NORGES HANDELSHØYSKOLE
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Economic consequences of a large oil spill for the cod and herring fisheries in Northern Norway

Erling N. Faugstad

Advisor: Rögnvaldur Hannesson

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NORGES HANDELSHØYSKOLE

Summary

The rich and valuable fish stocks of the Northeast Arctic cod and the Norwegian spring-spawning herring spawn in the waters in and around Lofoten and Vesterålen. Seismic data suggests that the same areas contain large deposits of oil and gas. If oil production is initiated in this area it will involve a risk for oil spills. If an accident occurs during the spawning period the large concentrations of hydrocarbons in the seawater can cause lethal damage to the spawning products. The purpose of this thesis is to estimate the economic consequences of such an incident on the fisheries.

Preface

Norway is a small nation where most of its wealth comes from the production and exportation of oil and gas. The large offshore petroleum deposits have made Norway one of the wealthiest nations in the world. The petroleum resources have also made it possible for Norway to establish one of the best welfare systems and the highest standard of living in the world (UNDP 2009).

The largest deposits of oil and gas have so far been found in the North Sea and in the southern Norwegian Sea, on Haltenbanken. Now there are indications that the sea areas in Lofoten and Vesterålen in Northern Norway contain major deposits of oil and gas. There are many arguments against exploration and production of the deposits in this particular area. Opponents argue that this is a vulnerable area, where corals, sea birds, fish, and the fragile eco-system may be severely and irreparably damaged if a large oil spill occurs. For this reason the opponents of oil production in Lofoten and Vesterålen invoke the precautionary principle.

The question of the exploitation of these resources involves vast values that can have a great impact on the future generations of Norwegians. The debate also indicates that the mindset has changed over last decades, in terms of the environment. The environment did not get the same attention when oil first was discovered in Norway in the 70s. For these reasons I want to explore one of the main arguments in this discussion; the effects a large oil spill will have on the fisheries in the region. I will through this thesis take a closer look at how an oil spill will influence the main fisheries of Northern Norway, and determine the possible economic effects.

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1. Introduction

1.1 Background for the paper

There are indications that the continental shelf around Lofoten and Vesterålen in Northern Norway include major deposits of oil and gas. The same areas are also the most important spawning areas for the Northeast Arctic cod and an important spawning area for the Norwegian spring-spawning herring.

The debate on oil production in Lofoten and Vesterålen is high on the agenda both in the media and on the political arena, as it involves several conflicting interests. On one hand there is the rich and powerful oil industry, which plays the largest role in the Norwegian economy by generating 25% of GDP (OED 2009). On the other hand there are the environmentalists, which have gained a lot of support and attention the last decade because of global warming and other human caused environmental problems. The environmentalists sympathize and share the similar views of the fishing industry. And since the potential oil reserves are in the same area as the spawning area of two important fish stocks, the Norwegian fisheries have a great interest in the debate. The Norwegian fisheries have a very long tradition, which have made them well respected and protected politically. The Institute of Marine Research, which expresses great concern regarding oil production in the area, plays an important research role on this side of the debate. Because of the risk of an oil spill many politicians and scientists claim that oil production in these areas could have large negative consequences for many of the fisheries.

1.2 Main purpose

With this master thesis, I want to gauge the possible economic consequences a major spill can have for the Norwegian fishing industry. I will focus on cod and herring, since these are the most important fish stocks in the area. The catch of Northeast Arctic cod and Norwegian spring-spawning herring accounts for 50 % of the revenue from Norwegian fisheries (SSB 2007).

Although the focus of the thesis will be on the consequences relating to an oil spill I additionally want to make the reader aware of the actual risk involved. A section about the possibility of a large oil spill will therefore be included. This part will be based on findings from government research.

Bioeconomic models will be necessary for this type of economic analysis. The theoretical part will therefore include a review of the Beverton-Holt model, which is the most important tool for the analysis section.

1.3 Structure

I will start by introducing the areas of interest and briefly discuss the oil and gas deposits that may be available in these areas. Continuing, I will present some background information on the cod and herring fisheries in Norway. I find this insight important in order to understand the dynamics of, and the possible economic consequences from, a large oil spill.

A part of the purpose with this thesis is to make people aware of the risk for large oil spills that follows offshore oil production. The next section will therefore go into details on oil spills. The focus will mainly be on the probabilities of different types of oil spills. This will be based on other scientists' research.

The next section will be on the research made on how oil affects the fish. The impact on the fish stocks depends on a number of factors, which will be presented. Finally, the estimated damage on spawning products and year-class recruitment will be presented. These numbers will play an important role in the later analysis.

The next section is the theoretical section. The model that will be used throughout the thesis, the Berverton-Holt model, will be presented and derived in this section.

After presenting the model the main focus will be on the analysis. Prior to the analysis key numbers regarding fishing mortality, selectivity, abundance, etc. are determined. The selected numbers will thereby be used in modeling different scenarios, based on estimates from official government reports and scientists.

The results will be followed by a discussion of the results of the analysis and potential implications for the fisheries, and a conclusion.

2. Insight

2.1 About the possible oil resources

The reason why the areas of Lofoten and Vesterålen appear to be among the most attractive with regards to oil and gas deposits is the geological similarity between this area and the areas further south where large oil and gas deposits have been found (OED 2003). To determine the resource potential of this area seismic surveys have been conducted. Earlier reports have however been based on geophysical data of variable quality, and the uncertainty regarding the estimates have been very high.

To improve the quality of the estimates The Norwegian Petroleum Directorate (NPD) initiated a new collection of seismic surveys and a new mapping of Nordland VI and VII and Troms II. In the period from 2007 to 2009 more thorough seismic investigations were conducted in these areas. New technology facilitates better and more reliable surveys (NPD 2010). Figure 2.1 illustrates the area of interest and the most promising prospects.

As the resource analysis is based only on seismic surveys knowledge remains limited and considerable uncertainty is still linked to the estimates. One of the main reasons for the large uncertainty is that no exploration wells have been drilled in the area of interest. Exploration wells are crucial to determine whether there is oil and gas in the area (NPD 2010).

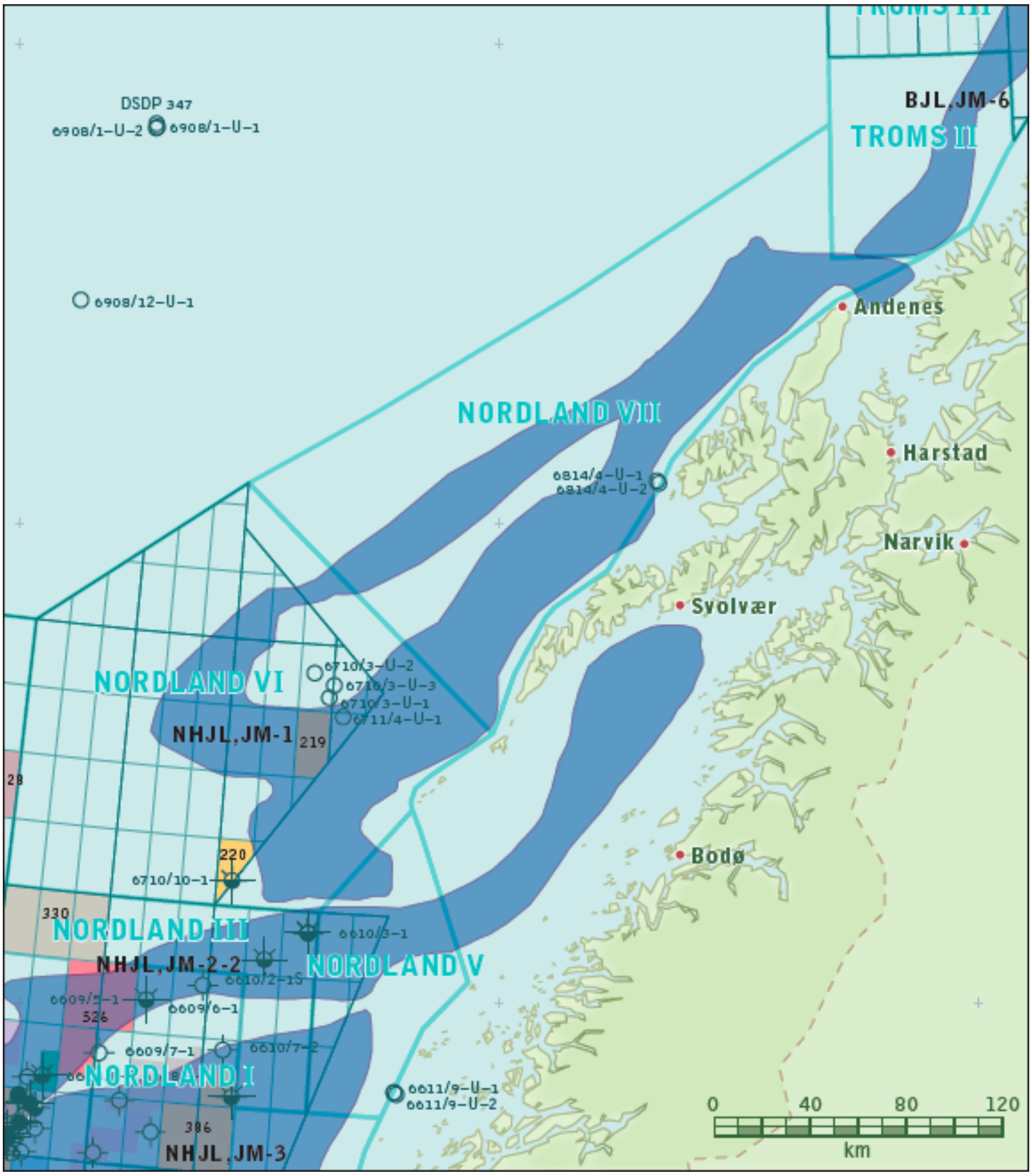

Figure 2.1: This exploration model (Jurassic) illustrates the areas with the largest potential resources (NPD 2010:20).

The main conclusions from the 2010 report:

- Nordland VI is the most promising area. 43 % of the expected exploitable deposits are assumed to come from Nordland VI.
- The total resource estimate for Nordland VII and Troms II is approximately the same as the estimate for Nordland VI alone. 21 % of the expected exploitable deposits come from Nordland VII and 20 % from Troms II.
- The resource estimate for oil is greater than the estimate for gas in Nordland VI and VII. In Troms II, it is likely that there is a higher proportion of gas.

As Nordland V will be more involved in the later parts of the thesis it should be mentioned that 4 % of the exploitable deposits are expected to come from this area.

Figure 2.2 illustrates the total exploitable deposits one could expect to discover in the area. Total expected exploitable deposits are assumed to be 202 million Sm^3 oil equivalents. It is 95 % certain that the resources are more than 76 million Sm^3, and the possibility of discovering more than 371 million Sm^3 is 5 %.

The report further calculates the economic value of these resources. This depends on many factors, the price of oil being the most important of them. A stochastic method was used in order to deal with some of the elements of uncertainty. Expected gross income is 600 billion Norwegian kroner (NOK). The expected present value of the project, using a 4 % discount rate, is 105 billion NOK (NPD 2010).

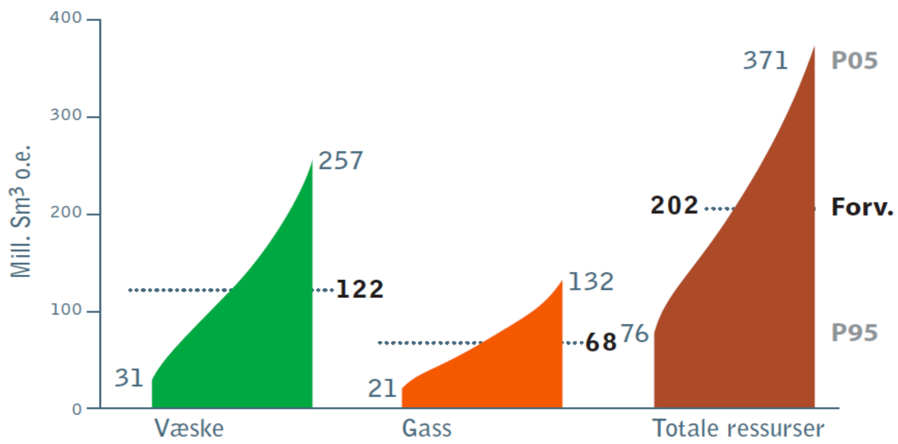

Figure 2.2: Total resources for the complete area. The dotted lines represent the expected values. P95 is the 95 % certain exploitable deposits. (NPD 2010:22)

2.2 *About the fish resources*

There are several species of fish in the areas of interest. However, the scope of this thesis limits how many fish species that can be considered.

The Northeast Arctic cod is the single most important fish stock in the relevant area. Lofoten and Vesterålen are the most important spawning areas for the Northeast Arctic cod. And since eggs and larvae are most vulnerable to an oil spill, an oil spill in this area could have a great impact on this fish stock. Additionally the Norwegian spring-spawning herring spawns in the same area. The area is not the single most important spawning field for this fish stock, but as we will see an oil spill could cause significant effects on Norwegian spring-spawning herring as well.

2.2.1 Northeast Arctic cod

The Northeast Arctic cod is one of the largest commercial fish stocks in the world. It is a non-pelagic and predatory fish. The stock is now in a fairly good condition (ICES 2009). The size of the total stock and the spawning stock varies, and there have been large fluctuations in total catch of the Northeast Arctic cod. During the mid 1970s total catch was reported at around 900 000 tonnes, which steadily declined to around 300 000 tonnes in 1983-1985. Since 2000 the landings have been between 400 000 and 500 000 tonnes (ICES 2009).

The cod is recruited to the fishable stock at around 3 years old. More specifically, the International Council for the Exploration of the Sea (ICES) imposed a minimum length requirement of 47 cm in 1982 (Nakken 2008). It typically reaches this length at the age of 3.

The Northeast Arctic cod matures in the Barents Sea and off the west coast of Svalbard. When it reaches maturation it migrates to the Norwegian coast to spawn. The Northeast Arctic cod typically reaches maturation at about 6-7 years old. Approximately one third of the spawning stock spawns in Lofoten, in Nordland VII. Another third spawns at the Røst Bank in Nordland VI. However, some years as much as two thirds of the spawning stock will be spawning at the Røst Bank (Sintef 2003). Spawning areas are illustrated in figure 2.3 (orange).

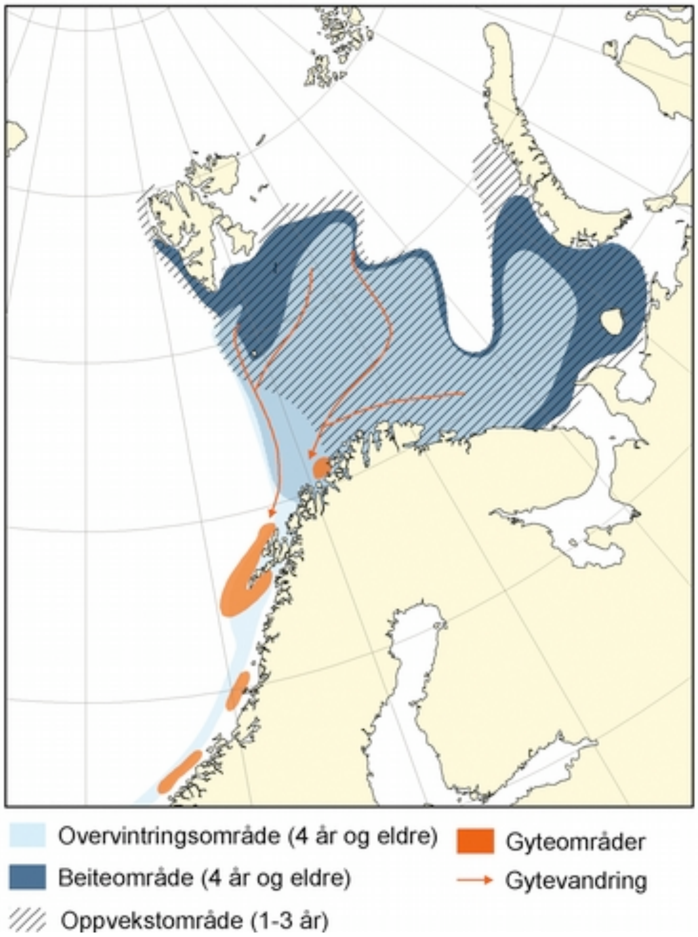

Figure 2.3: Spawning areas in orange. (imr.no)

Pelagic spawning takes place at 50-200 meters depth, and the fertilized eggs rise to the surface and hatch after approximately 15 days (Føyn et al. 2002). Floating near the surface of the water makes them vulnerable to an oil spill. The grown fish is not directly vulnerable to an oil spill as it can avoid the oil by swimming away.

It should also be noted that 70-80% of the cod caught is caught by trawl (Nakken 2008), even though trawlers are prohibited in some areas. Hence, pipelines and platforms might be an obstacle and cause problems for the trawlers if oil production take effect in the areas where trawling is allowed. However, the problems can be alleviated, as the subsea installations can be designed in such a way that the trawling equipment would not be damaged. This is however a minor issue and will not be discussed further in this thesis.

2.2.2 Norwegian spring-spawning herring

The herring fisheries have in the past been the most important Norwegian fisheries. Together with the Northeast Arctic cod it is one of the largest and commercially most important fish stocks in the North Atlantic. The Norwegian spring-spawning herring is in a good condition now, but was on the verge of collapse during the 1960s (Nakken 2008). Landings dropped from 2 million tonnes in 1966 to less than 100 000 tonnes in 1969. This resulted in increasing regulations through the 1970s and a total fishing ban during 1973-1975.

There is now a minimum landing size requirement of 25 cm. Herring typically reaches this size when it is 2-3 years old (Nakken 2008). In my analysis I will assume that the herring recruits to the stock at the age of 3.

The grounds off Møre have been the most important spawning area for the Norwegian spring-spawning herring. In the later years an increasing share of the herring spawning stock has also been spawning on the Røst Bank in Nordland VI. Approximately one third of the spawning stock spawns in this area (Sintef 2003). Additionally, eggs and larvae follow the currents, which result in further spawning products around Lofoten and Vesterålen (figure 2.4). Hence, a discharge of oil in this area will pose a great threat to a large share of the Norwegian spring-spawning herring larvae.

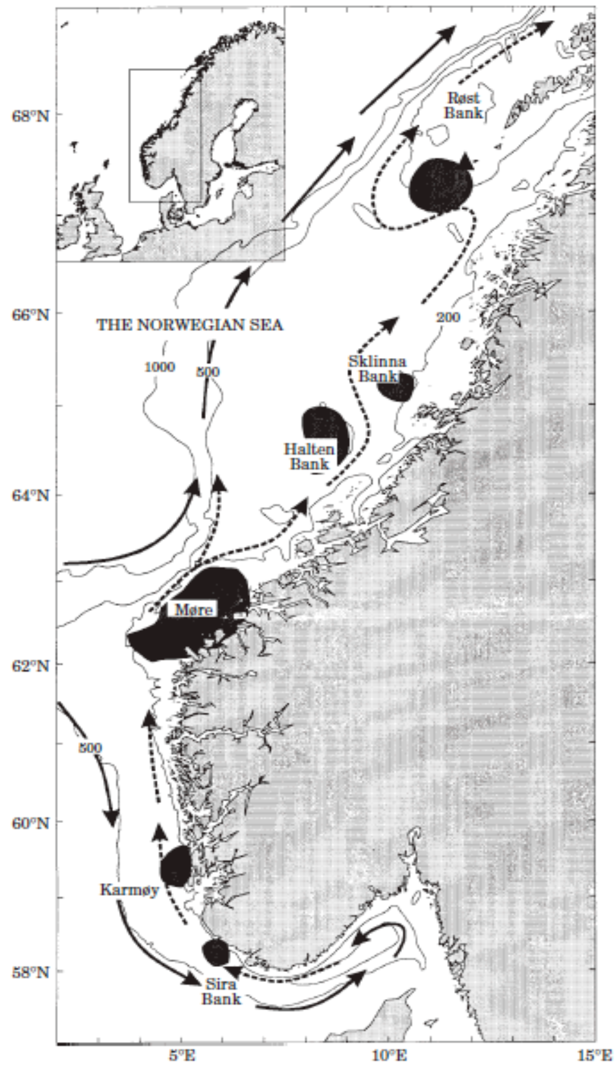

Figure 2.4: Spawning areas and the migration of the Norwegian spring-spawning herring. The black areas are the spawning areas (Sætre et al. 2002:726).

3. Oil spills

The risk of an oil spill is inherently present for activities that involve exploration drilling and oil production. Oil spills occur in different ways, and there are mainly four types of accidents that can lead to large acute oil spills in offshore petroleum activities:

- Breakage of pipelines
- Blowouts
- Spillage from FPSO units (Floating Production Storage and Offloading)
- Tanker accidents

One of the properties of oil is that it is lighter than water. This causes the oil to form an oil slick on the water surface when it is discharged into the sea. The biggest threat after an oil spill is therefore directed at organisms that live in and make use of the water surface. As explained in the previous section, fish eggs and larvae are one of the organisms that float near the surface.

Spillage from FPSO units and tanker accidents will typically be a surface discharge of oil. Whether it blends with the water and forms a thinner and more widespread oil slick depends on the size of the accident and the weather at the time of the accident. High concentrations of hydrocarbons in the water will not necessarily be widespread after these types of accidents. Underwater discharges such as blowouts and breakage of pipelines will however cause the easily water-soluble part of the hydrocarbons to dissolve when the oil rises to the surface (Sintef 2003). This leads to higher concentrations of hydrocarbons that pose a larger threat to the marine environment. How damaging the oil spill will be to the fish therefore depends on the type of oil spill.

The lighter hydrocarbon fractions are the most toxic to eggs and larvae, because they have the highest solubility in water. An important property with these lighter fractions is that they evaporate rapidly. It is expected that between one and two thirds of these fractions evaporate in a few days after an oil spill (Spiro & Stigliani 2003).

The largest oil spill in Norway was the 1977 blowout on the Bravo platform in the Ekofisk area of the North Sea. The blowout lasted for 8 days, and released 9000 tons of oil. Luckily, the blowout occurred at a favorable time weather wise, which caused half of the oil to evaporate. There was no proven harm to the sea life after the accident (NOU 1977:57). In more recent times, a similar accident occurred in Australia. In August 2009 an uncontrolled blowout lead to a large oil spill in the Pacific Ocean. The blowout lasted for more than 2 months and unofficial reports estimates that between 4 000 and 30 000 tonnes of oil were released into the sea (Wikipedia).

There are relatively large uncertainties associated with the probabilities of oil spills. One of the reasons is lack of observations, particularly in Norway alone, where very few accidents have occurred. It is hard to build statistical proof on few observations and small data sets. Few observations of accidents are however a clear indication that the probability for oil spills is small.

In 2003 Scandpower made an oil spill analysis on behalf of the Norwegian governmental working group working on coexistence between the fishing industry and the oil industry. The results from the analysis are presented in table 3.1.

Accident	Activity level 1	Activity level 2	Activity level 3
Long-term leaks	650-1100	190-450	90-220
Short-term leaks	2200	660	320
Blowouts	1300	630	460
Spillage from FPSO	3000	1500	750

Table 3.1: Expected number of years between accidents, based on international statistics (OED 2003:29)

Activity level 3 refers to 3 exploration drillings per year in addition to 6 offshore production fields. The numbers refer to the number of years between each specific accident. According to Scandpower a blowout will only happen once every 460th year. This is a conservative analysis to use for Norwegian conditions, as it is based on international statistics and is thus not directly transferable to Norwegian conditions. Norwegian regulations and safety systems are more developed than safety regulations in many other offshore oil producing countries (PSA 2010). The Norwegian parliament has set as a target that the petroleum sector is to become an international leader in health, safety and the environment.

A more recent analysis by Proactima has not yet been published. Some of the results from this analysis were however published in the 2010 report from DNV (Det Norske Veritas) on the consequences of acute oil spills for fish. The probability of a blowout lasting 50 days discharging 225 000 tonnes of oil is 0.0059 %. The most likely accident according to this recent analysis is a breakage of a pipeline discharging 9 000 tonnes of oil into the sea. The probability for this accident to occur is 0.041 %. (DNV 2010)

The probability of oil spills will not be further emphasized in the following economic analysis. In this thesis, it is first and foremost the actual economic impact of a possible oil spill on the fisheries that will be analyzed. One should nevertheless bear in mind that the probability of a major spill most likely is very low.

4. Effects

The purpose of this section is to describe how an oil spill could cause damage to the stocks of the Northeast Arctic cod and the Norwegian spring-spawning herring. Many studies have been made on how oil spills affect the marine environment. Some properties have already been explained in section 3. In this section I will however mainly focus on the studies from the area of interest. Research on the effects of a discharge in Lofoten/Vesterålen was initiated by the Norwegian parliament. The Norwegian Petroleum Act of 1996 requires a thorough impact assessment of an area before it may be opened for oil and gas production. Such impact assessments ensure that all the important trade-offs are considered, and that the local society and other affected interests are heard. As the Lofoten area is claimed to be particularly vulnerable, and because it has gained a lot of attention in the media and on the political agenda, a number of different research institutions have been taking part in the studies. The first study was conducted in 2003. The work, however, has continued in the years after 2003 and in April 2010 a new report was announced. The results from these studies will act as the basis for this section. Criticism from the Institute of Marine Research (IMR) will also be presented.

As previously mentioned, it is not expected that adult fish will be directly affected by an oil spill. Research has shown that adult fish can sense very low concentrations of oil in seawater, and that they will swim away from the contaminated area (Hellstrøm & Døving 1983). There are few cases of clear negative effects on adult fish after acute oil spills. The largest threat of an oil spill is therefore to the eggs and larvae. Examinations done after previous oil spills have shown clear negative effects on these spawning products (Sintef 2003). The eggs and the larvae die after being poisoned by high concentrations of hydrocarbons in the seawater. The higher the concentration of hydrocarbons, the more damage it will cause to the spawning products. In this way, an oil spill can cause a reduced year-class of fish.

In order for the effect to be significant the oil spill must occur during a period when there are large concentrations of spawning products in the waters, i.e. the spawning period. If the spawning areas are contaminated during the spawning period the damage will last for several fishing seasons, as a smaller year-class will affect the fish stock for many years to come. This will become clearer in the analysis section.

Additionally, an oil spill will cause significant damage to the fisheries, no matter which time of the year the accident occurs. The coastal fleet will lose the ability to engage in fishing activities as long as the fishing areas are contaminated. This could generate a dramatic loss of income, depending on the size of the oil spill and how long it takes for the oil to evaporate. The effect will however only be temporary, and the fish can be caught again at a later point in time.

4.1 Sintef-report 2003

Sintef, Det Norske Veritas and Alpha Miljøforskning were the research institutions behind the study from 2003. I will only use Sintef when referring to their report. A quantitative analysis was made and the proportion of lost spawning products as a result of oil spills in the spawning period was estimated. The damage done by accidental discharges of oil to the marine environment is not easy to predict. There are many factors that will influence the extent of the damage. Sintef based its analysis on events with an intentionally high degree of conflict between oil and spawning products; a worst-case scenario (Sintef 2003:5).

Concentrations of hydrocarbons in the water will, among other factors, depend on whether we are facing an underwater discharge or a surface discharge of oil. As mentioned in section 3, underwater discharges generally result in higher concentrations of hydrocarbons in the water compared to surface discharges (Sintef 2003). The easily water-soluble part of the hydrocarbons dissolves when the oil rises to the surface. The oil that reaches the surface will then form an oil slick that will be much thinner than an oil slick created by a surface discharge. Since the report from 2003 is based on worst-case incidents the analysis primarily focuses on the consequences of an underwater discharge of oil.

Sintef further argues that the mortality rate of the eggs and larvae depends largely on the drift and diffusion of the leaked oil. The oil slick is obviously not as harmful if it drifts away from the important spawning areas. The drift of the oil slick was assumed to be disadvantageous. Sintef gathered information on the sea currents in order to make the simulation of the oil slick as realistic as possible.

The highest concentrations of oil will diminish quite rapidly. If the accident occurs at a different time of the year the critical losses will be far lower. Oil discharged more than two weeks after the hatching period will result in little or no damage to the herring and cod larvae (Sintef 2003). Also keep in mind that the oil spill must occur in the same geographical area as the spawning products.

According to Dervo and Blom-Jensen (2003) 70 % of underwater blowouts on the Norwegian continental shelf will last for less than 7 days. 85 % of the underwater discharges will last for less than 28 days, and the expected duration is 14 days. In other words, it is highly unlikely that we will experience a blowout lasting longer than 28 days.

4.1.1 Cod

Area	Spawning product	Duration	Proportion of spawning products
Nordland VI	Cod eggs	14 days	3.7 %
		28 days	8.3 %
Nordland VII	Cod larvae	14 days	3.6 %
		28 days	21.7 %
Troms II	Cod larvae	14 days	3.4 %
		28 days	16.4 %

Table 4.1: Proportion of spawning products exposed to lethal concentrations of hydrocarbons. (Sintef 2003:57)

In the Nordland VI case the start of discharge is assumed to be in March, when the spawning outside Lofoten has begun. At this time of year the accident will cause greatest damage to the cod eggs in this area. The Nordland VII case assumes that the underwater discharge occurs in May. The Troms II case assumes the accident occurring in June, when the cod larvae have drifted further north from Nordland VI and VII.

How harmful the accident is depends on the duration of the underwater discharge. It seems logical that the longer duration of the discharge, the bigger the area containing lethal concentrations of hydrocarbons will be. The expected loss of spawning products is around 3.5 % in all three areas for a blowout lasting 14 days. Should a blowout last for 28 days we could expect the greatest damage if this occurs in Nordland VII, where 21.7 % of the eggs are expected to be exposed to lethal concentrations of hydrocarbons.

4.1.2 Herring

A major proportion of the herring spawning takes place in the Røst Bank, making Nordland VI the area of interest for the herring simulation. The effects of a similar discharge of oil in Nordland VII will not be as damaging as there are no large spawning areas for herring in Nordland VII. These estimates are based on the worst-case wind-direction and that the oil-spill occurs during March/April. The larvae reach the surface in April, just after hatching.

Area	**Spawning product**	**Duration**	**Proportion of spawning products**
Nordland VI	Herring larvae	14 days	5.6%
		28 days	8.2%

Table 4.2: Proportion of spawning products exposed to lethal concentrations of hydrocarbons. (Sintef 2003:57)

An underwater blowout lasting 14 days is expected to eliminate 5.6 % of the herring larvae. The estimates of a blowout lasting 28 days indicate losses in excess of 8 percent in Nordland VI.

The numbers presented in table 4.1 and 4.2 will be used later in my analysis to determine the economic effects the loss of spawning products will have the next 15 fishing seasons.

4.3 Criticism

It is important to emphasize that these numbers are only estimates and that shortcuts have been made in order to quantify the effect from a large oil spill. The reliability of these estimates has been criticized from several quarters, and I will point out some of these arguments.

Environmentalists have criticized the report for being too uncertain. They argue that their figures and models are highly speculative and that an oil spill can lead to more damaging effects to the fish stocks in the area. These arguments are not backed up by scientific evidence, but they simply invoke the precautionary principle based on the uncertainty of the research (Bellona).

The Institute of Marine Research has criticized the report but has not made an alternative analysis. They have criticized the basis and the conclusions of the risk analysis. In an e-mail correspondence with Erik Olsen it is claimed that the shortcomings of the used method was made clear when the management plan for the Norwegian Sea was presented. The management plan did not open the area for oil and gas production. Erik Olsen is the head of the 'Oil – Fish' department at the IMR. He provided me with a note that points out the fundamental weaknesses of the existing risk analyzes. I will in the following present the main points from this note:

1. The data sets used do not cover the natural fluctuations in the fish stocks. The IMR emphasize that the dynamics of the stocks throughout the last 60 years are not captured because the data used only cover a short time horizon (1990-2004).

   As I have argued earlier in the thesis I do not find it necessary to include the earlier years. I justify this in the fact that the fisheries management has been improving during the last decades (Nakken 2008). We are not likely to see a collapse like this again. The collapse was indeed caused by natural fluctuations, but it was also caused by overfishing and fishing of young fish (Nakken 2008). In conclusion, there are both positive and negative effects of including a larger data set.

2. Basic knowledge of the survival from egg to adult fish is deficient. The Sintef-analysis assumes that the probability of survival is the same for all spawned eggs. According to the IMR this assumption is wrong. Conservative numbers are used in the Sintef-report to account for this. The IMR claims on the other hand that the lacking knowledge cannot be compensated by simple safety factors. The survival from egg to adult fish varies with a number of biological and physical factors, which is too complicated to simplify to a constant factor.

3. Indirect, ecological effects through the food chain are not sufficiently taken into account. The main diet of fish larvae in this area, copepods, has a high

tolerance for the toxin in the oil. The copepods absorb and store the oil in the body. Cod that eats the affected copepod are expected to experience increased mortality. The consequences are not yet quantified, and the IMR is afraid that the mortality rate may change dramatically. To account for this uncertainty Sintef uses a conservative mortality rate. Because the actual consequences are not known the IMR believes that one cannot possibly know whether this is sufficient.

4. Because of natural fluctuations it is not unlikely that the fish stock at some point during the next 50 years becomes very small. The IMR further explains that if this was the case the spawning areas will become smaller and maybe also consist of only one area. If an oil spill occurs in that area the worst-case effect would be destruction of an entire year-class of fish.

Given the uncertainties associated with the existing risk analyzes of an oil spill in Northern Norway the IMR invokes the precautionary principle.

4.2 Det Norske Veritas (DNV) report 2010

In April 2010 DNV published an update of the Sintef-report from 2003. New methods were adopted and some of the results are relatively different from the 2003 report. As this report was published late in the semester of the thesis writing I will mainly focus on the major changes from the 2003 report and the most important results regarding the expected damage to the spawning products and year-class recruitment.

Five major changes have been made:

1. The model for distribution of the larvae has been improved. A wider span of observation is now considered and the new model is perceived as more dynamic than the previous.

2. The oil-drifting model is improved. The new model ensures a more reliable prediction of hydrocarbon concentrations in the water. This is an important new feature of the analysis.

3. Considerable effort has been devoted in finding realistic limits for larvae survival regarding concentrations of hydrocarbons. The report contains thorough documentation on this work.

4. How the oil spill affects the year-class recruitment is included in this analysis. The loss of year-class recruitment is not necessarily the same as the loss of fish larvae. In the previous analysis one assumes that the loss of fish larvae results in an equal loss of year-class recruitment.

5. Discharges from Nordland V are considered. The results indicate that an oil discharge in this area will have the most dramatic effect on year-class recruitment for both cod and herring.

Many different discharge scenarios are modeled and analyzed. I will only focus on the scenarios with the largest effect. Many of the scenarios concerning smaller discharges of oil do not result in concentrations above the limit and is thus not considered to be of any potential harm to the fish.

	Northeast Arctic cod		Norwegian spring-spawning herring	
	Expected	Worst-case	Expected	Worst-case
50 days discharge (4500 t/d)	7.9 %	40 %	16.9 %	50 %

Table 4.3: Expected and worst-case loss of year-class recruitment from a 50 days underwater discharge in Nordland V (DNV 2010).

The expected damage to the year-class of cod is less compared to the 2003 report. An underwater discharge lasting 50 days and releasing 4500 tonnes per day into the seawater is expected to set one year-class of cod back by 7.9 %. It is a less than 5 % possibility that more than 40 % of the year-class is lost.

The oil spill is expected to cause worse damage to the affected year-class of herring. Assuming the same 50 days blowout, it is expected that 16.9 % of the year—class recruitment is lost. Additionally there is an 8.3 % probability that the loss of year-class recruitment will be more than 50 %. Thus, I use a 50 % loss as the worst-case scenario.

The loss will be substantially lower if a similar accident occurs in one of the other areas. These estimates are not considered in this brief review of the 2010 DNV report.

Further, the difference between an underwater discharge and a surface discharge is emphasized. With a tanker accident at Røst with 60 000 m^3 oil there is a less than 0.5

% probability that 5 % of the year-class recruitment is lost. In my analysis I will only focus on underwater discharge of oil as surface discharges have a very limited effect on the spawning products.

The estimates are based on the discharge of Balder crude oil. This type of oil is considered to be an especially heavy crude oil. Compared to lighter types of oil this oil evaporates more slowly from the surface of the sea. The damage is expected to be smaller if lighter oil is leaked into the seawater.

Additionally, the lethal effect limit concerning hydrocarbon concentration is set to be low. Conservative measures are used to account for some of the uncertainties regarding long-term effects of oil spills.

5. Theoretical part

The bio-economic Beverton-Holt model will be the modeling tool for my analysis. This is the only model that will be put to use throughout the thesis. It will be used to model the catch of Northeast Arctic cod and Norwegian spring-spawning herring. Before deriving the model, I will present a short background of the model. In the end of this part I will point out some challenges with the model.

5.1 Background

Raymond Beverton and Sidney J. Holt first presented the model in 1957 in their book "On the Dynamics of Exploited Fish Populations". The model is a discrete year-class model. Fisheries biologists use this model for fish stocks in temperate climates, such as for the Northeast Arctic cod and the Norwegian spring-spawning herring. A year-class model is necessary since we are dealing with fish stocks with many year-classes. Additionally, it is appropriate to use a discrete model, as spawning and fishing takes place during certain periods of the year – not continuously. (Hannesson 1993)

The purpose of the model is to follow each year-class from recruitment until it disappears from the stock. The population of the specific year-class will be reduced over time due to natural mortality and fishing mortality. The population will however also increase, in terms of weight, as the fish grow larger over time.

The model has been modified since it was first developed, and the model used throughout this analysis will be based on the version presented in Hannesson (1993).

5.2 Beverton-Holt model

If we exclude the possibility of fishing, the number of fish in a year-class will change over time at the rate of natural mortality, M. The change in number of fish in the year-class, N, over time can therefore be expressed as:

$$\frac{dN}{dt} = -M \cdot N_t$$

By adding the possibility of fishing, a fishing mortality rate, F, will be added to the natural mortality rate, and we will get the expression:

$$\frac{dN}{dt} = -(M+F)\cdot N_t$$

Which means that in addition to the natural mortality rate, M, the fishing mortality rate, F, is assumed to have an effect on the population of a predetermined year-class N(t).

By solving the differential equation of the time derivative we can find the formula for the total number of fish that remain in the stock at each certain period of time.

$$N_{t+1} = N_t \cdot e^{-(M+F)}$$

Which again makes it possible to calculate how much of the particular year-class that disappears during one period of time (one period = one year).

$$N_t - N_{t+1} = N_t - N_t \cdot e^{-(M+F)} = N_t \cdot \left[1 - e^{-(M+F)}\right]$$

Out of this total we know that the share $F/(F+M)$ have disappeared because of fishing. The total catch can therefore be expressed as

$$\left[\frac{F}{(F+M)}\right] N_t \left[1 - e^{-(M+F)}\right]$$

By summing the catch over the year-classes we can find the total catch from one fishing season (one year).

$$Y_t = \sum_{h^*}^{h^{**}} \left[\frac{F}{F+M}\right] N_{ht} \left[1 - e^{-(M+F)}\right]$$

where h* is the age of the fish when they are recruited to the stock and h** is the age of the fish when it disappears from the stock.

The parameter F, fishing mortality, varies between the different year-classes. An age-specific selectivity parameter, s_h, is therefore added. There are several reasons why the selectivity differs. One is that the early year-classes might not be profitable to catch. The fish need to reach a certain age (size) in order to take the advantage of their growth potential. By regulating the mesh size of the fishing nets and trawls it is to some extent possible to control the size of the caught fish. In the Norwegian economic zone the mesh size for cod must be at least 135 mm. Additionally there is a minimum requirement on the length of the cod of 47 cm (Nakken 2008). F acts as a basis for fishing mortality and the selectivity parameter acts as an adjustment to this basis, based on how accessible the specific year-class is.

It is further common to measure a fish stock and fish catch in weight, and not in numbers of fish. That is why the weight of each year-class is added as an extension of the first yield function. The weight is typically the average weight of the caught fish from each specific year-class.

After adding selectivity and weight the catch (yield) function for time t will be

$$Y_t = \sum_{h^*}^{h^{**}} \left[\frac{s_h F}{s_h F + M} \right] N_{ht} \left[1 - e^{-(M + s_h F)} \right] w_h$$

5.3 Challenges

The Beverton-Holt model has both strengths and weaknesses, as the model is a simplified representation of reality. In this context the model will be used to forecast future catch of cod and herring based mainly on average historical numbers.

Uncertainty will always be present when modeling the future. The parameters will be inaccurate as they change over time. For this reason it is important to run the model for different likely parameter values. As we will see, the size of the affected year-class has a large impact on the results. Not considering the natural fluctuations of the fish stocks is perceived as a weakness, as abundance of new recruits could vary by up to 1500 % from one year to another (Nakken 2008). Different values will also be used for the other parameters. Hopefully, this will provide us with enough information to draw useful conclusions on the effects of an oil spill. More details on these values will be provided in section 6 and 7.

The Beverton-Holt model can also be extended by including stochastic terms, which would provide us with more accurate results. For example one could include stochastic terms that directly take natural fluctuations into account. Such extensions would however involve a far more complex model. Stochastic terms will not be included in my modeling tool.

In conclusion, the main advantage with the model is that it is fairly simple to use and understand. The simplicity of the model is, however, at the expense of the accuracy.

6. Key numbers

To be able to put the Beverton-Holt model to use, we need to decide on the values of several variables and parameters:

- The natural mortality rate.
- The fishing mortality rate.
- The selectivity.
- The abundance of each year-class
- The weight of the fish

The number decided upon in this section will be used for the further analysis in section 7.

6.1 Natural mortality (M)

In fisheries science there are two types of fish mortality; natural mortality and fishing mortality. The natural mortality refers to the death of fish caused by natural reasons, such as predation, cannibalism and disease. The natural mortality **rate** refers to the percentage share of fish that is removed from the fish stock for such natural reasons. To determine the natural mortality rate in a fish population can be very difficult, and several models have been developed for this purpose.

Without going into further details on these models, the natural mortality rates of Norwegian spring-spawning herring and Northeast Arctic cod have been estimated by fisheries scientists. The natural mortality rate used by the ICES on the Norwegian spring-spawning herring is 0.15 (ICES 2009). This is consistent with the findings of Toresen and Østvedt (2000), which was that the natural mortality rate for the Norwegian spring-spawning herring is considered to be less than 0.2, for the adult part of the stock. They also found the natural mortality rate to be relatively stable.

The natural mortality of the Northeast Arctic cod has been slightly higher than for the spring-spawning herring. The ICES report from 2009 used a natural mortality of 0.2 on the Northeast Arctic cod (ICES 2009).

6.2 Fishing mortality (F)

Fishing mortality is the second type of fish mortality and it refers to the deaths in a fish stock that are caused by fishing.

The fisheries are to a large extent controlled by fish quotas. These quotas come close to being a given share of the spawning stock, which causes the fishing mortality to be relatively stable. However, the fishing mortality rate has probably varied more than the natural mortality, especially in the past before quota controls were introduced. This is mainly because fishing mortality is affected by less stable factors. The variability in F is primarily caused by the variability in fishing activity. The fishing activity has a major influence on the fishing mortality, as the fishing activity is decisive for the catch of a fish.

The level of the fishing activity will change over the years, due to several reasons. One of the main reasons is profitability. Consider the case where the catch of one fish becomes more profitable. As far as the fishing equipment allows it, this will cause fishermen to increase the catch of the more profitable fish, and thereby increase the fishing mortality. The fishing mortality of the fish that becomes relatively less profitable will naturally be reduced. Many factors affect the profitability of fisheries, such as demand, abundance and accessibility. For instance, if a fish stock is unusually inaccessible from the coast one season, the coastal fleet will catch less, and fishing mortality, compared to a normal year, could be reduced.

The size of the stock is not necessarily considered as one of the factors affecting the fishing mortality. However, for a given effort level the fishing mortality will be lower if the spawning stock grows larger. The effort will not necessarily increase as the population grows, which causes the size of the stock to have an indirect effect on the fishing mortality.

Average values for fishing mortality will mainly be used in the analysis. However, historical data shows that fishing mortality changes over time, and other values for F will therefore be tested.

6.2.1 Fishing mortality of Norwegian spring-spawning herring

After the collapse in the 60s and 70s the fisheries management became more strict and imposed restrictions concerning the fishing mortality. In order to maintain a desirable level of spawning stock biomass (SSB) the target reference point of fishing mortality is now 0.125 for the Norwegian spring-spawning herring. If SSB should fall below the reference point of 5 million tonnes the fishing mortality rate is adjusted further down (Nakken 2008).

The ICES report from 2009 contains historical data on age-specific fishing mortality. ICES calculates an overall fishing mortality in order to control whether or not they meet their target. This overall fishing mortality is calculated by taking the average fishing mortality for the ages 5 to 14 and weight them by the age-specific stock numbers (ICES 2009). Since 2000 the fishing mortality of Norwegian spring-spawning herring has been fairly stable around 0.15.

In the analysis F = 0.125 will be used as the F generated by the fishing fleet, as this is the target reference point. 0.125 is also close to the average observed fishing mortality ($F_{5\text{-}14\ weighted}$ weighted by stock numbers) from 2000-2008 (ICES 2009, table 7.7.3.2).

6.2.2 Fishing mortality of Northeast Arctic cod

The fishing mortality of the Northeast Arctic cod has also been varying. Everything from 0.3 to 1.0 is considered normal. A study by Kovalev and Bogstad (2005) indicated a relatively stable long-term yield for a range of fishing mortality from 0.25 to 0.60. The fishing mortality reference point used in the ICES reports is 0.40.

The fishing mortality for cod is calculated by the age-specific F for ages 5-10 weighted by stock numbers. The average observed fishing mortality from 2000-2008 is 0.418, which is very close to the target reference point (ICES 2009).

Based on this information I find it reasonable to use 0.4 as the F generated by the fishing fleet in my analysis. But as for the Norwegian spring-spawning herring other values of F will be tested as the F varies on a yearly basis.

A fishing mortality of 0.40 will be used in my main analysis of the Northeast Arctic cod. A sensitivity analysis using different values for F will however also be conducted.

	Norwegian spring-spawning herring	Northeast Arctic cod
Natural mortality	0.15	0.2
Fishing mortality	0.125	0.4

Table 6.1: Natural mortality and fishing mortality for both fish stocks.

6.3 Selectivity

The fishing mortality varies between the different year-classes. It is never 0.40 for all year-classes of cod or 0.125 for all year-classes of herring. Since the analysis will be on a year-class detailed level it is necessary to adjust the F. As shown in the theoretical part an age-specific selectivity parameter is therefore added. The selection process is possible by adjusting the mesh size on the fishing equipment.

The most important reason for the selection process is that the fish caught young will not have exploited its potential for growth. The fish typically has an exponential growth for some years and it is important to take full advantage of this property. By letting the fish grow older it is possible to increase total yield. Additionally, a certain size of the spawning stock is required in order for there to be rich year-classes in the future. Above a certain size no reliable correlation has been found between spawning stock and recruitment. Recruitment is primarily determined by the survival of the eggs and larvae, which again depends on many factors. However, the catch of too many young fish was considered to be the main reason for scarce supply of herring in the early 1900s (Nakken 2008).

As we will see, the selectivity of the older year-classes of fish is the highest. The equipment used and where the different year-classes are located compared to where the fishing takes place determine the selectivity.

The selectivity chosen for this analysis is based on the year-class specific fishing mortality provided in table 3.20 (cod) and table 7.7.3.2 (herring) in the ICES report from 2009. Age-specific selectivity will be given by the year-class specific fishing mortality divided by the weighted fishing mortality. This weighted fishing mortality will be based on the average values registered from 2000-2008 on ages 5-10 for cod and ages 5-14 for herring. The relatively short range of years is chosen because of the large differences in the fisheries management over the past decades. The average values from the 2000s will bring a more realistic reflection of future values than including numbers from 1950-1980. As the IMR argued this might suppress some of the dynamics in the stocks, as large and long-term fluctuations will not be considered in these average values. The range from 2000-2008 does however include some fluctuations, and I believe it is a more accurate measure for the years to come.

For details on the calculation of the selectivity see appendix A.

Selectivity		
Age	NEA cod, F=0.4	NSS herring, F=0.125
3	0.033	0.098
4	0.237	0.416
5	0.674	0.639
6	1.124	0.823
7	1.512	0.986
8	1.778	1.158
9	1.781	1.281
10	1.736	1.566
11	1.560	1.527
12	1.824	1.873
13	1.824	2.505
14	1.824	2.564
15	1.824	2.564

Table 6.2: Assumed age-specific selectivity for the Northeast Arctic cod and the Norwegian spring-spawning herring. See appendix A for details on the calculation of the selectivity.

6.4 Age-specific abundance

The precise pattern of fluctuations in fish stocks is yet to be discovered. Fisheries scientists have however discovered that the main factors affecting the recruitment to the fishable stock are the sea temperature and the supply of food (Nakken 2008). Large fluctuations in recruitment have been observed for both Northeast Arctic cod and Norwegian spring-pawning herring due to these uncontrolled factors.

The age-specific abundance in year 1, the year of the accident, is assumed to be the same as the average abundance from 1990-2008. ICES numbers from the 2009 report are used to calculate this average abundance.

	Year 1	
Age	Cod (thousands)	Herring (billions)
3	615,000	9.9505
4	404,699	8.8008
5	263,376	6.6682
6	149,835	4.8409
7	75,793	3.3221
8	32,619	2.4605
9	11,988	1.7875
10	4,589	1.1734
11	1,673	0.7156
12	522	0.4867
13	259	0.3158
14	0	0.1802
15	0	0.2153

Table 6.3: Assumed age-specific abundance in the year of the accident. Average values from 1990-2008 (ICES 2009).

Assuming average values can however bring on misleading results. The impact from a large oil spill will depend on how rich the affected year-class is. Large fluctuations can occur on a yearly basis. For example, the number of recruits in the herring stock (3-year-olds) varied from 2.40 billion in 2004 to 28.15 billion in 2005. For this reason I will be using different states of recruitment in my analysis. I will create states of weak, rich and average year-classes of the fish stocks, and compare these answers.

	Rich state	Average state	Weak state
Recruitment, herring (in billions)	28.15	9.95	2.40
Recruitment, cod (in thousands)	880 000	615 000	305 000

Table 6.4: Recruitment in year 3

For the rich and weak states I will use recent rich and weak recruitments. For the herring the recruitment values are the same as for 2005 (rich state) and 2004 (weak state). While for the cod, the rich state is the same as the registered abundance in 2007, whereas the weak is the one from 2004.

Average abundance of cod and herring at age 3 are 615 million and 9.95 billion respectively. The standard deviation is 191.8 million for cod and 9.25 billion for herring. This means that the standard deviation for the Northeast Arctic cod is 30 % of its average recruitment, which is substantial. This is, however, far less than the typical variation for herring, which is almost 100% of its average value. This describes the large fluctuations in the fish stocks, especially for the Norwegian spring-spawning herring. It is worth noticing that the recruitment is not normally distributed. The recruitment is far below the average for most year-classes. The populations are carried mainly by a few rich year-classes. This is especially the case for the Norwegian spring-spawning herring. See figure 6.1.

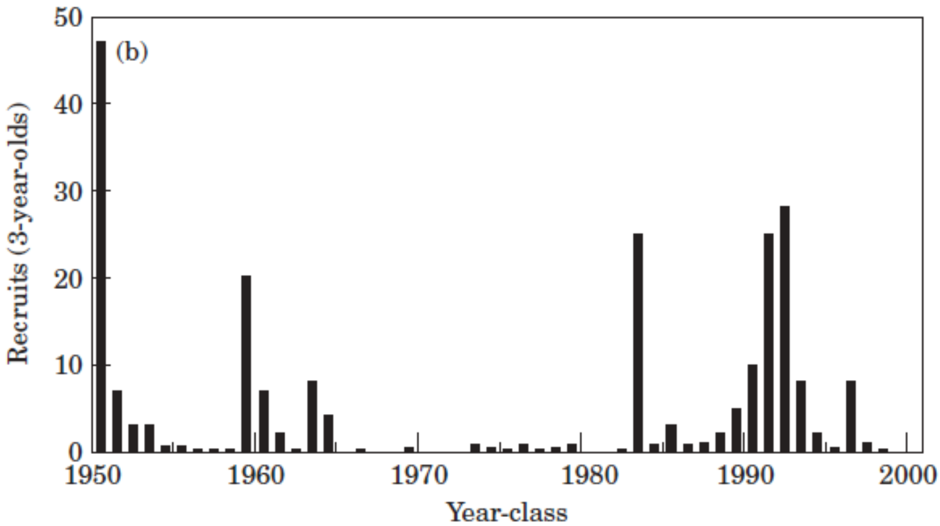

Figure 6.1: Recruitment (billion) for the year-classes 1950-1999 for Norwegian spring-spawning herring (Sætre et al. 2002:727). The 2000s are unfortunately not included in this figure, but there have been 5 rich recruitments during this period.

6.5 Weight of the fish

The weight of the year-classes varies over time. For example, the average weight of a 5-year old herring in 1997 was 207 grams, and in 2007 it was 271 grams. That is an increase of 31.8%. Since we are doing a long-term analysis average weight values will however generate a realistic picture of total weight. The analysis in section 7 is over 15 years and it is likely that the average weight over these years will correspond to the average value the last 19 years. ICES numbers from 1990 to 2008 are used to calculate the average values.

NEA cod	
Age	Weight
3	0.89
4	1.35
5	1.94
6	2.76
7	3.85
8	5.20
9	6.72
10	8.19
11	9.84
12	11.90
13	12.58
14	13.20
15	17.05

NSS herring	
Age	Weight
3	0.17
4	0.22
5	0.26
6	0.29
7	0.31
8	0.34
9	0.35
10	0.37
11	0.37
12	0.38
13	0.40
14	0.40
15+	0.42

Table 6.5: Average weight values for Northeast Arctic cod and Norwegian spring-spawning herring.

7. Analysis

In the following I will start the process of calculating the economic consequences for the fisheries. The Sintef report from 2003 and the DNV report from 2010 provide us with the estimated effects a large oil spill will have on fish eggs and larvae and year-class recruitment.

By the use of the Beverton-Holt model and the numbers previously presented I will first calculate the total catch if no accident happens, then the total catch if an oil spill should occur. Finally, the results of these calculations will be compared to give an estimation of the economic consequences for the fisheries.

7.1 Northeast Arctic cod

The age composition of the stock in year 1 is the average values from 1990-2008. The recruits, 3-year old cod, are the same every year, as discussed in section 2.2. Since we have assumed 15 year-classes, the effect of the oil spill will disappear after 15 years. Total catch with and without the discharge will be the same after 15 years.

7.1.1 28 days blowout (Sintef 2003 estimates)

The Sintef report estimates that 21.7 % of the eggs and larvae would perish if Nordland VII were exposed to a 28-day underwater discharge. If this proportion of the spawning products disappears in year 1 we assume the recruitment in year 4 to be reduced by the same proportion, as the cod recruits to the fishable stock when it is 3 years old.

As described in the theoretical part one single year-class is fished down over several years. The effects of a blowout will therefore be spread over time. Since the affected year-class does not recruit to the stock until the age of 3, the accident will not have an effect on total catch until year 4.

Year	Normal catch[1]	Catch if blowout	Difference	%-difference
1	564,977	564,977	0	0.00%
2	618,373	618,373	0	0.00%
3	688,855	688,855	0	0.00%
4	759,677	758,223	1,454	0.19%
5	815,100	803,156	11,944	1.47%
6	849,277	815,743	33,534	3.95%
7	866,603	820,781	45,822	5.29%
8	874,950	833,055	41,895	4.79%
9	878,918	850,499	28,419	3.23%
10	881,058	866,270	14,788	1.68%
11	881,981	874,871	7,111	0.81%
12	882,397	879,161	3,235	0.37%
13	882,635	880,717	1,918	0.22%
14	882,635	881,834	801	0.09%
15	882,635	882,303	332	0.04%
	12,210,071	12,018,819	191,252	1.57%

Table 7.1: The expected catch (in tonnes) under normal circumstances and in the case of a 28-days blowout, and the difference.

[1] Normal catch is higher than expected. It is not likely that the normal catch will be as much as 880 000 tonnes. The reason for the large modeled catch is the simplified assumption of keeping the same recruitment every year (average recruitment). This also applies to the analysis of herring in section 7.2.

The largest difference is found from year 5 to year 10. These are the years when the damaged year-class represents the largest part of total catch. At its worst the blowout will cause a yearly loss of almost 45 000 tonnes. Which represents more than 5% of total landings. Assuming a price of 16.8 NOK/kg[2] this equals an economic loss of more than 700 million NOK for one year. For 4 years the decline in catches will be more than 3 percent. Accumulated loss over the 15 years is almost 200 000 tonnes, or 1.57%. Assuming 16.8 NOK/kg the total loss is 3.2 billion NOK.

In the scenario where 21.7 % of the eggs are destroyed the worst effect will be a 5 % loss, assuming the accident affects an average year-class of Northeast Arctic cod. 5 percent is a considerable share, but it is common that the fisheries experience variations in yearly landings (section 7.1.6).

7.1.2 50 days blowout (DNV 2010 estimates)

The DNV report estimates an expected loss of 7.9 % of year-class recruitment. Such loss results in the following table:

Year	Normal catch	Catch if blowout	Difference	%-difference
1	564,977	564,977	0	0.00%
2	618,373	618,373	0	0.00%
3	688,855	688,855	0	0.00%
4	759,677	759,148	529	0.07%
5	815,100	810,752	4,348	0.53%
6	849,277	837,069	12,208	1.44%
7	866,603	849,921	16,682	1.92%
8	874,950	859,698	15,252	1.74%
9	878,918	868,572	10,346	1.18%
10	881,058	875,675	5,384	0.61%
11	881,981	879,393	2,589	0.29%
12	882,397	881,219	1,178	0.13%
13	882,635	881,937	698	0.08%
14	882,635	882,344	291	0.03%
15	882,635	882,514	121	0.01%
	12,210,071	12,140,445	69,626	0.57%

Table 7.2: The expected catch (in tonnes) under normal circumstances and in the case of a 50-day blowout, and the difference.

As we can see the economic loss is substantially smaller than under a 21.7 % loss. Yearly loss will never exceed 2 % and will only exceed 1 % for 4 years. In total over

[2] 16.8 NOK/kg was the average price of cod in 2007 (SSB 2007).

15 years one can expect a loss of 0.57 %, which equals 1.1 billion NOK (assuming 16.8 NOK/kg).

7.1.3 Rich year-class vs. poor year-class

The previous two examples have been of average sized year-classes. As described in section 6.4 the size of the year-classes are usually not average sized. The stock usually varies between several small year-classes and a few rich year-classes that ensure a large population. It is expected that the damage will be larger if the oil spill affects a rich year-class. I will assume a 50-day underwater discharge where the year-class recruitment loss is 7.9 %.

Year	Normal catch	Catch if blowout	Difference	%-difference
5	838,817	832,595	6,222	0.74%
6	915,866	898,397	17,469	1.91%
7	957,591	933,721	23,870	2.49%
8	958,139	936,315	21,824	2.28%
9	935,348	920,544	14,804	1.58%
10	910,423	902,720	7,704	0.85%
Total all years	12,589,839	12,490,211	99,628	0.79%

Table 7.3: Results when the discharge of oil affects a rich year-class[3].

Year	Normal catch	Catch if blowout	Difference	%-difference
5	787,356	785,199	2,156	0.27%
6	771,382	765,327	6,055	0.78%
7	760,164	751,891	8,273	1.09%
8	777,633	770,069	7,564	0.97%
9	812,904	807,774	5,131	0.63%
10	846,707	844,037	2,670	0.32%
Total all years	11,765,815	11,731,285	34,530	0.29%

Table 7.4: Results when the discharge of oil affects a poor year-class.

The rich state refers to 2007 when 880 million fish was recruited to the stock. The poor state refers to 2004 when the recruitment of 3 years old fish was 305 million.

When a potentially rich year-class is destroyed it causes a larger effect than if a less dominating year-class was struck by the catastrophe (table 7.3 and 7.4). If the underwater discharge occurs during the spawning in the rich state it will lead to a reduction in catches of more than 2 % for year 7 and 8. If the oil spill affects the poor

[3] Only year 5-10 are shown, as these are the years when the oil spill will have the greatest effect.

year-class the accumulated effect over all 15 years would be 0.29%. At its worst, the decline in catches is just above 1 %.

These results are as expected. A rich year-class will dominate the total landings for many years, and cause improved catches. A very small year-class plays a minor part of total catches. Since the affected year-class makes a larger contribution to the total catch in the rich state, the damage done in this state will cause more significant effects for the total catch. Notice however that even if a rich year-class is affected by a 50 days discharge it will only result in a total accumulated loss of 0.80 %.

7.1.4 Sensitivity analysis of fishing mortality (F)

The chosen fishing mortality generated by the fishing fleet is not necessarily the same over the years. As with the other parameters it typically varies from year to year. It is therefore necessary to determine the effects of a change in fishing mortality. Long-term yield is fairly stable for a range between 0.25 and 0.60 (Kovalev and Bogstad 2005). We are still considering a 50 days blowout in Nordland V.

F	Total all years	Year 6	Year 7	Year 8
0.20	0.62%	0.87%	1.33%	1.51%
0.25	0.61%	1.01%	1.50%	1.61%
0.30	0.59%	1.15%	1.65%	1.69%
0.35	0.58%	1.29%	1.80%	1.73%
0.40	**0.57%**	**1.44%**	**1.92%**	**1.74%**
0.45	0.56%	1.58%	2.04%	1.73%
0.50	0.55%	1.72%	2.13%	1.71%
0.55	0.55%	1.85%	2.21%	1.66%
0.60	0.54%	1.98%	2.27%	1.60%
0.65	0.54%	2.11%	2.31%	1.54%
0.70	0.53%	2.22%	2.34%	1.46%

Table 7.5: Percentage loss for different values of fishing mortality.

When fishing mortality is high, each year-class is utilized over a shorter period of time. The period, in which the specific year-class dominates the fishing, will experience a larger loss if fishing mortality increases.

This is why the effect for years 6 and 7 increases as the fishing activity for cod intensifies. For these years there are large differences in the percentage loss from the lowest to the highest tested fishing mortality. On the other hand, a higher fishing mortality will lead to a marginally lower total effect on the catch over the 15 years following the disaster.

It is not unlikely that the fishing mortality could increase to 0.6 (ICES 2009). It has been 0.6 and more within the last decade. According to the Beverton-Holt model this would not have a large impact on the total effect, but it would increase the declining catch in year 6 from 1.44% to 1.98%.

Increasing fishing mortality will increase the impact of the oil spill in some years. Total economic effect on the fisheries will however be marginally less.

7.1.5 Worst-case: 50 days blowout (DNV 2010 estimates)

As mentioned in 4.3 the worst-case scenario is a 50 days underwater discharge resulting in a 40 % loss of year-class recruitment. We have also seen that the effect is larger when a rich year-class is affected and it will therefore be assumed that the discharge harms a rich year-class.

Year	Normal catch	Catch if blowout	Difference	%-difference
5	838,817	807,314	31,503	3.76%
6	915,866	827,416	88,450	9.66%
7	957,591	836,732	120,860	12.62%
8	958,139	847,638	110,501	11.53%
9	935,348	860,391	74,957	8.01%
10	910,423	871,418	39,006	4.28%
	12,589,839	12,085,393	504,446	4.01%

Table 7.6: Effects of a 40 % year-class recruitment loss to a rich year-class.

The effects are relatively high. At its worst the total catch is 120 000 tonnes (13.8%) less than under normal circumstances. In terms of economic value this equals a loss of 2 billion NOK (cod price 16.8 NOK/kg). The damage from the oil spill is quite dramatic from year 6 to year 9, and the total effect over 15 years is a 4 % loss. The total loss is almost eight times the loss of an oil spill wiping out 7.9 % of an average sized year-class (section 7.1.2). However, this is the absolute worst-case scenario, regarding the fisheries. The effect will be noticeable for several years and fishermen will be harmed by the economic effect. But it only takes a few years before the catch is the same as if no accident occurred. It is mitigating that the oil spill affects a rich year-class. If the same accident affects a less dominating year-class the effect would certainly be less dramatic.

7.1.6 Yearly variations in the cod fisheries

The last 10 years, the reported catches of Northeast Arctic cod have been between 450 000 and 530 000 tonnes. From 2003 to 2004 there was an increase of 11.8 % in total reported catch (from 465 000 to 520 000 tonnes), but from 2006 to 2007 the cod fishery experienced a decline of 8.5 % (from 497 000 tonnes to 455 000 tonnes). That is an 8.5 % decline over just one year. The fisheries are used to deal with varying conditions and should be able to easily adapt to the small changes the oil spill will cause.

7.1.7 Summary

The estimates from Sintef (2003) and DNV (2010) lead to very different results in terms of yearly economic loss. In the Sintef report it was expected that a larger share of the eggs were exposed to lethal concentrations of hydrocarbons, even by a smaller accident. The focus will however be on the results from the DNV report as this is the most recent study using more reliable data and models.

The Beverton-Holt model predicts that a small share of the normal catch will be lost if an accident occurs. A catastrophe such as the 50 days blowout is not expected to cause a greater loss than 0.79 % over the 15-year period. This is an insignificant effect that the fisheries would be able to adapt to. It is only in the worst-case scenario that the yearly effect will cause larger problems for the fisheries, when up to 12.6 % of the yearly landing value is expected to be lost.

Furthermore, it is important whether a rich or a poor year-class is affected by the accident. The consequences of an oil spill will be very small if it affects a poor year-class. The loss will be greater if a rich year-class is affected.

It is also worth noticing that increased fishing mortality leads to increasing losses during the years where the effects of an accident are the most severe. Total losses over the 15 years are however marginally less the higher the fishing activity.

7.2 Norwegian spring-spawning herring

As with the Northeast arctic cod the age composition of the Norwegian spring-spawning herring in year 1 is the average values from 1990-2008 (table 6.3). The Norwegian spring-spawning herring is also recruited to the stock at the age of 3. The fish stock is no longer affected by the oil spill after 15 years. The damaged year-class will after 15 years be fully utilized and is therefore no longer a part of the fish stock.

7.2.1 28 days blowout

As shown in table 4.1 an underwater discharge lasting 28 days could harm 8.2% of the herring larvae. Consequently, the recruitment in year 4 is 8.2% less than it would be without an oil spill. Average recruitment from 1990-2008 is used as yearly recruitment throughout the 15-year period.

Year	Normal catch	Catch if blowout	Difference	%-difference
1	924,447	924,447	0	0.00%
2	953,576	953,576	0	0.00%
3	1,007,585	1,007,585	0	0.00%
4	1,053,213	1,051,649	1,564	0.15%
5	1,091,398	1,084,208	7,190	0.66%
6	1,123,270	1,112,886	10,383	0.92%
7	1,146,999	1,135,148	11,851	1.03%
8	1,162,206	1,150,385	11,820	1.02%
9	1,174,642	1,163,443	11,199	0.95%
10	1,186,786	1,177,116	9,670	0.81%
11	1,192,904	1,184,056	8,849	0.74%
12	1,196,470	1,190,278	6,193	0.52%
13	1,193,745	1,188,327	5,418	0.45%
14	1,193,745	1,188,731	5,014	0.42%
15	1,193,745	1,190,566	3,179	0.27%
	16,794,730	16,702,400	92,330	0.55%

Table 7.7: Effects of a 28-day blowout in Nordland VI to the catch of the Norwegian spring-spawning herring.

Within the first three years the herring fisheries will not experience reduced landings.[4] In year 4 the effect is only 0.15% of normal catch. During the 5 worst years the yearly loss is approximately 1 %. The effect is very small for the average recruiting herring case.

[4] The herring (and cod) fisheries will not notice reduced catch because of the death of the herring larvae during the first year. One could however experience reduced catch the first year because the oil slick can make it difficult to fish in otherwise important fishing areas.

7.2.2 50 days blowout (DNV 2010 estimates)

As presented in table 4.3 it is expected that a 50 days blowout will cause a 16.9 % year-class recruitment loss for the Norwegian spring-spawning herring. For this case we are assuming the blowout to harm an average sized year-class.

Year	Normal catch	Catch if blowout	Difference	%-difference
1	924,447	924,447	0	0.00%
2	953,576	953,576	0	0.00%
3	1,007,585	1,007,585	0	0.00%
4	1,053,213	1,049,989	3,224	0.31%
5	1,091,398	1,076,579	14,819	1.36%
6	1,123,270	1,101,870	21,400	1.91%
7	1,146,999	1,122,575	24,424	2.13%
8	1,162,206	1,137,844	24,362	2.10%
9	1,174,642	1,151,561	23,081	1.96%
10	1,186,786	1,166,857	19,929	1.68%
11	1,192,904	1,174,668	18,237	1.53%
12	1,196,470	1,183,707	12,763	1.07%
13	1,193,745	1,182,579	11,166	0.94%
14	1,193,745	1,183,412	10,333	0.87%
15	1,193,745	1,187,193	6,552	0.55%
	16,794,730	16,604,440	190,290	1.13%

7.8: Effects of a 50 days blowout to the catch of the Norwegian spring-spawning herring.

The economic loss is noticeably higher in this scenario compared to the previous. According to the estimates by the 2010 DNV report the fisheries can expect a 2 % loss for 4 consecutive years if a 50-day blowout should occur. Assuming a herring price of 2.5 NOK/kg[5] this equals a yearly economic loss of approximately 60 million NOK.

Total accumulated loss over the 15-year period is 1.13 %, or approximately 500 million NOK. The herring fisheries can expect only small economic losses assuming that a 50-day blowout affects an average sized year-class.

7.2.3 Rich vs. poor year class

The fluctuations in recruitment of the herring stock are large. They are even larger than for the cod stock. It is therefore important to study the effects of a disaster on

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[5] 2.50 NOK/kg was the average price of herring in 2007 (SSB 2007).

both a rich and a poor year-class. An underwater discharge lasting 50 days is assumed, reducing the recruitment in year 4 by 16.9 %.

Year	Normal catch	Catch if blowout	Difference	%-difference
5	1,251,815	1,209,885	41,930	3.35%
6	1,354,921	1,294,372	60,549	4.47%
7	1,411,384	1,342,279	69,105	4.90%
8	1,425,917	1,356,988	68,929	4.83%
9	1,424,488	1,359,183	65,305	4.58%
10	1,402,512	1,346,125	56,387	4.02%
11	1,390,315	1,338,716	51,599	3.71%
12	1,334,630	1,298,518	36,112	2.71%
13	1,314,615	1,283,022	31,593	2.40%
14	1,305,597	1,276,361	29,236	2.24%
15	1,264,666	1,246,129	18,537	1.47%
	18,854,584	18,316,179	538,405	2.86%

Table 7.9: Effects of a 50-day blowout in Nordland V affecting a rich year-class of Norwegian spring-spawning herring.

Year	Normal catch	Catch if blowout	Difference	%-difference
5	1,024,825	1,021,256	3,568	0.35%
6	1,027,133	1,021,980	5,153	0.50%
7	1,037,277	1,031,396	5,881	0.57%
8	1,052,764	1,046,898	5,866	0.56%
9	1,070,954	1,065,397	5,558	0.52%
10	1,097,258	1,092,460	4,799	0.44%
11	1,110,978	1,106,587	4,391	0.40%
12	1,139,134	1,136,060	3,073	0.27%
13	1,143,583	1,140,894	2,689	0.24%
14	1,147,325	1,144,837	2,488	0.22%
15	1,164,312	1,162,734	1,578	0.14%
	15,939,881	15,894,060	45,820	0.29%

Table 7.10: Effects of a 50-day blowout in Nordland V affecting a poor year-class of Norwegian spring-spawning herring.

The rich state refers to the herring recruitment in 2005, when 28.15 billion herring was recruit to the fish stock. The poor state is the same as the recruitment in 2004 when only 2.4 billion was recruited to the stock.

In the analysis of the Northeast Arctic cod it was shown that an oil spill occurring in the rich state would have more significant effects on total catch. There are no reasons why the same should not apply for the herring. This is confirmed when reading the tables above.

Assuming the rich state, the yearly loss is approximately 60 000 tonnes, or more than 4 % of normal catch, from year 6 to year 10. The loss is more than twice the loss in the average setting in section 7.2.2. The loss assuming the poor state is almost nonexistent. At its worst, 5 800 tonnes of herring are lost. That is the equivalent of the herring quota on two medium sized fishing vessel.

In conclusion, the size of the affected year-class seems to be crucial for the modeled losses. If the oil spill affects a poor year class the fish stock will not be affected. Historical data shows that there are more poor year-classes than there are rich year-classes (ICES 2009). In other words, the oil spill will most likely affect a poor year-class.

7.2.4 Sensitivity analysis of fishing mortality (F)

Not only the cod can expect variations in the fishing mortality. There have been and will continue to be fluctuations in the fishing mortality of herring, depending on the various factors mentioned in section 6.2. For this case a 50-days blowout is assumed resulting in a loss of 16.9 % of the recruitment in year 4.

F	Total all years	Year 6	Year 7	Year 8	Year 9
0.075	1.13%	1.59%	1.80%	1.82%	1.78%
0.100	1.13%	1.75%	1.97%	1.97%	1.89%
0.125	1.13%	1.91%	2.13%	2.10%	1.96%
0.150	1.13%	2.06%	2.28%	2.20%	2.02%
0.175	1.12%	2.21%	2.41%	2.29%	2.05%
0.200	1.11%	2.35%	2.54%	2.37%	2.07%
0.225	1.10%	2.49%	2.65%	2.43%	2.07%
0.250	1.09%	2.63%	2.76%	2.47%	2.05%
0.275	1.08%	2.77%	2.86%	2.51%	2.03%
0.300	1.07%	2.90%	2.95%	2.53%	1.99%
0.325	1.06%	3.03%	3.03%	2.54%	1.95%
0.350	1.05%	3.16%	3.10%	2.54%	1.90%

Table 7.11: Percentage loss for different values of fishing mortality.

Total percentage loss over all 15 years becomes less the higher the fishing mortality. The difference between the lowest fishing mortality of 0.075 and the highest fishing mortality of 0.35 is however very small in terms of percentage. In terms of economic value it equals a difference in income of 25 million NOK[6].

As explained in section 7.1.4, we will experience a larger loss during the worst years if the fishing mortality increases. For the herring the loss in year 6, 7 and 8 all becomes larger when the fishing activity of herring intensifies. The loss in year 6

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[6] Assuming herring price is 2.5 NOK/kg.

increases with 65 % from a fishing mortality of 0.125 to 0.35. Total loss for year 6 at a high fishing mortality rate is 3.16 %, which equals 100 million NOK[7].

7.2.5 Worst-case: 50 days blowout (DNV 2010 estimates)

According to the DNV report there is an 8.3 % probability that a 50-day blowout in Nordland V results in a 50 % loss of year-class recruitment (see section 4.3). For the worst-case analysis it is assumed that such damage occurs to a rich year-class.

Year	Normal catch	Catch if blowout	Difference	%-difference
5	1,251,815	1,127,763	124,053	9.91%
6	1,354,921	1,175,782	179,139	13.22%
7	1,411,384	1,206,931	204,453	14.49%
8	1,425,917	1,221,985	203,932	14.30%
9	1,424,488	1,231,278	193,210	13.56%
10	1,402,512	1,235,688	166,824	11.89%
11	1,390,315	1,237,655	152,660	10.98%
12	1,334,630	1,227,789	106,841	8.01%
13	1,314,615	1,221,144	93,471	7.11%
14	1,305,597	1,219,100	86,497	6.63%
15	1,264,666	1,209,822	54,844	4.34%
	18,854,584	17,261,670	1,592,914	8.45%

Table 7.12: Effects harming an otherwise rich year-class with a 50 % year-class recruitment loss.

The effects of such an event is significantly greater than the other analyzed cases. The economic loss is more than 10 % for six consecutive years. At its worst the total catch is 14.5 % (205 000 tonnes) less than under normal circumstances, which equals an income loss of more than 500 million NOK[7].

As we can read from the table the total effect over the 15-year period is substantial. 8.45 % of the accumulated income over these years is expected to be lost if an accident occurs during the spawning of a rich year-class. Loss of this magnitude cannot be ignored. It is however important to remind the reader that the probability of such an event is very low. Again, it should be noted that there are more poor year-classes than there are rich year-classes in the herring population. If the year-class recruitment of a poor year-class is reduced by 50 % it will result in a total income loss of only 0.85 %.

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[7] Herring price 2.50 NOK/kg

7.2.6 Yearly variations in the herring fisheries

The herring fisheries are used to large fluctuations in total catch. From 2000 to 2001 the total landings dropped 36 % from 1 210 000 tonnes to 770 000 tonnes. In 2004 total catch was 800 000 tonnes, and only one year later total catch was 1 000 000 tonnes, an increase of 25 %. The standard deviation from 1990 has been 462 000 tonnes, with an average total catch of 850 000 tonnes. In other words, the standard deviation is more than a 50 % deviation from the average value. An oil spill would produce an economic loss, but there is little hold in arguing that this will have a damaging effect to the herring fisheries. The historical large fluctuations in catches indicate that the fisheries will be able to adapt to the temporary income losses presented above.

7.2.7 Summary

Given a 50-day underwater discharge the most recent estimates suggest that economic loss is 1.3 % of total income over the 15-year period. At its worst the fisheries will experience a yearly loss of 2.13 %, or 60 million NOK if the herring price is 2.50 NOK/kg. This is considered as small effects both in terms of value and percentage.

The analysis further shows that we can expect a larger effect if the accident occurs during the spawning of a rich year-class. The effect of striking a rich year-class is larger for herring than it is for cod. The reason is the large variations in abundance between rich and poor year-classes.

Since the fishing mortality for herring is lower than for cod the effect from the oil spill will be more evenly distributed over the years. The sensitivity analysis of the fishing mortality gives us however the same conclusion as in section 7.1. Increased fishing mortality leads to increasing losses during the hardest affected years.

Compared to the cod fisheries the herring fisheries are the most affected in terms of percentage loss. While the total effect for the 50-day blowout is 0.57 % for cod it is 1.13 % or herring. In the worst-case scenario the Beverton-Holt model calculates a total economic loss of 4 % for the cod and 8.5 % for the herring. However, in terms of economic value these losses amount to 8.5 billion NOK and 4 billion NOK, respectively[8].

[8] Cod price: 16.8 NOK/kg. Herring price: 2.50 NOK/kg.

8. Final comments and conclusion

This master thesis has estimated and analyzed the economic consequences of a large oil spill for the cod and herring fisheries in Northern Norway by the use of the bio-economic Beverton-Holt model. The economic consequences turn out to be small, even if we experience a 50-day blowout. The fisheries are used to adapt to income variations because of the natural fluctuations of the fish populations, and are therefore likely to continue to exist as normal once the oil slick no longer causes hindrance to the fishing vessels. A serious economic loss that will cause problematic effects for the fisheries is not to be expected unless we consider a worst-case scenario.

The probability of an accident of this size is very small, and the accident must occur in Nordland V in order to cause significant economic effect. Additionally, the study has shown that the disaster must occur during the spawning period and it must affect a potentially rich year-class. The potential value of the petroleum resources is under any circumstances much higher than the economic loss for the fisheries.

In the public debate the economic consequences for the fisheries have been used as a main argument against oil and gas production in Lofoten and Vesterålen. On the basis of this study, I find this argument to be weak.

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Appendix A:

F	0.4

	NORTH EAST ARCTIC COD					
	Average values 2000-2008					
	Stock number	F	Stock number	Weighted	Weighted F	Selectivity
0						
1						
2						
3	598945	0.0136				0.03411
4	423990	0.0990				0.23694
5	293516	0.2815	293516	50.088%	0.14101	0.67396
6	169916	0.4694	169916	28.996%	0.13610	1.12361
7	77404	0.6318	77404	13.209%	0.08345	1.51246
8	31351	0.7428	31351	5.350%	0.03974	1.77816
9	10235	0.7440	10235	1.747%	0.01299	1.78100
10	3584	0.7252	3584	0.612%	0.00444	1.73610
11	1150	0.6515				1.55965
12	349	0.7619				1.82383
13	169	0.7619				1.82383
14						1.82383
15						1.82383
	1,610,610	F from table 3.20 in the ICES report	586006	100.00%	0.417730	

F	0.125

	NORWEGIAN SPRING-SPAWNING HERRING					
	Average values 2000-2008					
	Stock number	F	Stock number	Weighted	Weighted F	Selectivity
0	146.83	0.000				
1	69.48	0.003				
2	33.32	0.004				
3	12.33	0.014				0.098
4	11.45	0.058				0.416
5	7.76	0.089	7.76	30.800%	0.02755	0.639
6	5.58	0.115	5.58	22.165%	0.02551	0.823
7	2.88	0.138	2.88	11.442%	0.01578	0.986
8	2.95	0.162	2.95	11.705%	0.01896	1.158
9	2.54	0.179	2.54	10.073%	0.01805	1.281
10	1.55	0.219	1.55	6.173%	0.01353	1.566
11	0.82	0.214	0.82	3.261%	0.00697	1.527
12	0.53	0.262	0.53	2.105%	0.00552	1.873
13	0.35	0.350	0.35	1.401%	0.00491	2.505
14	0.22	0.359	0.22	0.874%	0.00314	2.564
15	0.34	0.359				2.564
	298.92	F from table 7.7.3.2 in the ICES report	25.180	100.00%	0.139911	