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Atlantic salmon in the north -
Possible effects of oil pollution



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9296 Tromsø, Norway
Tel. +47 77 75 03 00
Faks +47 77 75 03 01

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Atlantic salmon in the north -
Possible effects of oil pollution

Forfatter(e) / Author(s)

Geir A. P. Dahl-Hansen
Guttorm N. Christensen
Anatoly Lukin, Akvaplan-niva Barents

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Increased activity related to exploration, production and transport of oil in the Barents Region, increase the risk of an oil spill outside the Norwegian coast. The largest and most important Atlantic salmon rivers in the world are located in Northern Norway and northwest Russia. In the present report life-history traits of Atlantic salmon that are important in the assessment of potential effects of an oil spill on Atlantic salmon individuals and populations are described. The knowledge about the marine ecology of Atlantic salmon and the possible negative affect an oil spill may have on this species is limited. However, experience from laboratory studies and experience after the Exxon Valdez oil spill in Prince William Sound in Alaska in 1989 have revealed that oil spill accidents can have seriously negative effects on Pacific salmon. Most studies conclude that the young stages of a fish species are more vulnerable than adult ones. The fry of Atlantic salmon lives in the river and will not be affected by an oil spill in sea water. The salmon will smoltify and migrate out of their home river at the age of 3 – 7 years and a length of 10 – 18 cm. They will return to their home river after 1 – 3 years. An oil spill in coastal areas may thus affect smolt and mature fish that are returning to their home rivers to spawn.

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Preface

During the past two decades there has been an increasing transport of oil along the North Norwegian and Russian coasts, following the expanded oil production in the north-west territory of Russia and the Barents Sea, and there is good reason to believe that this transport will continue to increase. There is a growing concern that this transport can lead to accidents where large amounts of oil are released into the environment. A near-coastal oil spill can have severe effects on many of the coastal resources, and one important resource that may be affected is the Atlantic salmon (*Salmo salar* L.) that spawn in many rivers along the coast of Northern Norway and Northwest Russia. Oil spills close to the salmon home waters will be a stress factor on top of all the others that may have negative effects on the abundance of salmon.

In the present report we present some aspects of the marine life of Atlantic salmon and possible effects of oil pollution on salmon production. Information on the subject is limited, and during the project it became clear that the knowledge about North-Norwegian and Russian populations is very limited. Due to this gap of knowledge it has been necessary to present salmon life history data obtained from studies carried out mostly in the southern part of Norway, in Scotland and in Iceland. However, it is believed that there are general traits in the behavior of post-smolt salmon in the marine environment so that at least part of this information also is true for the northern populations. We have considered information about life history of post-smolt and homing adult salmon spawners in near-coastal areas, in fjords and in the estuaries as most relevant for drawing up possible effects of oil pollution. Life-history traits are described in the first part of the report. Since the focus of this reports has been potential effects of an oil spill in the coastal area we have left out most of the information that exist about the ocean life of post-smolts and pre-adults, even though much information on this field has been obtained through extensive studies in the Northwest and Northeast Atlantic Ocean during the last 15 – 20 years.

As for marine salmon life in the north, there is an almost total lack of data on the effects of oil on Atlantic salmon. Therefore, it has been necessary to present information obtained from other salmonid species, in particular Pacific salmon. Most of the available data that exist has been achieved from studies carried out after the Exxon Valdez accident in Alaska, an area with an Arctic climate. It is therefore assumed that some of the information from these studies can be valuable in the discussion of possible effect on Atlantic salmon. An overview of knowledge concerning effects of oil exposure on salmon is presented in the second half of the report.

1. The marine life of Atlantic salmon

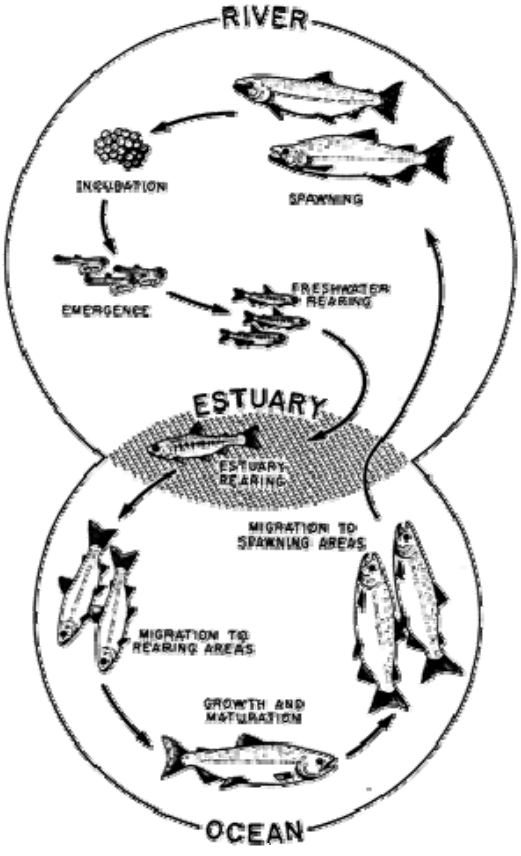
1.1. Introduction

Northern Norway and North-West Russia have some of the most important and most healthy Atlantic salmon (*Salmo salar* L.) stocks in Europe, and the two countries have a special responsibility to manage these populations. There are over 2000 salmon rivers in the Northern Atlantic, including ca. 200 rivers in Russia, where the species occurs from the Norwegian – Russian border to the Kara Sea in three regions: Arkhangelsk region, Karelia and the Kola Peninsula.

During the freshwater and the marine life there are several natural (temperature, occurrence of prey etc.) and anthropogenic factors (e.g. pollution) that can influence the life history of Atlantic salmon. For many years a strong decline in the abundance of Atlantic salmon has been registered throughout almost the entire range of its distribution. However, this decline has not been so profound in the northern salmon populations. Through several marine studies carried out during the past 20 years it has become more and more obvious that oceanic factors play a major role in the regulation of growth and survival and thus, population densities of salmon.

Some questions are essential when possible negative effect of an oil spill in the home waters of Atlantic salmon are to be assessed: When are Atlantic salmon present along the long coast of Northern Norway and Russia? What size groups are present where at different times of the year? How do salmon from different rivers migrate in space and time? What do they eat and where do they feed? What are the behavioral and physiological responses of salmon to marine oil pollution? Will oil spills affect survival and growth of salmon?

To answer these questions we have searched the literature concerning the marine life of Atlantic salmon in coastal regions, with special focus on Northern Norway and Northwest Russia and the literature concerning effects of oil on different life stages of salmon. During this process it became clear that there is an almost total lack of knowledge about the behavior and presence of salmon in the sea in these regions. Almost no written information about the marine life of Atlantic salmon populations from these northern areas exists. Most of the data on European salmon are derived from the southern and mid part of Norway, Scotland and Iceland and from ocean studies on mixed population in their marine feeding areas.



During the last 50 - 60 years several studies describing different aspects of Atlantic salmon life in freshwater has been conducted within areas where salmon is naturally distributed. However, knowledge of the marine life history of salmon is scarce. Only during the last two - three decades studies of the marine life of salmon have been carried out. All aspects of marine life; survival, feeding, migration etc. have until recently been

regarded as a more or less "black hole", but studies undertaken since the late eighties, in particular by Norwegian and Scottish scientists, have generated a lot of new information about salmon in the sea. Since 1991 extensive research on the distribution of post-smolts and pre-adults in the East Atlantic Ocean and the Nordic Seas have given valuable information on the marine Atlantic salmon life. Data suggests that a major part of post-smolts caught in the Norwegian Sea during summer and autumn belong to populations with home rivers south of Norway and in southern Norway (Haugland *et al.* 2006). The results show that post-smolts are widely distributed in the Norwegian Sea. Post-smolt from Norway are most represented in the samples from the eastern part of the area, and the catches are closely linked to the surface currents. New methods for tagging and the use of data storage tags and near-shore tracking systems (electronic tags) on post-smolts and pre-adults have provided new information on migration routes, timing, and oceanographic factors which influence the early migrations. But, still there are many aspects of the marine salmon life that is not understood or described.

1.2. Smolt migration



Atlantic salmon spend their first years in small streams and rivers. At a length of 12 to 24 cm and a weight up to 200 grams the salmon parr undergo a springtime transformation into smolt. The preparation for a marine life includes development of silvery coating and schooling behavior that prepare the fish for a pelagic life. In addition the smolt develops the capacity to regulate their body salinity in a marine environment. In Northern Norway the smolt age can be up to 5 - 6 years, while in the southern part of Norway, where the growing season is long, the salmon parr can smoltify at the age of 2 - 3 years. However, there are indications that the smolting age is more variable in North-Norwegian rivers than in southern rivers (Økland *et al.* 1993).

Smoltification start in the spring, and the seaward migration normally takes part during the period late May/early June - late July in Northern Norway and late April/early May - early June in Southern Norway (Jonsson and Ruud-Hansen 1985, Hesthagen and Garnås 1986, Heggberget *et al.* 1993, Forseth *et al.* 2003, Jensen 2004). In Kola rivers smolt migration takes place in June - July, although some individuals may migrate as late as August. Along the coast of Norway the main smolt migration takes place after the spring flooding at the time of the spring/summer when the sea temperature has reached approximately 8°C (Hvidsten *et al.* 1998). Records of seaward smolt migration in northern rivers are scarce, but data from river Utsjoki (tributary of river Tana) (Svenning *et al.* 2005), river Saltdalselva (Hvidsten *et al.* 1998) and Alta river (Ugedal *et al.* 2006) show that the time window of smolt migration may have a duration of 3 - 6 weeks. Data from Western Norway show that the smolt migration window can be as long as 2 months, but that the main migration takes place during a period of 20 days (Forseth *et al.* 2003). However, the start of the migration and the timing of the migration peak may vary a great deal between years and between rivers within the same region, depending on temperature and timing of the spring flood (Hvidsten *et al.* 1995, Antonsson and Gudjonsson 2002). For example, in river Utsjoki the smolt migration starts in the beginning of June and end in the middle of July. The migration peak may vary annually, but normally maximum migration occurs during the first 2 weeks of July (Svenning pers. com.). In Alta river, smolt migration normally peaks around late June–early July (Heggberget *et al.* 1993). In some Norwegian rivers some smolts migrate as late as August (Muladal pers.

com.). In river Varzuga and river Umba that flow out in the White Sea in the southwestern part of the Kola Peninsula, smolts migrates at water temperature of 15 - 20° C and 9 - 12° C, respectively (info from Lukin). Smolt migration has been observed at temperatures down to 5° C. In eastern rivers of the Kola Barents coast fast water warming can shorten the run to 2 - 3 weeks. In cold summers, smolt migrates gradually in small groups, for about two months. This implies that smolt in Northern Norway and northwest Russia can be found in the estuaries, in the fjord systems and close to the coast during all three summer months. However, based on the average time for peak migration, the highest densities of smolts in the fjords and close to the coast will be in July. Written information on smolt migration from other rivers in Northern Norway and Russia has so far not been obtained.

1.3. Post-smolt – early marine life



Several authors suggest that the first weeks after entering the marine area is the most critical period for the post-smolt, and much of the variation observed in marine survival of Atlantic salmon may be explained by differences in early post-smolt feeding and subsequent growth. During this period the smolt is particular sensitive to environmental stress factors, like pollution, that may have strong influence on growth and survival.

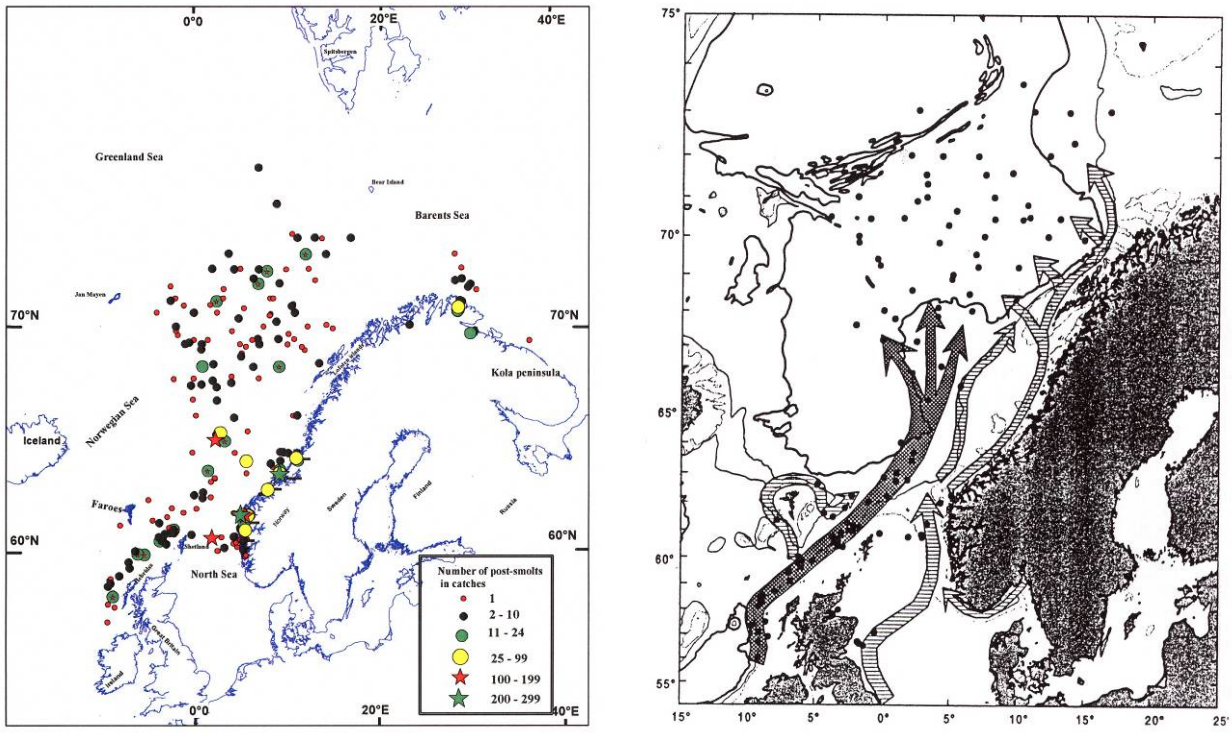
The limited information that is available on estuary- and coastal behavior, feeding etc. during seaward migration of post-smolts and pre-adults is mainly obtained from populations in South- and Mid-Norway, from Scotland, Iceland and the Canadian east coast (e.g. Holm *et al*. 2000 and 2003, Holst *et al.* 2000, Jacobsen and Hansen 2000, and 2001, Levings 1994, Sturlaugsson 2000, Hvidsten *et al.* 1995, Lacroix and McCurdy 1996). For salmon populations in Northern Norway and Northwest Russia, almost no information is available, except results from studies carried out by Richardsen *et al.* (2004) and Knudsen *et al.* (2005). However, it is hypothesized that migration and feeding behavior in fjords and coastal waters and the use of ocean feeding areas of salmon from this region may differ from southern populations. The results from the studies carried out by Richardsen *et al.* (2004) and Knudsen *et al.* (2005) indicate that there might be large variations in post-smolt feeding and feeding migrations between different estuaries/fjords along the coast of Norway. The data indicate that there is prolonged fjord residency and more extensive feeding immediately after sea entrance in North-Norwegian (NN) estuaries and fjords that in the Mid- and Southwestern part of Norway. In the fjords of Northern Norway fish larvae were the most important prey (both by frequency of occurrence and by mass), in contrast to further south were insects and intertidal crustacean prey were more important (Hvidsten *et al.* 1994, Sturlaugsson 2000, Andreassen *et al.* 2001). Also insects made up a major part (by mass) of the post-smolt diet in both southern and northern fjords, and there was a general tendency for increasing proportions of fish in the diet towards the outer part of the fjords. The more extensive feeding in the northernmost fjords may be due to differences in e.g. fjord morphology (shorter and wider in the NN), fjord currents, production, prey availability and longer period of light at high latitudes during summer. This means that in Northern Norway the time smolts stay in coastal waters is prolonged compared to further south, and that the possibility for exposure to pollution in case of an oil accident near the coast is higher.

Despite the lack of information from Northern Norway, data from Mid- and Western Norway on post-smolt behavior, feeding and migration can give some basic insight in post-smolt behavior also in the north. The data indicate that the time post–smolt stay in the estuaries and

fjords is brief and that they within few (2 - 7) days after entering salt water leave the fjord system and rapidly migrate in small shoals towards open sea (Hvidsten and Hansen 1998, Andreassen *et al.* 2001, Gudjonsson *et al.* 2005). In river Orkla (mid Norway) salmon smolts migrated to the sea within few hours after having left the river. Data from River Tana in Finnmark indicate that a majority of the smolts descend through the estuary and enter open sea during a short period (1 - 2 weeks) (Svenning *et al.* 2005). Indirect evidence for rapid movement through the estuaries comes from few records of smolt in fjords and coastal areas in late summer and autumn and the presence of smolts in oceanic areas in the Northeast Atlantic in the same time period. In the White Sea salmon smolt tends to stay and feed in the estuaries and in near-coastal areas for a longer period (until late August – early September).

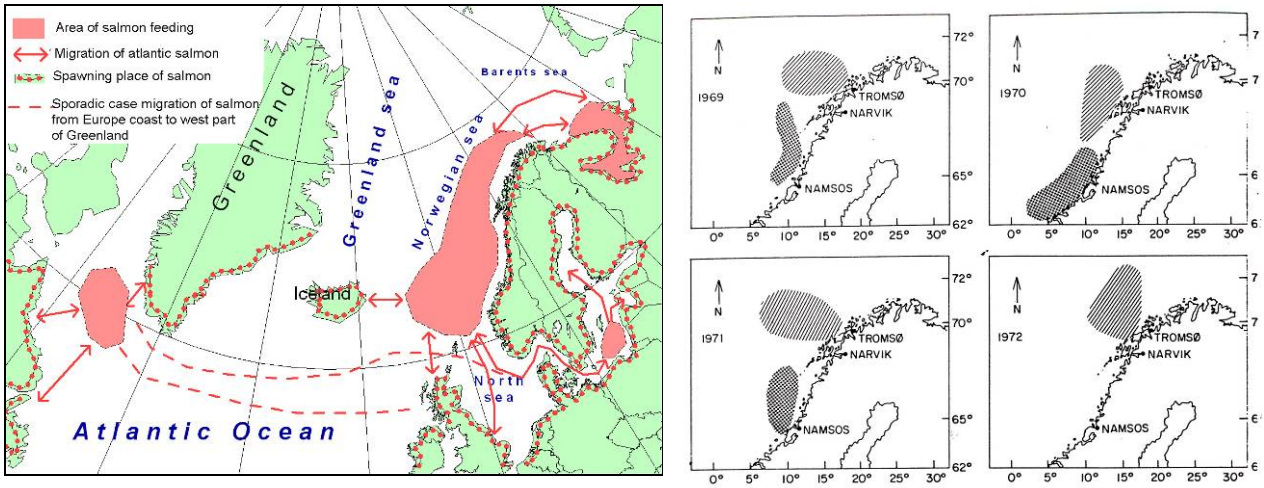
After having left the river the smolts do not seem to be distributed randomly in the estuary, but those that leave the river together tend to stay together during the outward fjord migration (Sturlaugsson 1994, Shelton *et al.* 1997). The smolts swim actively, but there seems to be no specific directed movements or precise navigation within the fjord system (Økland *et al.* 2006). However, most movements and thus, the net movements, are directed out of the fjord. Some studies suggest that freshwater and tidal currents may influence the migration pattern in the fjord system (Tytler *et al.* 1978, Gudjonsson *et al.* 2005) and that the smolts are transported with the surface current by passive drift and therefore follow the freshwater and brackish water layers in the fjords (Tytler *et al.* 1978, Hvidsten *et al.* 1992, Hvidsten *et al.* 1995, Forseth *et al.* 2003). This implies that there might be great regional differences in the time spent on outward migration due to differences in speed of the fjord currents. "Passive" transport with the ocean currents also seems to be the case along the coast of Norway after the smolts have entered open sea (Friedland *et al.* 2000). Hvidsten *et al.* (1992) showed that in the Trondheimsfjord post-smolts migrated with a speed from 0.8 – 2.8 km per hour. The smolts do not seem to stay in the river mouth for acclimatization to salt water (Jonsson *et al.* 1992). In the pelagic fjord systems smolts mostly stay in surface layer, but smolts are also found in shallow water close to the shore. Evidence for this comes from hydro-acoustic tracking, catches of smolts in gillnets put close to the shore, and from the finding of surface insects, fish larvae and crustacean plankton prey and inter-tidal benthic and semi-benthic animals (e.g. amphipods, gastropods, polychaets, sand eel) in the diet of post-smolt (Hvidsten *et al.* 1992, Rikardsen *et al.* 2004, Sturlaugsson 1994). However, studies from Mid-Norway indicate that post-smolts to a small degree are located close to the shore during outward migration in the fjord (Hvidsten *et al.* 1995). Other studies show that some of the postsmolts migrate close to the shore (Sturlaugsson 1994). Studies of migration of post-smolts in coastal waters of Iceland in the beginning of the feeding migration showed that they spent most of their time very close to the sea surface (majority at < 3 meters depth), especially during night (Sturlaugsson 1994, Sturlaugsson 2000). However, even though post-smolts are most frequently observed near the surface, they make short, but frequent dives to deeper water, probably related to feeding or to predator avoidance. It is also likely that post-smolts actively change depths seeking for optimal temperatures (Reddin *et al.* 2006). In a study by Reddin *et al.* (2006) smolt spent more than 90 % of the time in water temperatures between 8º and 15º C, probably near the surface.

The distribution of post-smolts in the Nordic Seas in 1990 – 2000, as well as migration routes for post-smolts along the Norwegian coast, is shown in Figure 1. In the sea, Atlantic salmon grows into one of the most effective predators – hunting for pelagic fishes like herring, capelin, mackerel, sand eel and smelt. However, the bulk of the salmon diet in the sea is crustaceans (shrimps, krill).



A **B**

Figure 1. A: Distribution of Post-smolts in the Nordic Seas, 1990 - 2000 (from Holm *et al.* 2000, In Hansen *et al.* 2002). B: Observed and inferred (horizontally lined) migration of post-smolt (from Moore *et al.* 2000).



A **B**

Figure 2. **A**: Ocean feeding areas and migration routes of Atlantic salmon (picture provided by A. Lukin). **B**: Ocean feeding areas of Atlantic salmon outside Northern Norway. Fish caught by long-line (from Hansen and Pheton 1985).

1.4. Home migration of adult salmon

The exact locations of ocean feeding grounds for northern salmon populations is still almost unknown, but it is believed that the feeding grounds cover a large area of the Northeast Atlantic Ocean (Figure 2). For example, salmon from the Kola Peninsula has been found at feeding grounds north of the Faroe Islands, and 20 % of tagged salmon from this feeding area has been recovered in North-Russia (Hansen and Jacobsen 2003). Salmon shoals can be encountered in a vast area from the western Spitzbergen to the northern coast of Iceland. The North Sea, Canadian coastal waters, Western Greenland are feeding areas for the fish born in streams of Southern Norway, Scotland, Ireland and Canada. Re-catches of salmon tagged as smolt in Alta River, in the ocean areas of Faroe Islands, Iceland and Greenland indicate that salmon from this river use the same marine feeding areas as salmon originating from Southern- and Mid- Norwegian rivers.

Statistically, ca. 5% of the fish that run down to the sea as smolts return to the river to spawn after the feeding period in the sea. The sea life duration varies between individuals. Some fish return to the stream a year after migrating into the sea. This fish is called grilse or one-sea-winter (1SW). After a year of feeding in the sea they weigh from 1 to 3 - 4 kg. Other fish return after 2 - 4 years (2SW - 3SW - 4SW). These are massive fish weighing 5 - 12 kg. Such fish are most often encountered in rivers of the Barents Sea watershed. A few individuals stay in the sea for up to 7 years.

The timing and routes of salmon from different populations on return migration are still relatively unknown. Likewise, there is a gap of knowledge about how they migrate in the coastal area and how long salmon from different populations stay in the fjords and estuaries before they enter the rivers. Catches of river Alta salmon in coastal commercial fisheries in Northern Nordland and Troms counties indicate that salmon from this river enter the Norwegian coast in the Lofoten area and migrate towards the north following the coastal current (Heggberget *et al.* 1998). Only a few salmon from river Alta is caught east of the Alta fjord. It is possible that this migration route is representative for the migration of salmon from other population from Northern Nordland, Troms and Finnmark counties as well, but this is still unknown. However, Heggberget *et al.* (1998) suggest that Lofoten is a main entrance area from the ocean to the coast for salmon populations in both North-, Mid- and West-Norway, and that this area is a segregation point for northern and southern populations. After having entered the coastal area of Northern Norway almost nothing is known about the near-coastal migration and behavior of the returning salmon, but it is obvious that salmon found along the coast and in fjords may be a mix of many different populations.

Adult salmon are present in the coastal area and in fjords of Northern Norway from late April/May - September (sometimes even later). Salmon originating from different rivers are known to return as adults at different time of the summer, and there are also annual differences in the timing and peak of these migrations. In general, the first salmon ascend rivers in Troms and Finnmark counties in early June (Berg 1964), and in Troms county commercial catches along the coast normally peak during 2-3 weeks, starting in late June. Towards the end of the fishing season (August), catches strongly decrease, indicating



that most of the salmon has returned to their rivers. Old, large salmon (2 and 3 sea winter (SW)) (females predominate) return to the coast earlier than the smaller 1 SW fish (grilse). In some rivers salmon is present soon after ice-breakup in mid - late May, e.g. the rivers Tana, Neiden, Grense Jakobselv, Stabburselva, Repparfjordelva and Målselv (Berg 1964). However, peak migration varies between late June/early July – late July/early August. In some Russian rivers a high number of fish enter in late September and October (e.g. river Ponoi and river Varzuga on the Kola Peninsula). This is particularly fat fish that stay in the lower parts of the rivers during winter and continue their upward migration to the spawning areas in the fall. This phenomenon is also reported from rivers in Northern Norway (e.g. Alta and Tana (Richardsen pers.com.). In his book "North Norwegian salmon rivers" M. Berg describe this migration as common in rivers in Northern Norway, and most common far north (Berg 1964).

Information gathered from old, local fishermen in Northern Norway indicate that silvery, adult salmon are present near the coast in some fjords in November/December and even in January, February and March. In some areas (e.g. in some fjords in south-west Finnmark county) (Fredriksen pers. com.) it was a tradition to catch fat, silvery adult salmon just before Christmas and also in January/February, and in Varanger fjord in east Finnmark County there used to be a "commercial" fishery for salmon in February – March/April (Muladal pers. com.). After the introduction of aquaculture in Northern Norway, by-catch of adult wild salmon in catches of escaped hatchery salmon during winter time has also been reported from the northernmost parts of Norway, but the number of fish caught is low.

1.5. Coastal behavior of homing salmon

Homing migration of Atlantic salmon from the ocean feeding areas consist of an initial phase with orientation towards the coast, and a second phase with more precise orientation in coastal and estuarine waters (Hansen *et al.* 1993). The migration seem to be active, and when homing to the rivers the fish approach the fjords from both north and south and may have followed the coast line for long distances (Hansen *et al.* 2003). How salmon behave during their near-coast migration is not well known, but in Northern Norway salmon are caught close to the shore in fjords and at the outer coast far away from any salmon rivers. However, some limited information on salmon behavior exists. During the spawning migration in the coastal area adult salmon tend to spend most of their time very close to the sea surface, in the uppermost 3 meters of the water column and most often in the depth interval 0 - 1 meter, and to migrate close to the shore (Sturlaugsson 1995, Sturlaugsson 2000, Sturlaugsson and Thorisson 1997). The presence of migrating salmon close to the shore in the fjords and in coastal areas is a general knowledge that e.g. is used by Norwegian commercial fishermen who always place their fishing gear close to the shore in shallow areas.

In the fjords salmon travel rates seem to slow down and the salmon tend to move up and down in the water column (Westerberg *et al.* 1982). Occasionally deep dives, down to 10 - 123 m, have been recorded with continuous movements in deep water layers (Sturlaugsson 1995). The purpose of this migration behavior of homing fish may be to detect some environmental cues for orientation (Westerberg *et al.* 1982) or it may be a response to tidal currents (selective tidal transport). The dives recorded by Sturlaugsson (1995) often started with the outgoing tide, suggesting that one reason for this behavior is that the salmon were swimming down below the strongest outward current in order of selective tidal transport. Records from tagging studies of migrating salmon in Iceland have shown migration speeds of about 1.2 - 1.8 km/hour.

1.6. Population status

There has been a continuous decline in catch of Atlantic salmon (*Salmo salar*) over the entire North Atlantic since about 1973 and towards year 2000 (Figure 3), and this decline has been the subject of concerned comment (Mills 1986; Shearer 1992; Shearer 1999). Attention has focused on the oceanic phase (Potter & Crozier 2000), but no clear consensus on causes of ocean mortality has emerged. The possibility of marine pollution has received little attention to date (Scott 2001).

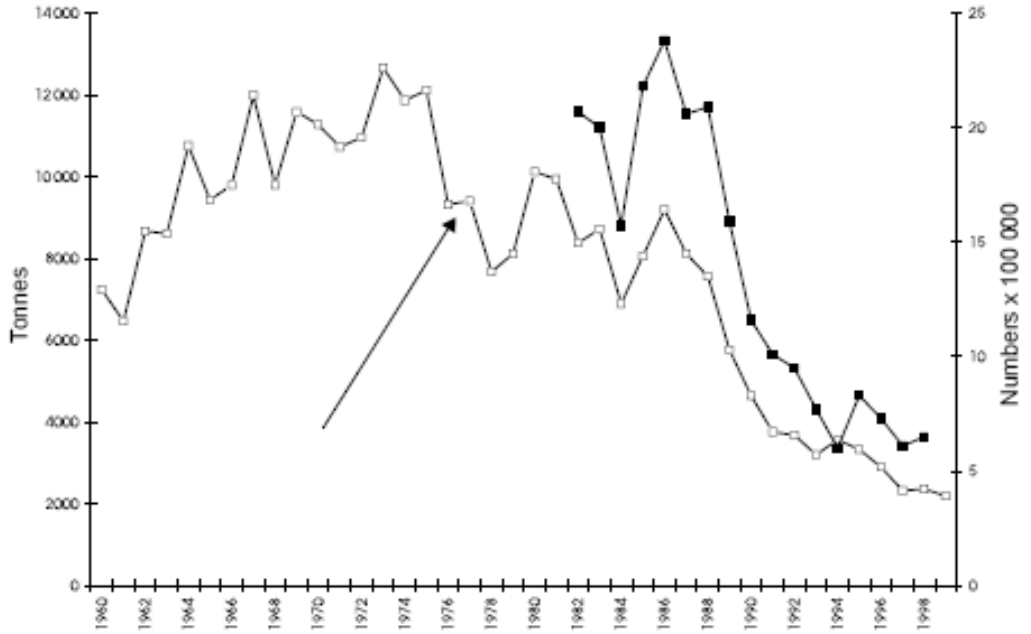


Figure 3. North Atlantic catch as fresh weight (tones – open squares) and numbers (black squares) Unreported catch not included. Arrow indicates start of catch restriction (Anonymous 2000a). (from Scott 2001).

1.7. Conclusions

- In Northern Norway salmon are present in near-coastal waters and in the fjords from May until late August/September.
- Highest densities of fish are found during the period of peak migration in mid June – late July/early August when adult spawners on home migration and post-smolts on outward migration are present together in the fjords and at the coast. Before and after this time period salmon in the sea are basically adults. Post-spawners on seaward migration are found in coastal waters during late May and June.
- Smolts are present in the estuaries, fjords and along the coast from mid June to late August with peak migration in late June – mid July.
- Smolts migrate in small shoals both close to the shore and in the pelagic area in surface water.
- Smolts feed on a variety of prey (insects, benthic animals in the tidal zone, fish larvae, crustacean plankton).
- Smolts stay in the near-coastal area for short time (3 - 14 days) before migration to open sea.
- In the coastal area adult homing salmon migrate close to the shore-line towards their home river, but take occasional deeper dives. Migration in deep water layers has been reported.
- Most adult salmon arrives the rivers in late August.
- Late autumn runs of non-spawners (spawn next fall) is common in some rivers at Kola Peninsula, but has also been reported from Norwegian rivers
- There is a great gap of knowledge on the marine life of Atlantic salmon in Northern Norway and northwest Russia.

2. Possible effects of oil pollution on salmon

2.1. Introduction to oil

The term petroleum includes crude oils and a wide variety of refined products. Crude oil is a complex mixture of thousands of hydrocarbons and non hydrocarbon compounds, but crude oil varies in chemical composition, color, viscosity, specific gravity, and other physical properties. Hydrocarbons comprise more than 75% of most crude and refined oils. Polycyclic aromatic hydrocarbons (PAH) are hydrocarbons, with two or more fused carbon rings, that have hydrogen or an alkyl group attached to each carbon. Crude oils contain 0.2 - 7% PAHs, with configurations ranging from two to six rings. In general, PAHs have low solubility in water, high melting and boiling points, and low vapor pressure.

Petroleum discharged on water spreads quickly to cover large areas. Oil layers with thicknesses varying from micrometers to centimeters forms on the surface. Some oils, especially heavy crude and refined products, sink and move below the surface or along the bottom of the waterbody. Wave action and water currents mix oil and water and produce either an oil-in-water emulsion or water-in-oil emulsions.

Residence time for petroleum in water is usually less than six months. Residence time for petroleum deposited on nearshore sediments and intertidal substrate is determined by the characteristics of the sediments and the substrate and by the degree of exposure to wave actions etc. Oil-retention times for coastal environment range from a few days for rock cliffs to as much as 20 years for cobble beaches, sheltered tidal flats, and wetlands. Total petroleum hydrocarbons or individual PAHs in undisturbed estuarine subtidal sediments can remain as identifiable deposits for many decades.

2.2. Petroleum activities in Northern Norway and Northwest Russia

Offshore oil exploration and production is moving towards Arctic regions. The knowledge about the environmental impact of such activities in these regions is limited and has to be expanded. In the coming years there will be an increased activity related to petroleum exploration in Northern Norway and Northwest Russia. For petroleum operations in the "Barents Sea area," (Figure 4) the Norwegian government has signaled strict environmental regulations, i.e. a "zero discharge framework", which will eliminate most operational discharges. However, there will be an increased transport of oil with tank ships from Russia and along the coast of Norway (Figure 6). There will also be an increased number of oil tankers in the fjords when reloading (transfer) of oil tankers are taking place. Therefore, possible environmental spill scenarios on the marine environment from the oil industry are mainly focused on accidental spills. These include massive as well as small repeated discharges related to oil spill events in the course of production, processing or transport. The largest and most important Atlantic salmon rivers are located in Northern Norway and Northwest Russia, but there is limited information on how oil spills may affect Atlantic salmon. However, several studies of effects of oil on pacific salmon and other fish species have been performed.

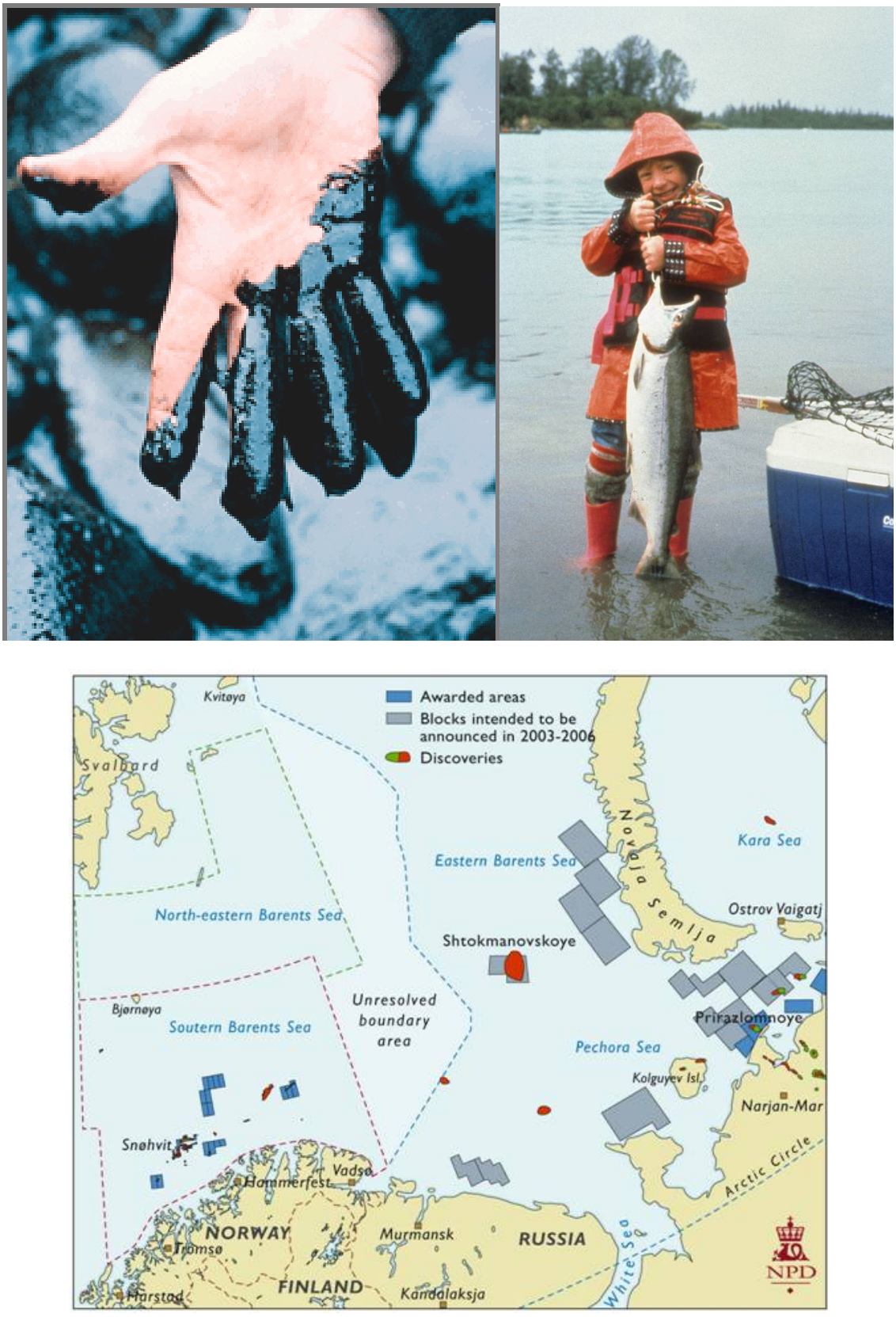


Figure 4. Map of some of the most important petroleum areas in the Barents Sea (from NPD).



Figure 5. Transfer (reloading) of oil from one vessel to another.

New agreements between The International Maritime Organisation (IMO) have adopted new sailing regulations along the northern Norwegian coast (Figure 6). According to the new shipping regulations, all ships carrying oil, gas or other risk material will have to follow fixed shipping routes along the coast. The routes are located 30 sea miles off the coast. One two sea mile wide lane will be reserved vessels heading north, while a similar lane will be reserved ships heading south. The distance between the two lanes will be three sea miles. The new regulations will make it easier to handle maritime emergency situations. It will also be easier for trawlers to operate in the area. The regulations will come into force six months after adoption.

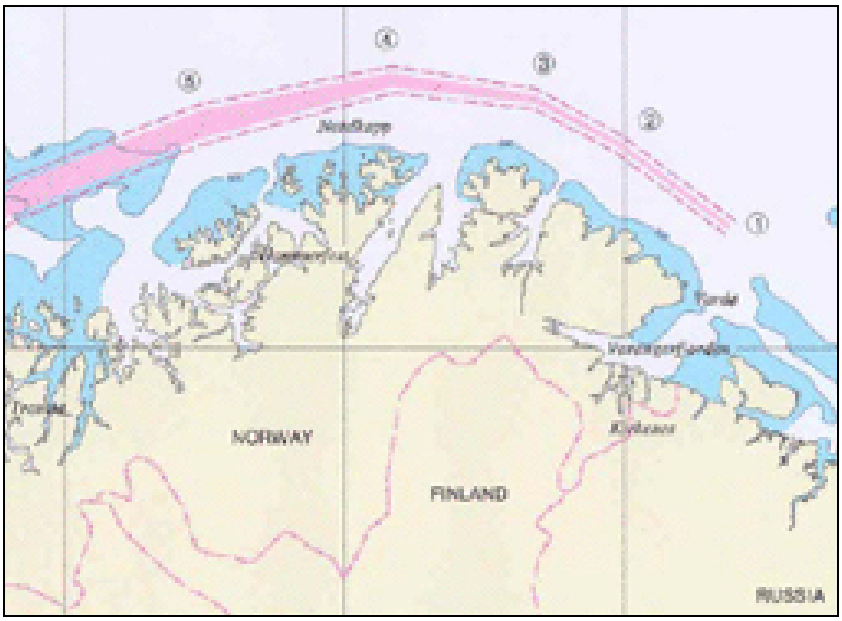


Figure 6. Map showing transport route for oil tanker from Murmansk, Russia along the Norwegian coast (from Barentsobserver.com).

2.3. Historical oil spill accidents

There has been several major oil spills the last two decades. Examples of these are: The Exxon Valdes in Prince William Sound in Alaska in 1989 (42 000 tons spilled), the Braer accident in 1993 (85 000 tons) close to Shetland, the Erika tanker (10 000 tons) in 1999 at French Atlantic Coast and the Prestige tanker (70 000 tons) in 2002 outside the northwest coast of Spain. All these were large oil spills, but the affect these accidents had on nature was extremely different. Thus, the impact on nature is not necessarily dependent on the amount of oil, but also on the type of oil and on natural factors like weather conditions, location, type of animals in the area etc.

One of the largest and most studied oil spills is the Exxon Valdez accident in Prince William Sound in Alaska in 1989 (Figure 7), where nearly 42 000 tons of crude oil was spilled. Following the spill hundreds of kilometers of shoreline was affected (Spies *et al.* 1996). The nature and the climate in Prince William Sound have many characteristics that are very similar to the Barents region. Therefore, it is especially important to consider what happened after this accident when potential effects of oil spill along the North-Norwegian and Northwest-Russian coast is being assessed. Numerous scientific investigations related to the oil spill have been carried out and several of these have focused on effects of oil pollution on the Pacific salmon populations in the area.



Figure 7. The Exxon Valdez accident in Prince William Sound in March 1989. 42 000 tons of crude oil were spilled.

2.4. Effects of oil pollution on aquatic life

Petroleum can adversely affect organisms by physical action (smothering, reduced light), habitat modification (altered pH, decrease food availability), and toxic action. Large discharges of petroleum are most likely to produce notable effects from physical action and habitat modification. Adult and juvenile fish, larvae, and eggs can be exposed to petroleum through contact with whole oil, dissolved hydrocarbons, particles of oil dispersed in the water column, or ingestion of contaminated food or water. Death of adult fish in a natural environment usually requires a heavy exposure to petroleum, probably because adult fish are able to swim away from oil polluted water. Consequently, it is unlikely that large numbers of adult fish inhabiting large bodies of water would be killed by the toxic effects of petroleum. Fish kills are usually caused by large amounts of oil moving rapidly into shallow water. However, young life stages of fish are sensitive to PAH pollution and petroleum-contaminated water can affect the commercial quality of the fish even at very low environmental concentrations (Heras *et al.* 1992).

Chronic exposure to low levels of oil may cause a suite of different effects in fish. Recent evidence demonstrates that oil exposure can alter the endogenous levels of steroids, like testosterone and estradiol, in plasma of fish (Martin-Skilton *et al.* 2006). These hormones are involved in the reproductive physiology of the fish and the modification of their levels could impair the reproductive success of the fish. For instance, fecundity can be lowered and the egg size reduced (Trippel and Neil 2004). This can have dramatic consequences on the recruitment of the next generation.

The aromatic fraction of petroleum is considered to be responsible for most of the toxic effects, and exposure to PAHs may cause cancer (carcinogenic) and immunological effects (Reynaud and Deschaux 2006). Fish are to a certain degree able to metabolize the lipid-soluble PAH compounds to more water-soluble compounds that can be excreted through urine or bile, through the cytochrome P450-enzyme system. Planar aromatic hydrocarbons trigger the induction of cytochrome P450 1A proteins via an intracellular aryl hydrocarbon receptor (Ah-R) (Poland and Knutson, 1982), predominantly found in liver but also in extrahepatic tissues. Several laboratory studies and studies of farmed Atlantic salmon and other wild salmonid populations have detected increased enzyme activity in liver and gills (induction of cytochrome P450) However, some of the metabolites that are formed may be even more toxic than the mother compound. Therefore, although unmetabolized PAHs can have toxic effects, a major concern in animals is the ability of the reactive metabolites of some PAHs, such as epoxides and dihydrodiols, to bind to cellular proteins and DNA (Collodi *et al.* 1984, Krahn *et al.* 1992, Carls *et al.* 1996, Hom *et al.* 1996, Wiedemer *et al.* 1996, Wilette 1996, Stagg *et al.* 1998, Jewett *et al.* 2002). The resulting biochemical disruption and cell damage can lead to mutations, developmental malformations, tumor and cancer. After the Erika oil spill, close to the French Atlantic Coast, a high amount of DNA adducts was found in fish from all oiled locations, amounting to 92–290 DNA adduct per 10^9 nucleotides. Then total DNA adduct levels decreased to reach about 50 adducts per 10^9 nucleotides nine months after the spill. *In vitro* experiments using human cell cultures and fish liver microsomes provided evidence of the genotoxicity of the Erika fuel. They also proved the formation of reactive species able to create DNA adducts. Furthermore, *in vitro* and *in vivo* DNA adducts fingerprints were similar, thus confirming that DNA adducts are a result of the oil spill (Jewett *et al*. 2002).

Jewett *et al.* (2002) carried out a study on three biomarkers of hydrocarbon exposure, CYP1A in liver vascular endothelium, liver ethoxyresorufin O-deethylase (EROD), and biliary fluorescent aromatic compounds FACs) in the nearshore fishes, masked greenling (*Hexagrammos octogrammus*) and crescent gunnel (*Pholis laeta*), collected in Prince William

Sound, Alaska, 7 – 10 years after the Exxon Valdez oil spill (EVOS). They found that all biomarkers were elevated in fish collected from sites originally oiled, in comparison to fish from unoiled sites. In 1998, endothelial CYP1A in masked greenling from sites that were heavily oiled in 1989 was significantly higher than in fish collected outside the spill trajectory. In 1999, fishes collected from sites adjacent to intertidal mussel beds containing lingering Exxon Valdez oil had elevated endothelial CYP1A and EROD, and high concentrations of biliary FACs. Fishes from sites near unoiled mussel beds, but within the original spill trajectory, also showed evidence of hydrocarbon exposure, although there were no correlations between sediment petroleum hydrocarbon and any of the biomarkers. The data from this study show that even 10 years after the spill, nearshore fishes within the original spill zone were still exposed to residual hydrocarbons.

Collodi *et al.* (1984) studied coho salmon exposed to the water soluble fraction (WSF) of Cook Inlet crude oil for a maximum of 30-days and the results showed a greater than three-fold increase in cytochrome P-450 enzyme activity. Persistence of the induced enzyme activity was dependent on the length and the concentration of WSF exposure. The results from this study show that coho salmon respond to the presence of dissolved aromatic hydrocarbons by increasing the P-450 enzyme activity.

PAHs are also immunotoxic and carcinogenic, and the best studied are 7,12-dimethylbenz(a)anthracene (DMBA), benzo(a)pyrene (BaP) and 3-methylcholanthrene (3-MC) (White 1986, Davila *et al.* 1995). BaP and 3-MC are found environmentally, whereas certain methylated PAHs, such as DMBA have been synthesized as model compounds (Krieger *et al.* 1995). Petroleum hydrocarbons have also been shown to affect both non-specific and specific immunity. However, the effects observed depend on the type of PAH, the route of administration, the concentration used and the species studied. The capacity of PAHs to induce immunotoxicity implies different intracellular mechanisms, such as PAH metabolism by cytochrome P450, binding to Ah-receptor and intracellular calcium mobilization.

Fishes collected from PAH-polluted waters have external abnormalities thought to be related to immunosuppression, including lesions of gills, skin, and fins caused by opportunistic infections (Seeley and Week-Perkins, 1991). Recent studies in fish have investigated the mechanism of PAH-induced immunotoxicity (Faisal and Huggett, 1993; Reynaud *et al.* 2001, 2002, 2003, 2004; Carlson *et al.* 2004a, b; Reynaud and Deschaux, 2005) and the knowledge on effects of PAH on the immune system of fish is review by Reynaud and Deschaux (2006).

2.5. Effects of oil pollution on salmon

After the Exxon Valdez oil spill in the Prince William Sound in March 1989, many studies of effects on oil on different Pacific salmon species, like Pink salmon (*Oncorhynchus gorbuscha*), coho salmon (*Oncorhynchus kisutch*) and chum salmon (*Oncorhynchus keta*), were carried out. In addition, several laboratory studies of effects of oil on different salmonids have been carried out under controlled conditions. Most of the studies were related to the embryo and fry stages (juvenile stages), but some studies were performed on adult salmon. These studies have documented both immediate (short-term) and long-term negative responses. From laboratory studies and from field studies in Prince William Sound negative impact on different levels of organization have been reveled. It is well known that even small amounts of oil can have effect on enzymes activity in salmonids, but there are also studies that indicate effects on survival, growth, migration, etc. The biology of the Atlantic salmon differs from the Pacific salmonids, and therefore the effects of an oil spill can vary between

species. However, it is believed that some of the effects that have been observed on Pacific salmon, also may apply to Atlantic salmon. An overview of the studies of salmon that were carried out after the Exxon Valdez oil spill is given in the following text.

When reviewing studies carried out after the Exxon Valdez accident it is important to be aware of the fact that these studies usually fell into two categories: Those contracted with Exxon, and those funded by Exxon Valdez's oil spill (EVOS) Trustee Council (Rice *et al.* 2001). In some cases these studies agreed, but in several cases, especially the areas involving effects on various life stages, similar studies, but different experimental designs, led to different findings and conclusions. Studies have examined both short- and long-term effects, and disagreed on the extent of damage. Several studies examined the same issue but were seldom conducted identically. The consequent of this is that most of the research effort is more complimentary and open to differences in interpretation. However, the effects of the impacts from the Exxon Valdez are reviewed by Rice *et al.* (2001), Jewett *et al.* (2002) and Short *et al.* (2003).



Figure 8. The shore line in Prince William Sound after the oil spill in March 1989.

2.2.2 Effects on embryo and juvenile stages

It is known that fish embryos and fish fry often are more sensitive to pollution compared to larger (older) fish (Thomas *et al.* 1989, Barron *et al.* 2004). Polycyclic aromatic hydrocarbons (PAHs) can cause a variety of effects in early life-stages of fish that have been chronically exposed as embryos, including mortality, deformities, and edemas. Recent research indicates that chronic PAH exposures in fish embryos can cause early life-stage mortality and a suite of sublethal effects that appear similar to the blue-sac disease attributed to more persistent planar halogenated aromatic compounds, such as tetrachloro-dibezodioxine (TCDD). Effects in a variety of fish species include early mortality, edema, hemorrhaging, disruption of cardiac function, and deformities (Barron *et al.* 2003; Billiard *et al.* 2002; Marty

et al. 1997). The embryonic toxicity of PAHs in fish appears to occur because of sensitivity to planar PAHs, high bioaccumulation and limited biotransformation, and exposure during critical developmental periods (Petersen and Kristensen, 1998).

Studies have revealed that fry (juvenile) entering or migrating through oil polluted areas are exposed to oil and suffer from a decreased growth rate (Rice *et al.* 2001). Both wild and hatchery pink salmon (*Oncorhynchus gorbuscha*) juveniles were exposed to Exxon Valdez oil in 1989, as proven by elevated PAH concentrations in tissue, induction of P4501A (Carls *et al.* 1996a, Willette 1996), and oil globules in the stomach of juvenile fish (Sturdevant *et al.* 1996). Carls *et al.* (2005) studied the Cytochrome P4501A (CYP1A) induction in pink salmon embryos exposed to crude oil. The results revealed that the CYP1A induction is linked to adverse effects at cellular, organism and population levels, and that it can be used to predict these responses. The results from the field study as well as results from an experiment designed to examine CYP1A induction during embryonic stages and growth after emergence, demonstrated that CYP1A induction was related to a variety of lethal and sublethal effects, including poorer marine survival, reduced growth and abnormalities. The lowest observed concentration of total PAH in water that caused significant physiological responses (< 0.94 µg/l), including reduced size 6 months after ended exposure, was lower than the lowest concentration that caused significant CYP1A induction (< 3.7 µg/l).

Thomas *et al.* (1989) studied the differences in hydrocarbon uptake and mixed function oxidase activity between juvenile and spawning adult coho salmon exposed to Cook Inlet crude oil. The results clearly revealed that juvenile salmon were much more sensitive to oil pollution than adult fish. Coho salmon smolts accumulated up to 30 times more hydrocarbons in selected tissues than did coho salmon jacks (males) when exposed to water-soluble fraction of Cook Inlet crude oil. Aryl hydrocarbon hydroxylase (AHH) activity continued to increase during 12 days of exposure in coho smolts, in contrast to jacks, in which AHH activity peaked at 2 days and remained elevated during 20 days of exposure. Cytochrome P-450 concentrations peaked after 48 hr and then returned to control levels in exposed smolts. In exposed and control jacks, cytochrome P-450 decreased during the 20 day experimental period. However concentrations of P-450 were significantly greater in exposed jacks than in control jacks. Aryl hydrocarbon hydroxylase (AHH) activity and cytochrome P-450 concentrations were greater in non-exposed coho smolts and jacks than in non-exposed pre-spawning adults. Coho jacks were not as responsive as coho smolts in terms of P-450 induction; however, they were more responsive than anticipated for a fish in a terminal life stage.

Gagnon and Holdway (1999) studied immature Atlantic salmon (*Salmo salar*) that were exposed to water accommodated fraction (WAF) of Bass Strait crude oil or to Corexit 9527-dispersed crude oil for 6 days, followed by a depuration period of 29 days. Serum sorbitol dehydrogenase (SDH) levels, an indicator of liver damages, remained low during the experiment. Hepatic EROD activity was induced within 2 days following the onset of the exposure in both treatments, and persisted for 2-4 and 4-6 days after transfer to clean sea water in the WAF and dispersed oil treatment, respectively. Naphthalene-type metabolites, determined by fixed-wavelength fluorescence detection, appeared in the bile of the fish with 2 days' delay compared to EROD induction. In both treatments, EROD activity induction and levels of naphthalene-type metabolites in the bile were significantly correlated. The biliary levels of naphthalene-type metabolites were over 15 times higher in fish exposed to dispersed crude oil relative to fish exposed to the WAF of Bass Strait crude oil. BaP-type metabolites appeared only in the bile of the fish exposed to the WAF, possibly due to BaP-type compounds remaining associated with the dispersant in the water column or to an inhibition of Phase II detoxification enzymes by the dispersant. They concluded that bile metabolites as

determined by fixed-wavelength fluorescence and EROD induction appear to be sensitive and complementary biomarkers of exposure to PAH.

Bue *et al.* 1996, 1998 concluded that between 1989 and 1993 pink salmon (*Oncorhynchus gorbuscha*) eggs deposited in the intertidal sections of oiled-beach streams had higher mortality rates than eggs in similar sections of streams in unoiled beaches. The results from these studies suggest that chronic damage occurred to some populations of pink salmon. Significantly elevated embryo mortalities were observed from 1989 through 1993 in populations inhabiting streams previously contaminated by oil. No statistically detectable difference in embryo mortality was observed in 1994 and 1995. Significantly increased embryo mortality was detected for embryos originating from the oil-contaminated lineages in 1993 but not in 1994, which indicated that the significant differences detected in the field in 1989-1993 were not induced by naturally occurring environmental variables. However, similar studies were performed later and the results from these studies indicated that the negative effects on salmon eggs were an artifact due to other reasons than oil pollution (Brannon *et al.* 2001, Cronin and Maki 2004).

Roy *et al.* 1999 studied in an experiment the frequency of mutations in pink salmon embryos exposed to Exxon Valdez oil. Their study was based on the studies preformed by Bue *et al.* 1996, 1998 showing a reduced survivorship of pink salmon embryos that were exposed to Exxon Valdez-released oil compared with populations from matched nonoiled streams. Survivorship was also significantly decreased in embyros from lineages that were oiled in Prince William Sound and reared in clean water under controlled hatchery conditions compared with the descendants of nonoiled lineages. This suggests that the effect of oiling on pink salmon populations was persistent and could be transmitted intergenerationally. These results indicate that exposure of pink salmon embryos to weathered Prudhoe Bay crude oil under controlled laboratory conditions can elicit somatic cell mutations in high frequency at mutational hotspots in genes such as K-ras. However the frequency of these events in oiled natural populations of pink salmon and other vulnerable species in Prince William Sound and the heritability of these mutations within oiled lineages have yet to be evaluated.

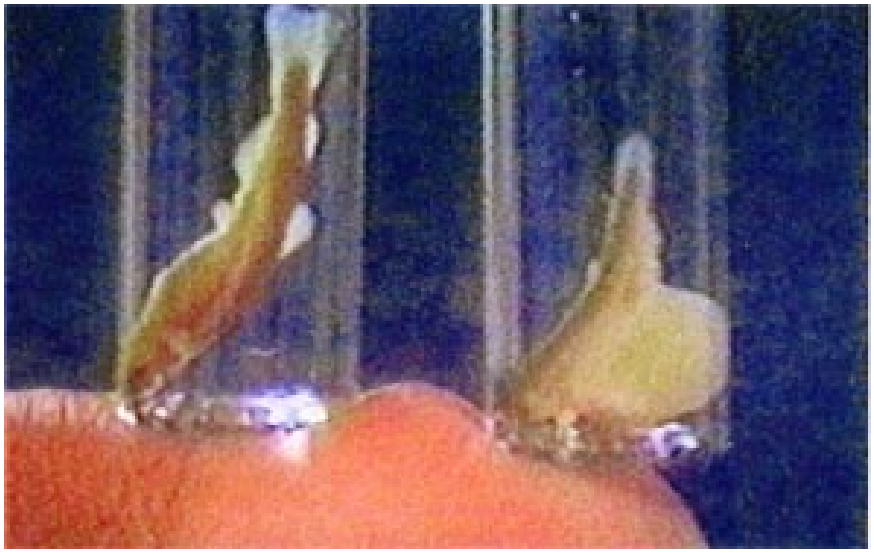


Figure 9. *Left:* A normal fish untouched by oil, *Right:* An abnormal fish touched by Valdez oil in 1999.

Heintz *et al.* 1999 incubated pink salmon embryos under three exposure conditions, direct contact with oil-coated gravel, effluent from oil-coated gravel, and direct contact with gravel coated with very weathered oil (VWO). Embryo mortalities and polynuclear aromatic hydrocarbon (PAH) accumulation in embryo tissues during the direct-contact and effluent exposure experiments were not significantly different, indicating that PAH accumulation was mediated by aqueous transport. Mortality rates for embryos exposed initially to a total PAH concentration (TPAH) of 1.0 ppb were significantly higher than controls when the PAH were derived from VWO. The same aqueous TPAH concentration failed to increase mortality rates when the PAH were derived from less weathered oil, indicating that toxicity of effluents from the VWO was primarily associated with the larger PAH. They concluded that water quality standards for TPAH above 1.0 ppb may fail to protect fish embryos. Further, pink salmon embryos incubating in Prince William Sound after the Exxon Valdez oil spill may have accumulated lethal concentrations of PAH from interstitial water that was contaminated when it percolated through oil reservoirs located upstream from salmon redds.

Carls *et al.* (1996) studied if the juvenile pink and Chum salmon in the Prince William Sound were contaminated by hydrocarbons after the Exxon Valdez oil spill. They collected juvenile fish from the oiled nearshore marine habitats in 1989 and 1990 and also fish from non-oiled areas. In 1989 the PAH concentrations were significantly higher in pink salmon tissues from oiled areas (181 ng/g) than from non-oiled areas (54 ng/g). In 1990 the PAH concentrations (51 ng/g) were not significantly different from oiled and non-oiled areas. They also found that cytochrome P-450 was significantly induced in juvenile fish from the oiled locations in 1989 and not in 1990. Based on these results they conclude that Exxon Valdez crude oil caused these differential changes in PAH concentration and induced cytochrome P450 enzyme activities. They further believe that contamination of juvenile salmon was physiologically significant and contributed to the reduced growth observed in juvenile pink salmon from oiled areas of Prince William Sound in 1989.

Petroleum products are known to have greater toxicity to the translucent embryos and larvae of aquatic organisms in the presence of ultraviolet radiation (UV) compared to toxicity determined in tests performed under standard laboratory lighting with minimal UV (Barron and Ka'Aihue 2001). Barron *et al.* 2005 studied the acute phototoxicity of the water accommodated fractions of weathered Alaska North Slope crude oil (ANS) to juvenile pink salmon, which are a heavily pigmented life stage. Fish in the highest ANS treatments exhibited melanosis, less mobility, reduced startle response, erratic swimming, and loss of equilibrium. Gills from fish exposed to ANS had elevated levels of hydroperoxides in oil-only, UV-only, and oil + UV treatments compared to control fish, which was indicative of increased lipid peroxidation in gill tissue. Under the test conditions of moderate salinity, low UV and high short-term oil exposure there were no indications of photoenhanced toxicity as assessed by elevation of mortality, behavioral impairment, or gill lipid peroxidation in oil + UV treatments. The results of this study suggest that pink salmon may be at less risk from photoenhanced toxicity compared to the translucent early-life stages of several other Alaska species.

2.5.1. Effects on growth and marine survival

Moles *et al.* (1981) carried out a study were they investigated how two petroleum components, toluene and naphthalene, affected the growth of juvenile coho salmon. Juvenile fish were exposed to four different concentrations of toluene and naphthalene for 40 days. The results revealed that juvenile salmon exposed to sublethal concentrations of toluene and naphthalene grew significantly less than unexposed fish. Further, juvenile salmon exposed to naphthalene had a slower growth rate than fish exposed to equivalent concentrations of toluene.

Heintz *et al.* (1999) showed that embryonic exposure to oil reduces the number of pink salmon fry produced from a population of eggs. Similarly, Heintz *et al.* (2000) demonstrated that these survivors experienced lower survival than unexposed fry in the marine environment. Integrating the survival effects described for each of the developmental stages described in these reports indicates that a population of 1,000 eggs exposed to 19 μg/L TPAH during incubation will ultimately produce less than half the number of adult salmon an unexposed population produces. Thus a modestly sized pink salmon run that produces 10 million eggs, of which 0.85% would normally survive to adulthood (i.e., 85,000 adult fish), could produce 46,000 fewer adult fish if the eggs were exposed to 19 μg/L total PAHs from oil (Figure 10). Reductions in juvenile growth could account for the reduced marine survival observed in the released fish. The demonstration of delayed effects on growth and survival support claims of delayed effects in pink salmon after the 'Exxon Valdez' oil spill, and indicate the potential for population-level effects resulting from embryonic exposure to oil.

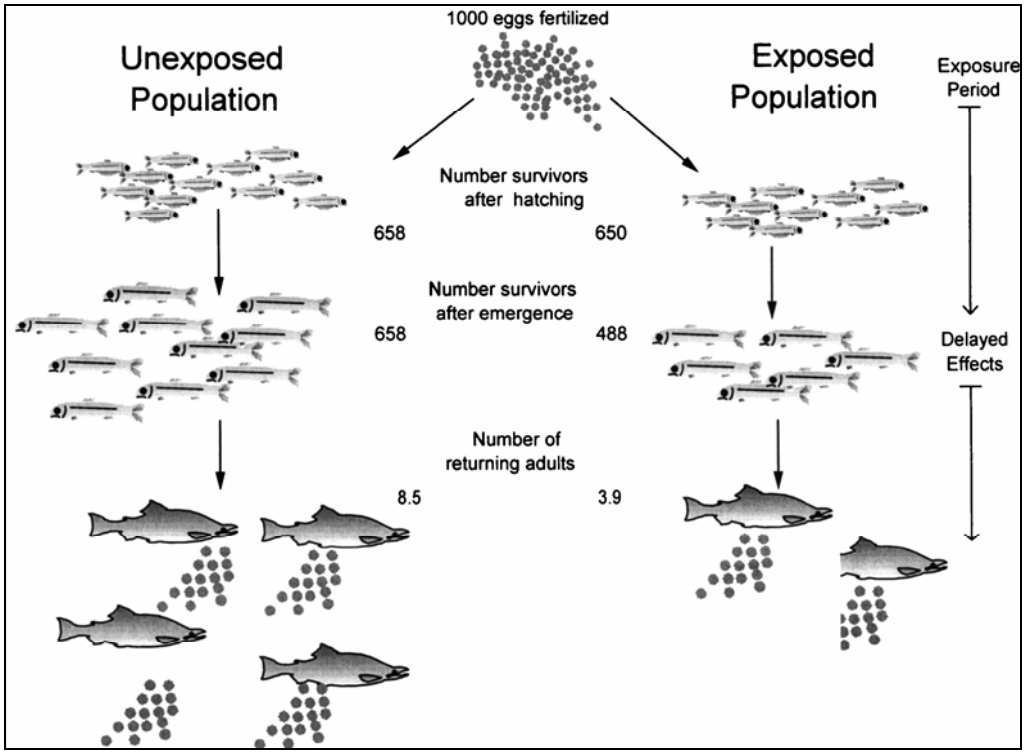


Figure 10. Reduction in overall production of adult salmon after embryonic exposure to a total aqueous PAH concentration of 19 μg/L (parts per billion). Initial reductions in the number of fry produced after incubation are compounded by delayed effects that reduce survival during the marine phase. Survival rates during incubation taken from Heintz *et al.* (1999) and marine survival from Heintz *et al.* (2000), (From Short *et al.* 2003)

Carls *et al.* (1999) also found in a laboratory experiment that growth of pink salmon fry was reduced by oil contaminated food. Feeding and survival were reduced at high oil concentrations (34.8 mg total oil per gram of food). They conclude that their experiments support the hypothesis that juvenile pink salmon in Prince William Sound were contaminated with hydrocarbons from Ezzon Valdes oil spill by ingesting oiled prey and that this contamination was responsible for reduced growth of fry in oiled habitats.

Birtwell *et al.* 1999 studied the survival of pink salmon (*Oncorhynchus gorbuscha*) fry to adulthood following a 10-day exposure to the aromatic hydrocarbon water-soluble fraction of crude oil and release to the Pacific Ocean. Saltwater-acclimated, coded-wire tagged, and adipose fin clipped pink salmon (*Oncorhynchus gorbuscha*) fry were exposed for 10 days to seawater (control) or 25–54 μg·L–1 (low dose) or 178–349 μg·L–1 (high dose) of the water-soluble fraction (WSF) of North Slope crude oil. After exposure the fry (30 000 per treatment) were released into the Pacific Ocean to complete their life cycle. The experiment was replicated in 1990, 1991, and 1992. There was no consistent significant dose-dependent effect of the 10-day exposure to the crude oil WSF on growth of the pink salmon prior to their release. Adult pink salmon from this experiment were captured in fisheries and also recovered from their natal Quinsam River, British Columbia. Pink salmon from each treatment group were recovered in similar numbers. Exposure of populations of fry to the WSF of crude oil and release to the Pacific Ocean did not result in a detectable effect on their survival to maturity. Fry from all treatment groups incurred typically high mortality following release, and there were no discernible effects on survival that were attributable to exposure to the WSF of crude oil.

2.5.2. Migration and homing

Salmonid life histories are characterized by high levels of swimming activity. Adequate levels of swimming performance are necessary for food capture, avoidance of predators, migration, and reproductive behavior. A reduction in the swimming performance of salmonids could therefore severely impact the distribution, survival, and abundance.

It is known that Atlantic salmon and other anadrome salmonids migrate back to the river where they were born (homing migration). Homing of salmon is well documented and a number of studies on salmonid migration have demonstrated the importance of chemical information in homestream discrimination. Fish detect chemical stimuli through at least two different channels of chemoreceptors, olfraction (smell) and gestation (taste). Chemoreception is an important contributor allowing fish to respond to their environment, and olfaction is believed to be the predominant chemical sense in fish (Hara, 1986); indeed, predator avoidance, reproduction, and dominance behaviors all involve olfaction to some extent (Chivers and Smith, 1993; Moore and Waring, 1996b; Griffiths and Armstrong, 2000). Literature concerning the impacts of toxicants on the olfactory system has been reviewed numerous times (e.g. Rehnberg and Schreck, 1986; Døving, 1991; Tjälve and Henriksson, 1999), and the majority of previous research has focused on the effects of trace metals. After entering the olfactory system, some toxicants cause cell death or sublethal damage of the olfactory system. There appears, however, to be different mechanisms of toxicant-induced cell death, with some toxicant exposures inducing necrotic cell death (Saucier and Astic, 1995) and others are causing programmed apoptotic cell death (Julliard *et al.* 1996). These two scenarios could result in different functional consequences of toxicant exposure, though this has yet to be verified. By accumulating in cells of the olfactory system and subsequently causing cell damage or death, toxicants can disrupt electrical transmission of sensory information from the olfactory epithelium to higher levels of the brain. In addition to trace metals, several pesticides disrupt electrical transmission within the olfactory system of fish.

Moore and Waring (1996a, 1998; Waring and Moore, 1997) exposed the olfactory epithelium of male Atlantic salmon parr to atrazine, diazinon, or carbofuran and measured the electro-olfactogram (EOG) response to the female priming pheromone, prostaglandin $F_{2\alpha}$ ($PGF_{2\alpha}$). Acute exposure to all three pesticides reduced the EOG response, which correlated with decreased expressible milt and plasma testosterone in exposed males who were subjected to $PGF_{2\alpha}$.

This means that oil pollution might affect both the swimming performance and the salmon's ability to find back to its homestream. If so this could have affects on an individual and a population level.

After the Exxon Valdez oil spill, extraordinary rates of straying of wild pink salmon were observed in Prince William Sound. Sharp *et al.* 1993 reported relatively high straying rates from 9 – 53% (averaged 25%) for wild pink salmon returning in 1991 from both oiled and non-oiled streams. The reason for the high portion of straying might be related to the oil pollution in the area. Another study preformed by Wertheimer *et al.* (2000) detected only small and not significantly differences between fish eggs incubated in oiled gravels and the control group.

Population impacts on wild pink salmon were revealed by Geiger *et al.* (1996). They used a model to estimate the loss in adult pink salmon returns of 1.9 million fish. These estimates were however refuted by Maki *et al.* (1995), who pointed out the high returns for the Prince William Sound region. Rice *et al.* (2001) conclude that there were certainly no catastrophic effects caused by the spill, mainly because of favorable marine survival conditions through the early years after the oil spill. The natural straying rate in Prince William Sound is very high (as much as 50% according to Sharr *et al.* 1995), but the weight of the evidence indicates that fewer salmon returned to oiled streams.

Rice (1973) studied oil avoidance behavior of pink salmon fry in laboratory studies. He concluded that that fry have the ability to detect concentrations of oil in water that are substantially lower than acutely toxic concentrations. This conclusions and observations by others, indicates that migration patterns could be changed by sublethal concentrations of oil.

Thomas *et al.* (1985) studied the effects of oil exposure on the swimming performance of juvenile coho salmon. The results indicate that short-term exposures of fish to the water soluble fraction (WSF) of crude oil induce an increased metabolism which reduces the energy available for swimming. Due to the reduction of swimming capacity, long-term exposures of several days, even at relatively low concentrations, may significantly impact the population level because of the importance of swimming activity to salmonids life histories.

Behavioral tests using a fish, medaka (*Oryzias latipes*), from which the olfactory organs were resected confirmed that fish avoid aquatic contaminants such as surfactants and pesticides mainly by olfaction (Hidaka and Tatsukawa 1989).

In the marine Arctic ecosystem of the Prince William Sound, long term impacts of oil-contaminated sediment on wildlife was documented. Nearshore environments were severely impacted by the spill and associated cleanup efforts, especially in the first three years subsequent to the spill (Spies *et al.* 1996). More than 20 fish species examined after the spill showed evidence of exposure to and effects of petroleum, including cytochrome P4501A (CYP1A) induction, genetic damage, physical deformities, reduced abundance and growth, and/or compromised survival of some life stages (Table 1).

Table 1. Summary of effects of the Exxon Valdez oil spill on salmonids, 1989 – 1992 (from Jewett et al., 2002).

Species	Life stage	Year	Conclusion	Source
				Baker, 1996
Pink salmon—*Oncorhynchus gorbuscha*	Eggs, fry, juveniles	1989–1991	No observed spill effects	Brannon, Moulton, Gilbertson, Maki, and Skalski, 1995
	Eggs, alevins	1989, 1991	Cytochrome P4501A induction only in alevins	Wiedmer et al., 1996
	Embryos, preemergent fry	1989–1992	Embryo mortality	Bue, Sharr, Miffitt, and Craig, 1996
	Juveniles	1989–1990	Oil in diet, but no conclusive spill effects on diet	Sturdevant, Wertheimer, and Lum, 1996
	Juveniles	1989–1990	Cytochrome P4501A induction	Carls, Werthiemer, Short, Smolowitz, and Stegeman, 1996
	Juveniles	1989–1990	Lower growth, abundance, survival	Wertheimer and Celewycz, 1996
	Juveniles	1989–1991	Lower growth, cytochrome P4501A induction	Willette, 1996
	Adults	1989	Aromatic compound metabolites in bile—MS/GS	Krahn et al., 1992
	Adults	1989–1990	Aromatic compound metabolites in bile—FACs	Hom, McGurk, Marty, Hinton, Brown, and Baker, 1996
	Adults	1989–1991	No observed spill effects	Maki, Brannon, Gilbertson, Moulton, and Skalski, 1995
Chum salmon—*O. keta*	Juveniles	1989–1990	Cytochrome P4501A induction	Carls et al., 1996
	Juveniles	1989–1990	Oil in diet, but no conclusive spill effects on diet	Sturdevant et al., 1996
Coho salmon—*O. kisutch*	Adults	1989–1990	Aromatic compound metabolites in bile—FACs	Hom et al., 1996
Cutthroat trout—*O. clarki*	Subadults, adults	1989–1990	Lower growth, survival	Hepler, Hanse, and Bernard, 1996
Dolly Varden—*Salvelinus malma*	Subadults, adults	1989–1990	Lower growth, survival	Hepler et al., 1996
	Adults	1989–1990	Cytochrome P4501A induction, bile FACs	Collier et al., 1996

2.5.3. Long time effects of oil pollution on Pacific salmon in the Prince William Sound

Synthesis of 17 years of Exxon Valdez oil spill studies documents the contributions of delayed, chronic, and indirect effects of petroleum contamination; the most striking information is that oil persisted beyond a decade in surprising amounts and in toxic forms in the sediments in shallow areas, as sufficiently bioavailable to induce chronic biological exposures and had long-term impacts at the population level (Peterson *et al.* 2003). In 2001, it was estimated that 55600 kg of little weathered Exxon Valdez oil were present in intertidal subsurface sediments (Short *et al.* 2004) which represents a decay rate from 1992-2001 of only - 0.22 to -0.30 year-1 (20 to 26% loss over a year) (Peterson *et al.* 2003). This chronic persistence of oil led to population impacts to species closely associated with shallow sediments, notably early life stages of fish in close association with the sediment (Peterson *et al.* 2003 for review).

Field studies of embryos incubating in freshwater streams of Prince William Sound revealed significant new evidence that persistent reservoir of crude oil-induced mortality of embryos at the individual stream level (Rice *et al.* 2001). The persistence of PAH in the spawning environment supports the probability of new exposure to embryos in the years following the oil spill rather than a genotypic damage that occurred in the first years of the oil spill and was passed on in succeeding generations.

Habitat damage resulting from oil contamination in sub-Arctic region is underestimated by acute toxicity assays. Nearshore substrates oiled by spills may become persistent pollution sources of toxic polycyclic aromatic hydrocarbons (PAH). Recent findings (Carls *et al.* 1999,

Short *et al.* 2003, Peterson *et al.* 2003) resulting from research following the Exxon Valdez oil spill include: (1) PAHs are released from oil films and droplets at progressively slower rates with an increasing molecular weight, leading to greater persistence of larger PAHs; (2) eggs from demersally spawning fish species accumulate dissolved PAHs released from oiled substrates, even when the oil is heavily weathered; and (3) PAHs accumulated by embryos from aqueous concentrations of < 1 μg/L can lead to adverse effects appearing at random over the lifespan of an exposed cohort, probably as a result of damage during early embryogenesis. Polycyclic Aromatic Hydrocarbons (PAH) can be a slow-acting poison, and toxic effects may not manifest until long after exposure.

Brannon *et al.* (2006) have studied the returns of adult pink salmon in Prince William Sound, Alaska for sixteen years following the 1989 Exxon Valdez oil spill. They did not find any evidence of spill effects for either intertidal or whole-stream spawning fish. From 1989 through 2004 mean densities for oiled and reference streams tracked each other, illustrating similar responses of oiled and reference stream adult populations to naturally changing oceanographic and climactic conditions. Hatchery fish strayed into the study streams, but similar incursions occurred in oiled and reference streams, and their presence was compensated for to eliminate their influence on determining the success of the returning natural populations. These results, showing no detectable effects of oiling on pink salmon spawning populations, are supported by published field studies on pink salmon incubation success in oiled streams.

Carls *et al.* (2006) studied intertidal sediment surrounding many spawning stream for pink salmon in western Prince William Sound 10 years after the oil spill. Biochemical and egg-dig evidence suggested that oil reduced the survival of pink salmon embryos for several years after the oil spill. Previous research also demonstrated that dissolved oil can be transferred to developing embryos from surrounding oil sediments via drainage of interstitial water as a result of tidal cycling. 10 years after they studied stream water with passive membrane sampling devices, collected sediments and pink salmon eggs for hydrocarbon analysis, and examined juveniles for induction of cytochrome P4501A. The results indicate that there still are some oil left in a few of the most polluted streams but the main conclusion is that the pink salmon spawning habitats have recovered or is recovering from the oil spill. These findings are also supported by a study performed by Murphy *et al.* (1999).

3. Possible effects of oil pollution on Atlantic salmon

There are a limited number of studies on how oil pollution can affect Atlantic salmon. An oil spill in open waters (offshore) will probably not affect the Atlantic salmon very seriously as long as the oil stays in open water. However, if an oil spill occurs in a fjord or near the coastline the negative impact on a salmon population could be severe. The same will happen if oil pollution enters the coastline from an accident in open waters. The harm will depended on the amount of oil, what type of oil, weather conditions, time of year, etc. However studies related to the Exxon Valdez accident in Prince William Sound in Alaska reveal that oil spill can have severe effects especially on the juvenile stages of pacific salmonids. Atlantic salmon and Pacific salmon have some similarities in their life cycle but also some important differences. However some of the results from the studies on Pacific salmon are comparable with possible affects on Atlantic salmon.

The Atlantic salmon use different areas in different life stages. The salmon will smoltify and migrate out of their home river at the age of 3 – 7 years and a length of 10 – 18 cm. How long the smolt will stay in the fjord and inshore before they migrate offshore will differ between

areas. They will return to their home river after 1 – 5 years. On their way back from offshore waters they migrate into the coast and follow fjords and shoreline back to their home river. Atlantic salmon will mainly be in the fjord and close to shore from May to September but this will differ between different rivers and areas. The knowledge about important issues like migration routes and the time Atlantic salmon spent in different areas are very limited.

An oil spill in open waters (offshore) will probably not affect the Atlantic salmon very seriously as long as the oil stays in open water. However, if an oil spill occurs in a fjord or near the coastline the negative impact on a salmon population could be severe. The same will happen if oil pollution enters the coastline from an accident in open waters. The harm will depended on the amount of oil, what type of oil, weather conditions, time of year, etc. Studies on Pacific salmon and other fish species have demonstrated that the young stages of fish are more vulnerable than adult stages.

Most studies conclude that the young stages of a fish species are more vulnerable than adult ones. The fry of Atlantic salmon lives in the river and will not be affected by an oil spill in sea water. The salmon will smoltify and migrate out of their home river at the age of 3 – 7 years and a length of 10 – 18 cm. How long the smolt will stay in the fjord and inshore before they migrate offshore will differ between areas. They will return to their home river after 1 – 3 years. On their way back from offshore waters they migrate into the coast and follow fjords and shallow shoreline back to their home river. Atlantic salmon will mainly be in the fjord and close to shore from May to September but this will differ between different rivers and areas. The knowledge about important issues like migration routes and the time Atlantic salmon spent in different areas are very limited.

An oil spill in a fjord could have negative impact on the smolt of Atlantic salmon. Studies of juvenile fish that are exposed to oil might get reduced swimming performance. This is probably also the case for smolt of Atlantic salmon. Adequate swimming performance is necessary for food capture, avoidance of predators and migration. A reduction in the swimming performance of smolt could therefore severely impact the distribution, survival, and abundance.

Chemoreception is an important contributor allowing fish to respond to their environment, and olfaction is believed to be the predominant chemical sense in fish; indeed, predator avoidance, reproduction, and dominance behaviors all involve olfaction to some extent. The chemoreceptors of both smolt and adult Atlantic salmon might be affected of oil pollution. This could indeed have an impact on, predator avoidance, reproduction, migration and dominance behaviors all involve olfaction to some extent.

Studies have revealed that an oil spill in shallow water could have considerable impact on invertebrates and fish species in these habitats. Atlantic salmon smolts do feed in shallow areas and negative impact on their food items will also have negative impact on smolt.

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Personal communication

- Fredriksen, Arvid, Øksfjord, Finnmark County
- Muladal, Harald, The County Governor in Finnmark
- Rikardsen, Audun, Norwegian College of Fishery Science (NFH), University of Tromsø
- Svenning, Martin, Norwegian Institute of Nature Research (NINA), The Norwegian Polar Environmental Center, Tromsø

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Akvaplan-niva AS
Polarmiljøsenteret/Polar Environmental Centre
N-9296 Tromsø, Norway

Tel.: (+47) 77 75 03 00
Fax: (+47) 77 75 03 01

E-mail: info@akvaplan.niva.no