trush, 2004) that these measures implicate that a zero-risk approach to limit the introduction of diseases is not admissible if it comes to the trade of animals. The decision about which measures can be taken to reduce the risk of an introduction of a disease to an acceptable level, must be decided by governments, which makes risk management a political decision.

5.1 Preventive measures

Olstad (2013) argues that in regions such as parts of Finland or Russia no preventive measures against *G. salaris* are needed as the species is native and causes no significant problems to those salmon stocks. However, since 2002 *G. salaris* infections are declared a registered disease in Sweden. Regulations for a release of fish in rivers where salmon are native have been put in place to prevent a dispersal of the parasite to water courses that are known to be free of infected fish. Additionally, the Swedish Board of Fisheries created posters and leaflets to be posted in affected areas. This was done to create awareness amongst concerned groups of interest such as fish farmers, fishermen or anglers to avoid inadvertently transmissions.

The OIE (Office International des Epizooties) (2019) proposes several measures to control and prevent a spread or infection of *G. salaris*. These measures are mainly applicable for restocking of fish-farms but might nevertheless be interesting to mention. Proposals are resistance breeding or restocking with resistant species. Those two measures are not suitable in wildlife. Resistance breeding would imply a continued infection that might spread to other river systems, whereas restocking with resistance species of Atlantic salmon is not compatible with strain management and would have an impact on the gene pools of the salmon population originating to a water course. Additionally, it is proposed to disinfect eggs, especially in contaminated fish farms and prior to a transfer to another unit. The recommendation to disinfect fishing gear, such as nets or angling clothes before using them in another water course can be claimed to be important for avoiding a spread of *G. salaris* even in wildlife.

5.2 Guidelines

The European Commission set into force a regulation that "regards the placing on the market and import requirements for consignments of aquaculture animals intended for Member States or parts thereof with national measures" (COMMISSION REGULATION (EU) No 346/2010 of 15 April 2010). This regulation also includes measures to minimize the spread of *Gyrodactylus salaris*. It allows member states of the EU to impose requirements on supplies of aquaculture animals from areas where the existence of *G. salaris* is known, into their own territory that is considered free of *G. salaris*. Furthermore, it is proposed to include an animal health certification into a consignment of aquaculture animals to ensure that they are free of infection.

The Scottish government implemented a contingency plan for *G. salaris* (The Scottish Government, 2011). The UK is currently classified as free of the parasite and their salmon populations are suspected to be highly susceptible for a *G. salaris* infection. The contingency plan contains clear regulations in case of a discovery of *G. salaris* in Scottish waters. It focuses on three steps: identify the source of the outbreak and all contaminated sites, limit infected areas, and prevent spreading and finally, if possible, to eradicate the parasite from all infected sites. However, the plan also includes strategies of saving genetic lines in case of an outbreak and before eradication. The role and possible tasks of each involved authority in case of an outbreak are already clearly defined. *G. salaris* is recognized as a Notifiable disease since 1988 in Scotland. If an outbreak is presumed, the suspected area will be designated until the case is fully investigated. If the outbreak is confirmed the area will be designated as such and further measures will be discussed. A designated area can request removal and disposal of dead and dying fish, which will be classified as special waste and needs to be disposed at suitable disposal sites. A person that might recognize a *G. salaris* infection or outbreak is committed to report it to the relevant authorities and is otherwise guilty of an offence. Inspectors are encouraged to monitor water bodies and take samples of water and animals to inspect it for possible infections. If a *G. salaris* outbreak is confirmed, transport of live fish will be stopped in entire Scotland until all infected areas are identified by monitoring. Around those zones, so called buffer zones will be implemented. The declared zones will underlie movement restrictions to limit a possible spread. Furthermore, the problem will be communicated publicly to raise awareness. So far, the contingency plan has not been applied yet, as *G. salaris* has not yet been introduced to Scotland. Nowadays, imports of live fish are inspected strictly, and limitations can be imposed to imports from areas where *G. salaris* is known. Imports of salmon eggs are only allowed when disinfected.

5.3 Treatment of *G. salaris* infections

G. salaris shows sensitivity to changes in the chemical composition of the water. In conditions of fish farms the parasite showed sensitivity to bath treatments, such as salty water, solutions containing iodine or chlorine and formaldehyde. The parasite is also sensitive to acidic solutions such as aluminum sulphate (OIE, 2019). Following the *G. salaris* outbreaks in Norway, the major treatment method has been the use of the pesticide rotenone. This is a very effective medium to eradicate *G. salaris* yet it is also toxic to its hosts and other fauna such as invertebrates. Furthermore, in most cases it needs to be applied multiple times and might be slow in degradation (Sandodden et al., 2018; Eriksen et al., 2009). As alternative to rotenone, aqueous aluminum, and sulfuric acid (AlS) was used as treatment method in Norway. This treatment does not kill the host and was in a short-term study less aggressive to invertebrates than a rotenone treatment. It was nevertheless affecting some species negatively (Eriksen et al., 2009).

A successful eradication of *G. salaris* in some rivers in Norway has been shown with treatments of rotenone, although it eliminates most of the aquatic fauna. The long-term consequences of this treatment for the ecology of the water courses are unknown. It is presumed that such a treatment is environmentally inacceptable for most aquatic ecosystems (Peeler and Thrush, 2004).

Salte et al. (2010) argue that treatments with both biocides were successful in small rivers but not in big or more complicated river systems even after multiple treatments. They argue that improving the genetic ability of salmon to resist a *G. salaris* infection should be used as disease control measure.

5.4 Adaptation of salmon and potential of recovery after a *G. salaris* infection

The existence of salmon stocks that are resistant to gyrodactylosis and can survive a *G. salaris* outbreak are known for example in rivers that drain into the Baltic Sea, where the parasite is an endemic species. Although the Baltic salmon is geographically separated from the North Atlantic salmon it can be considered that a genetic adaption to the parasite can be possible on the long term. Yet, it is unknown, why most Atlantic salmon stocks have not yet genetically responded to the *G. salaris* infections (Salte et al., 2010). It is suggested that resistance to *G. salaris* is at least partially genetic and can be inherited. Yet, to study evolutionary adaption of salmon to *G. salaris* is complex. It is assumed that before an adaptation of salmon to the parasite is taking place, it is rather the parasite adapting to the host populations. This is because of the faster reproduction rate of *G. salaris* compared to salmon. On the other hand, each *G. salaris* population per host can be assumed to be a single deme and therefore striving for the maximization of just the deme which leads to a high virulence. However, it shows that the parasite can be most successful in large host populations, where a spread between individuals is easier (Karlsson et al., 2020).

6 Results and discussion

According to Davis et al. (2000) there are three factors that affect a possible spread of an invasive species to a modified ecosystem: the sum of pressures affecting the new system, the properties of the species and the proneness of the environment for an entry of the invasive species into the system.

It is difficult to estimate which new pressures the Kungsbackåan area will face after restoration measures and in particular weir removals. Unfortunately, no studies on the spread of *Gyrodactylus salaris* following weir removals could be found. However, several studies were conducted about the effects that weir removals can have on the spawning grounds of salmonid species. Fjeldstad et al. (2012) describe the impact of weir removal on the habitat for salmonids in a Norwegian river. The study monitored the abundance of juvenile salmon and salmon eggs before and after the removal of the dams. It was shown, that spawning sites for salmon recovered naturally due to the change in water velocity and the number of salmons and eggs increased significantly already in the first season after the restoration. Another study of Birnie-Gauvin et al. (2018) investigated the impact on brown trout (*Salmo trutta*) smolt migration in a Danish river after weir removal. The study showed an overall increase in migration and number of individuals and smaller size of migrating fish, suggesting that migration was facilitated for younger fish due to the weir removal.

When looking at the characteristics of *Gyrodactylus salaris* in chapter 3.3, one can conclude that the survival and dispersal of the parasite is higher in larger spawning areas with large salmon populations. On the other hand, as e.g., described by Garcia de Leaniz (2008), see chapter 4.2, a spread of an invasive species can be higher if migration barriers lead to the appearance of crowded fish at the entry of the water course. Considering, that salmon is always swimming to the same river (chapter 3.4) and that the migration barriers in Kungsbackaån are in use since many years, it can be assumed, that the factor of a possible crowding of salmon or other species that might be hosts for *G. salaris* is implausible. *G. salaris* is a species that can only survive in fresh or brackish water respectively (chapter 3.3). Since salmon spawns usually upstream in the river systems (chapter 3.4) a possible change of salinity in the lower parts of the river system due to the removal of migration barriers can be neglected to have impact on a possible invasion. However, a possibility of an augmentation of brackish water areas in the Kattegat (see chapter 3.3.2 and 4.3) in which the Kungsbackaån flows can impact the spread of the parasite in a long-term perspective. In this scenario, induced by climate change, a spread of the parasite from individuals from other catchment areas to individuals swimming to Kungsbackaån for spawning might be possible, as a death of *G. salaris* cannot be guaranteed anymore by the salinity level of the Kattegat. Even though this possible phenomenon is an important fact to take into account when discussing the spread of *G. salaris*, it can be considered that even in this scenario a removal of migration barriers will not favor the spread of the parasite other than offering easier access to spawning areas.

Concerning the susceptibility of the environment of Kungsbackåan to let *G. salaris* enter its system it is clearly high (chapter 3.3.3; 4.1; 3.5). Firstly, *G. salaris* has already been detected in Kungsbackåan previously. Secondly, the ecosystem is offering ideal conditions for the parasite (chapter 3.3), which will be even more favorable if the salmon stocks will recover, and the number of individuals will increase (chapter 4.2 and 5.4). An existence of *G. salaris* in the study area could be found in 2017 (chapter3.3.3), a spread or invasion with the parasite is probable if preventive measures (chapter 5.1) and guidelines (chapter 5.2) to minimize a possible spread will not be followed and considered in the river management.

On the Swedish west coast, a decrease of salmon populations has been detected since the 80s, yet the impact of *G. salaris* on population decrease is unknown. Rivers with and without *G. salaris* occurrence have not been sufficiently studied regarding this. Furthermore, it is discussed that salmon populations from the Swedish west coast are not as sensitive to the *G. salaris* strains occurring in that region like for example salmon strains from Norway that have been infected with the same *G. salaris* strain (Olstad, 2013). Genetic studies of *G. salaris* strains of the Swedish west coast propose that not all strains have the same origin. This in addition to the fact of genetical differences between salmon strains studied in the same area could lead to the conclusion that some of those *G. salaris* populations might be native to the area (Olstad, 2013). Studies have shown that salmon populations on the west coast of Sweden have genes of Baltic and Atlantic strains. Additionally, water conditions at the Swedish west coast seem to be unfavorable for *G. salaris* at least in summer when temperatures can be too high for reproduction of the parasite. The previous mentioned information is understood as reasons, wherefore *G. salaris* outbreaks at the Swedish west coast were not as devastating and clear to population developments of Swedish salmon populations as in Norway (Karlsson et al., 2020).

To evaluate a risk of spread of *G. salaris* and the possible impact that it can have on Atlantic salmon populations in western Sweden, it is recognizable, as mentioned earlier, that despite its existence and declining salmon populations after its introduction, the impact is not comparable to for example the effects of the outbreaks in Norway in the 70s. This surprising fact requires further investigate regarding the relation between parasite, host, and the physico-chemical environment, see chapter 4. Furthermore, it shows the importance that the genotype of the salmon strain and the *G. salaris* strain owns for the resistance to a lethal outbreak (Harris et al., 2010). Imports of *G. salaris* to Denmark and Germany have been reported, but no decline in salmon populations following the introduction of the parasite has yet been reported. If this is because wild salmon populations have already been notifiable reduced in Denmark and Germany in the time pre introduction, because the salmon strains have a degree of immunity or because the chemical conditions of the water are not favorable for *G. salaris* is unknown (Peeler et al., 2006). Investigating the reasons in Denmark, Germany or other areas could however be interesting to find out more about the parasite and to possibly apply the findings in Sweden or other regions. Considering this, further research of the genetics of salmon and parasite populations as well as environmental conditions is required. However, the knowledge we already have indicates the importance that single salmon strains can have for the survival and development of the entire salmon species.

Due to a lack of studies and knowledge about the effects of river restoration on parasite spread and particularly on the spread of *G. salaris*, it is difficult to estimate the impact. On one hand, the river restoration will facilitate the access to spawning grounds and with this potentially lead to a higher abundance of salmon in the area. That might induce an easier spread of the parasite between salmon individuals and to other salmonids (chapter 4). On the other hand, a larger salmon population will also be more capable to adapt to a *G. salaris* outbreak or develop resistance (chapter 5).

In a similar future study, it could be helpful to model the outcome and results of the restoration measures as well as to pay more attention on each restoration method of the different barriers. Then possible impacts of different restoration methods can be studied closer. Furthermore, it can be recommended to monitor the site prior and after restoration.

A literature review is a suitable tool to sum up and display information. Yet, it is impossible to include all existing studies and data. Moreover, new findings are limited to be based on the existing. In this study no fieldwork was conducted due to time and resource limitations. In the future, monitoring and studies of the site in question could be interesting tools to collect additional data and shed new light on specific questions such as the physiochemical composition of the water body. It is nevertheless clear, that a literature review is an important step in the process of creating a theoretical basis for further studies. The results of this thesis will be used by Melica ek for risk management and for the future planning of the river restoration process of Kungsbackaån.

7 Conclusion

G. salaris is a parasite that nowadays mainly disperses anthropogenically. The need to create spawning areas and habitats where fish can follow their natural cycle is needed and a dispersal of the parasite to new water courses is unlikely to happen naturally. The risk of natural dispersal of the parasite to restored spawning grounds is minimal while the benefit of new spawning grounds is major for salmon populations. Salmon has high economic and sociocultural value and many of its original habitats and spawning areas are not accessible for the species anymore due to a bad water quality, migration barriers or other anthropogenic reasons. The benefits of restoring spawning areas for salmon are stronger and more important than the risk of spreading *G. salaris*. It is however important to create measures to minimize a possible spread and dispersal of the parasite. The possibility of recovery of salmon populations in their normal habitats could lead to an evolutionary adaptation between the parasite and its hosts, which might result in stable naturally spawning salmon populations. Habitat restoration and removal of migration barriers can contribute to conservation of the gene pool of wild salmon populations. Climate change and wrong handling of fishing gear or fishing or the release of cultivated fish that might be infected are major factors that might lead to a spread or dispersal of *G. salaris.* A natural spread of the parasite is nowadays not as likely as an anthropogenic induced transmission. Yet, transmission routes of *G. salaris* need to be investigated further. No reports about a *G. salaris* outbreak following river restoration measures could be found yet only after the final removal of migration barriers a possible impact can be seen. To control the spread of *G. salaris* or eradicate the parasite after an outbreak is difficult and limited to just a few measures. Eradication methods used for example in Norway have had major side-effects, which have unknown long-term impact. The consequences of a possible introduction, spread or establishment of the parasite can be fatal for a susceptible salmon population and the associated economy or cultural factors. Further studies about the parasite, its transmission routes and possible adaptation of salmon populations are needed to limit the risk that an accidental introduction of *G. salaris* can have on nonnative ecosystems. The complex interaction of the impact that restoration measures can have on species and ecosystems need further studies, too.

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