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Mining industry and tailings disposal

Status, environmental challenges and gaps of knowledge

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Summary - sammendrag

The existing base of experience regarding disposal of waste rock and tailings and environmental assessments relating to the use of chemicals in the mining industry have been collated. National and international experience has been applied, with a focus on disposal of tailings in the marine environment. Sea disposal requires fulfilment of a number of prerequisites in terms of both knowledge of the area where disposal is planned, design of the outfall system and requirements on the actual discharge. There is also an emphasis on identifying knowledge gaps related to the dispersal of tailings and environmental impact.

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Island Copper Mine, British Columbia. Filling of the open pit mine with seawater from the Rupert Inlet fjord after mining was phased out in 1995. The world's highest seawater waterfall!

Foreword

The Norwegian Institute for Water Research (NIVA) has been assigned the task by the Norwegian Climate and Pollution Agency (Klif) to prepare a status report on the level of knowledge of mining and environmental challenges, with a principal focus on sea disposal and use of chemicals.

A draft report was prepared by a resource group formed by Klif. This implies that the report in whole does not necessarily express the views of the individual members.

The resource group comprised the following members:
Harald Sørby, Klif (Chairman)
Glenn Storbråten, Klif (secretary)
Grethe Braastad, Klif
Mads Løkeland, Friends of the Earth Norway
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Maria Thornhill, Norwegian University of Science and Technology (NTNU)
Reidulv Bøe, The Geological Survey of Norway (NGU)
Henrik Rye, SINTEF
Jan Helge Fosså, the Institute of Marine Research (HI)
Trygve Dekko, Multiconsult AS
Tor Jensen, Det norske Veritas (DnV)
Jens Skei, NIVA

We would like to thank all the members for their hard work.

Please note that the resource group's work was limited to contributions within the members' individual areas of expertise. It is therefore possible that the views in the report do not necessarily represent the same views of the members' respective institutes.

Oslo, October 2010

[Signature]

Jens Skei
Report editor

Content

Summary

Mining of metals, minerals and precious stones creates environmental challenges. There is need of comprehensive and long-lasting environmental solutions regarding management of waste products such as waste rock (coarse material) and tailings (fine grained material).
Mining of metals and minerals includes extraction of a few percent of the ore, causing a large volume of waste material. Historically, waste rocks have been disposed on land, close to the mine, assuming that the waste rock cannot be utilised. If seepage from the pile of waste rock is handled, waste rock is not considered a problem, with the exception of waste rock containing pyrite ores – a more severe environmental problem.
Fine grained tailings has traditionally been disposed in artificial dams or natural lakes. Norway and Canada have a long tradition concerning sub aquatic disposal of tailings from pyrite mines and the lessons learned is that sub aquatic disposal reduces the oxidation of sulphides and formation of acid water and elevated levels of dissolved metals. Disposal of tailings in artificial dams which are permeable has shown to cause problems regarding dust during dry seasons and leakage of metals during wet seasons.
In Norway, the problem regarding disposal of mine tailings from sulphide ores was early recognised. About 1960, the first plans for sub aquatic disposal were made. The disposal site at Hjerkinn was established in 1969. Later the technique was implemented at all mines in Norway with sulphide ores (Grong Gruber, Sulitjelma Gruber, Løkken Verk, Skorovas Gruber, Røros Kobberverk, Bleikvassli Gruber).

The objective of sub aquatic tailings disposal was to slow down the weathering process, using water as an oxygen barrier. Internationally, this was a new approach. As disposal sites, artificial dams and natural lakes, or part of lakes, were used. During many years of experience, a lot of data on effects have been collected through monitoring programmes, also after closing of the mines. The experience is related both to sulphide ores with low sulphur content (<5 %) and high sulphur content (> 30 %). Development of model tools to predict the water quality has been a necessity. Experience data has now been gathered from several deposits and these are used in comparison with estimated data.
As a conclusion, it should be emphasised that sub aquatic disposal in dams and lakes is not straight forward. The largest benefit is related to control of metal mobilisation. The transport of metals from disposal sites depends on the chemical composition of the tailings and other physio-chemical properties. Problems regarding transport of particles are a challenge which is managed more easily in dams compared to lakes. Shallow lakes exposed to wind often create problems.

Investigations have shown that several ore deposits are located near the Norwegian coastline. As a consequence, sea disposal of tailings has to be considered and evaluated. Comprehensive environmental impact assessments (EIAs) are required. There is a need of multidisciplinary competence within natural as well as technical science. If sea disposal will be accepted, site-specific knowledge and use of best available techniques (BAT) will be crucial. A set of requirement specifications should be prepared in relation to the environment. One obvious requirement is that the best available techniques are used at all times.
Sea disposal of tailings has been implemented nationally and internationally for more than 30 years. Experience regarding outfall design, EIAs and monitoring has been collected. However, gaps of knowledge have been identified. A majority of the sea disposal projects has been considered acceptable from an environmental point of view in those cases where disposal has

taken place in locations which are suitable, and BAT has been implemented regarding outfall systems. Non-successful projects lack EIAs, which are supposed to identify environmental risks and uncertainty ahead of the project implementation.

The largest database connected to sea disposal of mine tailings is the Island Copper Mine (ICM) at Vancouver Island, where tailings were disposed in a fjord during a period of 23 years (annual disposal of 12 million tonnes of tailings per year). The monitoring programme has provided a lot of information about dispersal of fine tailings and ecological impacts in the fjord. The most comprehensive EIA for the mining industry was carried out in Alaska related to plans of establishing a molybdenum mine at Quartz Hill (planned for disposal of 24 million tonnes of tailings per year). An extensive impact assessment was carried out and its results will be of value for future studies on marine deposits.

Both these projects comprise deposit of very high volumes of mass, respectively 12 million tonnes and 24 million tonnes of tailings per year to fjord systems that are very similar to Norwegian fjords. The disposal at ICM took place at - 50 metres (relatively shallow) compared to the sea disposal from Titania in Norway at - 113 metres and a planned sea disposal project on the west coast of Norway at - 300 metres depth.

The most important suppositions for sea disposal are:

1. The tailings should be mixed with seawater to achieve a density of the suspension exceeding the density of the seawater where the tailings are disposed. Accordingly, the tailings plume will sink towards the bottom. It is a supposition that the fine particles in the tailings move as a density current along the sea floor instead of dispersal higher up in the water column.
2. The tailings suspension should not contain air bubbles. Such air bubbles would rise in the water masses from the discharge pipe and will carry small particles up to the surface. A system to reduce entrainment of air into the tailings pipe should be installed to avoid air bubbles bringing fine particles to the surface.
3. It is assumed that the levels of sulphides and metals in the tailings are low.
4. The tailings should not contain soluble toxic compounds. The flotation reagents and flocculation compounds to be used should be easily degradable. The mining companies should put an effort into minimising the use of chemicals.
5. The tailings slurry should contain minimum 30 % solids.
6. The site where the disposal takes place should be geotechnically stable to avoid unexpected submarine slides.

These suppositions contribute to predictable sea disposal with respect to environmental risks. There are also some additional critical factors which contribute to reduction of environmental risks:

- Selection of depth of disposal with respect to water stratification.
- Knowledge of site-specific conditions (bottom topography, hydro-physical conditions like salinity, temperature, currents, oxygen levels and ecological status like biodiversity and threatened species as well as user interests like spawning areas, fishery and aquaculture).
- Use of criteria for suitability and acceptance criteria.
- Carry out EIAs and monitoring.

Monitoring is an important element as monitoring results allow adjustments and optimisation of discharge design to minimise environmental effects. A monitoring programme should be comprehensive to assure that the effects of the sea disposal develop as planned. If the environmental responses develop differently, actions should be taken and, if necessary, the disposal should terminate.

The mining industry uses large quantities of chemicals, if flotation is involved in the process. The chemicals include both organic and inorganic substances. Except from a few chemicals, the majority of the chemicals are degradable and non-toxic. However, the volumes involved are large and, although not all the chemicals follow the tailings to the recipient, it is important to model or in the best case measure the concentrations of chemicals in the influence zone at different distances from the outfall point.

Ecotoxicological tests at realistic recipient concentrations in the water will document the environmental risk. The lessons learned from chemical management and routines and systems from the offshore industry should also be considered in the mineral industry.

Overskrift 4

1. Introduction

The Norwegian mining industry has a long history dating back several hundred years. Operations in pyrite mines lasted up to the 1970s, with the last mine closed in 1995. Mining for other materials including sand, aggregates, stone, industrial minerals, iron ore and coal on Svalbard has been significant.

Over the past decade, there has been increasing attention on metals and minerals with an optimistic outlook to the industry’s future, based on increased demand and periodically good prices. This has resulted in an increase in exploration, and the number of claims (or exploration permits, according to the terminology in the new Norwegian Minerals Act) has seen a substantial growth in Norway, from both Norwegian and foreign mining companies.

When new businesses are founded or closed mines reopened, it is important to organise operations so that they can be executed in harmony with society and nature, and other industries. It has been frequently highlighted in recent times that the principle of social acceptance is the most important prerequisite for the success of the mining industry. This requires the industry to identify good solutions for management of waste, which are environmentally acceptable and technically viable. One particularly major environmental challenge in this context is the management of the large volumes of residual substances (waste rock and tailings) and the use of chemicals (flotation and flocculation chemicals). The potential for value creation in this industry relies on environmental solutions that are long term (eternal perspective). The operational period for a number of mining companies may be restricted to a few decades, if the resources are limited in scope. In such a situation, it is important that the technology applied to extract the resources and manage the waste minimises environmental problems.

Knowledge and insight into the technical challenges of the mining industry are required to identify and use the correct environmental solutions. Knowledge can be obtained via use of existing know-how from national and international operations. If the existing experience is not sufficient, new knowledge must be obtained via R&D programmes. The decision-makers need research and knowledge on which to make their decisions. Normally, a major project in the mining industry will require an environmental impact assessment (based on the size of the material extraction or areas impacted). Such processes require knowledge and resources, but are absolutely essential to ensure sufficient clarification of the consequences for the environment, society and natural resources.

2. Boundaries for the work

In connection with Klif's case management for mining issues, it is important to summarise knowledge of environmental solutions for the mining industry in a report that can be utilised as a reference document for Klif. In addition, the establishment of a resource group will provide expert support for Klif's work.

The report and resource group shall in principle be limited to new operations. The focus shall be on tailings disposal and in particular sea disposal, as experience of sea disposal is more limited than knowledge of disposal in fresh water. The work shall also cover the use of chemicals in the industry and consequences for the environment. As such, it is mainly the water-related environmental challenges that are highlighted.

It is nonetheless important to collect experience from environmental work in general related to closed mines and mining. As there are no pyrite mines open in Norway today, the experience data is from closed mines. In the event of future landfills for tailings containing pyrite ore, it will be important to have an overview of alternative methods of managing the environmental problems (for example, different techniques to deal with seepage of acidic and metalliferous water). This is a complex and comprehensive field that is not discussed in detail in this report, but which requires a separate study.

Minimising waste and purification technology for seepage are important subjects in this industry and should be flagged as subjects for research and innovation within environmental technology.

The work shall identify the most important environmental challenges and at the same time assess whether there is sufficient knowledge on which to classify these challenges with regards environmental risk. In addition, the work shall assess alternative technical solutions (for example, outfall systems, use of flocculation agents to limit the dispersal of fine material in the water etc.) which will be of use for the industry and authorities.

The report also contains a comprehensive reference list in addition to a bibliography on the disposal of tailings and use of chemicals. Furthermore, the report contains an Annex at the end updating the status of sea disposal knowledge obtained during the period 2010-2018 (written by Jens Skei, Skei Mining Consultant)

3. Overview of relevant legislation

3.1 The Norwegian Pollution Control Act

The purpose of the Norwegian Pollution Control Act dated 13 March 1981, no. 6 is to protect the outdoor environment against pollution and to reduce existing pollution, to reduce the quantity of waste and to promote better waste management. The discharges of solid substances, liquids or gas to air, water or ground, and noise and vibrations that cause or may cause damage or a disturbance of the environment are defined as pollution. Waste is defined as scrapped movable property or substances that are unsightly, cause damage or disturbance of the environment. The fundamental premise of the Pollution Control Act is that it is prohibited to pollute and litter unless this has been legalised by means of a permit or exemption in regulations laid down pursuant to the Pollution Control Act. The pollution control authorities are authorised to establish terms and conditions for such permits. Permits granted pursuant to the Pollution Control Act normally stipulate the discharge limit values for pollutants, in areas where the enterprise has significant discharges of such substances.
Ref. https://www.regjeringen.no/en/dokumenter/pollution-control-act/id171893/

3.2 The Norwegian Product Control Act

The purpose of the Product Control Act dated 11 June 1976 no. 79 is to prevent products from causing damage to health or environmental disturbance in the form of disturbance of ecosystems, pollution, waste, noise etc. The Act applies to the production, including testing, and to the import, placing on the market, use and other handling of products. The term “product” means raw materials, auxiliary materials, intermediate products and finished goods of any kind. Any person that handles products that may cause such effects shall exercise due care and take reasonable steps to prevent or limit such effects. The Act aims to ensure that society has sufficient knowledge of the health-related and environmental impact of different products, and the producer shall have in-depth knowledge of these impacts. Producers are therefore obliged to obtain such knowledge of their products so that they are able to assess whether they cause negative health and environmental impacts. Any enterprise that uses products containing chemical substances that may have effects such as are mentioned in section 1 shall evaluate whether there are alternatives that entail a lower risk of such effect. This is referred to as the substitution principle.
Ref. https://www.regjeringen.no/en/dokumenter/product-control-act/id172150/

3.3 Regulations relating to the recycling of waste (Waste Regulations), chapter 9, Landfill of waste (1999/31/EC)

Section 9-2 states that the provisions in this chapter do not apply to
b) ... the deposit of unpolluted soil or of non-hazardous inert waste resulting from prospecting and extraction, treatment, and storage of mineral resources as well as from the operation of quarries
Ref. http://www.lovdata.no/cgi-wift/ldles?doc=/sf/sf/sf-20040601-0930.html.

3.4 The Directive on the management of waste from extractive industries (Mining Waste Directive)

The Mining Waste Directive is currently being implemented in Norwegian legislation, and a proposal has been submitted to incorporate the Directive as a chapter of the Waste Regulations. The Directive distinguishes between disposal at sea and on land, and will comprise both types of disposal. The disposal of mining waste in the sea/water bodies shall be regulated in accordance with the environmental targets according to the Water Regulations. For landfills, the deposits shall be classified e.g. according to the type of tailings material.
Ref. http://www.regieringen.no/nb/sub/europaportalen/eos-notatbasen/notatene/2004/nov/mineralavfallsdirektivet.html?id=523719

3.5 The Water Regulations

The purpose of these regulations is to provide a framework for establishment of environmental targets that shall ensure the most comprehensive protection and sustainable use of water bodies. The different RBD Competent Authorities (RBD is river basin district) shall ensure characterisation of the water bodies and prepare management plans. The objective is for the water bodies to, as a minimum, have a good ecological and chemical condition. Section 12 of the Regulations opens the door to new operations or new interventions. These are permissible even if this implies that the environmental targets in sections 4 to 6 cannot be met or that conditions are impaired, if this is attributable to a) new changes in the physical properties of a surface water body or changed level in a body of ground water, or b) new sustainable activity that implies an impairment to the environmental condition of a water body, from very good to good – more detailed conditions must also be met.
Ref. http://www.lovdata.no/cgi-wift/ldles?doc=/sf/sf/sf-20061215-1446.html

3.6 The Pollution Regulations, chapter 30

Companies that produce aggregates, gravel, sand and shingle are governed by chapter 30 of the Pollution Regulations. Requirements have been established in relation to protection and measures to reduce dust, including a requirement for dust extraction with purification on drilling rigs. The equipment shall be integrated in the rig or have water spraying technology. Moreover, limits are imposed on dust fallout and discharge of suspended substances to water, and there are requirements relating to the recipient. The companies are also governed by noise requirements, and shall keep noise measurements and a log.
If a company generates mining waste that is stored for more than three years or is deposited, a plan shall be made for management of such waste. The plan shall be available for presentation to the pollution control authorities on inspection.
Ref. http://www.lovdata.no/for/sf/md/xd-20040601-0931.html#map084

3.7 Regulations relating to restrictions on the use, etc. of certain dangerous chemicals

Dangerous chemical substances and products produced in or imported to Norway in volumes of 100 kg or more per year for private or professional use shall be reported (declared) to the Product Register. This data provides the authorities with an overview of the chemical substances used in Norway. The information is used in the work to reduce utilisation, exposure/damage and discharge of hazardous and environmentally harmful substances. Public information from the Product Register is available at http://www.pib.no/

1. The REACH regulation came into effect in June 2007. The main purpose of the regulation is to achieve improved protection for health and the environment in the EU/EEA by achieving more control of production, import, use and discharge of chemical substances. This shall be achieved by means of systematic registration of chemicals on the market, with requirements imposed on the health and environmental impact of the chemicals. Limits are imposed on the use of the most hazardous chemicals or such use is governed by stringent requirements for approval. The industry is assigned main responsibility for the assessment of the chemicals used, for proposing and implementing safety measures during use and for ensuring information throughout all parts of the supply chain (producer, importer, distributor and downstream users).

Ref. https://www.miljodirektoratet.no/ansvarsomrader/kjemikalier/regelverk/reach/

3.8 The Norwegian Planning and Building Act

The Regulations relating to environmental impact assessments lay down an obligation to carry out environmental impact assessments for the extraction of ore, minerals etc. (according to defined threshold values).
Operations that require major deposits on land and in the sea shall be subject to detailed evaluation for environmental impact assessments, cf. the Regulations relating to environmental impact assessments, section 4.

Permits pursuant to the Pollution Control Act may not be granted in violation of adopted land use/zoning plans in the municipality in question, and without consent from the municipality. Ref. https://www.regjeringen.no/en/dokumenter/planning-building-act/id570450/

3.9 The Norwegian Nature Diversity Act

The purpose of the Nature Diversity Act dated 1 July 2009 is to protect biological, geological and landscape diversity and ecological processes through conservation and sustainable use. Section 8 states that: "Official decisions that affect biological, geological and landscape diversity shall, as far as is reasonable, be based on scientific knowledge of the population status of species, the range and ecological status of habitat types, and the impacts of environmental pressures. The knowledge required shall be in reasonable proportion to the nature of the case and the risk of damage to biological, geological and landscape diversity." Sections 9 and 10 specify the precautionary principle. If there is a risk of serious or irreversible damage to biological, geological or landscape diversity, lack of knowledge shall not be used as a reason for postponing or not introducing management measures. Any pressure on an ecosystem shall be assessed on the basis of the cumulative environmental effects on the ecosystem now or in the future.
Ref. https://www.regjeringen.no/en/dokumenter/nature-diversity-act/id570549/

3.10 Norwegian salmon fjords

29 Norwegian salmon fjords have been established. The purpose of designating national salmon fjords is to provide a selection of the most important salmon stocks in Norway with special protection against harmful intervention and activities in watercourses and against breeding operations, pollution and interventions in estuaries in the nearby fjords and coastal areas.

3.11 The Norwegian Water Resources and Energy Directorate (NVE)'s regulations

The NVE's regulations may be relevant to a number of measures involved in mining. These comprise e.g. the requirement for security and classification systems pursuant to the Regulations relating to dams. For more information, go to www.nve.no

3.12 The Norwegian Food Act

The Food Act is relevant for companies that have an impact on food resources. This may be relevant in terms of food safety for seafood in general, and the health and welfare of animals in aquaculture facilities.

4. Status regarding disposal of waste rock and tailings

The term status is defined as our knowledge platform and experience (national/international) regarding waste management in the mining industry (stone and aggregates, metals and minerals). The status encompasses our experience from disposal of waste rock and tailings (defined in this report as finer than gravel – <20 mm) in lakes or artificial dams on land and in shallow or deep-sea recipients.

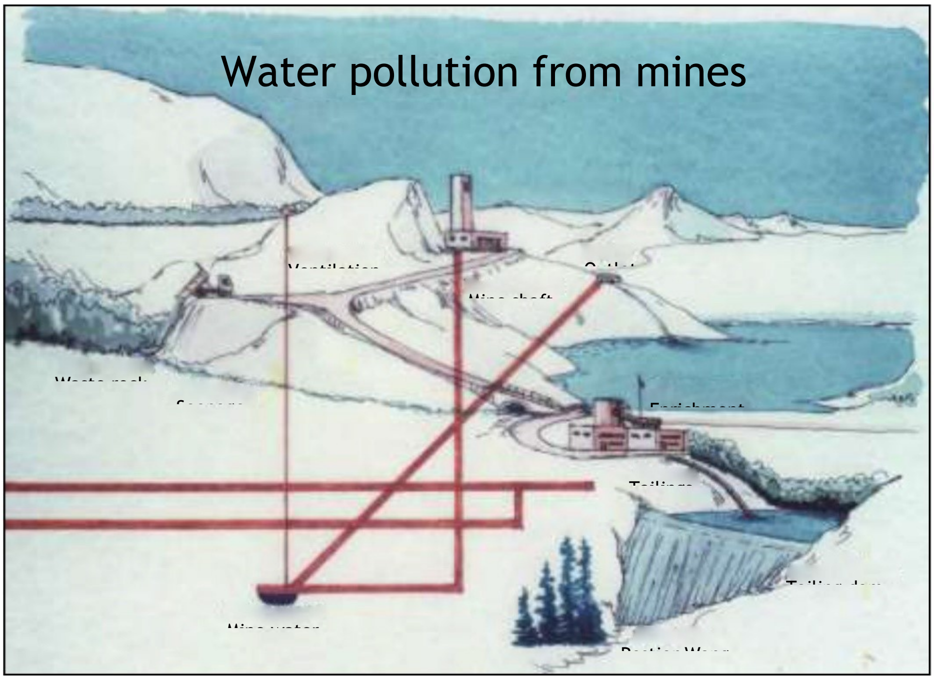
4.1 Disposal of waste rock and tailings on land in Norway

Mining operations require disposal of non-exploitable material either in the form of so-called waste rock or as ground processing waste from the enrichment process. The waste is referred to as enrichment waste or just tailings. Seepage water from such deposits may have very different properties, depending on a number of factors that relate to the type of mine, oxide ore, sulphide ore or industrial minerals. Some segments of the industry, such as the industry for construction raw materials and natural stone, also face challenges in finding good application and disposal solutions for waste rock and fine material.

Seepage from waste rock deposits may be a major source of pollution in many areas, particularly surrounding open pit mines. Such operations require the disposal of large volumes of waste. In Norway, operations in sulphide ore mines have primarily been underground. For this reason, the volumes of waste deposited are relatively low. The environmental problems have related to seepage from rock piles. This applies to a type of rock pile that would not occur with a modern mine, as the problematic waste is generated by old techniques with poor efficiency and that are no longer in use. The waste has a relatively high content of sulphides. Those areas in Norway where the problem of metal seepage from rock piles is most severe are Løkken Verk, Folldal Verk, Killingdal mine and Kjøli mine. Measures have been implemented at the latter two mines. Efficient measures – carried out after mining has stopped – to remedy the above are very expensive and complex if problems are encountered with the development in the water quality in the seepage water from a rock pile. For this reason, it is very important to prepare good prognoses for how water chemistry will develop in such sources.

Comprehensive research projects in this field are under way and have, with time, produced successful tools for such prognoses (MEND, 2009). According to the Mining Waste Directive, such prognoses are a requirement in connection with environmental impact assessments.

The figure below is a principle drawing of a pollution sources from a mine (underground mine).



The most severe environmental problems are found in relation to mining for sulphide minerals. This is due to the weathering properties of the sulphide minerals, which cause release of metals. In Norway, some other types of mining operations have also caused various environmental problems. In Norway, an overview of the environmental status at the most important mines has been developed over time, covering both closed mines and those still in operation. The environmental surveys at most mines started in the 1960s, but there are also examples of individual mining companies independently carrying out environmental surveys much earlier as a result of the damage caused by the company. Over the past 50 years, a lot of documentation has thus been obtained about the environmental effect of waste disposal with outfall to fresh water recipients.

When evaluating the mining industry's environmental problems, it is important to be aware of the major technological developments that have occurred within this industry. These relate in particular to sulphide ore operations. The waste generated at the time of writing differs significantly from that generated only a few decades ago. The enrichment processes are now much more efficient, and attempts are always made to exploit a much higher proportion of the waste. New directives place much more stringent requirements on planning, operations and closing mines.

For closed mines, issues involving cultural monuments have also with time become a difficult subject. Such problems are now on the agenda both at home and abroad. They place new requirements on how to manage environmental challenges.

Below, we will briefly summarise the pollution situation and experiences gained at several central Norwegian mines.

4.2 Sulphide ore mines in Norway

Metals such as nickel, copper, lead and zinc are found in large volumes as sulphide ores in the rock. In Norway, we have a number of pyrite mines that have existed for more than a century and that were closed in numbers in the 1970s, mainly because of poor profitability. Although the mining operations have been terminated, the pollution problems have continued and, in many occasions, increased. Seepage of acidic and metalliferous mine water and seepage water from piles and deposits have been a major problem for water quality in many rivers and lakes, and have had a very negative impact on the ecosystem, in particular fish, in theses water bodies.

Below is a description of some of the classic pyrite mines in Norway.

4.2.1 Folldal Verk

Copper mine, operating from 1748-1941 (Folldal centre).

The environmental problems at Folldal Verk are multifaceted. The most severe problems relate to seepage from the oldest installations at Folldal Hovedgruve (main mine) in Folldal centre. Measures implemented in 1992 to 1994 had no effect of significance in terms of metal seepage. The two largest sources are seepage from waste in the open pit (see photo below) and mine water (Iversen, 2009 a).

Folldal main mine in Folldal centre. Photo: Eigil Iversen 2005

The mine area is protected by the Directorate for Cultural Heritage as a cultural monument. This imposes substantial restrictions on what measures can be taken. As it is impossible to remove or cover the waste in the open pit or seal the old open pit mine where operations started in 1748 (Tyskholet), the only option available is to treat the drainage water. Discharge from the mine area causes pollution of a relatively long stretch of watercourse and can be traced quite some distance down the Glåma river.

The choice of treatment technology will rely on how far to proceed in terms of efficiency and the economic investment made.

The situation at Folldal Verk's last mine in Tverrfjellet mountain in Hjerkinn is completely different. This mine was in production from 1968 to 1993. During planning of the new plant in Hjerkinn, Folldal Verk was already aware of the substantial environmental problems in Folldal centre. They planned therefore to introduce a completely new disposal technique at Hjerkinn by depositing the tailings under water in an artificial dam on what was the Hjerkinnmyra moor. The purpose was to limit the scope of the weathering process and have more control over the dispersal of tailings particles. This proved a successful and forward-looking decision. At that time, this was an innovative disposal technique both at home and abroad. The Hjerkinn dam was therefore the first water-covered deposit for tailings containing sulphide in Norway. The sulphide content reduced with time and was less than 5 % when the mine produced concentrates of copper, zinc and pyrite.

During operations and after the mine in Hjerkinn was closed, the environmental problems were relatively minor. Disposal continued throughout, in compliance with acceptable limits. Particle transport was approximately 300 tonnes/year from the deposit during operations. When compared with the deposited volume of 300 000 tonnes per year, the loss seems moderate, but it still had an effect on benthic fauna communities covering an area of approximately 2 km downstream of the deposit (Iversen et al. 1999 and 2005). The chemical discharges also caused extreme changes in water quality in Folla when compared with original water quality, with much higher than natural calcium and sulphate concentrations in the entire stretch of river in Folla down to the area where it meets the Glåma. The discharge of heavy metals was moderate during operations and these were mainly bound to particles. After disposal was phased out, the water quality quickly returned almost to normal also at the closest station in Folla downstream of the Hjerkinn dam (see photo below).

Hjerkinn dam during operations. Photo: Rolf Tore Arnesen, 1990.

The transport of metals from the disposal site over the years after disposal was phased out have come from sources outside the dam, with constant discharges to the dam from Jernbanestollen were the loading facilities are located. Once the overflow from Jernbanestollen level started to flow to the mine, discharges from the mine have increased. Measures are currently being evaluated in this area. Fish were released to the dam in 1993. In subsequent years, the dam has been used for swimming and angling, and is now cherished as a beautiful part of the landscape. In order to stabilise the surface layer in recent years, large volumes of lime were added to the tailings. The sediment is now compact.

NIVA developed a calculation model to demonstrate how the metal concentrations in the dam will develop over time (Arnesen et al., 1993 and 1997). The model is based on the assumption that the weathering process in the tailings will be limited by the transport of air via the water phase and that the transport of weathering products from the sediment into the free water masses will take place by means of diffusion. In this case, however, the external sources are significantly larger than the discharge from the tailings.

4.2.2 Grong Gruber

Grong Gruber mine in Røyrvik municipality was the second sulphide ore mine where tailings were deposited under water. Two mines were in operation: Joma mine on the east bank of Huddingsvatn lake, which was the main mine; and Gjersvika mine at Limingen. The period for mine operations was 1972 to 1997. Tailings from the mine were deposited in the eastern part of Huddingsvatn lake. The only products from the mine were concentrates of copper and zinc. The iron pyrite was deposited in the eastern part of Huddingsvatn lake together with the other tailings. The sulphur content in the tailings was thus approximately 30 %. The photograph below shows Huddingsvatn lake from the east bank of the lake.

Huddingsvatn lake. The disposal site in east Huddingsvatn lake in the foreground. Photo: Eigil Iversen, 2002.

When operations started in 1972, there was little knowledge of the consequences of such a solution for disposal. It was assumed that the disposal of tailings under water would allow control of the release of heavy metals. The industry had little practical experience of technical solutions for disposal and the effects of such disposal in a lake system. Before mining operations started, Huddingsvatn lake was an excellent lake for fishing, known for its trout. It was assumed that the tailings would sediment in the eastern part of the lake, partly due to the shallow thresholds between eastern and western Huddingsvatn lake.

Only a few years after disposal started, it was concluded that major problems had emerged relating to particle transport from the disposal site and out to the western part of Huddingsvatn lake and Huddingselva river. Studies using an electron microscope with EDAX showed that relatively large particles (250 µm) were transported several kilometres downstream in the watercourse, to the outlet of the next lake, Vektarbotn. Changes were made to the outfall system and settling chemicals were tested. One of the disadvantages with Huddingsvatn lake in terms of disposal is that the lake is very exposed to wind. The wind is often an east-westerly and stirs up the water masses down to the greatest depths, approximately 30 metres. The greatest depth in the disposal site is approximately 20 metres. A gradual polluting effect was confirmed, emerging with the elimination of vegetation in the shallow areas (quillwort) and the disappearance of the amphipod Gammarus lacustris (Norwegian: marflo), an important part of the benthic fauna. Both eastern and western parts of Huddingsvatn lake always had fish, but stocks diminished and, after 1975, no large fish were caught. With time, fishermen started to notice tailings sludge on their nets.

The development in prices and costs triggered a doubling in production over the space of a few years. This development forced the mining company to carry out a shut-off procedure, filling the thresholds between the eastern and western parts of Huddingsvatn lake. The only opening was above a floating hatch at the threshold farthest from the outfall point, the so-

called Vestersundet sound. The two largest rivers flowing in to Huddingsvatn lake were redirected past the eastern part of the lake, directly to the western part.
The level of particle transport to west Huddingsvatn lake was never particularly high. Visibility depth in the lake was reduced from approximately 15 metres to approximately 6-7 metres, but the volumes were sufficient to cause effects that showed an increase over all the years before action was taken.

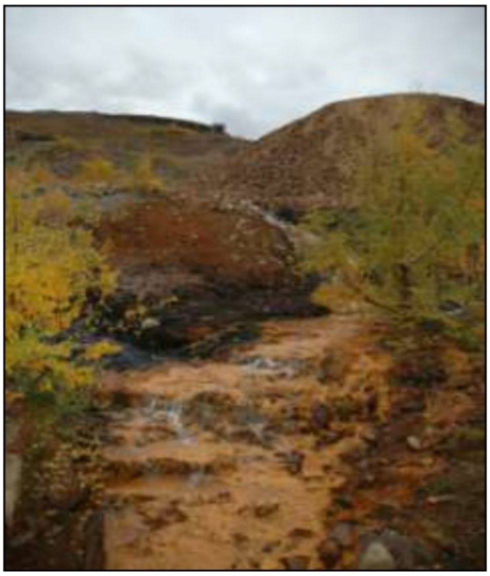
From 1990, once action had been taken, there was a gradual improvement in the environmental status. The situation was monitored until 2002, five years after operations ended. At that point, the status of Huddingselva river had practically returned to normal, but the fish caught in western Huddingsvatn lake still showed no signs of Gammarus lacustris in their stomachs. Vegetation was observed to be recovering in the shallow areas in western Huddingsvatn lake (Iversen et al., 2004). The actual cause of the damage identified up to 1990 was never discovered. It was assumed that it involved purely physical effects in that the crushed tailings particles had biological effects.

The heavy metal concentrations in the Huddingsvassdraget watercourse were never particularly high, but they were observed to diminish once operations had ended. The metal concentrations were somewhat higher in eastern Huddingsvatn lake when compared with the western part. This is due to the weathering of the tailings, releasing some bivalent iron and zinc. Hydrolysis of the iron causes a slight fall in pH in the disposal site. The metal concentrations were on the decline up to the last year of observations in 2004 (Iversen, 2006).

NIVA carried out an evaluation of whether to cap the sediments in eastern Huddingsvatn lake. The model mentioned above was used as part of the evaluation. This model can also simulate the effect of capping. It was concluded that the costs of such a measure would not be proportionate to the benefits (Arnesen, 1998).

4.2.3 The Sulitjelma field

Copper and iron pyrite mine, operational from 1887 to 1991.
There are many diverse and complex pollution problems in the Sulitjelma field in Fauske municipality. The mines are located on both banks of the Langvann lake in the Sydgruve field and Nordgruve field (see photo below).



Waste rock pile at Jakobsbakken mine, Sydgruve field. Photo: Eigil Iversen, 2008.

In principle, the mines were operated as underground mines. Consequently, there is a relatively low volume of waste rock in the area. The pile of waste rock that has been left behind produces acidic seepage, but these sources are of little significance in relation to the discharge of mine water to Langvann lake. The most severe problems relate to the mine water in the Nordgruve field, which is very acidic and metalliferous. The enrichment process was amended in 1973. In 1974, the decision was made to dispose of tailings under water in Langvann lake. Concentrates of copper and zinc were produced at the mine, along with iron pyrite when there was a market for this product. Disposal was carried out satisfactorily up to the mine closure in 1991. It is difficult to assess the impact of the tailings disposal today as other sources have a much more significant impact on pollution. However, it may be claimed that the pollution problems would have been much more severe if the company had continued with their disposal technique utilised prior to 1974, when the tailings containing sulphide were deposited in a landfill directly outside the processing plant.

There are fish in lake Langvann today (see photo below). The copper concentrations in the lake have seen a slight decline since the mine closed, and to such an extent that fish can survive in the lake (Iversen et al., 2009). Under the water surface, the lake can be described biologically as a “desert”. The fish in the lake eat what comes from the water surface and via several clean rivers draining into the lake.

Catches of trout and char from Langvatn, Sulitjelma. Photo: Torstein Kristensen, 2008

4.2.4 Løkken Verk

Copper mine operational from 1654 to 1987.

Løkken Verk in Meldal municipality has for approximately 100 years caused the most severe pollution of all the sulphide ore mines in Norway. The area therefore has a long history of pollution. Up to 1984, mine water was definitively the largest source of pollution in the area. Up to 1984, the mine water was pumped directly into the Orkdalsfjord via a 30 km long pipeline to relieve the impact on the Orkla river. In 1984, the pumps were stopped and Wallenberg mine was filled by the natural inflow of water. It overflowed in 1992. Since then, discharges from the mine have represented a minor source of pollution. Today, seepage from the waste rock and process waste in the mine area are the most significant sources of pollution. There are many different types of mine waste in the area that have been deposited over a period of several centuries. This is the area in Norway with the largest disposal of waste rock containing sulphides and processing waste.

Waste from the final operating period from 1974 until the mine closed in 1987 represents the most severe potential pollutants. This waste is tailings from the enrichment process, where selective flotation was used for production of concentrates of copper and zinc, while the iron pyrite was disposed with the other tailings under water in an artificial dam, Bjønndalsdammen. This was the first disposal under water in Norway of tailings with a high sulphide content (36 % S). The tailings are extremely reactive in air. NIVA has monitored water quality in the dam during the disposal period and for several years after disposal was phased out. A disposal model has been utilised – developed by NIVA – to estimate the future development of water quality in the disposal site after disposal stopped, and then compare this with the actual development in water quality. The estimates proved to concur with the monitoring data (Arnesen et al., 1997, Iversen, 2001; 2006 and Thornhill and Bjerkeng, 2006).

Experience from the disposal site in Bjønndalen provides a good example of the vast difference between the disposal methods used formerly in Løkken and the modern disposal technique under water. For the pollution budget for Løkken mine area, the discharges from tailings disposal in Bjønndalen are insignificant when compared with the other sources, despite the fact that the disposal site has the highest pollution potential in the area.

Bjønndalsdammen dam viewed from the crest of the dam. Photo: Maria Thornhill, NTNU, 2003.

4.2.5 Skorovas Gruber

Skorovas Gruber, operated by Elkem AS, is located in Namsskogan municipality. The period for mine operations was 1952 to 1984. In 1976, the enrichment process was changed by introducing production of concentrates of copper and zinc by means of selective flotation, while the pyrite was disposed along with the other tailings in the closest lake, Dausjøen lake, originally a lake with a natural volume of heavy metals.

After a short time, the pollution situation practically exploded. It emerged that the mine water became acidic very rapidly. In addition, the waste rock tip (Gråbergtippen) outside Grunnstollen produced seepage water that was very acidic and metalliferous. This was the main problem during operations and for a period of 10 years after the mine closed. The problem was solved by increasing the water level in the mine practically to the top. The outlet was then transported to a stream running in to the Skorovasselva river, thereby relieving the impact on Tunnsjøen lake.

The decision was also made to move the waste rock tip and deposit it under water in Dausjøen lake (see photo below).

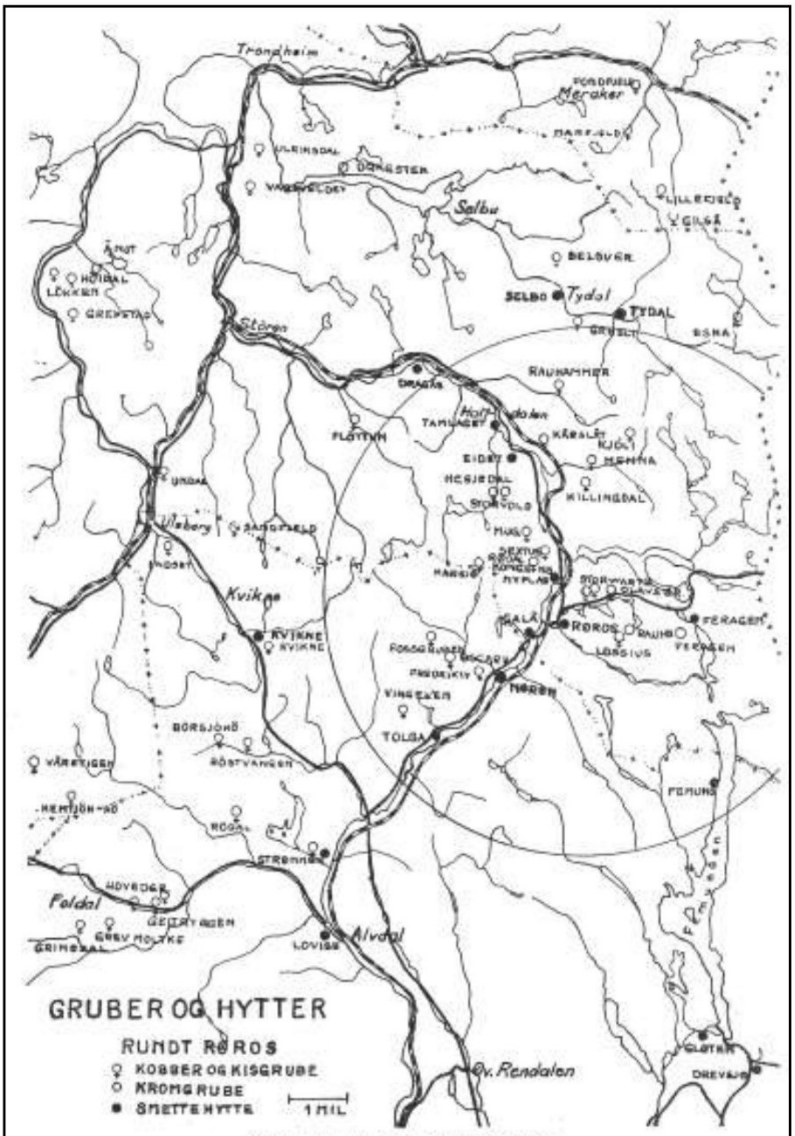
Mine in Skorovatn lake with the waste rock tip. Photo: Rolf Tore Arnesen, 1988.

The measures for Skorovas mine were adopted in 1995. A seepage study was carried out in 2002, showing that the total seepage from the area, in relation to copper, was down by approximately 95 % (Iversen, 2004).

After the change to the enrichment process in 1976, it was also interesting to note the decline in the metal concentrations in the Dausjøen lake. Seepage from the waste rock tip mixed with the alkaline tailings. This provided a very efficient elimination of heavy metals due to adsorption on rock minerals and iron pyrite surfaces. The latter effect is particularly efficient in removing copper, as the copper ions are adsorbed by the iron sulphide surfaces. During disposal in the Dausjøen lake, the pH level in the lake waters was around 9. This provided an efficient precipitation of metals. During periods, lower copper concentrations were achieved than those provided by chemical precipitation of copper with lime, demonstrating an additional effect as a result of the adsorption of copper ions on mineral surfaces.

4.2.6 Røros Kobberverk

Operations at the Røros Kobberverk copper mine lasted 333 years (from 1644 to 1978) and covered a number of mines distributed over a large area (see map below).



Kart over gruver og smeltehytter

i Sør-Trøndelag og Nord-Østerdal. Sirkelen viser den 4 mils sirkumferanse fra Gamle Storwartz gruve.
(Tegnet for Røros Kobberverks historie av ingeniør ved verket, Karl Ingvaldsen).

Mines and smelting plants in the Røros field, with the Circumference marked (centre Storwartz).

Seepage from the waste rock and tailings disposal site cause the most severe environmental problems in this area. The two largest sources are the Nordgruve field, with the main sources seepage from rock piles at the Sextus and Kongens/Arvedalens mine and a tailings pool at Kongens mine (Iversen, 2009b). The largest source of pollution in the Storwartz field is seepage from disposed tailings from the processing plant (Iversen, 2004).

The World Heritage Røros Mining Town and the Circumference Association now plan to include the entire area within the Circumference. This significantly limits the options for efficient measures to limit pollution.

Tailings and piles at the enrichment plant at Storwartz, Røros. Photo: Eigil Iversen, 2002.

4.2.7 Bleikvassli Gruber

Bleikvassli Gruber in Hemnes municipality was in operation from 1957 to 1997. The mine was a sulphide ore mine, initially mined for iron pyrite, but later used for the production of concentrates of copper, lead and zinc. In the last years of operation, the main products were lead and zinc concentrates.

There is a small open pit mine in the area, but once normal operations started in 1957, the mine was operated as an underground mine up to the autumn of 1997, when operations had to be terminated abruptly due to a rockfall in the mine. Tailings from the plant were initially disposed of in an artificial dam in Lille Bleikvatn lake. In 1981, the discharge of tailings was moved to Kjøkkenbukta bay, a part of Bleikvatnet lake. The tailings were deposited at a depth of approximately 40 metres. Kjøkkenbukta bay is particularly suitable for deposits as it is divided into deeper basins by relatively shallow thresholds. These form natural obstacles to particle dispersal to the water masses in Bleikvatnet lake. The lake is substantially regulated with transport of water via a tunnel to Røssvassbukta bay in Røssvatnet lake.

While the mine was open, it was proven that the water masses in Bleikvatnet lake were affected by the tailings disposal, most clearly the zinc concentrations but also lead. Once disposal stopped, the water quality was monitored up to 2002. Monitoring showed that the metal concentrations throughout the lake were on the decline. After a sampling process in the autumn of 2008 (Aanes et al., 2009) there were barely any traces of the effect on the chemical water quality in the lake. One contributory factor here is the impact of the comprehensive regulation of the water level due to hydropower production. This causes erosion in the deposits of sediments in the highly varying littoral zone. With time, tailings and polluted sediments are covered significantly by clean masses.

4.2.8 Bidjovagge Gruber

The Bidjovagge Gruber mines in Kautokeino municipality were operational for two periods; from 1975 to 1980 and from 1985 to 1991. Only copper concentrate was produced during the initial period. When gold was found in the adjacent rock, operations restarted in 1985. Up to the closure in 1991, a copper concentrate containing gold was produced. During the first period, the mine was operated as an underground mine. During the second period, ore was also extracted from a number of smaller open pit mines, but with some underground operations.

Tailings from the mine were deposited in artificial mud ponds where the ground water level was almost at the surface. The surface was ultimately protected by covering it with waste rock. Fully exploited open pit mines were also used to deposit tailings, and were finally covered in the same way.

With time, a number of waste rock tips also appeared in the area – material removed from the open pit mines.

No problems were identified with acidic seepage from the area, neither from the waste rock tips, mines or tailings disposal. The total transport of copper from the area was estimated as approximately 100 kg/year (Iversen and Efraimsen, 1995). Seepage disappears into the loose matter below the mine area. No impact was detected from the mine area discharges in the closest watercourse, the Sieidasjokka, which is a tributary river in the Alta/Kautokeino watercourse.

4.2.9 Nikkel og Olivin

Nikkel og Olivin AS in Ballangen municipality was operational from 1988 to 2002. The mine produced nickel concentrate. There was no market for the olivine, which was deposited with other tailings in two landfills close the Ballangen fjord. The largest landfill was built on Ballangsleira, covering old tailings containing sulphide from the closed Bjørkåsen mine. Total deposits amounted to approximately 7 million tonnes (see photo below).

Deposits from Nikkel og Olivin AS at Ballangsleira. Photo: Eigil Iversen 2007.

The mine was operated as an underground mine, but some ore was also extracted from a small open pit mine. There is little waste rock in the mine area. However, an area was prepared for a tip for loose materials, which were removed before the open pit mine was opened. Seepage from the natural sediments is the largest source of metal seepage in the area (nickel).

When disposal started in Ballangsleira, the company encountered some problems related to dust during the summer. These were resolved by means of a sprinkling system. Once disposal came to an end, the surface was thinly covered with bog land, which was then seeded and artificially fertilised. Fertilisation is absolutely necessary to establish a layer of vegetation to prevent erosion damage. The most significant challenge in the future is to ensure that the vegetation established is not damaged. It is probable that artificial fertilisation will be necessary in the long term. Leakages of metals from the disposal site in the fjord are moderate (Iversen, 2007).

4.2.10 Knaben molybdenum mines

Knaben molybdenum mines in Kvinesdal municipality were operational from 1885 to 1970. The tailings were deposited in a landfill directly outside the mine (see photo below).

Tailing masses at Knaben molybdenum mines. Photo: Eigil Iversen 1996.

The tailings release some molybdenum and copper. The most significant problem in the area, however, is the transport of tailings materials downstream in the watercourse. The closest pond, Store Knabetjern, is about to be filled up.

The surface of the disposal site is also hazardous for the public, and measures will be taken to stabilise sand erosion.

4.2.11 Kjøli and Killingdal mines

Kjøli (1766-1941) and Killingdal mines (1674-1986) are two relatively small sulphide ore mines (copper and zinc) in the northern parts of Gauldalen valley in Holtålen municipality. The most substantial problem with these mines was seepage from rock piles that generated acidic water. Both mines are good examples of how relatively small volumes of mass can have a major impact on watercourses. An extensive area of Øvre Gaula had no fish stocks due to seepage from these rock piles. The rock piles comprised waste rock with a relatively high content of sulphides, a type of waste that would not exist in a modern mine.

The piles were covered in 1989 (Kjøli) and in 2000 (Killingdal). At Kjøli, a plastic membrane was used as a sealing layer, while suitable natural moraine from the area was used at Killingdal. Both projects to cover the tailings had an efficiency rate of more than 90 % and were therefore apparently successful. However, neither project was successful in completely reducing the supply of air to the disposed materials. A high oxygen content can be measured inside both disposal sites. These cause a certain leakage of metals from the disposal sites, evidence that it can be very technically challenging to carry out a successful strategy involving covering disposal sites. This is a topic subject to international research. When plastic membrane is used as a sealing layer, it can be difficult to achieve a sealing towards the underlaying rock.

Covered pile at Killingdal mine. Photo: Eigil Iversen 2000.

4.3 Non-sulphide mines in Norway

The mineral industry comprises the extraction of ilmenite, rutile, marble, olivine, graphite, quartz, anorthosite, limestone and nepheline syenite, to mention a few examples. Industrial minerals are extracted for various industrial applications. The metal content in industrial minerals is normally low, so that the main environmental challenges relate mainly to the disposal of residual substances that, to date, cannot be classified as a resource. The volume of residual substances (tailings and waste rock) varies significantly. With the extraction of rutile, the resource extracted corresponds to perhaps 5 % of the total volume extracted, while the opposite is true for the extraction of limestone, where the major volume is the actual resource and the volume of residual substances is minor in relation to the total amount of rock extracted.

Below are a few examples of extraction of industrial minerals and the related environmental problems.

4.3.1 Titania

In 1989, the company was ordered by the government to build a landfill for tailings. Now, after around 20 years of experience of operations from this landfill, there is sufficient material on which to make a decision on the consequences of continuing to deposit tailings in a landfill. One of the problems with the landfill is that the choice was made to use a permeable dam. As a consequence of this, parts of the tailings have access to air and are exposed to weathering. The tailings contain some sulphide, with a nickel content. It has been discovered that the landfill, after some time, has started to mobilise a certain amount of nickel.

Titania is described in more detail in chapter 4.5.1.

4.3.2 North Cape Minerals, Lillesand

Tailings from this mineral mine were retained in a tailings pond. The overflow water was de-watered in several settling basins downstream. There was concern at one point in time that the relatively high content of fluoride in the outlet would cause damage. Attempts to recycle the hydrofluoric acid were not successful, as the fluoride content was bound to very strong silicon complexes. This also implies that it is not possible to demonstrate any damage caused by the fluoride discharge. The process of fluoride determination involves firstly adding a very strong complexing agent that releases the fluoride ions so that they can be analysed, e.g. by means of ion-selective electrodes.

4.4 International experience of disposal of waste rock and tailings on land

Production at Norwegian mines has been relatively moderate compared to the volumes in many other countries, although there are examples of production volumes in these countries that are similar to those in Norway. The problems can vary significantly when dealing with a mine where annual production amounts to several million tonnes. In relation to the sulphide ore mines we have in Norway, we have been aware of the challenges in advance as we knew the extent of the weathering processes. It can be more difficult to plan new operations in a new area where there is no experience data to support the plans.

It may be most relevant to present some experience obtained in comparable countries in Europe and North America. History has shown that mistakes have been made in most countries due to a lack of expertise. International cooperation only emerged after the first ICARD conference in Røros in 1988.

4.4.1 Equity Silver Mines, BC, Canada

The mine area is located north of Vancouver near the town of Smithers. The mine had complex ore containing a number of metals and precious metals. Gold was mined, and cyanide used in the process. Annual production was approximately 20 million tonnes of crude ore from an open pit mine. Operations continued for 20 years up to the mid-1990s.

Several consultants were recruited for the planning process to calculate the type of seepage produced by the waste rock tip. The majority of consultants concluded that the seepage water would be unproblematic. The process was successful for a long period of time, but the pollution levels suddenly exploded when the tip started to produce acidic, very metalliferous seepage water in increasing volumes (see photographs below).

In this area, the authorities were responsible for the indigenous population that used the watercourse downstream for commercial fishing. It became necessary to build a purification plant, using lime for precipitation of the metals. After the mine was closed, the waste rock tip was covered with a suitable moraine, available in large volumes in the local area. A number of instruments were installed in the tip to measure oxygen consumption, water balance etc. It was found that it would take around 40 years before the cover achieved a sufficient effect. The tip was large, and it is still necessary to add lime to the seepage from the tip, a very expensive measure. There were also problems, for a period of time, with the water quality in the tailings disposal site covered with water due to oxidation of cyanide in the ammonium pore-water. Complexing agents with ammonium caused increased leakage of e.g. copper from the deposit. The results of research programmes in this area have been published.

The covered waste rock tip with collection of seepage (Equility Silver Mine, B.C., Canada).

4.4.2 Idaho Springs – Leadville, Colorado, USA

Today, Idaho Springs is a small community located in the high mountains outside of Denver. The winters here are long and cold, and the area can in many ways be compared with Folldal. As in Folldal, there was a focus on preserving the residue after mining, which started in the mid-1800s with a gold rush. A lot of work has been invested in preserving the environment and showing it to visitors. Many of the small mines were linked early on with a tunnel system that collected all the mine water and transported it to one outlet to a watercourse. The problem is that the watercourse runs into the drinking water supply for Denver city. As the metal discharges were so high, action had to be taken. With funding from the federal authorities, a purification plant was built, using lye to achieve precipitation of the metals. The plant was planned and built as a demonstration plant. The mud was deposited in a landfill close by. The purification plant has to be in operation for a long time.

Uphill from Idaho Springs is Leadville, the highest town in the USA. The area is well known for its comprehensive mining and vast pollution problems due to unsatisfactory disposal techniques. The seepage water from the mines runs towards the Arizona River. The neighbouring state is not interested in receiving large inputs of polluted seepage water. Climax is the world’s largest molybdenum mine, where they encountered vast heavy metal leakages from the tailings disposal site. They chose to collect the tailings behind a permeable dam, as with Titania. This caused comprehensive weathering in those parts of the tailings that were exposed to oxygen, as they were not the groundwater surface. The company planned comprehensive alternatives for how to cover the disposal site. In the interim, they added lime to the seepage – a very expensive process. Lime is added directly to the watercourse downstream from the disposal site, and the watercourse is used as a purification plant, where mud settles in basins.

Leadville has a number of closed mines. A large mining museum has been built (ref. http://www.leadville.com/). When it became necessary to carry out measures to limit pollution, the initial action was to cover the old disposal sites. When the local community became aware of the consequences of these measures, major conflicts emerged between those who wanted to preserve cultural monuments and those who worked with environmental protection. The situation ended with a compromise, in that they chose to preserve some of the cultural monuments. A major purification plant was therefore built to treat seepage water. This was a lime precipitation plant where the seepage was processed in a wetland filtration system.

Photo from Idaho Springs. The purification plant and Argo Tunnel, where the mine water runs out.

Photo from Leadville. The tailing disposal site at Climax and Leadville, with the surrounding mines.

4.4.3 Zlate Hory - The Czech Republic

In connection with an old, closed mine area in north Czech Republic at Zlate Hory (golden mountains), a high mountainous area, seepage drains into a watercourse that runs into

Poland. There have been mine operations in the area since the 9th century. The location of the mine area is unfavourable as the waste, rock piles and tailings disposal sites produce a significant amount of metal seepage that is transported over the border into Poland. The watercourse is used as irrigation for agriculture.

The tailings disposal site was not built with a non-permeable dam, so that large volumes of the tailings are exposed to weathering. The disposal site is also located in a slope. Seepage water from the entire area is collected in an artificial ditch system and pumped up to a large lime precipitation plant. The mud is de-watered and placed on top of the tailings. The location of the waste obstructs other possible measures to limit pollution (Arnesen, 1993).

4.4.4 Aitik, Gällivare, Sweden

The Aitik mine is owned by Boliden and is the largest copper mine in Europe. The mine is operated as an open pit mine, and there are plans to extend production up to an approximately volume of 50 million tonnes of crude ore per year. In addition, significant volumes of waste rock require crushing. A new process has been developed, aiming to extract copper percentages down to 0.34 %. This will result in vast volumes of waste for disposal.
At the time of writing, major research projects are under way into the development of seepage water quality in the waste rock tips, covering options for the waste rock tips, development of water quality in the open pit mine after the mine is closed and filled with water, and closing the disposal site by covering it. The disposal site currently covers an area of approximately 11 km^2.

Impressions gained from Aitik. Open pit mine – covering of waste rock tip – the disposal site – attempts to cover the tailings. Photo: Eigil Iversen 2005.

4.5 Status regarding sea tailings disposal

Sea disposal of tailings has been carried out for approximately 30 years, so we already have a substantial experience database. Those countries that have practised sea disposal of tailings, in addition to Norway, are; Canada, USA (Alaska), Greenland, Turkey, Indonesia, the Philippines and Papua New Guinea. Plans for sea disposal have also been made in several other coastal states, but these plans have been stopped primarily due to significant opposition by environmental organisations and politicians. USA and Canada do not have a general prohibition on sea disposal, but it has been a complex process to obtain political acceptance for permits. In a number of cases, the US EPA has granted exemptions for sea disposal. In Canada, such exemptions must be issued according to the Federal Metal Mining Effluent Regulations. These require a maximum level of 15 mg/l of particles in waste water discharged to the marine environment or lakes, and this effectively prohibits discharges of mine tailings to water. However, it is possible to be granted exemptions from this requirement. The dumping of dredged masses is not covered by this legislation, even though polluted dredged masses can represent a more severe environmental problem than mine tailings.

In those cases in Canada where sea disposal of tailings has been permitted, a habitat compensation has been imposed, as a rule. If it can be shown that an area of a fish habitat is impacted by mine discharges, the mining company is requested to compensate for this loss by, for example, building a fish hatchery.

Most mine areas in both the USA and Canada are located inland and sea disposal is for obvious reasons not relevant. This can help explain why it has been easier for politicians in the USA and Canada to reject sea disposal and disregard professional knowledge-based experience.

It is important to highlight that the situation involving the location of the Norwegian deposits is completely different, as very many important resources are located close to the coast.

Sea disposal has been carried out in both deep water (> 100 metres), so-called Deep Sea Tailings Placement (DSTP) and at water depths of < 100 metres (Sea Tailings Placement (STP)). A principle exists to prevent tailings having an impact on the upper water layer, where primary production occurs (the upper 50 metres). There has also been an emphasis on carrying out the actual disposal via a pipeline system, ensuring that the suspension from the mining waste is not transported upwards in the water masses when it exits the outfall pipe. There are thus two important principles involved in sea disposal, which are prerequisites.

Principles for best practice for sea disposal of tailings

1. **The tailings should be mixed with seawater to achieve a density of the suspension exceeding the density of the seawater where the tailings are disposed. Accordingly, the tailings plume will sink towards the bottom.**
2. **The tailings suspension should not contain air bubbles. Such air bubbles would rise in the water masses from the discharge pipe and will carry small particles up to the surface. A system to reduce entrainment of air into the tailings pipe should be installed to avoid air bubbles bringing fine particles to the surface.**

It is important to ensure use of all available information and knowledge in connection with the design of outfall systems for tailings, to ensure that dispersal of tailings is as predictable as possible. It is important for the tailings to be transported from the outfall point to prevent undesired build-up of cones of tailings on the seabed, with such a steep slope that they could cause major, unexpected slides. Underwater landslides can transport loose material over long distances in the form of turbidity currents that erode the seabed. Large landslides can also have a tsunami effect.

BAT (Best Available Techniques) is a concept that will carry even more weight with the implementation of the EU’s Mining Waste Directive. This will also apply to technical solutions for discharge of tailings to sea, and requires knowledge of what is considered the best technical solutions available at any given time. At the same time, the solutions chosen shall be adapted to local conditions in order to ensure optimal benefit for the environment. Life cycle analyses are a tool that is now used in connection with the BAT principle, in which necessary documentation is secured of the conditions before operations start (preliminary studies), characterisation of the tailings to be disposed, choice of disposal site, environmental impact assessments, ROS analysis, disposal plan, water balance plan and phase-out and plan for closing/clearing up. The life cycle analysis covers all phases from design to closing of mining operations.

4.5.1 Sea disposal of tailings in Norway

There is limited experience of disposal of tailings in the marine environment in Norway, despite the long coastline in Norway and numerous resources related to stone, aggregates, sand and gravel, metals and minerals along the coast.

More than 20 localities have been registered where sea disposal has been practised (Kvassnes et al., 2009), but most operations have a limited scope and there is little documentation of environmental impact. The one exception is the sea disposal of tailings in the Jøssingfjord and Dyngadjupet over a period in total of approximately 30 years, and which has been monitored regularly (Bakke and Jensen, 2004). Discharges to the Bøkfjord nearby Kirkenes were practised in the period from 1981 to 1997, and sea disposal has now been reintroduced in connection with the start-up of mining operations at Sydvaranger AS. A third locality is Hustadmarmor in Elnesvågen bay, where sea disposal and monitoring have been carried out since 1982.

The Norwegian coastline is unique with its narrow, deep fjords, often with basins surrounded by thresholds and with water masses stratified due to the supply of fresh water and topographic conditions. Water exchange in the deep waters of some fjords is limited. In a number of cases, the oxygen conditions on the seabed are very poor (bottom water containing H_2S). The tidal differences along the Norwegian coast are minor when compared e.g. with Canada and Alaska. Typically, Norwegian fjords have a short distance from the shore to deep basins (> 100 metres) and the seabed is flat due to large volumes of sediment deposited since the Ice Age (Syvitski et al., 1987).

Norway has not adopted any principal prohibition against disposing mine tailings in the sea. The pollution control authorities assess such permits case by case, and place decisive weight on the type of tailings material (chemical/physical), the volume, outfall system and the suitability of the recipient. Documentation of the environmental conditions in the recipient and any potential user conflicts are important elements in the basis for decision-making. The requirement for an environmental impact assessment will ensure that all sides of an issue are presented and helps ensure that any decisions to grant a discharge permit are based on knowledge. This may be of particular importance in situations where the choice is between sea disposal of tailings and landfill.

There is relatively limited experience of sea disposal in the Norwegian mining industry as the industry has seen a number of closures in recent history (from 1970 up to present day). Moreover, a number of pyrite deposits are found inland in Norway (e.g. Røros, Folldal, Hjerkinn). At the time of writing however, the industry once again has an optimistic outlook and plans are being prepared for new mines and to revitalise closed mines. Those plans that involve exploitation of resources along the coast will, in many cases, necessarily comprise sea disposal of tailings. It is therefore important to emphasise the suitability criteria related to use of fjord basins and a thorough analysis of the advantages and disadvantages of alternative disposal solutions (land or sea).

Extraction of the ilmenite at **Titania as in Sokndal** was practised with disposal of tailings in the Jøssingfjord from 1960 to 1984 (see photo below). With discharge of approximately 2.5 million tonnes of tailings per year, the Jøssingfjord was filled from a basin depth of 70 metres to a threshold depth of 20 metres, and the company was granted a permit to dispose of the tailings in a basin just outside the Jøssingfjord (Dyngadjupet) from 1984 to 1994. The basin depth in this area was 170 metres, and outfall depth was 113 metres. The basin depth was reduced to 140 metres after the 10 years of tailings disposal. Protests from environmental protection organisations, local fishermen and the Institute of Marine Research (HI) required termination of the sea disposal, and the tailings were deposited in a landfill behind an artificial dam (see photo below). The reason was that the tailings in the Dyngadjupet dispersed to a larger area than expected, and that this had an impact on fish and shellfish.

Jøssingfjord. Photo: Tor Jensen, DnV.

The photo above shows disposal of tailings from ilmenite production at Titania via a pipeline to a landfill. Photo: Ann-Heidi Nilsen, Titania AS.

The photo below shows the landfill in Tellnes in 2009.

Photo: Ann-Heidi Nilsen, Titania AS.

One problem reported in relation to the landfill is the leakage of nickel that is transported with the seepage water to the sea. Another problem is sand drift during periods when the surface of the landfill has dried out (see photo below).

Photo: Ann-Heidi Nilsen, Titania AS.

The main reason for the upwards dispersal of the tailings deposited at 113 metres deep in Dyngadjupet was that seawater was not mixed with the tailings in the pipeline at that time and neither was there any aeration system for the tailings pipeline. As such, the most important prerequisites for successful sea disposal were not met. Fresh water with small particles, and most probably also air bubbles, moved upwards in the water masses due to low density and thus caused dispersal of fine material. Moreover, the percentage of solid substances in the tailings discharge was only 20-25 % and this is low compared with many other similar discharges abroad (40-45 % solids).

Det Norske Veritas (DnV) have monitored the Jøssingfjord and Dyngadjupet since 1983. One problem observed in connection with disposal in Dyngadjupet was the discolouration of the gills on shrimp (and fish) caused by black tailings particles (see photo below).

Photo: Tor Jensen, DnV.

Monitoring also uncovered that recolonisation of benthic fauna started immediately after the disposal of tailings ended, but that it took around five to 10 years for the fauna to recover. Another fjord where tailings have been disposed is the **Bøkfjord in Kirkenes** (see photo below). Disposal in this fjord totalled 1.7 to 3.5 million tonnes per year from 1971 to 1997, at depths of 20-25 metres. In total, approximately 56 million tonnes of tailings were deposited in the Bøkfjord, before production restarted in 2009. These are shallow water discharges where seawater is mixed with tailings in the pipeline to ensure the tailings plume moves down to the seabed and not upwards in the water masses. With new operations, discharges will increase to 4 million tonnes per year. Studies carried out by NIVA in 1994, while Sydvaranger still was in production, showed that the particle plume from the outfall point moved outwards at approximately 30-40 metres depth (outfall depth was 20 metres) (Skei et al., 1995). Studies of the seabed in 1998 showed that an area of 26 km^2 was affected by tailings (based on the composition of bottom sediment), but that benthic fauna was moderately affected in around half of this area (Skei and Rygg, 1989). The distance from the outfall point where tailings particles could be traced in the water masses was approximately 7 km. The relatively large size of the area impacted is most probably attributable to the fact that the tailings were deposited in shallow water with a current predominantly affected by the tide.

Kirkenes with Sydvaranger gruve AS' processing plant.

As with the benthic fauna studies at Titania, corresponding studies in the Bøkfjord show that after a period of 10 years with no discharges, there was little impact observable on the fauna from sedimented tailings (Skaare et al., 2007). The most evident impact is that the seabed is compact in areas where there are large volumes of tailings, and that the fauna that forms there has to adapt to a somewhat special bottom substratum. This is because sandy tailings with fine material tend to consolidate and have a very low water content.

In **Elnesvågen bay in Molde**, tailings (calcium carbonate) have been deposited from Hustadmarmor since 1982 (see photo below). Disposal in 2008 totalled approximately 460 000 tonnes of tailings. The ratio of solid substances in the discharge is low (approximately 10 %) when compared with many other tailings disposed to sea. Seawater is mixed with the tailings in the pipeline to increase the specific weight of the plume, and a system is installed to aerate the pipeline. In this case, the discharge permit is unique in that it does not make specifications in terms of tonnes of discharge per year, but in terms of a set of acceptance criteria. The most important acceptance criteria are the size of the area impacted (size of area of seabed where smothering exceeds a specific size and that may affect the benthic fauna), and turbidity in the water mass.

Photo: Tor Jensen, DnV.

The outfall (shallow water outfall) comprises dispersed marble in suspension (see photo below) and the tailings form a cone with an angle of repose of 1:20. Studies of the seabed's topography and morphology show that submarine slides occur in the disposal cone causing dispersal of tailings in the fjord basin. The basin depth outside the outfall point is approximately 40-50 metres.

The photo shows the mud plume of dispersed calcium carbonate exiting the tailings pipe at approximately 22 metres deep. Photo: Tor Jensen, DnV.

The examples mentioned in connection with larger discharges of tailings to Norwegian fjords are all shallow water discharges (< 100 metres), with the exception of Titania in Dyngadjupet (- 113 metres).

4.5.2 Sea disposal of tailings in Canada

Canada is one of the countries where sea disposal has been practised since the start of the 1920s. In 1977, a new Canadian law was introduced (Metal Mine Liquid Effluent Regulations) specifying limits for the metal content of mine water (in liquid phase) that could be disposed of in seawater. The Regulations also included a requirement not to permit discharges that exceeded a particle content of 15 mg/l to water. This in effect prohibits all discharges to water, whether it is fresh water or fjords. This applied to mines established after 1977, while mines already practising sea disposal could continue to do so.

The best known and most studied locality is Island Copper Mine, British Columbia that was operational from 1971 to 1995. The mining company was granted a permit to discharge 33,000 tonnes of mine tailings per day (corresponding to 12 million tonnes per year) to the Rupert Inlet fjord on Vancouver Island. The average grain size in the tailings was 20 μm, and the tailings were mixed with seawater at a ratio of 2:1. In principle, this was a controversial project, but was permitted as the company committed to carrying out a comprehensive monitoring programme for the 24 years of operations, and which has continued for a further 14 years after the mine was closed. There is therefore an extensive database on the environmental impact of mining operations on marine environments (Ellis et al., 1995).

The ore deposit contained only 2 % copper so that 98 % of the deposit was classified as waste. Over the 24 years of production, a total 800 million tonnes of waste rock were generated, and this was deposited in the littoral zone, with 400 million tonnes deposited in the sea. The ore was sulphidic and disposal of the waste under water was seen as an advantage as it would have generated acidic and metalliferous seepage if deposited on land. As is known, seawater is a good buffer for acidic discharges. The discharge permit specified the following requirements: "Underwater disposal should not be permitted where settling characteristics of the tailings, or underwater currents, preclude rapid and complete settlement". The pros and cons of landfills or sea disposal were debated, and fish researchers etc. concluded that landfills would represent a greater risk to the marine environment than sea disposal. The reason for this conclusion was that seepage from the landfill would affect the upper water layer, where species such as salmon migrate (Ellis, 2002).

The tailings, after having passed through the thickener (to remove water) were mixed with seawater and pumped out at approximately 50 metres deep in the fjord, a shallow water discharge. No flocculation agents were used (with the exception of Magnafloc in the thickener) as the seawater was deemed to be a good flocculation agent. As a part of the discharge permit is was demanded that if sea water flocculation was insufficient,, a chemical flocculation agent should be used. This never occurred.

The main conclusion once the mine was closed was that the tailings had dispersed to a larger area than expected, particularly due to the large tidal difference in the area and upwelling, causing the tailings to rise all the way to the inter-tidal area. However, less than 1 % of the tailings were dispersed farther than approximately 8 km from the outfall point. This did not cause a copper-related problem in the fjord. It took less than five years for a new benthic fauna to re-establish in those areas were the tailings had sedimented after the mine was closed. The greatest impact proven on the marine environment was that the bottom depth was reduced by 40-50 metres in the areas close to the outfall point (Moore et al., 1998). However, it was pointed out that more resources should have been invested in documenting the prior conditions in the fjord, allowing more accurate documentation of the impact of mining.

The summary from a report prepared by Moore et al. (1998) after closure of the Island Copper Mine was as follows:

- Smothering and destruction of the benthic fauna community in the areas close to the outfall point were as expected. However, there was no proof of 100 % dead seabed, even in the areas close to the outfall point. In certain areas, an increased biodiversity was registered on the seabed, thought to be the result of the establishment of a sandy bottom (tailings sand), where the seabed was previously mud.
- The establishment of new benthic fauna over a period of five years (primarily opportunistic polychaetees (Burd, 2002)).
- No negative impact was registered on the stocks of fish and crab in the area.
- No increase in metals in marine organisms was registered.
- The tailings discharge did not cause any significant change in the water chemistry

in the fjord.

- Increased turbidity in the upper water masses caused by upwelling in connection with the high tidal forces had no impact on the primary production in the fjord (plankton).
- No impact was proven on zooplankton, either in terms of numbers or species diversity in the fjord.

The figure below illustrates the photo of Island Copper Mine when closed after 24 years of continuous operations.

The photo above shows the mine in the last month of operation, in 1995.

To close the mine, the open pit was filled with seawater by creating a channel from the fjord (Rupert Inlet) into the open pit mine. When closed, the bottom of the open pit mine was 370 metres below sea level. This created a deep lake (Pit Lake) with salt water at the bottom (2 x

1.5 kilometres). All acidic seepage water has subsequently been transported to the lake, which functions as a natural purification plant for metals (precipitation of metal sulphides as a result of the formation of bottom water containing H_2S).

Filling with seawater (Pit Lake)

When filling the open pit mine with seawater, a waterfall was established – the world's highest salt water waterfall. This became a popular tourist attraction.

Other mines in Canada where seawater disposal was used include Jordan River copper mine, which had operations for a short period of time (1972-1974). With this mine, tailings were discharged to shallow water in a coastal area exposed to high waves and where problems occurred involving pipeline breakages. As a result of the breakage, large volumes of tailings were found on the water surface. This is an example of a project that should never have been implemented as the preliminary preparations were not sufficient or the locality chosen for sea disposal was not suitable.

Britannia Beach mine (copper and zinc) disposed of tailings in the Howe Sound fjord, British Columbia in shallow water (initially just below the tidal zone then at 30 metres depth) for 47 years (1927 to 1974). Approximately 44 million tonnes of tailings were deposited in the fjord. The fjord has a deep basin at 285 metres deep surrounded by a threshold at 55 metres deep. The bottom water is anoxic at times (no oxygen and containing sulphides). The sedimentation rate of the tailings was approximately 2 cm per year in the deep basin. The tailings built up in a fan shape on the slope outside the mine, and small landslides have transported the tailings into the deep basin. In this area also, a relatively quick re-establishment of benthic fauna has been reported in areas where the tailings have sedimented.

Kisault molybdenum mine on the west coast of Canada operated with sea disposal of tailings from 1981 to 1982. The recipient was the Alice Arm fjord, with a deep basin of around 300 metres depth. The tailings were transported through a pipeline, as in Island Copper Mine, and deposited in the fjord basin as expected. Measurements of molybdenum in the pore-water in the sediment where the tailings were found showed higher levels than in normal seawater. As such, the escape of molybdenum from the tailings to the seawater above was registered. It was concluded that the fluxes of molybdenum were so low that they would not affect the levels of molybdenum in the seawater above the tailings. This shows how important it is to quantify the environmental impact by utilising refined monitoring methods. Monitoring in general of the fjord recipient outside the mine also showed that the benthic fauna was only affected in the actual disposal site for the tailings (Pedersen et al., 1995).

The outfall system was designed so that the seawater from 20 metres deep was mixed with the tailings slurry. The low temperature of the seawater helped reduce the temperature and increase the density of the slurry. It was confirmed that the 2:1 mix of seawater with tailings increased sedimentation of the tailings by a factor of four, from 11 cm/hour in fresh water to 49 cm/hour with the seawater mix (Pedersen et al., 1995). It is important to ensure that the residence time of the slurry in the mixing tank is sufficient to allow de-aeration, in order to prevent air bubbles transporting fine tailings particles to the surface of the sea. The incline of the tailings pipe was a drop of 40 metres over a length of 110 metres (20-degree incline). Discharges were made at 50 metres deep and the pipe followed the sloping seabed. Between 92 % and 98 % of the tailings were deposited on the slope leading down to the fjord basin. A particle plume was observed in the deep waters (65-125 metres) and which was identifiable up to 5 km from the outfall point. The particle content in this plume was, however, low (< 5 mg/l). By increasing the volume of solids in the tailings pipe and reducing the speed through the pipeline, the magnitude of this particle cloud was reduced. The reduction in flow speed in the pipe reduced the resuspension of sediments close to the outfall point. A decision was also made to relocate the pipeline in a longitudinal direction in the fjord, instead of crosswise.

It should be noted that studies of turbidity data gathered before establishment of the tailings showed a water mass with higher turbidity at the same depths (65-125 metres). This is therefore a clear indication that the particle plume was to some extent a natural phenomenon in Alice Arm that had no connection with the mining operations. This is proof of the importance of thorough studies before establishing disposal. Detailed oceanographic measurements were also carried out in Alice Arm to allow estimates of how a large particle outfall would behave in the fjord. It is of particular importance to evaluate the density of the slurry in relation to the density of the seawater at the outfall point. One important prediction made regarding the discharge from Kisault Mine was that: “even if — over half the tailings solids would settle out of the effluent plume, its density would continue to be greater than that of the seawater and hence the plume would continue to descend to the bottom of the fjord") (Burling et al., 1981). On this basis, an important principle for the discharge of mine tailings to the marine environment can be established;

Principles for best practice for sea disposal of tailings

1. **It is a supposition that the fine particles in the tailings move as density current along the sea floor instead of dispersal higher up in the water column.**
2. **It is therefore important to ensure that the density ratio between the tailings plume and the surrounding seawater is sufficiently high.**

One other important observation was made regarding the discharges to Alice Arm. During deep water exchange in the fjord, there were no observations of the transport of tailings particles up to the upper water layers (Pedersen et al., 1995). Ecological studies also concluded that there was little impact on the aquatic organisms, and that the benthic fauna recovered after two to three years from the date the discharges stopped.

One common factor for all these areas on the west coast of Canada is that the sea disposal of tailings was to relatively shallow waters (< 100 m deep). In some areas, the discharges have been at the water surface, causing completely different consequences than with deep water discharge (> 100 m). Despite this, and the fact that the mines involved were sulphide ores where mine tailings had a higher level of metals and sulphides, there are few reports of negative impact on the environment (Poling et al., 2002). Moreover, there are reports of a rapid re-establishment of benthic fauna in those areas were massive smothering of the tailings has occurred (two to five years after the discharges stop). Neither are there reports of negative impact on marine resources and stocks (fish, including salmon and shellfish). The effects of blasting in the mine on fish in the fjords (pressure waves) have not been a subject in any of the projects mentioned.

4.5.3 Sea disposal of tailings in the USA

Evaluations have been carried out for sea disposal permits in two fjords in Alaska; Quartz Hill molybdenum mine (operations planned, but not implemented due to economic reasons) and the Alaska-Juneau gold mine. Sea disposal permits are governed by the Clean Water Act (CWA) that specifies limits in relation to water quality criteria.

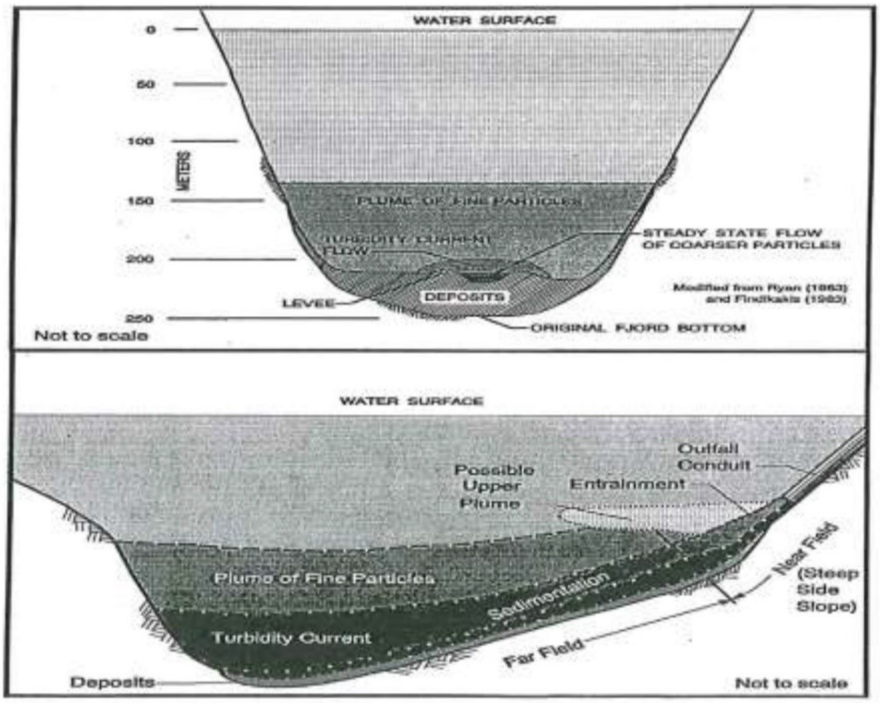
The case for **Quartz Hill molybdenum mine** is included in this document as a very detailed environmental impact assessment was carried out of sea disposal in the Wilson Arm fjord, alternatively the Boca de Quadra fjord. A major project was carried out including preliminary studies and modelling, and the experience gained from this process provides an important knowledge base.

In principle, the EPA was of the opinion that marine disposal in this case would be preferable. However, the EPA decided to reject the application in 1990. The planned disposal would amount to approximately 24 million tonnes per year. The planning phase, including the study phase, lasted for 20 years, and the results of this work will be of value for future planned sea disposal of tailings. A comprehensive process was carried out for the outfall design (mix of seawater and de-aeration) along with modelling of the dispersal of particles both close to and at distances from the outfall point. A total of USD 100 million was spent on planning, USD 31 million of which related to the environment. It was concluded that a landfill would be more harmful to the environment than sea disposal (Hesse and Reim, 1993).

The plan was to extract 12 million tonnes of ore per year from an open pit mine, then to increase the volume to 24 million tonnes per year after several years. The planned operating period was 55 years. In connection with the environmental impact assessment, there was a major focus on the salmon resources in the fjord, in the area for the planned sea disposal. Fish experts claimed that the salmon and smolt would only be dependent on the water quality in the upper 20-30 metres of the fjord (Wilson Arm/Smeaton Bay) and that the deep-water sea disposal would not be of any significance (Hesse and Reim, 1993). If Wilson Arm was chosen as a disposal site, it was estimated that 1% of the tailings would be transported more than 18 km from the outfall point (maximum estimate). It was also pointed out in the environmental impact assessment that as the fjords are stratified due to the supply of fresh water, the mine tailings would not be transported to the surface. It was also mentioned that the tailings were not expected to be transported to higher water depths than the planned disposal depth (- 50 metres). The plan was to mix the tailings with seawater at a ratio of between 1:1 and 4:1 (seawater: slurry). The ore deposit contained few trace metals, and the tailings are characterised as mainly inert and similar in chemical composition to the deposits already found on the seabed in the two fjords that were chosen for sea disposal. It was therefore concluded that the deposits would only potentially have a negative impact on the marine environment as a result of the large volumes of tailings. 18 % of the tailings had a grain size of < 10 µm (and as in this document, defined as fine fraction) that can be transported in suspension. Toxicity tests were performed of the flotation chemicals planned for use, concluding that none of the chemicals (commonly used in the mineral industry) were characterised as toxic.

Tests were also performed to establish the concentration of fine material suspended in the water phase close to the seabed that would be required to have a negative ecological impact. It was confirmed by experiments that concentrations higher than 560 mg/l suspended substance with 40 days of exposure had a negative impact on the ecosystem. In other words: as long as the tailings do not include toxic components, aquatic organisms have a high tolerance of particles in seawater. This also concurs with the results reported in Smit et al., (2008).

The plan was for the slurry containing the tailings to have 45 % solids in order to achieve optimal flow through the pipe system. Modelling was conducted of the dispersal of the fine fraction close to and at a distance from the outfall point. In addition, water circulation models were utilised to predict how high the fine fraction may disperse upwards in the water mass. This showed probability that a density current would form close to the bottom with a thickness of 5-25 metres and a varying ratio between solids and water (highest ratio of solids close to the bottom). Above this layer, a particle plume would form with a low particle content, in which the concentration of particles would be lower than 5 mg/l. These two layers (turbidity current and plume of fine particles) are illustrated in the figure below.



The figure above illustrates a cross-section of the fjord and the figure below shows the longitudinal direction of the fjord. The discharge is at 50 metres deep and the upper limit for the “plume of fine particles” is approximately 130 metres deep (80 metres below the discharge depth) (source: Hesse and Ellis, 1995).

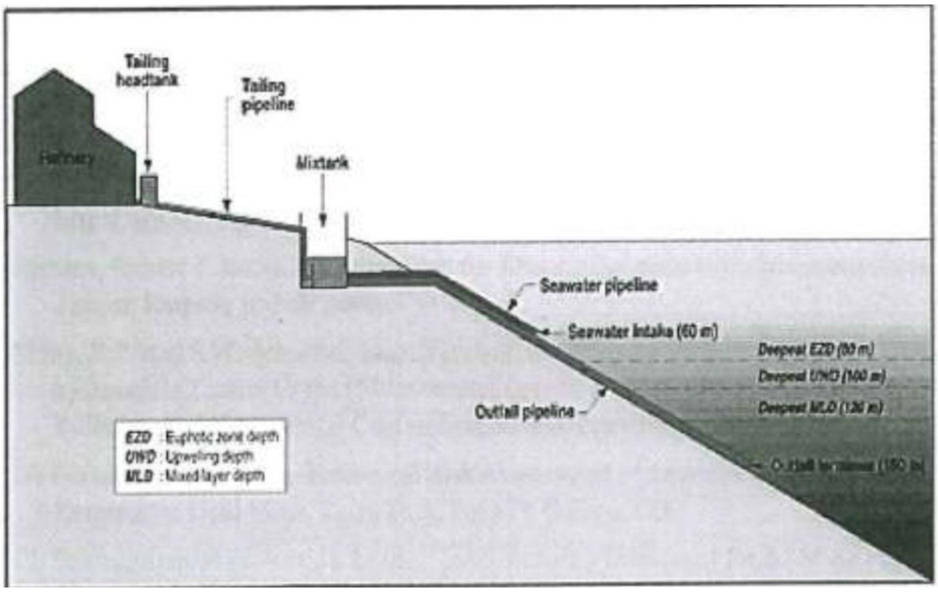
Deep water exchange was also modelled in order to estimate whether there was enough energy to resuspend tailings from the bottom, and whether this could then be transported to the surface (upwelling). It was concluded that this was not possible. Small landslides in the actual tailings cone may cause short-term resuspension, but the particles would not be transported to the surface due to the stratification in the water mass (Hesse and Ellis, 1995). The other case involving sea disposal of mine tailings in the USA is the Alaska-Juneau gold mine at Berners Bay. Mining operations started in 1937, with the deposit of tailings on land. In 2004, an environmental impact assessment was carried out to evaluate sea disposal as an alternative.

In 2004, mining operations comprised extraction of 12,000 tonnes of ore per day, with disposal in a natural lake. 25 % of the tailings were mixed with cement to form a paste that was then returned to the mine (underground operations). The proposed alternative plan was to deposit the tailings at a depth of approximately 180-200 metres in the fjord in Berners Bay, which has a basin depth of 200-300 metres. The tidal difference in the fjord is approximately 7 metres, so the tidal current in the fjord is significant. Studies and evaluations were performed of the consequences of tailings disposal on demersal fish. It was documented that demersal fish had no preference for choice of habitat (natural sediment – tailings), if the tailings were covered with 2 cm of natural sediment (Johnson et al., 1998). This implies that the higher the rate of natural sedimentation there is in an area for sea disposal of tailings, the quicker the seabed will recover as a habitat for demersal fish. In many fjords, the natural sedimentation rates vary between 2-10 mm per year.

Studies conducted by the U.S. Bureau of Mines, in relation to the plans for sea disposal of tailings in Berners Bay, reached a conclusion on the following prerequisites for minor negative impact on the marine environment:

1. **That the content of sulphides in the tailings is low**
2. **That the tailings including chemicals do not contain toxic components that are water-soluble**
3. **That the processing of the ore does not generate secondary toxic substances that are transported with the tailings**
4. **That the tailings slurry should contain a high percentage of solids (> 30 %)**
5. **That the tailings are aerated and mixed with seawater**
6. **That the density of the water phase in the slurry is not lower than in the seawater at the outfall point**
7. **That the disposal site is stable (geotechnically)**

A principle drawing of the outfall system planned for Berners Bay is provided in the figure below.



Source: Robinson et al., 2004

4.5.4 Sea disposal of tailings in Greenland

Greenland has rich deposits of minerals and metals, and a number of these are located on the coast. Due to the topographical and climatic conditions, it is difficult to operate landfills. For this reason, fjords have been used to a certain extent in connection with disposal.

The most renowned mining project with fjord disposal is the **Black Angel lead and zinc mine** in Maarmorilik that opened in 1973 and closed in 1990 (Poling and Ellis, 1995). This was a mine where seawater was used for the actual flotation process, a rather uncommon process. It became evident relatively early during the operational period that the disposal of tailings in the fjord outside the mine caused substantial metal contamination of the water and marine organisms. Discharges of 1,350 tonnes of tailings per day with a content of six tonnes of lead and 12 tonnes of zinc caused significant problems as these metals were partly present as oxides that are soluble in seawater. The ratio of solids in the tailings slurry was approximately 25 % and the slurry had a density of 1.215. The tailings were discharged at 30 metres deep and the total depth of the fjord was approximately 80-100 metres. A de-aeration system was fitted after several years of operations. The tailings were not mixed with seawater as seawater was used in the actual flotation process.

Greenland's fjords have strong stratification during the summer due to the large inputs of fresh water. In the winters, the fjords are covered in ice. When the fresh water at the surface layers freezes, water with a high salinity and high density forms and sinks to the bottom, mixing with the water column and resulting in water with high salinity and high metal content flowing over the threshold into the next fjord. This is an example of processes that were not studied in advance and that had a negative impact on the environment. Moreover, waste rock was deposited in the littoral zone (see photo below). Monitoring showed that the waste rock was the greatest source of metal contamination in the fjord, not the tailings. This had not been predicted. During the operational period, a number of remedial measures were implemented so that the magnitude of pollution was reduced.

The photo illustrates the waste rock deposit in the Affarlikassaa fjord at Maamorolik, Greenland.
Photo: Gert Asmund, National Environmental Research Institute of Denmark (DMU), Denmark.

The conclusion is that due to the lack of initial, thorough mineralogical analyses of the tailings, it was not uncovered that the tailings contained soluble lead and zinc compounds and it was assumed that the metals were bound as sulphides with low solubility in water. Leaching tests in seawater would have revealed this. The same applies to the oceanographic conditions, which lacked sufficient preliminary studies, in particular in relation to phenomena involving the fjords being covered in ice during the winter. An environmental impact assessment was not performed at the start of the process and was only conducted many years later.

4.5.5 Sea disposal of tailings in Asia

Mines in several Asian countries (Indonesia, Papua New Guinea, the Philippines) have practised sea disposal of tailings for a long time. It is in these countries that we also find the most obvious examples of unsuccessful projects, either because the natural conditions were not suitable for sea disposal or due to the lack of sufficiently thorough environmental impact assessments in advance, or because professional advice has been ignored. A number of mining companies in Asia have been strongly criticised for implementing major projects with no knowledge base and without sufficient consideration for the environment and local communities.

It is evident that the disposal of tailings from the mining industry is an even more significant challenge in the tropical part of the world, where e.g. large volumes of rainfall combined with earthquake activity make it difficult to dispose of tailings in ponds on land. As a result, tailings have been deposited directly in rivers, causing major destruction downstream of the discharges, and tailings have been transported without control to the sea, impacting the productive surface layer in coastal areas. Smothering of the coral reef has been a problem that has attracted major attention.

As a result of the major environmental problems that have occurred in connection with the disposal of tailings on land, a number of mining companies have applied for permits to dispose tailings in the sea, preferably disposal in deep water.

One of the most renowned mine projects is the **Minahasa gold mine** in Indonesia, where operations started in 1998. An 8.4-kilometre-long tailings pipeline was laid from the processing plant to the coast, with a further 1 km to the outfall point at 80 metres deep. The volume of tailings deposited is 2,000 tonnes per day, i.e. a moderate volume. The most severe problem has been repeated pipeline breakages at the surface (< 10 m deep). The tailings contain mercury and arsenic, and it has been claimed that this has harmed both the environment and the local community. Irrespective of whether this can be proven or not, outfall systems that result in pipeline breakages are unacceptable.

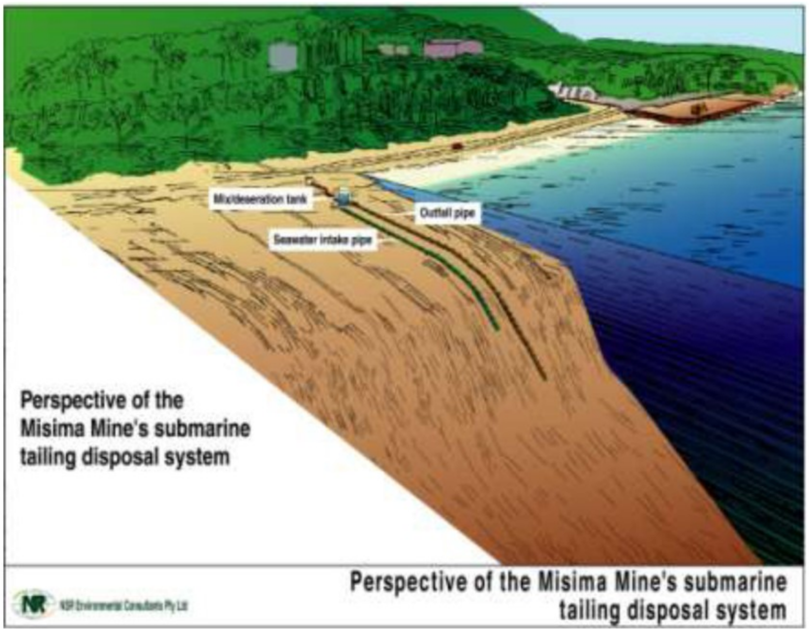
Another gold mine is in Papua New Guinea, **Misima gold mine** (see photo below), a classic sea disposal project where tailings are deposited at 112 metres depth on a slope, and the prerequisite is that the tailings shall be transported via a turbidity current to a deep basin at depths of 1,000-1,500 metres. Mining operations started in 1989 as an open pit mine. This was the first project with sea disposal of mine tailings outside of Canada and the first with deep water disposal. The discharges comprise 18,000 tonnes of tailings per day. Seawater is pumped up from 82 metres deep and is mixed with tailings in a mixing tank (one part tailings to seven parts seawater). The water masses in the outfall area are stratified and there is no evidence that the tailings are transported upwards in the water masses above the outfall depth. One prerequisite in connection with the discharge permit is that the tailings do not affect the upper 0-100 metres of the water mass (Jones and Ellis, 1995). The tailings contained cyanide, and fish mortality has been documented as a result of the discharge. The mine operated until 2001 and measures have since been taken to clear up the area, including re-vegetation of the open pit mine (see photo below).

The ratio of solid substances in the tailings in the pipeline was 50 % before seawater was mixed in, to ensure that the tailings flowed like a turbidity current along the seabed. The density of the slurry was 1.08, significantly higher than the water mass into which the tailings were discharged. Underwater images have shown that the plume is homogeneous and there is little evidence of split-up. Sedimentation rates of 1-2 cm/year were registered in parts of the seabed area and up to 10 metres/year in the deep basin, and studies have shown that as much as 20 km^2 of the seabed at > 100 metres deep are covered by up to 1.5 metres of mine tailings. These are high settlement rates in oceanic basins, with the exception of areas where there are frequent landslides in continental shelves that cause large slides and high sedimentation rates in the deep basins.

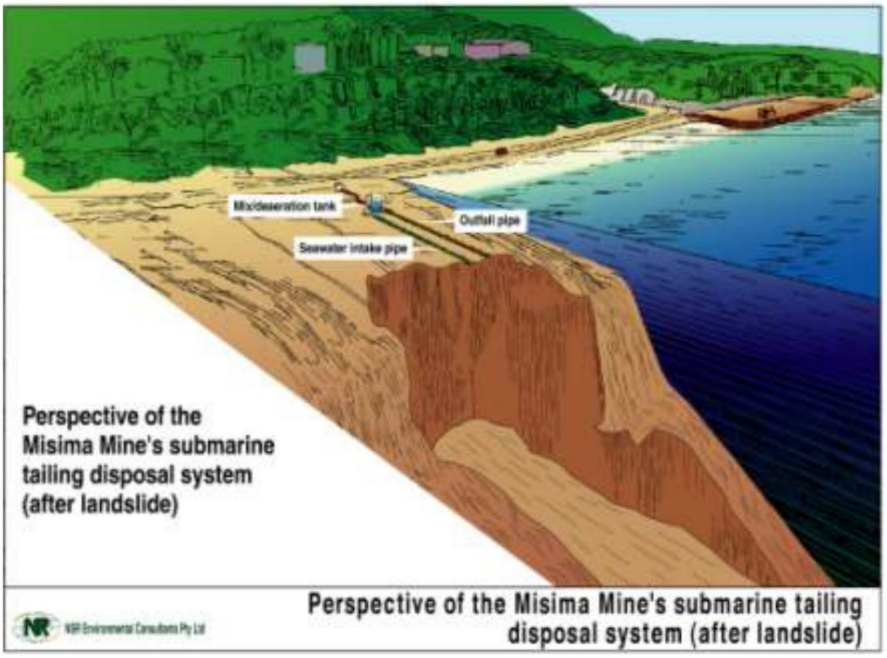
Misima gold mine in Papua New Guinea.

Re-vegetation in the open pit mine.

One of the problems that occurred in connection with this sea disposal project was pipeline breakages caused by earthquakes (see photos below).



The photo shows the tailings pipeline with outfall at 112 metres deep and the seawater intake at 82 metres deep. A mixing tank for seawater and a de-aeration system have been installed on the tailings pipeline.



Underwater landslides caused by earthquakes damaged both the tailings pipe as well as the sea water intake pipeline.
This illustrates the potential challenges with underwater pipelines in areas where earthquakes may occur.

Monitoring programmes have shown that the actual outfall system has functioned as expected, i.e. fulfilling the prerequisite that the tailings shall not be transported from the outfall depth upwards in the water mass. Some problems have been encountered with pollution of the surface layer caused by waste rock deposits close to the littoral zone with seepage to the sea. The reason for this problem is that some types of rock have a very soft consistency, so that there is a lot of fine material in the waste rock tip that is washed out.

5. Summary of lessons learned from existing and planned activities

The objective of this report is to summarise what we know about landfills (with and without water cover) and with sea disposal of residual masses and chemicals from the mining industry. When opening new mines, it is important to make decisions regarding environmental solutions based on reported facts and specific experience from projects that have been completed.

There is a lot of knowledge that has been learned, but in principle this information is found in reports and unofficial documents (grey literature), and to a lesser extent, in published articles.

5.1 Disposal of tailings on land

Landfill of mine tailings has been a practice since mining was established. Three types of landfills have been in use:

1. Use of natural recessions in the ground (landfill with or without water cover).
2. Building dams around the landfill (landfill with or without a water cover).
3. Depositing masses in an existing lake.
4. Backfilling of mine tailings in mine shafts.

The choice of type of landfill and functionality will therefore depend on natural conditions. Several factors have an impact on the consequences of landfills:

1. Rainfall (climatic conditions).
2. Physical consistency of tailing mass (grain size distribution) and chemical composition/stability and weathering potential.
3. Degree of vulnerable water bodies downstream of the disposal site.
4. Degree of area and user conflicts.

In addition to the more traditional landfill solutions, a number of situations will also allow for backfill of tailings in empty mines. This will depend on the type of mining technology. One principle should be that backfilling is evaluated in all plans relating to new mining operations. However, at the same time, an evaluation should be conducted of the impact of filling water into the mine when operations have terminated, and the consequences this could have on the environment in the long term, when contaminated mine water seeps out of the mine. Backfilling is not suitable if there is potential for subsequent extraction of resources from the mine.

In addition to the disposal of fine-grained tailings, it may be necessary to dispose of waste rock, which is a coarse mass comprising aggregate to large stones and does not contain commercial resources that might be utilised. Normally, waste rock is deposited in the immediate proximity of the mine in order to avoid long transport. The volume of waste rock from an open pit mine can be large, while underground mining produces small volumes of waste rock. In environmental terms, the challenges relate to seepage from the landfill, particularly with waste rockpiles from sufide mines (acidic and metalliferous water). In addition, seepage water may in many cases contain a lot of mineral dust. This implies that the seepage water from waste rock piles often requires management to avoid pollution of water bodies.

5.1.1 Physical and chemical stability

Processing to separate the different minerals from each other requires crushing and grinding of rocks. In most cases, the largest volumes of the mineral fraction to be disposed of will comprise relatively uniform fractions of fine sand and silt.

When sedimentation of stone particles with approximately equal specific weight and equal shape and size in water occurs, a deposit forms with large pore volume, creating a permeable sediment. There will be low friction between the grains, which together with the water-filled pores make up an unstable sediment structure with a high potential for landslides until the masses gradually consolidate. A sandy sediment will also have relatively high permeability, of significance for the leaching of substances in the pore-water. Although the tailings comprise various fractions, transport and settlement in water will result in the sorting of particles according to grain size, shape and specific weight, so that unstable strata may form in the deposited masses. This is possible e.g. if the outlet is moved so that fine and coarser layers interchange.

Sediment with improved mechanical stability will theoretically be achievable by mixing coarser and finer fractions and by ensuring that the mass settles on the bottom quickly, without being separated into different grain fractions. In practice, this will most probably be difficult to achieve.

During rock formation, there is a more or less stable chemical balance between the minerals of which the rock is made up. As most rock types are formed by a process of crystallisation or cementing that occurs under completely different pressure and/or temperature conditions than we normally encounter on the surface of the earth, almost all minerals are chemically unstable when exposed to air and water and various mechanical processes on dry land, in rivers and the sea. Mechanical weathering causes the mineral grains to separate from each other and be broken down into smaller particles. Chemical weathering causes the minerals to dissolve in part or in whole, and elements from the minerals to dissolve and be transported by water. With the exception of a few minerals that are both hard and chemically stable under most chemical conditions on the earth's surface, such as zircon, rutile and chromite, most minerals will with time break down or metamorphose into other, more stable minerals, e.g. clay minerals. When deposited under water, however, common minerals such as quartz and feldspar etc. will also become very stable in relation to chemical weathering.

Minerals that are unstable in contact with water and/or air comprise sulphates and carbonates (including normal limestone) and in particular sulphides of various metals. Sulphide minerals such as iron pyrite (pyrite) are unstable when in contact with humid air. During weathering, sulphuric acid is formed, accelerating the weathering process. Under water, with very low levels of oxygen, the chemical weathering process will be much slower. If anaerobic conditions occur, there is the potential for precipitation of iron and other heavy metals such as sulphides.

Chemical weathering and dissolution in water and transport to the sea result in small or large volumes of practically all substances in the periodic system in the seawater (in addition to a high content of common salt). The residence time for chemical substances in the sea differs greatly however, and depends on how quickly the substance precipitates or is adsorbed on clay particles or colloids in the seawater. The residence time for aluminium and iron, for example, in the sea is specified as 100 and 140 years respectively, and 4.2×10^4 years for mercury, while sodium and chlorine have respective residence times of 4.5×10^7 and 1.1×10^7 years. (Mason, 1966).

5.1.2 Ecological impact

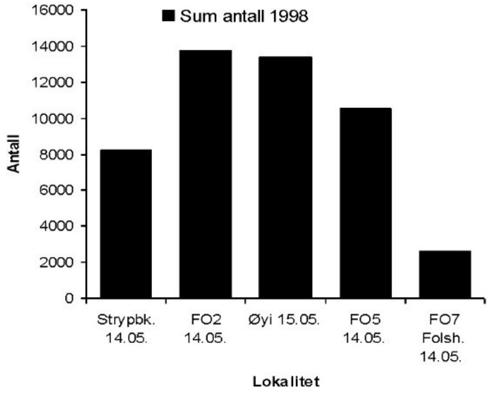
Experience gained from closed mines
Norway has several centuries of history when it comes to mining on the mainland to extract and process ores and minerals (Arnesen, 1999). As a result, many watercourses are currently affected by this activity, even though the mines closed some time ago. Seepage from waste rock piles, tailings disposal and mines create pollution problems in many areas (Iversen and Arnesen, 2003). The problems with the old sulphide ore mines primarily relate to seepage of acidic water with a high metal content. The recipients in the immediate area experience a characteristic red-brown colour from iron precipitation (see photo below) and are often referred to as Raubekken (red stream) or similar. The water quality is poor, and the utility value of the water is significantly impaired. The biological impacts in such recipients can often be predominant, with the loss of many species of flora and fauna which would normally thrive. This has a negative impact on biodiversity, for the fish and its food and for much of the fauna along the watercourse. Measures to reduce/eliminate these problems, which have a very long duration if measures are not taken, are often both difficult and costly.

Today, there are no active sulphide ore mines in operation in Norway, the last being closed in 2002 (Nikkel og Olivin AS, Ballangen). However, 20-30 years ago, many such mines were in operation (Løkken, Folldal, Grong, Sulitjelma etc.). The experience gained from these mines is extensive, as they were all governed by a control programme from the pollution control authorities during operations. This provides us with substantial knowledge of how to develop new similar mines with discharges to fresh water recipients in the future in order to minimise/eliminate the impact we can currently observe from previous mining of ores containing sulphides. At the same time, there has been a major focus internationally throughout the same period on identifying the best possible techniques and solutions to reduce the environmental problems in the recipients.

The photograph illustrates the channel built past Bleikvassli Gruber while the transfer tunnel from Bleikvann lake to Røssvann lake was repaired. The channel shows signs of having received large volumes of mine water during the period from 2005 to 2008. (Aanes et al., 2009).

Norway was one of the first countries to introduce disposal of tailings from the enrichment process of sulphide ores under water. This was carried out to reduce oxidation and thus the production of sulphuric acid and leaching of toxic metals, thereby minimising the biological impact on the recipients. To this purpose, natural lakes nearby the mine (Grong, Bleikvassli, Sulitjelma) or artificial tailings ponds (Løkken and Folldal Verk in Hjerkinn) were used.
The experience gainedvaries: small artificial dams have proved successful, but require a considerable focus on the discharge system and factors such as sedimentation properties, residence time and measures to reduce the impact of wind. Hjerkinn dam is, to a great extent, one example of a mainly successful solution with a high focus on achieving optimal sedimentation conditions during the operational phase. Various measures were introduced to reduce the loss of tailings particles to the recipient, Folla, and thereby the negative impact this had on the biological communities in this part of Folla. The dam has a small watershed, an important factor in terms of residence time and flow through. Monitoring of the water quality in the upper parts of Folla (Iversen and Aanes, 2005) showed some particle impact during the operational phase, and particularly during the spring flooding. This reduced considerably when operations were terminated and the conditions in Folla primarily returned to normal after a short time. The conditions in the dam also appear to have had a positive development in that a stock of trout has established here, providing the basis for some angling. In terms of the landscape, the dam now appears to be a natural part of the area. Further downstream, the Folla is a recipient for seepage from the old mining area surrounding Folldal village, where mining started as early as 1748. The conditions here remain affected by severe pollution reaching many kilometres downstream of the village.

Results from studies of benthic fauna (number of animals) in the Folla (May 1998), five years after the mine in Tverrfjellet was closed are shown in the figure below. The Strypbekken stream provides drainage of Hjerkinnsdammen dam. The Fo 2 and Øyi stations are located upstream and downstream respectively of the confluence with this stream. The Fo 5 and Fo 7 stations are located upstream and downstream of the old mines in Folldal (Iversen et al., 1999 a).



The use of larger lakes has proven to be slightly more problematic. Østre Huddingsvatn lake was used as a disposal site when Grong mines opened, but tailings gradually dispersed throughout the watercourse and formed a much larger influence area than originally expected. The solution to obtain acceptable conditions was to build an expensive dam dividing the lake and conducting the river from the watercourse upstream past the new tailings pond. When capacity in the original tailings pond was full, Bleikvassli Gruber chose to conduct the tailings to a new watercourse and use a relatively sheltered part of this as a disposal site. The Bleikvatn lake chosen was highly regulated for hydropower, causing increased dispersal of the tailings material. The effect on biological conditions was clear and there was a marked increase in the metal content in the fish, including lead. As the lake had major variations in water level, there was also erosion and washout of fine material from the littoral zone, which will in time cover the tailings and reduce the leaching of metals.

Studies conducted in 2008 show that the metal content in the fish was still above the natural level, but significantly lower than the levels recorded while the mines were still operational (Aanes et al., 2009). The studies conducted of the fish in relation to lead and cadmium in the fish flesh concluded each time that the levels were not so high as to represent a hazard regarding human consumption.

In addition to the leakage of metals from the tailings to the surrounding area, tailings particles will change the bottom conditions in the lake. The bottom is smothered, and parts of the benthic fauna disappear, also as a result of changes in the physical-chemical conditions in the sediment. The impact depends on the extent to which the acid-neutralising properties of the tailings have the capacity to neutralise the oxidation products and the physical-chemical conditions in the water directly above the tailings. These are factors that will control the leakage of metals from the tailings to the water phase above, and subsequently the bioavailability (environmental risk) of these metals. This will be decisive for the impact on the benthic fauna and how heavy metals are accumulated by animals and then passed on to the fish in the watercourse. There was a former tradition in sulphide ore mines to pump the acidic, metalliferous mine water formed in the mine into the tailings pipeline. The principle was that the highly alkaline tailings would neutralise the mine water and bind the loose metals to the tailings. This had a positive effect, but at the same time, consumed some of the buffer capacity in the tailings. Some tests of the tailings from Bleikvassli showed indications that there was, over time, a slight reduction in the leaching of toxic metals from the tailings that had not been mixed with acidic mine water (Aanes, 1996) than the tailings that had been mixed. The biological impact was also much more severe in the water above the tailings that had been mixed with acidic mine water. This subject, i.e. the treatment of mine water that becomes highly acidic over time and elevated metal content, requires a special focus when opening new mines for sulphide ores.

Another important impact caused by processing of ore and minerals is pollution from inorganic mineral particles. When these are discharged to rivers and streams, they cause smothering that can destroy spawning areas and reduce the food supply for fish in the watercourse. As a result, all or parts of the benthic fauna that survive by filtering food particles from the water disappear, thereby eliminating an important part of the self-purifying properties of the watercourse. Depending on the shape of the tailings particles, they may cause damage to the gills of fauna in the watercourse. Needle-shaped particles have proven to cause significant damage and can be hazardous for the watercourse (Jakobsen et al., 1987).

In recent years, Norway has introduced a technique of sealing mines and allowing them naturally to fill with water, in order to reduce the production of acidic mine water in closed mines. This reduces the oxidation of exposed sulphide minerals in the mine. However, when the mine is full, seepage water will occur that requires treatment before being transported to a recipient in order to avoid the problems we have previously encountered with former discharges of acidic mine water. During the operational phase, the biological impact, the magnitude and range of the impact in the affected watercourses were subject to comprehensive monitoring. However, after operations were terminated, there has been little monitoring of the ecological conditions in the same recipients.

In 1990, the results obtained from NIVA’s studies of the effect of metals from mine pollution on biological conditions in watercourses (Grande et al., 1991) were compared and evaluated. The main focus was on the impact on fish. Copper, zinc and cadmium are among the heavy metals most common in mine recipients and may well have a toxic effect to a somewhat greater extent. Of these, copper has the most significant impact. Data may indicate that the Cu concentrations presented as the annual average (total values) caused insignificant damage to fish and invertebrates/benthic fauna when the levels were below approximately 20 µg Cu/l. Species that are especially sensitive to fouling and invertebrates may be affected by lower concentrations of copper. In certain localities, data also shows that there were good stocks of salmon when concentrations were between 30 and 50 µg Cu/l, but with a water quality with a slightly higher conductivity and organic content (humus). In the localities studied, no evidence was found of significant toxic impact from zinc, cadmium or other metals.

Opening new sulphide ore mines

A lot of knowledge has been obtained in recent years and particularly abroad about how to manage water-related recipient problems from e.g. sulphide ore mines. New provisions and regulations have been issued, best available technologies developed and a cradle to grave mindset incorporated. The above is integrated as early as the planning phase. The EU's Mining Waste Directive also requires sufficient funds to be allocated during operations to the management of future environmental requirements once the ore deposit has been fully exhausted and the area shall be returned as close as possible to its former condition. If these prerequisites are satisfied, it should be possible to open new mines without encountering the environmental problems we have experienced with previous mining.

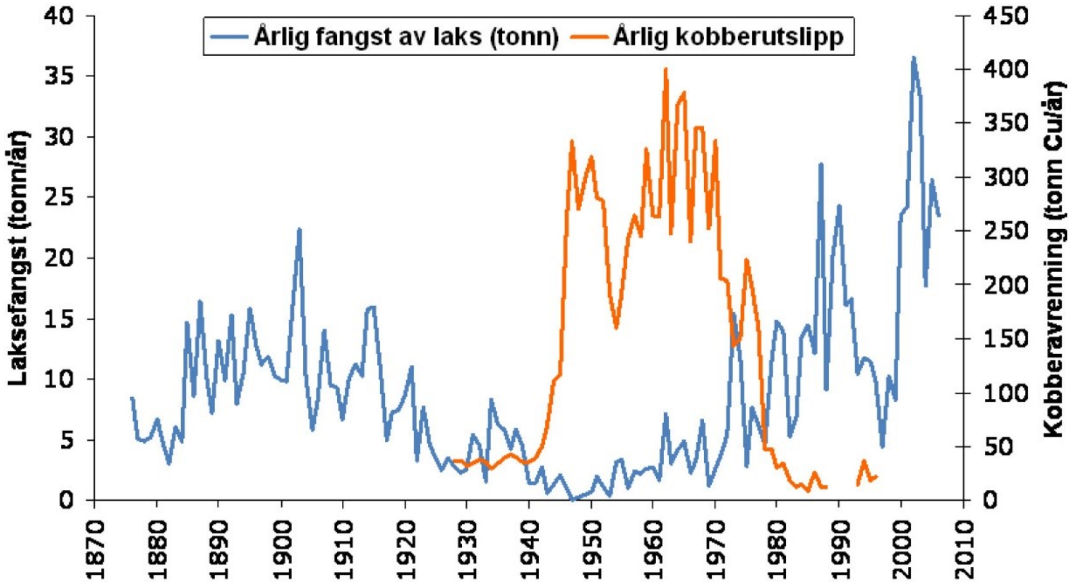
5.1.3 Impact on natural resources

Background

Fish, particularly salmon, represent a major natural resource. On a nationwide scale, salmon is estimated to generate values of NOK 500 - 1,000 million per year. The salmon in our rivers therefore represents a major natural resource. In some areas, seepage from abandoned sulphide mines is in conflict with the salmon industry (e.g. in river Orkla).

The hazardous effects of seepage from mining on fish are well known and documented over many years. There are historical datasets that document the correlation between seepage and population reduction, and a number of Norwegian lakes and parts of watercourses are still so badly affected by mine seepage that they no longer have any fish, or the stocks are reduced. There is a lot of existing knowledge on the toxic mechanisms of some metals on fish, and considerable knowledge of the tolerance limits for individual fish species to metals. Progress is continuously made on transferring this knowledge to models that can be used to estimate the impact on population levels in nature. Despite this, knowledge gaps remain and/or there is a need for more documentation in several fields. The complexity of both water chemistry and the sensitivity of different fish species and life stages make it difficult to establish universal limit values. The current practice of applying one fixed limit value for one metal (copper, 10 µg/L) will in many situations be misleading. There are examples where fish populations survive in an environment with higher concentrations of copper. At the same time, however, we know that much lower concentrations have a negative effect in natural water chemistry conditions during sensitive life stages.

The figure below illustrates the correlation between annual catches of salmon (in blue) in the Orkla (source: Norwegian Directorate for Nature Management) and discharges of copper (orange) from Løkken Verk (Iversen, 2009 c).



In order to avoid environmental measures related to mining operations and disposal that are either unnecessarily expensive or do not achieve the required protective effect, site specific evaluations of limit values are necessary in addition to increased efforts to identify tolerance limits for especially vulnerable life stages in fish.

Mining operations, disposal sites and fish

Two main components in seepage are connected to impact on fish: ionic metal compounds and particles. Of these two, toxic effect of metals is the most dominant and emphasised in impact studies and monitoring related to traditional mining. However, negative effects of tailings particles will also be an important component in connection with future mining and disposal sites.

Metals

Mobilisation and leaching of metals to the water phase is thought to be the main problem in many disposal sites, and design/downstream measures target the reduction of such leaching. Depending on the chemical and physical composition of the actual tailings and the design of the disposal site, the concentration and speciation of metals discharged to the external environment will be site specific. If metals are to present a toxic hazard for fish, they must be in a bioavailable form. Free metal ions are defined as most bioavailable and most toxic. The speciation (and thereby bioavailability/toxicity) depends on the chemical properties of each metal (Lydersen et al., 2002), and other water-chemistry factors such as the pH level of the water, alkalinity/hardness, salinity, the amount of dissolved organic material and the presence of complexing agent substances (Niyogi and Wood, 2004). One further complication is the speed of the different chemical reactions. Oxidation, hydrolysis, polymerisation, sequestering agents and precipitation occur when released metals are introduced to the external environment. Metals may be much more toxic before these reactions have reached an equilibrium, which may take hours and days in certain situations (Kroglund et al., 2001, Teien et al., 2004; 2008). Depending on the chemical properties of the different metals, the concentration required to have a toxic effect on fish differs greatly. Traditionally in Norway, limit values have been applied for copper alone, even though other metals in the seepage water have a toxic effect.

Toxicity of metals for fish

A significant amount of work conducted in Norway describe the toxic impact mechanisms of metals from mine seepage (Olsvik et al., 2001; Hansen et al., 2007). As the toxicity of metals relies strongly on water-chemistry factors, it is difficult to establish any general limit values from literature. With the EU's risk assessments of individual metals, attempts are made to introduce corrective factors for the effect of different water-chemistry components such as organic material (fresh water and seawater) and hardness (fresh water). Norwegian fresh water has in general very low levels of calcium and magnesium (Skjelkvåle et al., 2001), if carbonates represent the hardness/buffer capacity of the water. Several investigations have therefore been carried out with representative Norwegian waters properties to obtain sufficient knowledge of the modified effects of low hardness on metal toxicity (Källqvist et al., 2003; Haugen et al., 2007). It is nonetheless problematic to excessively interpret the data from experiments of individual metals when facing a situation involving complex mixtures of metals with the potential for agonistic and antagonistic effects. A risk evaluation should be performed for each situation, using knowledge of the actual water quality to modify the toxicity of a certain metal concentration.

Several analytical methods have been developed to determine the ratio of bioavailable metals tested (Røyset et al., 2005). For freshwater, different bioavailability models have been developed to calculate toxicity, e.g. "Biotic Ligand Model" (BLM) (Niyogi and Wood 2004, Deleebeeck et al., 2007). This type of model is now used by an increasing number of organisations, e.g. the EU. Both speciation techniques and chemical modelling should be introduced to a greater extent also in Norway.

Particles

The term "particles" is used to define many types of non-dissolved aggregates of varying sizes. In relation to mining, seepage/discharges will comprise inorganic particles with a site specific chemical composition, size distribution and shape. Particles may affect fish directly via impacts on the mucous membrane, skin and gills, and indirectly via an impact on the ecosystem. The indirect impact of particles may be summarised as three main elements:

- Smothering of bottom substrata resulting in destroyed/reduced spawning and nursing areas
- Reduced primary production caused by lower light penetration in the water
- Reduced visibility resulting in reduced feeding

Effects of particles on fish

The status of knowledge on direct effect of particles on fish is summarised in Dale et al., (2008), where it is indicated that the majority of knowledge on the effect on fish in fresh water originates from Pacific species of salmon. As a result, we lack specific limit values for the most common fish species in Norwegian freshwater fauna. For estuarine/marine fish, the number of impact studies is very low, and we therefore lack knowledge of the effect of particle discharges to the marine environment and marine deposits on fish (Dale et al., 2008). Turbidity measurements must be supplemented by information on the size distribution and shape of particles in order to gain a better understanding of effects and more accurate limit values for fish (Bilotta and Brazier, 2008).

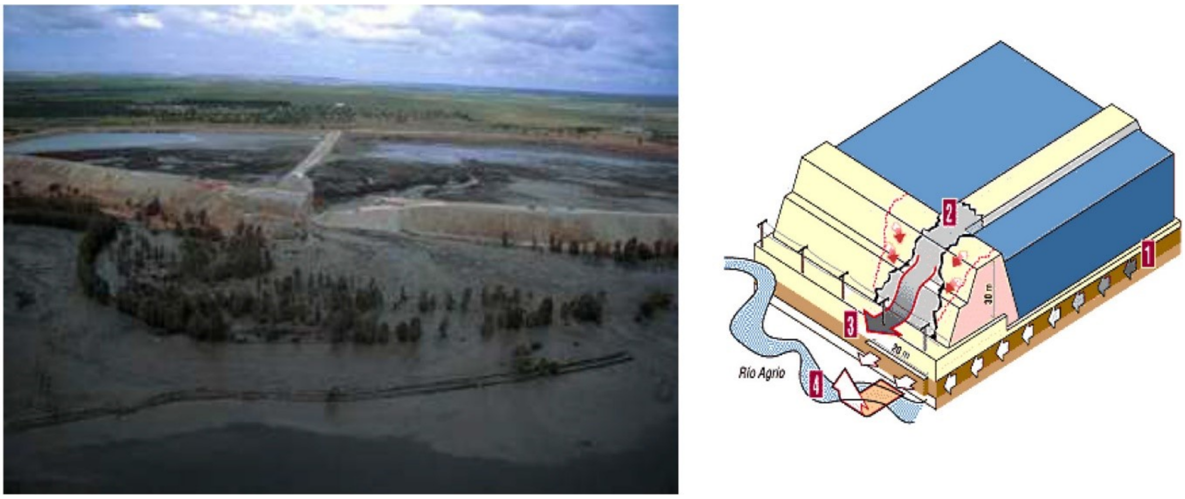
Life stages and sensitivity

In general, the life stages for fish during which major morphological and physiological changes occur are the most sensitive stages for all types of impact. The early life stages, involving development from egg to free-swimming fry is perhaps the most illustrative example. Several trials have been conducted involving exposure to metals during this stage. Puberty and spawning are also life stages with increased sensitivity, illustrated in fields for e.g. aluminium (Pettersen et al., 2007). For anadromous fish (migrate to the sea after nursing in freshwater), the smolt stage is extremely sensitive to metal exposure. Smoltification involves a complex physiological and morphological pre-adaptation to dealing with salt and the water balance when making the transition to life at sea (Hoar, 1988). During smoltification, sensitivity to a number of environmental factors increases. Increased sensitivity to low pH and aluminium during smoltification is fully documented (Staurnes et al., 1996; Kroglund et al., 2007a), and concentrations that have low effect during exposure in fresh water have been proven to cause reduced survival in the subsequent life stage in the marine environment (Kroglund et al., 2007b). These mechanisms involve the enlargement of central enzyme systems for sustaining salt balance (Kroglund et al., 2007b, Nilsen et al., 2010). Based on current understanding of the cause-effect mechanisms of metals, there is reason to assume that increased sensitivity also involves other metals. With the mine seepage from Meråker, tests have proven that smolt die much more rapidly than fry, and with major disturbance of the salt regulation enzymes

(Kristensen et al., 2009). Pilot trials with seepage from Løkken mines have provided similar results (Kroglund et al., not published). Disturbances to the sensory system are also significant for fish that migrate between different habitats, and the impact of copper on the sense of smell for salmon has been proven at very low concentrations (Baldwin et al., 2003; Sandahl et al., 2007).

5.1.4 Risk of accidents

The most predominant risk related to landfills is dams that fail. The climate is developing towards increased levels of precipitation and an increased frequency of flooding. This places major requirements on dam constructions. There are several examples from abroad in the past decades where the dams for landfill of mine tailings have collapsed, with the tailing masses causing major destruction to nature and problems encountered relating to life and health. In 1998, a tailings dam connected to a lead and zinc mine owned by Boliden in Los Frailes in Spain burst, causing 5-7 million m^3 of tailings to be released into the Rio Agrio river (see figure below). The cause was a landslide under the tailings dam (see photo on the right below). Large agricultural areas were covered with mine tailings.



Burst dam in Los Frailes, Spain, 25 April 1998. The figure on the right shows what caused the dam to burst. Photo: Google.

The most common trend is to decide to extend the height of the dam to increase capacity when the deposit is about to be filled up to its capacity limit. This places major requirements on the dam construction. Given that climate change may result in higher rates of precipitation than expected when the dams were designed, this represents a potential risk.

5.1.5 Monitoring and environmental documentation

As mentioned above, long time monitoring and documentation will be necessary at several disposal sites. This can be justified on the basis of several assessments:

1. Dam constructions and pollution potential make it necessary to maintain everlasting control and documentation of any changes in a negative direction.
2. The situation at several disposal sites is unstable in terms of water quality.
3. The Mining Waste Directive specifies requirements on closed disposal sites (articles 20 and 21). The requirements comprise e.g. documentation, follow-up of technical solutions and for information to be based on science. This implies that we require

continuous access to relevant competencies and that these are continuously updated. Contact with groups in other countries where research activity is more comprehensive than in Norway is important (Canada, USA, Sweden and the EU, Australia etc.).

4. A national research programme related to the mining industry and environmental challenges will ensure the competences required in Norway to comply with the requirements in the Mining Waste Directive.
5. Norway was one of the first countries to utilise disposal solutions for tailings that are now classified as modern thinking. We have a long series of observations of disposal sites and recipients, and important data in connection with the calibration of prediction models for metal leaching.
6. Sampling alone has a limited value. The evaluation of results in relation to prediction models utilised will provide more accurate information on the processes that occur in a disposal site.
7. Follow-up of the situation in the disposal sites, based on scientific data, will be extremely valuable when assessing applications for new permits.
8. Experience gained from monitoring fresh water disposal sites can be further developed to also cover disposal in marine environments, where the level of experience and knowledge is not as extensive.

One important principle related to water-chemistry monitoring in mine areas is to measure not only concentrations of particles and metals, but also flow rate allowing estimates of transport (flux). Concentrations are important in relation to biological impact. However, in order to understand the processes that occur, documentation of the transport of pollutants is required. If we are also to be able to estimate e.g. annual transport, the measurement data from all hydrological situations is required to produce a representative illustration.

When opening new mines that require disposal of tailings on land, it is important to obtain a good overview of the environmental conditions in the water bodies that may be affected by mining in order to distinguish between what is caused by the mining and what is caused by natural variations.

5.1.6 Examples of disposal sites that have functioned as intended

It can be extremely difficult to distinguish between successful and less successful disposal solutions. All disposal sites have an impact on the environment in one way or another. For this reason, characterisation of the individual disposal solution may depend on the situation in the specific mine area and the conditions for the recipient. One solution defined as acceptable in one location may cause a much greater impact in another location. The choice of solution will therefore always be evaluated in light of the natural environment where the mine is to be opened. Below are some key examples of successful and less successful disposal solutions in Norway. There are also some examples of solutions that may be justifiably characterised in a third category e.g. where we still do not have an overview of the long-term impact and where long-term monitoring is required in order to draw a conclusion and make a decision on any measures to be taken.

The Hjerkinn dam

The Hjerkinn disposal site was the first water-covered disposal site in Norway for sulphidic tailings (chapter 4.2.1). The disposal site was operational from 1968 to 1993. The tailings had a low content of sulphur (<5 %), gradually decreasing until disposal was phased out and the processing of the ore was improved.

When the disposal site was planned around 1964, there was opposition regarding the destruction of the Hjerkinnsmyra moor, which at that time was an area of wetland with a rich bird life. After disposal ended in the spring of 1993, the current Hjerkinnsdammen dam has been used for swimming and fishing and is now a popular and highly valued part of the landscape. The dam fits in the landscape and the actual dam construction is hardly visible for people travelling along the E6 and RV 29 roads from Folldal up to the Hjerkinnkrysset junction (see figure below).

Hjerkinnsdammen dam in June 2010. Photo: E.R. Iversen.

Today, it would be more difficult to establish mining operations in Hjerkinn with its location in a vulnerable high mountain area on the border between Dovre and Rondane national parks. Looking back over the operational period, there were no severe accidents. The disposal system functioned satisfactorily. However, the discharges from the Hjerkinnsdammen resulted in a significant change in the chemical water quality throughout the entire watercourse downstream to Alvdal, due to the use of lime and sulphates (sulphuric acid) in the ore processing. Other flotation chemicals (xanthates) were also noticeable some distance downstream in the Folla. Particle transport from the disposal site was relatively moderate and varied in the range of 10-60 tonnes per year. In total, approximately 300 000 tonnes of tailings were deposited every year in the dam. The discharges had an impact on the amount of benthic fauna for several kilometres downstream in the Folla. In the spring before the spring floods, it was also possible to observe accumulation of tailings particles in the river bottom sediments along this stretch of the river. In total, the situation was considered acceptable and did not deteriorate for the remainder of the operational period.

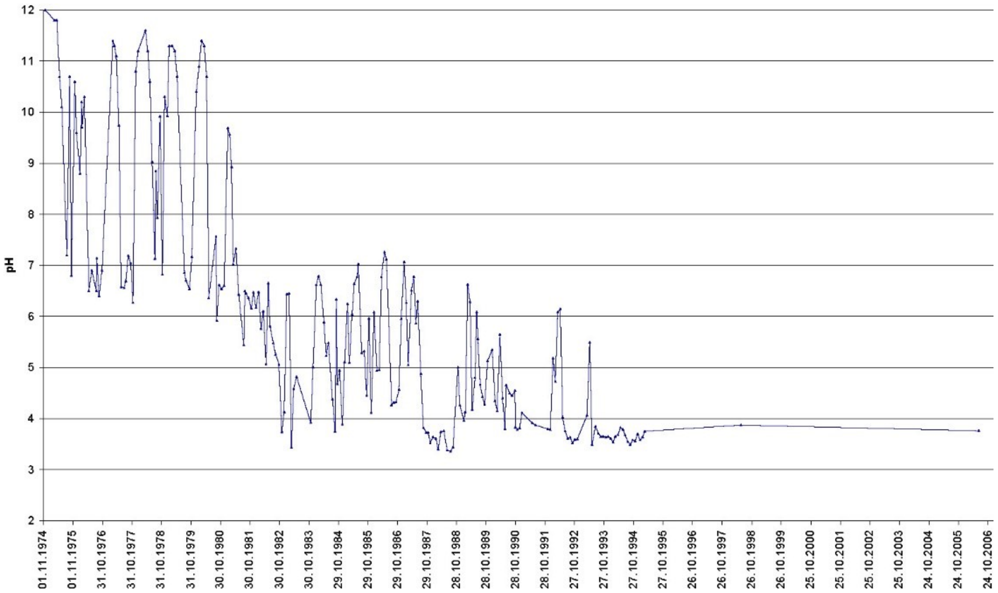
Once the mine was closed, the water quality in the watercourse downstream of the dam almost returned to its original condition after a relatively short period of time. Some zinc was identified in the overflow water from the disposal site, but this was attributed to discharges from the mine area under Tverrfjellet mountain (Jernbanestollen).

In total, the mining project in Tverrfjellet must be characterised as a successful project in terms of disposal of tailings (Iversen et al., 1999 a; Iversen og Aanes, 2005). The disposal of tailings was relatively successful even in difficult climatic conditions. Particle transport and heavy metal transport from the disposal site were relatively moderate during operations and the following years.

Bjønndalsdammen

Bjønndalsdammen at Løkken Verk (chapter 4.2.4) was the first under water disposal site in an artificial dam in Norway for tailings with a high sulphide content (36 %). Tailings were disposed of in the dam from 1974 to 1987. In total, approximately 3.2 million tonnes of very reactive tailings were disposed of in the dam. The copper content is approximately 0.2 %. As a result, theses tailings are the source of the highest pollution potential in Løkken, when compared with other waste disposed of in the area.

During operations, the water quality in the dam showed a relatively high pH level, as the tailings had a pH of around 9. However, the water phase contained a number of thiosulphates/polythionates. Downstream of the dam, these compounds oxidised to sulphates as the water was aerated, causing the formation of acid and a fall in pH in the two lakes downstream, Fagerlivatn and Bjørnlivatn. Particle transport from the dam was moderate. At times, a fall in pH in the actual dam was observable, for the same reason and resulting from the oxidation processes in the tailings, resulting in e.g. release of bivalent iron ions that oxidised to form trivalent iron in the dam. Hydrolysis of trivalent iron generates acid. The latter process became more prevalent after the disposals stopped, illustrated in the figure below.



pH measurements in Bjønndalsdammen 1974-2006.

The water quality and transport of pollutants were monitored closely during operations and during the subsequent years. A prediction model was prepared for how the levels of heavy metals would develop in the years after disposal came to an end (Arnesen et al., 1997). To date, the estimated concentrations have concurred with the actual situation in the dam (Thornhill and Bjerkeng, 2006) and (Iversen and Arnesen, 2001).

Given the situation in Løkken, the tailings disposal in Bjønndalen must be characterised as successful, and provides a clear illustration of the major differences between modern disposal techniques and past disposal practice. The discharges from the Bjønndal tailings disposal are very insignificant for total pollution in Løkken today. However, it must be noted that the structure of the disposal site will require constant control of the dam construction and water level/water quality. The dam is not maintenance-free in a long-term perspective. Taking into consideration the vast pollution potential represented by the contents of the dam and the valuable watercourse downstream, it is important to maintain regular inspection of the disposal site. It is also important to remember that this disposal technique is not 100 % efficient. In a different environment with a different situation in the area and the recipient, it is also important to consider the negative aspects of such disposal, despite it allowing control of the leakage of heavy metals.

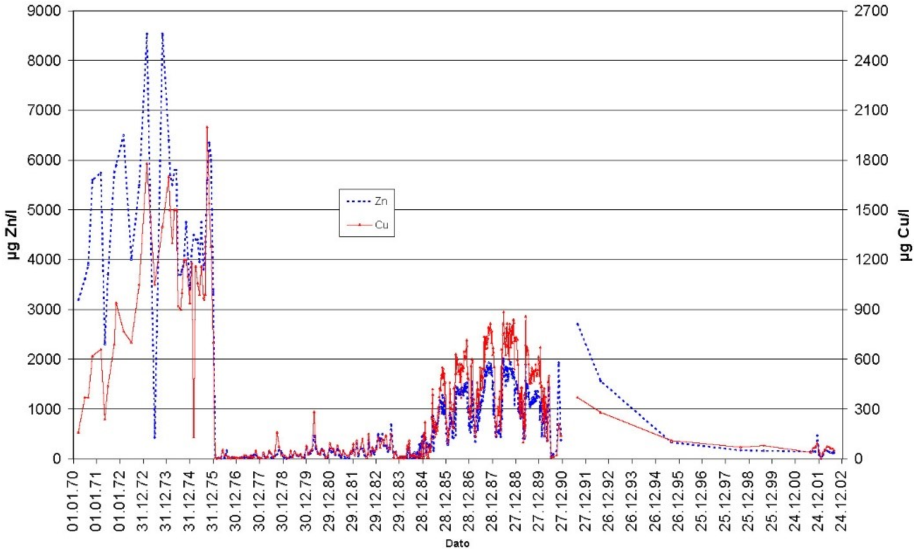
Dausjødeponiet (Dausjø disposal site)

Elkem AS - Skorovas Gruber (chapter 4.2.5) was operational from 1952 to 1984 and quickly developed into one of the most polluted sulphide ore mines in Norway. The two greatest sources of pollution were mine water and seepage water from the waste rock heap. The company utilised Dausjøen lake just below the processing plant for disposal of tailings. Up to the autumn of 1976, the water quality at the disposal site was very acidic and significantly polluted. This was attributed to the pH level in the tailings, from the process utilised, and that a part of the tailings was disposed of in the littoral zone of the lake.

In the autumn of 1976, the enrichment process was changed to selective flotation, with the production of copper and zinc concentrates. The pyrite was disposed of along with the other tailings at a depth of around 20 metres in the Dausjøen lake. A lot of the old tailings were also with time disposed of under water in the lake.

The new process generated discharges with a pH level of around 9, as in Løkken. This provided a significant improvement in the water quality in the outfall from lake Dausjøen. Two effects were achieved. The high pH level in itself provided precipitation of metal hydroxides. In addition, the mineral particles in the tailings also had the capacity to adsorb heavy metals. During certain periods, there were indications of e.g. lower copper concentrations in the lake than were expected based on solubility products for copper hydroxide (see figure below). This in turn resulted in the return of trout to the lower part of the Grøndalselva river. As in Løkken, the situation was also affected by the formation of thiosulphate/polythionates during the enrichment process. A lower pH level was recorded in the stream running out of the lake Dausjøen and downstream to lake Store Skorovatn, caused by oxidation of thiosulphate to form sulphates. During the winter, the oxidation was at times incomplete, causing sulphide formation in lake Store Skorovatn when the lake was covered with ice. However, this had no consequences for the lower stretches of the watercourse.

In 1989 to 1990, the decision was finally made to move the waste rock pile to an underwater disposal site in lake Dausjøen. As such, there are now ten underwater disposal sites in lake Dausjøen. The measures implemented in Skorovatn lake provided a 95 % reduction in the seepage of copper (Iversen, 2004). Although a number of pollution-related problems remain in the area, the disposal solutions in Skorovatn lake have to be characterised as very successful, particularly when taking into account the difficult pollution encountered in 1984 when the mine was closed.



Copper and zinc concentrations at the mouth of Dausjøen lake 1970-2002.

Huddingsvatn lake disposal site

Grong Gruber had operations from 1972 to 1997 (chapter 4.2.2). The company produced concentrates of copper and zinc, but had to dispose of the pyrite together with the other tailings for market-related reasons. Prior to start-up, a range of disposal alternatives were discussed, but the conclusion was to use Østre Huddingsvatn lake as a disposal site. It was assumed that there would be low dispersal of particles from this area as there were only a few shallow thresholds between Østre and Vestre Huddingsvatn.

After a short period of operations, tests revealed that the disposal system was not functioning as planned. Dispersal of tailings particles was found to have increased from the disposal sites, with a gradually negative impact on the entire watercourse downstream to Vektaren, where Huddingsvatnet lake meets the water masses from Namsvatn lake. Surprisingly large particles of up to 250 µm were found several kilometres from the outfall area downstream in Vektarbotn.

The question of whether the disposal solution chosen by Grong Gruber was successful is obviously open to debate. After the implementation of an expensive but effective shut-down measure in 1989-1990, the company was able to reverse this trend. The disposal system used by Grong Gruber can therefore be categorised according to two different periods. The first period up to 1990 was not successful in terms of particle dispersal. The measures implemented were, however, successful. The technique implemented stopped particle dispersal to a significant degree so that the biological condition of the watercourse downstream showed a continuous improvement up to 2004, the last year of observations.

The situation in Vestre Huddingsvatn did not show signs of a full recovery in 2004. It is thought that it will take more time to repair the damage there. In 2004, there were indications that the bottom vegetation was in the process of returning and that developments were positive, but the important Gammarus lacustris, a source of food for other fauna, had still not returned. This can be attributed to several causes. One possible cause for the slow return is the introduction of a new species of fish, minnow, to the watercourse in the 1970s. The minnow gradually formed large shoals in the shallower areas, potentially with a damaging impact on the stocks of benthic fauna (Iversen et al., 2004).

One lesson learned from Huddingsvatn lake is that even small volumes of tailings particles can cause damage. Before the measure was implemented, visibility depth in, for example, Vestre Huddingsvatn outside the disposal site could be around six to seven metres. After the measure was taken, the visibility depth returned to the estimated normal level of 12-14 metres. The volume of suspended mud per litre was relatively moderate throughout the period, but the impact remained clear.

In total however, the disposal system in Huddingsvatn can ultimately be characterised as successful once control was gained over particle dispersal. Disposal in a lake system places more stringent requirements on the operator than when disposing of tailings in a dam. The underwater disposal in this case also showed that the principle is suitable for maintaining control of the release of heavy metals. When comparing observed values with estimated values for heavy metal release, the figures concurred. It was concluded that even though improvements could be made by covering the tailings under water, the costs of such a project would not be proportionate to the utility value (Arnesen, 1998).

5.1.7 Examples of disposal sites with unexpected environmental problems

Røros Kobberverk

Operations at Røros Kobberverk copper mine (1644-1977) (chapter 4.2.6) could not be described as compliant with the requirements that would be imposed on such operations today. At that time, the focus was much more on economic yield and historical traditions than the environment. The disposal of tailings was catastrophic. The fact that the mining operation and the tailings disposal were relatively small saved the environment from major environmental consequences in the years to come.

The problems related to the disposal of tailings are most severe in the Storwartz field. In this field, the tailings from the enrichment plant were allowed to flow freely and are now exposed to weathering along the stretch from the actual plant and down to Djupsjøen lake (see figure below). The tailings produce substantial volume of weathering products, affecting the water quality for the entire watercourse (Hittervassdraget) downstream to the Glomma (Arnesen, 1996; Grande et al, 1996; Iversen, 2004 b).

The area has now been protected against all interventions and is part of the World Heritage Site for Røros.

Tailings with enrichment plant at Storwartz. Photo: E. R. Iversen, 2009.

Knaben molybdenum mines

Operations at Knaben closed in 1970. Tailings from the processing plant (chapter 4.2.10) were all the time discharged directly to the surroundings, similar to the practice at Storwartz plant at that time. The volumes of tailings were, however, much more substantial than at the Storwartz plant.

The heavy metal problems related to seepage from the disposed masses are considered moderate (Iversen, 1998). The most severe problems relate to particle dispersal from the masses. The current disposal site is not stable and will with time fill up Store Knabetjern if action is not taken. Measures will therefore be implemented. The measures will be technically difficult and expensive.

During the period of tailings disposal, the watercourse downstream was significantly affected as the tailings settled in the calmer stretches of the river all the way down to the Fedafjord. Today, these masses do not cause any problems (Traaen and Bækken, 2002).
The Knaben disposal solution is a good example of a bad solution which will be very expensive to repair. If the mine had been copper/zinc instead of molybdenum, the measures would have been much more expensive, and the tailings would have required covering.

Titania

The disposal solution at Titania was changed in 1994 with tailings being disposed of on land in a constructed landfill. Previously, the tailings were disposed of in the Jøssingfjord and Dyngadjupet outside the Jøssingfjord (see chapter 4.5.1). Due to the lack of control of particle dispersal, the company was ordered to build a landfill. A dam construction was designed to cover approximately 30 years of operations.

The disposal site is now almost full and, with time, some experience has been gained from operations and we have a better understanding of the challenges faced when the landfill shall ultimately be closed.

When the choice was made to build a permeable dam, there was no experience showing that the landfill would leak nickel (approximately 1-1.2 tonnes per year). This is caused by the fact that parts of the tailing masses disposed of above the groundwater surface in the landfill have been exposed to weathering. The heavy metal problem was not in focus when the landfill was planned. At that time, the focus was on dispersal of particles to the marine environment. It remains too early to conclude what may happen in the long term once the landfill is closed. At that point, the situation will have changed in that the landfill will no longer receive water via the tailings pipeline. It is possible that the groundwater level will be lower.

Another challenge related to the actual surface of the landfill, in addition to dust and air pollution, is that it may be difficult and expensive to achieve re-vegetation.

This landfill will require monitoring in the long term. It is therefore difficult at this point to provide a final evaluation of whether this solution was successful or not.

Nikkel og Olivin AS - Ballangsleira disposal site

A similar situation can be found at the disposal site for Nikkel og Olivin at Ballangsleira (chapter 4.2.9), although Ballangsleira is a disposal site in the littoral zone.

Initially, the mining company encountered a number of problems in connection with disposal. With time, they managed to gain control of tailings dispersal and sand dispersal, and encountered only minor problems with disposal at Ballangsleira. Subsequent studies show that the leakage of nickel from the disposal site was moderate and there was no significant negative impact on the fjord as a result of this disposal site (Iversen, 2007) and (Berge et al., 2008).

The disposal site was covered with a thin layer of peat and seeded. Some vegetation has established on the surface of the disposal site, but adding fertilisers is occasionally necessary to maintain the vegetation. It remains uncertain when fertilisation will no longer be necessary.

The vast area covered by the disposal site means that it is highly exposed to wind erosion, and sand drift may well re-occur if the vegetation is impaired. This disposal site requires long-term monitoring before a final conclusion can be drawn.

5.2 Disposal of tailings in the sea

More than 30 years of monitoring of sea disposal of mine tailings provide comprehensive information on the level of environmental disturbance during operations and the length of time it takes for the environment to recover once a mine has been closed.

5.2.1 Physical and chemical stability

The main difference between disposing of mine tailings in fresh water compared with salt water is the difference in chemical composition of fresh water and seawater. Seawater has a high buffer capacity and discharge of acidic tailings to the marine environment only causes minor acidification. In addition, the toxicity of metals in relation to aquatic organisms is greater in fresh water than in seawater. This is because the metals in seawater often form inorganic complexes with salts that are less toxic than metals in ionic form in fresh water. However, salt water corrodes e.g. pyrite minerals causing metals to be released more easily from tailings in seawater.

The hydrodynamic conditions are also substantially different between fresh water and seawater. The circulation pattern in lakes is often controlled by wind, particularly in shallow lakes. In addition, the exchange of bottom water in lakes will be controlled by temperature gradients, with cold water sinking to the bottom in the winter and warmer bottom water flowing up to the surface.

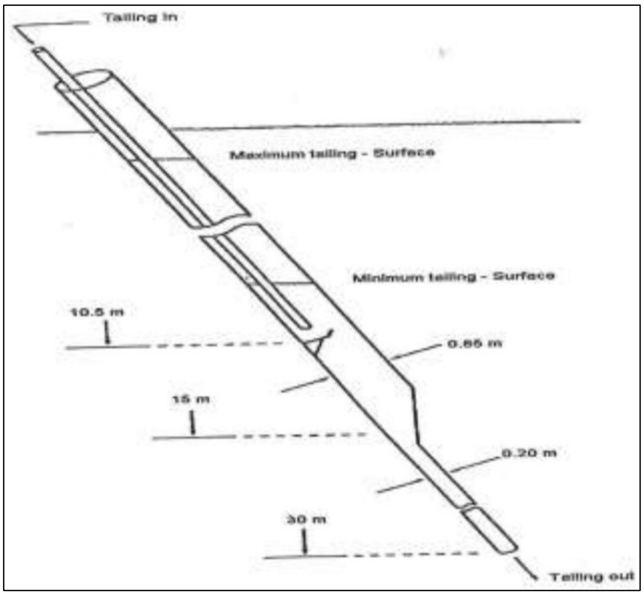
In seawater, in particular sill fjords, the circulation pattern is determined by the supply of fresh water, wind, tide and deep-water exchange, where heavy coastal water flows into the fjord basins and replaces the old bottom water. The circulation pattern in fjords is therefore more complex than in lakes.

5.2.2 Dispersal and sedimentation

It is a prerequisite that sea disposal takes place at depth and below the halocline (the boundary between brackish surface layer and salty water). The stratification of the water masses in relation to outfall depth is of major importance. This is a principle that not only applies to the discharge of mine tailings but all types of industrial discharges and sewage. When deep water discharges are selected, the main reason is to stop waste water affecting the upper water layers and to ensure that most of the dispersal and dilution takes place in a homogeneous water mass and that the waste water is retained below the halocline. The most common method for discharge of industrial and municipal waste water is to mix the waste with fresh water. As fresh water is lighter than seawater, the waste water will rise upwards and gradually mix with the salt water until the density difference between the waste water and the surrounding seawater is neutralised. This is the entrapment depth and should be below the stratified water. Density layering will normally function as a false bottom or a lid which mainly prevents vertical transport of water and small particles.

Sea disposal of tailings clearly requires the highest level possible of control and predictability. The goal is to ensure that the tailings reach the bottom as quickly as possible while the plume is homogeneous (with minimum possible splitting). At the same time the coarser tailings particles sink almost immediately from the outfall point and the fine fraction is transported slightly farther as a turbidity current, which mainly follows the seabed topography. It is not preferable that all the tailings discharged through the tailings pipe settle out close to the mouth of the pipe. A certain rate of dispersal is required to prevent the build-up of steep cones on the seabed, which become unstable and can cause large sub-sea slides. The goal is to build up fans of tailings with an angle of repose of < 10 degrees, where small and frequent sub-sea slides occur, stabilising the fan and the angle of repose.

Another principle is to ensure de-aeration of the tailings mass before it is released to the sea to avoid air bubbles following the tailings flow and transporting the fine fraction of the tailings to the sea surface.. Different solutions have been chosen for de-aeration of tailings, but the most common method is to use a mixing tank for seawater. The sea disposal from Black Angel mine in Greenland had a special device for de-aeration as shown in the figure below.



The figure illustrates a pipe system where the tailings are transported in an inner pipe and the air escapes through the outer pipe. Figure: Poling and Ellis, 1995.

Sufficient knowledge of the natural system in the area where disposal is planned is of decisive importance. This requires a comprehensive amount of work at an early stage of planning. A sea chart based on high resolution seismic methods is a prerequisite for producing a detailed image of the bottom topography. Angle of gradient and thresholds are important natural elements that must be included in the planning work related to sea disposal and the design of the outfall system.

The condition of the sediment in the area where disposal has been planned will provide some information on the natural sedimentation conditions. If the sediments mainly comprise silt and clay, the area has sedimentation of fine material, indirectly indicating low current velocity. If the sediments comprise coarse silt and sand, this indicates a seabed characterised by transport, where the current velocities are so high that the fine material is transported with the current. If the sediment comprises even coarser material, it is most probably a seabed characterised by erosion. Neither of the two latter types, transport and erosion, are suitable as disposal areas for fine-grained tailings.

The oxygen status in the deep water provides information on water exchange in a marine basin. Low oxygen values indicate low water exchange and the bottom sediments normally have a higher content of organic material. In some fjord basins, surrounded by shallow thresholds, the bottom water may be stagnant for long periods of time and, in the worst case, 100 % of the oxygen may be consumed and replaced by sulphides. The fjords are exceptions. Normally, deep water exchange takes place in fjord basins every year, depending on threshold depth.

Current measurements that cover every season will provide an insight into the velocities and directions of the current at varying water depths. If, in addition, current data is connected to measurements of turbidity, it will be possible to estimate natural particle transport in different water masses, and variations over time. These are important base studies when planning sea disposal of tailings. The current conditions will be of fundamental importance for the dispersal of fine material in the tailings, and are required in order to model dispersal and sedimentation (ref. Kolluru et al., 1998).

In addition to current, stratification in the recipient will also be significant and an important source of information when planning sea disposal. Salinity and temperature profiles and the estimation of density are also important prerequisites when choosing the correct outfall depth. Normally, deep fjords have a primary and secondary halocline in the water masses. The primary haloocline is normally found in the upper 10-20 metres (varies substantially throughout the year) and is controlled by the supply of fresh water. In addition, there is a secondary halocline that is normally defined by topographic conditions (for example, thresholds) or large-scale hydrographic conditions in coastal waters (100-150 metres deep). To the extent that a fjord is deep enough, it would be preferable to discharge below the secondary thermocline.

All these above-mentioned factors are covered by environmental impact assessments, which are a prerequisite for shedding light on all possible impacts of major disposal of tailings. All the fundamental prerequisites for acceptance of sea disposal also illustrate a need to prepare a set of *suitability criteria* and a set of *acceptance criteria*. Fundamentally, these criteria may be general and principal, but it is important to ensure they can be modified by taking into account local conditions and the circumstances involved in the disposal (volume, composition, duration etc.).

Use of near-field models

"Near-field models" are used in both offshore and mining to describe the behaviour of discharges immediately after leaving the discharge pipe. The near-field for a discharge is defined as within 100 metres (maximum) from the discharge point. Within this field, the specific weight and composition of the discharge are of major importance.

Models for the near-field have now been developed, providing a relatively complete description of what occurs in the near field, taking into account:

- Stratification of the recipient (depending on depth)
- Current (depending on depth)
- Velocity and direction of discharge
- Content of particulate material (particle size distribution included)
- Content of seawater
- Content of fresh water
- Content of water-soluble chemicals (low logPow)
- Content of oily chemicals that bind to particles
- Content of air/gas
- Time-variable conditions in recipient (current)

Different ingredients in the discharge determine the fate of the components in the recipient. If the discharge contains fresh water and air, this provides buoyancy (when discharged to seawater), while the content of particulate material provides specific weight and make the tailings plume to sink by gravity.

Another factor is the tendency of different ingredients in the discharge to split from the tailings plume to become entrained further up in the water column due to buoyancy. Examples are air (bubbles that rise from the tailings plume) and particulate material (which settles from the plume if the particle size and/or specific density of particles exceeds buoyancy).

Discharges from mining operations often contain fresh water that may create buoyancy when the tailings are released into the marine recipient. If the coarser fractions in the discharge fall out of the discharge, there will also be a balance (neutral equilibrium of the discharge in the marine recipient) when the particle content in the discharge compensates for the density difference between the seawater (around 1,025 kg/m^3) and fresh water (around 1,000 kg/m^3). With a particle content of approximately 25 kg/m^3 (or 25,000 mg/L) in the discharge, there will be an equilibrium between the density of the discharge and the density of the seawater (please note that the concentration of particles in tailings discharges from the mining industry is often a factor 20 higher). Seawater is mixed with the discharge to counteract buoyancy of the fresh water in the discharge.

When disposing of contaminated masses in fjord areas (by dredging), the problem is resolved by adding salt to the discharge in order to ensure that the density of the water in the discharge is higher than the recipient's water masses at the discharge point.

5.2.3 Ecological impact

In addition to the physical conditions of a marine recipient planned for the disposal of tailings, it is also important to evaluate both the local ecological conditions, marine resources and user interests. There is a general agreement that disposal should be made below the water layer where primary production takes place (the euphotic zone). In general, this water layer is defined as the lower limit reached by 1 % of sunlight. This will depend on a number of factors, such as natural turbidity in the brackish water layer and the stability of the water masses. In Norwegian fjords, the water layer where primary production takes place and where phytoplankton is produced will in general be limited to the upper 20-30 metres. It is therefore recommended to discharge tailings deeper than this in Norwegian fjords. In tropical areas, depending on distance from the coast, this zone may however reach down to 100 metres. For this reason, it is internationally agreed that sea disposal of mine tailings shall in principle be made below 100 metres water depth. However, this issue also includes local conditions and the requirement for suitability criteria that are site specific.

Comprehensive ecological base line studies are necessary to determine whether there are especially vulnerable fauna and flora communities or species in a recipient. If such exist, it will be important to avoid disposal, to the extent possible, in such areas. Mapping of marine resources such as spawning and nursing grounds for fish and shellfish is also necessary in order to enable evaluation of the consequences of a discharge, including for the migration routes for anadromous fish (salmon, sea trout).

The disposal of tailings on the seabed will have major consequences on the flora and fauna in the area that is covered by the tailings. Impact and magnitude of such disposal are determined by numerous factors, such as:

- the tailings disposed of (composition of tailings, distribution of fine material, content of other substances than minerals)
- the volume of the tailings (volume of tailings per time unit)
- depth of discharge and disposal
- current (e.g. related to periodic water exchange)

- duration
- biodiversity in the fjord

This chapter primarily relates to the negative impact of discharging large volumes of mine tailings to fjords. Examples of fjords in Norway where large volumes of mine tailings are or have been disposed of are the Bøkfjord (Sydvaranger Gruver), Jøssingfjord (Titania) and Frænfjord (Hustadmarmor). We will also compare the estimated ecological impact of the actual disposal process and the impact after the disposal process has been terminated. The descriptive text in this chapter is mainly based on experience gained from actual disposal sites, but also includes expectations based on general knowledge.

The chapter comprises ecological conditions in the seabed areas that are directly impacted by disposal, the surrounding seabed areas, the ecosystem in the water masses in the fjord and the benthic communities in more shallow waters (flora and fauna). A large number of studies have been conducted in the above-mentioned fjords, with the main focus on the impact on sediment-dwelling organisms, but some studies also include the impact on algae. The effect of chemicals from the disposal of tailings on animals that live on and in the bottom (benthos) and other fauna has hardly been studied. A few studies have been performed in the Frænfjord, where surface-active flotation chemicals have been discharged with the tailings. These studies show a clear impact on soft-bottom communities (comprising polychaetes, crustaceans and bivalves), but the smothering supersedes any impact caused by flotation chemicals discharged to nature.

The concept of re-colonisation is used to evaluate how flora and fauna are re-established once disposal of tailings is terminated. Re-colonisation implies that the animals return and gradually rebuild a new community in a disposal site and the adjacent influence area. As the new bottom habitats are normally different compared to the natural seabed, the re-colonised community will not necessarily be exactly the same as it was before disposal started. The new community will be adapted to the properties of the new bottom.

Impact during disposal period

This phase involves the continual discharge of tailings particles (inorganic particles) primarily to the bottom, but also finer particles to parts of the water column. In a disposal site, the impact on fauna is expected to be significant, but will vary within the disposal site depending on the level of disposal activity, and the volumes discharged. The impact in the disposal site most frequently relates to smothering problems, and these may also overshadow any impact related to chemicals that have a negative effect. The figure below provides an overview of the possible impact related to an excessive concentration of inorganic particles.

Larger particles will sediment rapidly and within the area defined as the disposal site, while the finer particles – in particular clay fractions – will remain in the water masses for a long period of time (depending on the level of flocculation) and may be transported with the current outside the area defined as the disposal site. Turbulence at the outfall point and sub-sea slides caused by unstable tailings build-up may transport a high level of suspended particles along the bottom. Experience from sea disposal also indicates a large difference in dispersal of particles, depending on whether the tailings include seawater or fresh water. The dispersal of particles is much more significant when the tailings are mixed with fresh water.

The following chapters describe the possible impact on algae, zooplankton, bottom-dwelling organisms and fish in areas that receive large volumes of tailings. The studies conducted over the past 25 years in Norway have focused on water quality, the impact on macroalgae and bottom-dwelling fauna. It has not been common practice to include the impact on plankton and fish during monitoring. Neither are these factors included in the status monitoring parameters developed by the Norwegian Climate and Pollution Agency (Klif). Monitoring has mainly involved those areas with potentially the most severe impact (water quality, macroalgae and soft-bottom fauna).

Impact on algae

There are few impact studies that include phytoplankton or algae. Increased turbidity in the water masses will probably result in less light penetration which in turn reduces the layer where

Definition of disposal site

It is difficult to estimate the size of a disposal area before defining the factors that delimit a disposal site. It will also be important to define the border area/transition zone between the disposal site and the area that does not receive tailings. One possible definition may be (DnV, 2010):

Disposal site

A delimited area that is selected for the disposal of tailings. The disposal site is delimited in extent and depth.

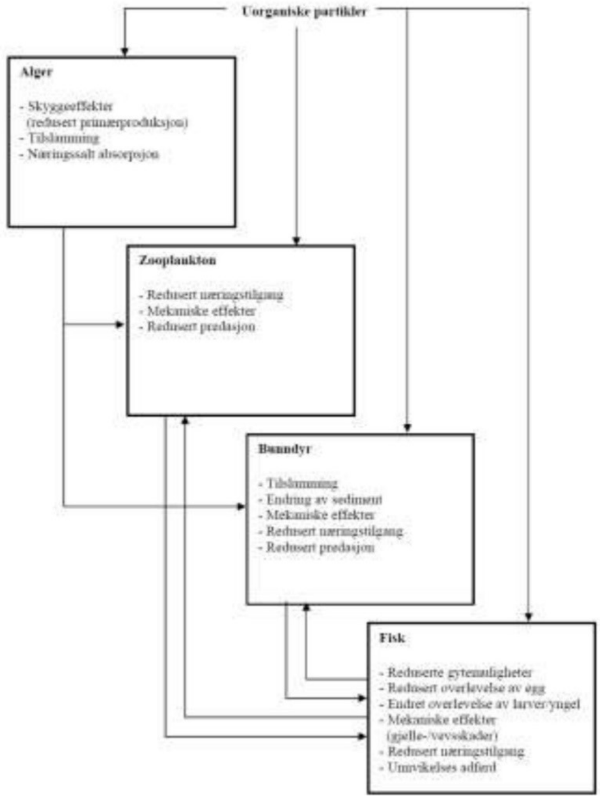
Border area/transition zone

The area outside the disposal site border that receives particles dispersed with the water current.

Outside the border area

The area outside the border area where the impact of particle dispersal is below the limit for negative ecological impact, and that will not cause user conflicts.

Disposal site + border area = influence area

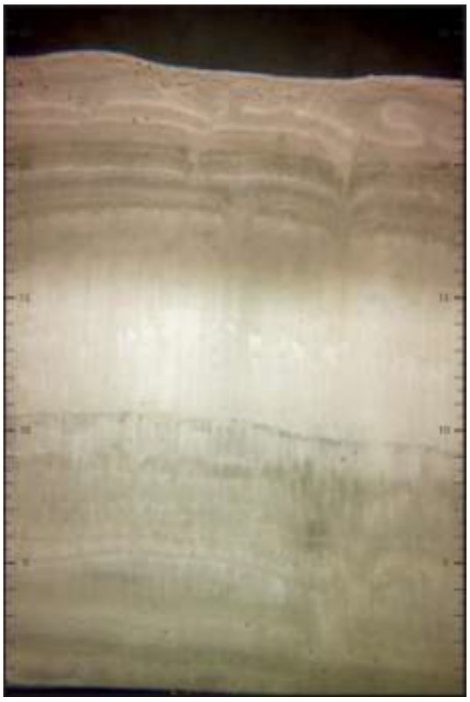


General sketch illustrating possible impact of inert particles at different biological levels. The arrows between the boxes illustrate the impact via the food chains (modified from Hessen, 1992).

primary production takes place. This can theoretically impact the uptake of nutrients. Increased eutrophication has not been documented in the examples of fjords reviewed in this document. However, a disposal site may imply significant smothering of macroalgae (seaweed and kelp). This will result in the reduction of both available hard bottom (smaller areas where algae can grow), increased smothering of the actual kelp leaves (which may well affect the growth of algae), but most importantly in the reduction of depth propagation of algae. Both tangle (*Laminaria hyperborea)*, sugar kelp (*L. saccaharina*) and red marine seaweed (*Delesseria sanguinea*) showed reduced depth propagation during the period of active disposal in the Jøssingfjord, which in turn resulted in a change in the algae community. Such impact will be typical for areas where the tailing masses may rise to the surface or at higher layers in the water masses. The subsequent studies in the Jøssingfjord also showed a very rapid establishment at greater depths once disposal teminated in the fjord (DnV, 1994).

Impact on zooplankton
There are also few studies that include plankton, and it is difficult to determine how vulnerable zooplankton are to hyper-sedimentation and high particle density in bottom water, but it can be assumed that small or large exclusion zones will emerge around the actual outfall point. Plankton are thought to "react to the discharge of particles, so a local behavioural reaction to discharges and increased particle volumes is to be expected" (Poling et al., 2002).

Impact on benthic fauna
The discharge of mine tailings may have several negative effects on benthic fauna. Continuous smothering is a physical stress factor. Some species may suffocate due to clogging of filtering organisms and gills (Miljøplan, 1981). The discharge of fine-grained mud causes a general reduction in the grain size of the bottom sediment and makes the sediment more homogeneous with less ecological niches. This results in a less rich benthic fauna community (Kathman et al., 1983).



The image shows the bottom profile of a disposal site in the Frænfjord (from a camera submerged in the actual disposal site). DnV, 2010.

During the disposal phase, it is primarily the rapid and large discharge of tailings that will have an effect on the fauna on the seabed. If the animals bioturbate in the sediment or on top of the sediment, the high level of sedimentation will bury existing fauna causing their death, or make the bottom unsuitable for new establishment of fauna. The image on the right shows a cross-section of the sediment (the top 25 cm of tailings) and illustrates that there are very few animals that have been bioturbating the bottom sediment (few vertical lines) (image taken by NIVA in the Frænfjord, DnV, 2010). The

Choice of bottom substrata
The choice of bottom substrata is often a complex process, where the larvae test the physical and chemical properties of the sediment, e.g. grain size, content and type of organic material and the presence of adult animals of the same species. It can therefore be expected that the tailing masses, a foreign sediment without natural organic material, will provide different stimuli to natural sediment. It is highly probable and natural that this will result in a community of different species than with a natural sediment. Literature provides many examples of this. During the disposal phase, such changes in fauna will most probably be completely overshadowed by the fact that animals that settle on the bottom will be buried.

thickness of the tailing masses varies significantly within a disposal site, so that the impact within the actual site will also vary.

The issue of whether the animals live inside the actual sediment or on top of it is probably less relevant in those areas that receive massive discharges of tailings. The bottom will be unsuitable for both adult animals and larvae that attempt to settle there.

The image on page 86 illustrates how tailings in this area settle in different piles on the bottom, and impact will be most prominent in and around these piles. Some types of benthic fauna will to a certain extent cope with continuous hyper-sedimentation (unnaturally high sedimentation). It can also be expected that animals that bioturbate in the sediment will have the highest tolerance in that they can keep pace with the new sediment surface, while animals building tubes will have to extend their tubes or build new ones. In other words, some groups of animals are more sensitive to smothering than others (Burd, 2002). Most species of benthic fauna have larvae that live in the free water masses for a period of time, and disperse to new areas. Recruitment for benthic fauna is principally a process whereby these larvae settle and change form and behaviour. In our areas, recruitment most commonly occurs once a year in connection with a spawning period.

Experience from monitoring of an area surrounding a tailings disposal site at Island Copper Mine, Vancouver Island, is that a settlement of < 1 cm per year had no documented impact on local sediment fauna (Ellis et al., 1995). Regarding the disposal from Hustadmarmor in the Frænfjord nearby Molde (DnV, 2010), an acceptance limit was established of 5 cm of tailings settled over time (over a period of several years). This was based on studies in areas with settlement of approximately 5 cm of tailings, compared with areas with only a minor impact of tailings. No differences in biodiversity and species structure were found between these areas. When settlement exceeded 10 cm of tailings, there were clear indications of stress on the benthic communities. Even in areas with many metres of tailings (i.e. the immediate area surrounding the discharge point), organisms established. This is explained in detail in the chapter describing examples for different disposal sites.

In connection with the risk assessment of the discharge of drill cuttings from offshore installations, a general tolerance limit has been established for macrofauna for burial with new sediment (Smit et al., 2008). One single episode resulting in a layer of 5.4 cm will destroy an estimated 50 % of animal species, while 95 % of the fauna will be able to cope with a 1 cm layer (a benthic fauna community is assumed to cope with a loss of up to 5 % of species without significant change). It may be assumed that tolerance is higher when sedimentation is more gradual than with sudden sedimentation.

The tailings will contain residues from process chemicals (see chapter 6). Some of these are easily degradable, while for others there is no information as to how decomposition takes place and some, in principle, are toxic for aquatic organisms. The decomposition of organic chemicals requires oxygen and may result in oxygen deficiency if oxygen capacity on the bottom is exceeded. Moreover, a sediment comprising particles with an unnatural size and structure and lack of natural organic material may have a negative impact on the bottom settlement of benthic fauna larvae.

In total, it is therefore assumed that a disposal site will in practice have significantly less fauna while disposals continue. The loss of bottom habitat and the loss of fauna can be expected to be in proportion. In practice, however, there may be patches of re-colonisation at the disposal site if there is strong variation in sedimentation (i.e. that the discharge of tailings is not deposited over the entire disposal site at one time).

Impact on fish

As with algae and plankton, there is little documentation of the direct impact on fish stocks (Poling et al., 2002). The impact on bottom-dwelling fish will also vary according to numerous factors. The most important impact will be the change in bottom substrate, low access to food and that the disposal site is not suitable as spawning ground. The size of the area affected in a fjord remains uncertain. The impact may be both direct and indirect, and comprise all stages of life for fish.

Very few studies have been conducted on the impact on fish and mine tailings. During monitoring of Titania's tailings to Dyngadypet, the surrounding areas were monitored based on by-catches of fish when trawling for shrimp. The only records taken were the number of fish and which species were caught over a period of around 20 years. The studies did not follow scientific criteria in relation to frequency, comparability of tools etc. However, no clear change in species structure was documented. The distribution of species varied greatly between trawling sessions (depending on the time of year and the time of day). During the lengthy period of monitoring, no clear impact on species structure was shown.

In general, high sedimentation of fine-particulate inorganic material will have an impact on any spawning ground as the bottom substrate is modified and thus unsuitable as spawning ground for fish that lay eggs on the seabed (benthic eggs) or bury their eggs. The spawning and nursing grounds are particularly vulnerable as they represent recruitment to fish stocks. Small but permanent changes in factors that are of importance for the survival of eggs and larvae (access to food and predator density) in these areas may have major consequences on recruitment to fish stocks. The disposal of mine tailings in a spawning and nursing area for marine fish is expected to have an impact in different manners, such as changes in the behaviour of spawning fish migrating to the spawning grounds, direct and indirect impact on larvae and fry. There is not much data on the scaling of this and how the process takes place, and results from laboratory studies are difficult to transfer to fish living in nature (Meager and Batty, 2007). This is an area in which we have some general knowledge but little specific knowledge. The fact box on page 83 provides some observations relating to this subject.

There is little literature describing the impact of inorganic particles on larger fish, particularly in the marine environment. It is however clear that any impact will depend on particle type and particle concentration. Different species of fish have varying capacity to cope with high concentrations of suspended material (Grande, 1987). Based on studies of marine fish and field observations in marine environments, Moore (1977) concluded that the most tolerant species were found among demersal fish, while filter feeders were most vulnerable. Within the individual species, the juvenile (not reached puberty) fish were more sensitive to suspended material than adult fish (Moore, 1977).

The impact of mine tailings on marine fish is therefore expected to be most severe in connection with reproduction and recruitment (spawning and survival during early life stages). It is also natural to assume that deep-water fish disappear from areas where a suitable bottom habitat disappears. These will be areas where the benthic fauna is buried by tailings so that food availability disappears.

In connection with the discharge of fine-particulate waste from the extraction of China clay in Cornwall, a study was conducted (trawling and line fishing) to compare the stocks of fish in the area affected with stocks in unaffected areas close by. Plaice (*Pleuronectes platessa*), dab (*Limanda limanda*) and sole (*Solea solea*) were the most important species commercially. Wilson and Connor (1976) found no major differences in the commercial catches in the two areas, and mackerel (*Scomber scombrus*) were caught in the area where there was a high content of suspended material. It appeared that the mackerel had no problems locating prey in the turbid water masses, despite the fact that this species normally uses eyesight to locate prey. On the other hand, the same study registered that individual species appeared to avoid the turbid water mass. A shoal of non-mature herring (*Clupea harengus*) were observed, visually and using an echosounder, actively avoiding the front of the turbid water mass (Wilson and Connor, 1976). It was also observed that the fish caught in the area affected by the China clay waste (light in colour) had pale dorsal pigmentation. Most of the fish had small particles in the oral cavity and gill cleft and between the primary and secondary gill lamellae, but the authors found no sign of local irritation of the tissue epidermis. The stomach contents of flat fish reflected the differences in benthic fauna between the affected and unaffected area, and the flat fish ate a smaller number of species in the area affected by the China clay waste, while the average number of individuals eaten was higher (Wilson and Connor, 1976).

From experimental studies of marine fish, it can be mentioned that significant damage was observed on the gill epithelium of cod with long-term exposure to high particle concentrations (550 mg/l, Humborstad et al., 2006). Tests involving increased turbidity showed that juvenile cod required more energy to find their own food, the ability to avoid predators was reduced while the choice of habitat was not influenced by high turbidity (Meager et al., 2005, Meager et al., 2006, Meager and Batty, 2007, Meager and Utne- Palm, 2008).

There are also few studies of the impact of particulate material in water on salmon. There is one case of documentation of damage to salmon fry in fish hatcheries caused by mud in the river water from construction work (Haarstad and Jacobsen, 1987, Jacobsen et al., 1987). The type of particles was most probably the most important cause of the damage in addition to the volume of mud. A significant share of the particles was needle-shaped chlorite and amphibolic particles, and electron microscope images of the salmon gills in the hatchery showed that these were penetrated by the needle-shaped particles. The particles had a more angular, sharper shape than normal eroded grains. The mud content in water samples was 0.2 g/l, while it was estimated that the maximum mud discharge was approximately 3 g/l during periods of flooding. This amounts to between 200 and 3,000 ppm.

In connection with a study of the dispersal of particles from an embankment adjacent to a fish farm, an overview was established of possible impact on the salmon in the fish farm, based on general experience from algae growth, contamination and other relevant information.

Possible impact of particulate material in the water on salmon in fish farms (reworked from Dragsund and Thendrup, 1990).

Cause	Impact	Comments
Reduced visibility in the water due to large volumes of mud in the water	Increased stress, which in general results in increased probability of outbreak of disease	The threshold level is not known. The type of particle may be decisive for stress levels, with highest stress caused by sharp particles and lowest stress caused by eroded, rounded particles.
Damage caused to gills by sharp particles.	Reduced capacity for osmoregulation.	Needle-shaped, sharp particles (fibres similar to asbestos) appeared to cause most damage.
	Increased probability of intake of contaminants from the water masses.	Wounds on the gills will be open to bacteria and virus in the water masses.

Long-term impact after disposal ends

There is a good amount of knowledge on the recruitment of benthic communities after physical disturbance such as dredging and disposal of different types of tailings (DnV, 2010; DnV, 2008). The recruitment speed depends on how quickly the sediment quality improves via the decomposition of hazardous discharge substances and natural sedimentation, and on biological factors such as reproduction strategy, growth rate and generation time for the species that settle in the area. Access to recruitment from surrounding areas via larvae dispersal and active immigration is also important.

Once disposal comes to an end, there will be a gradual re-establishment of a benthic fauna community in the disposal site. The key questions are:

- How fast will recruitment occur?
- What type of community will be re-established?
- How suitable is the new bottom as spawning and nursing ground for fish?

The recovery time for benthic fauna varies from ecosystem to ecosystem. To illustrate the above and experience from different disposal sites, several examples are provided from Titania (disposal in the Jøssingfjord/Dyngadjupet), Hustadmarmor (disposal in the Frænfjord) and for Island Copper Mine, Vancouver Island (with disposal in the Rupert Inlet fjord).

Experience from specific projects

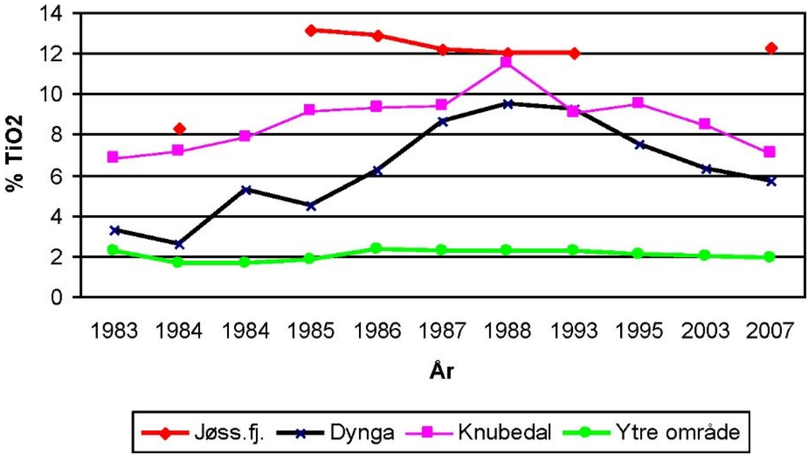
Jøssingfjord/Dyngadypet

Tailings from ilmenite production were disposed of in the Jøssingfjord up to 1984, then in Dyngadypet (approximately 130 metres deep) and partly Knubedalsdypet farther away. Environmental status was monitored annually from 1984 to 1993. Sea disposal was terminated in 1994 when a decision was made to use a landfill. Once sea disposal was terminated, there have been three chemical-biological studies in 1995, 2003 and 2007 (DnV, 1996; DnV, 2004 and DnV, 2008).

The most important experience gained in relation to the dispersal of particles and the impact on benthic fauna in connection with tailings disposal in Dyngadypet has been that the topography and currents are important for the dispersal of particles, and that the outfall design (use of fresh water in the tailings which increases particle dispersal). Nonetheless, all the studies conducted showed that the impact on the soft-bottom fauna and hard-bottom organisms is local. Significant impact was found in the actual disposal site and surrounding areas. However, fauna quickly returned after disposal was terminated.

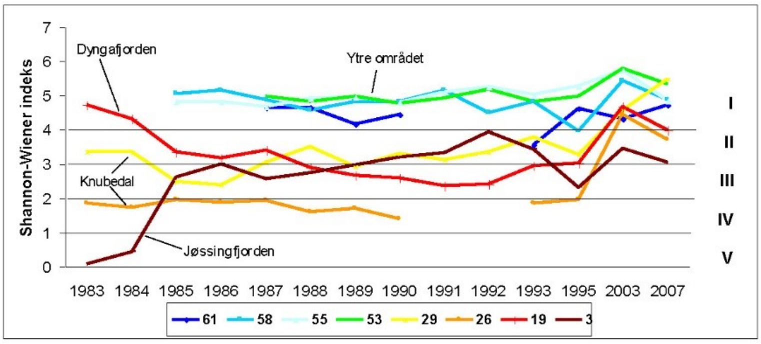
The ilmenite content ($FeTiO_3$) measured as titanium in surface sediment has been analysed to trace sedimentation of mine tailings. Titanium content is utilised to evaluate the degree of smothering, while the content in the fine fraction is utilised to trace dispersal. The concentrations of titanium in the Jøssingfjord were high during the entire period covered by the study. Some 10 metres of tailings were disposed of in the Jøssingfjord, and the fjord is significantly impacted by the tailing masses. In Dyngadypet, the TiO_2 content (i.e. tailings) increased significantly from the time the area was used for disposal until disposal stopped in 1994. Once disposal was terminated, the content of titanium has also dropped in the surface sediment. At Knubedalsdypet (area close to Dyngadypet), titanium reached a peak in 1988 then declined. In the areas outside the disposal site (i.e. the outer area approximately 3 km from the disposal site), there was a very weak increase from 1984 to 1986, after which concentrations reduced until 2007. Concentrations in 1983 and 2007 were at the same level. When compared with Dyngadypet and Knubedalsdypet, concentrations were low with minor changes from one year to the other.

It has been documented that mine tailings sedimenting outside Titania resulted in a lower content of organic material in the surface sediment.
This has resulted in a change in the availability of food for benthic fauna and thus a change in benthic fauna. The particles in the mine tailings have sharper edges than natural sedimented material (Gray, 1974). It is probable that this also has a negative impact on benthic fauna.



The total TiO_2-content in the surface sediment (0-2 cm) from Dyngadypet (the actual disposal site), Knubedalsdypet (within the influence area) and areas outside the disposal site (=outer area)

Once the disposal of mine tailings was moved from the Jøssingfjord to the area outside (Dyngadypet), a gradual and – with time an evident impact on the benthic fauna in the area was recorded.At the same time it was observed that the fauna in the Jøssingfjord – no longer exposed to tailing masses – quickly became richer. Once sea disposal was terminated in 1994, there was a corresponding rapid improvement in benthic fauna in Dyngadjupet and Knubedal (see figure below).



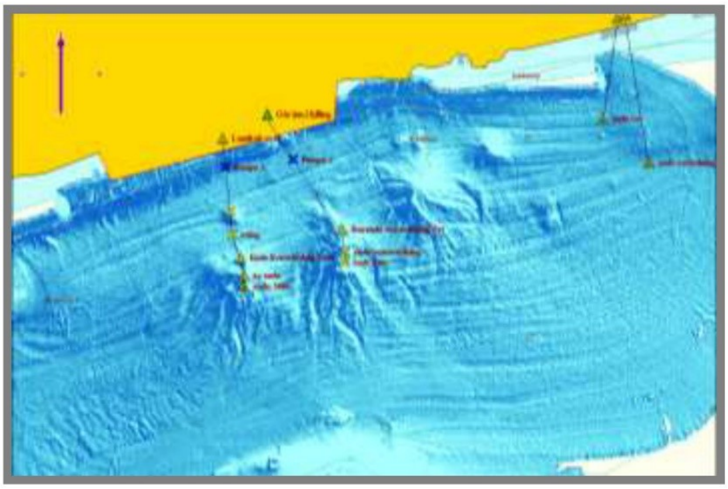
Diversity index H’, in period 1983 to 2007. The SFT's status categorisation is shown as dotted lines.

Very obvious effects of disposal in fjords are the loss of shrimp, crustacean and fish habitats, if previously existing in the area. Several time-studies were conducted in relation to siltation of shrimp (the gills) in Knubedal, Boen, Nesvåg-Rekefjord areas, all close to Dyngadypet where the tailings were disposed. The study performed from 1985 to 2008 has shown that shrimp may be exposed to siltation, but depending on the type of environment in which they live. Siltation of shrimp was proven in certain areas (inside the disposal site), but the level of siltation of shrimp over time was low. Most importantly, no differences were ever proven in either the length or the number of shrimps with roe in relation to whether they were exposed to siltation or not (DnV, 2008).

The Frænfjord

Finely ground limestone has been disposed of in the Frænfjord since the early 1980s. The Frænfjord has a maximum depth of approximately 70 metres. The tailings are transported into the fjord via a pipeline to an outfall depth of approximately 20 metres. Most of the tailings settle to the bottom, locally, at the end of the tailings pipes, while a minor fraction of the tailings, comprising very fine particles, remain suspended and travel far out into the fjord. Regular chemical-biological monitoring of the Frænfjord has been conducted since 1989. The discharge permit from Klif is worded so that a limit is defined for the size of the disposal site and thereby capacity for tailings storage. According to Hustadmarmor, it is in the company's interest to reduce the volume of tailings in order to increase the lifetime of the disposal site. In 2006, the lifetime was estimated to be approximately 70 years.

The discharge permit also defines what is an acceptable environmental impact in the border zone for the disposal site, by a defining acceptance criteria. The environmental studies are performed annually and shall indicate whether the acceptance criteria are met. Moreover, these studies show status both within and outside the disposal site borders. The studies have shown that the water quality in the Frænfjord is good, with good water exchange and good oxygen status. At times, “plumes” of particles are recorded in the water masses in the disposal site itself. The amount of particles in the water column outside the disposal site is normal for the area, and far below the acceptance limit defined for particle dispersal in the water masses.



The figure illustrates the bottom topography in the Frænfjord. The tailings form local piles at the outfall point.

The sediment in central parts of the disposal site is dominated by calcium carbonate tailings with more than 90 % calcium carbonate. Visually, calcium carbonate is measured in the core sample at more than 30 cm sediment thickness. Certain areas have been filled with more than 10 metres of tailings. There is a minor increase in calcium carbonate content in the sediment outside the zone defined as the actual disposal site. However, no clear impact has been proven in the area outside the disposal site, and the calcium carbonate content/thickness in the sediment is within the acceptance criteria limits.

The figure on the right shows a bathymetry chart illustrating the build-up of tailings over a period of approximately 25 years. The tailings form piles around the actual tailings pipe. As the sedimentation of tailings is very local, the pipes have in time had to be extended.

The soft-bottom fauna shows clear signs of impact in the active part of the disposal site. As the distance increases from the tailings pipes, conditions improve. No reduction in biodiversity has been proven at the outer limits of the disposal site.

Shallow water communities (i.e. flora and fauna visible along the shoreline and down to approximately 25 m deep) show in general little impact, even inside the disposal site. However, in areas that receive large volumes of particles (so that they settle on the bottom), a reduction must be expected in the area with a hard bottom (increasingly soft bottom) which in turn will affect the dissemination of flora and fauna locally. However, no changes in the species structure has been proven from station to station or from year or year that might indicate rapid changes in the shallow water communities.

In order to evaluate re-colonisation on the disposed masses, open boxes have been installed on the seabed outside the disposal site, which contain tailing masses. The boxes were left for three years as substrata for larvae settlement. By the end of the first year, a rich fauna/community had already settled on the boxes. This community changed slightly over the three years, and the community established on the tailings was very similar, after three years, to the natural seabed.

Island Copper Mine

The benthic fauna in the vicinity of the disposal of tailings from Island Copper Mine, Vancouver Island, has been frequently monitored since operations started around 1970 (Ellis et al., 1995). Burd (2002) concludes in his article *“Evaluation of mine tailings effects on a benthic marine infaunal community over 29 years”* (summarised):

Tailing masses can be divided into three impact zones: near-field (< 5 km from outfall); mid-field (> 5–16 km); and far-field (> 20 km) based on differences in tailings thickness, copper level in the sediment and univariate and multivariate biotic factors. Consistent faunal declines during mining were noted at sediment particulate copper levels >300 ug/g. The decline in biodiversity was not a gradient following distance from the disposal site, but rather an abrupt change at this copper level. At Island Copper Mine, the biodiversity of soft-bottom fauna in the near-field appeared still to be dominated by opportunistic polychaetes, with other species increasing in number during the three years after closure. The species with the most rapid re-colonisation was the polychaetes. Amphipods (crustaceans) and brittle stars were most affected by the tailings. The disposal of mine tailings in the Rupert Inlet System has had an impact on the soft-bottom communities, clearly related to the toxicity of copper, which affects the most vulnerable animal groups, but also mechanical disturbances.

5.2.4 Impact on marine resources

User interests such as fish farming also require evaluation. For such interests, it is of main importance to ensure that discharges take place in deep waters and that the tailings are not transported upwards in the water mass and that the water quality in the fish farms is not affected. It is important to carry out detailed evaluations related to the risk of affecting fish farms. Measurements of surface current may provide an indication of where tailings particles are transported in the event of an accident that affects the quality of the surface water.

The impact on marine wild fish and shellfish – important marine resources – must also be subject to environmental impact assessment.

The level of problems varies from one area to the next, depending in principle on whether commercial species are present in numbers that make them an economic resource. In addition to areas for fishing and catches, it is also important to take into account nursing and spawning areas.

In mine areas in Norway where sea disposal has been practised (e.g. Frænfjord and Bøkfjord), no impact on marine resources has been reported. However, it should be noted that it is a complex process to document such links and, as a result, few investigations have been conducted to prove such impact. Studies carried out in Canada at Island Copper Mine and interviews of fishermen and fish farmers (8 km from the mine discharge point) show that no complaints were registered from fishermen over the 24-year period the mine was operational (Moore et al., 1998).

5.2.5 Risk of accidents

Accidents involving sea disposal of tailings may be pipeline breakage caused e.g. by earthquakes which in turn result in underwater slides. Examples of such incidents are found in Indonesia (see chapter 4.5.5.). Not only may underwater slides cause broken pipelines and unintentional dispersal of tailings but could, in the worst-case scenario, cause a tsunami, if the movement of masses on the seabed is large enough. It is important to design sea disposal sites so that small and frequent landslides occur. This prevents the build-up of steep slopes in the disposal site, which would cause major movement of masses if a landslide occurred. It is therefore important to regularly monitor the disposal sites to make sure that minor build-up is taking place as expected. If this is not the case, remedial action should be taken (change outfall system, trigger a slide).

In Norway, problems occurred with the tailings pipe for Titania and the discharge at Dyngadjupet in the 1980s, causing a leak (Aure et al., 2002). The main cause of this problem was that the tailings were not aerated so the pipeline floated to the surface, causing the pipeline to break.

5.2.6 Monitoring and environmental documentation

When initiating new mining operations that exceed a specific size in terms of mass extraction and area occupied, a zoning plan with environmental impact assessment is mandatory. The environmental impact assessment helps ensure that e.g. the environment is an integral part of the mining projects from the planning phase. This ensures that environmental factors are naturally taken into account in line with technical engineering. It also helps ensure that focus is preventing environmental problems rather than remedying problems once they have occured. A detailed environmental impact assessment and a comprehensive baseline study are therefore necessary prerequisites for success.

The utility value of an environmental impact assessment relies on a focus on those areas where there is a real environmental risk. In this regard, scoping tools are important, where a team made up of persons with varying backgrounds and premises agree on the topics to be highlighted during the assessment, based on estimated importance. A prerequisite is that the assessment process is transparent, which will reduce conflicts and make it easier to gain social acceptance for mining operations. It will also allow for a juxtapositioning of advantages and disadvantages so that these can be weighted primarily for decision-makers.

Experience gained from all existing projects involving sea disposal clearly illustrates the importance of thorough monitoring programmes. **Comprehensive base studies are required to describe the environmental status before start-up**, monitoring of the different phases of the operational period and monitoring after operations have ended to document how nature recovers. The contents of the monitoring programme must be adapted to the project design and recommendations in the environmental impact assessment and public hearings.

Continuous reporting to the enterprice is also important so that remedial action can be taken rapidly if developments in environmental impact take a wrong direction. Online reports are also important, allowing all stakeholders an insight into developments. Key questions that require clarification during planning of sea disposal of tailings are:

1. **How far the mine tailings are dispersed from the discharge pipe?**
2. **Can the tailings be transported upwards in the water mass towards the surface?**
3. **What are the consequences of increased turbidity in the water mass?**
4. **What are the consequences of smothering due to tailings on the bottom and which magnitude of smothering causes damage to benthic fauna?**
5. **Will smothering affect the marine resources (fish and shellfish)?**
6. **How high is the risk of accidents in relation to the disposal of tailings and what are the potential consequences of different types of accidents?**
7. **How** long will it take for the environmental conditions in a disposal site to return to normal after a mine is closed, and what is the environmental risk represented by an underwater disposal site?

The environmental impact assessment shall shed light on these issues and provide answers based on baseline studies of the recipient, tests and experiments, existing experience-based data and projections prepared by means of modelling. Monitoring shall validate the results and conclusions presented in an environmental impact assessment and lay the foundations for changes and adjustments related to discharges, so that the environmental consequences are minimal. It will always be necessary to carry out tuning when full-scale operations are implemented, and in such an event, monitoring during the initial phase will be of major importance.

Studies prior to start-up and monitoring will provide an important basis for establishing acceptance criteria for discharges. Preliminary studies should comprise chemical and geochemical status in natural sediment and mapping of benthic fauna. The metal content in seawater should be studied to establish knowledge of local background values. Instead of basing the discharge permit on volumes of discharges per time unit, as is traditional, it may be more relevant to utilise concentrations and the size of the area of influence when it comes to discharges of tailings that are approximately inert and which are not normally potentially toxic.

5.2.7 Examples of sea disposal that have functioned as intended

The most widely documented sea disposal project is Island Copper Mine (ICM) on Vancouver Island, operational from 1971 to 1995. This documentation is summarised in Poling et al., (2002).

Despite the discharge of large volumes of fine-grained tailings (approximately 400 million tonnes over an operational period of 24 years) in a threshold fjord with a maximum depth of 180 metres and a discharge depth of 50 metres, the results from monitoring show surprisingly minor negative impact. During the start-up phase of mining, a number of problems occurred. The tidal difference in the area is several metres, and there is upwelling which transported tailings from 50 metres depth to the surface and onto the beaches. This was in principle underestimated. It should be noted that knowledge of sea disposal of tailings was very limited in 1971. They failed to utilise e.g. a de-aeration unit on the tailings pipeline (common practice now) so that air followed the tailings and air bubbles and fine substance floated to the surface. They also experienced problems with sub-marine slides due to the sloping seabed.

After the start-up problems had been resolved by means of adjustments to the design of the actual discharge, this sea disposal project functioned as expected. Comprehensive monitoring of the fjord continued throughout the operational period. Reports have indicated that more studies could have been performed before starting mining in order to enable better interpretation of the monitoring data. This is an important lesson to learn. Monitoring has continued after operations were closed, and there are now more than 10 years of monitoring data after discharges ended. Monitoring was performed by university researchers in cooperation with environmental consultants.

5.2.8 Examples of sea disposal with unexpected environmental problems

The disposal of tailings in a marine environment is not necessarily suitable in all locations. If comprehensive environmental impact assessments have not been carried out in advance, with an evaluation of the suitability of the location for sea disposal, unexpected environmental problems may be encountered.

The examples of sea disposal that have resulted in unacceptable environmental impact are mainly found in mines in Asian countries. In these areas, the special climate with periods of major rainfall place major requirements on land-based installations that may also have unexpected impact on the marine environment (e.g. pipeline breakage on land that causes tailings to flow freely into the sea). In many cases, the mines and processing plants are located several kilometres from the sea, requiring long pipelines on land.

Another problem that often causes unexpected environmental problems with sea disposal is found in areas exposed to major earthquake activity, which may result in unexpected slides and broken pipelines (see chapter 4.5.5).

One typical example of a mine where sea disposal was selected, but where this decision proved to be wrong, is Jordan River Copper Mine in Canada. A permit was granted in 1972 to dispose tailings in shallow water in an area with significant wave exposure, causing the tailings pipeline to break on several occasions and with fine-grained tailings visible on the surface (Ellis and Robertson, 1999).

In Greenland, sea disposal of tailings and waste rock has been practised for many years (Asmund and Johansen, 1999). Greenland has particular problems related to freezing of the fjords where the tailings were deposited, and problems related to waste rock deposited on the shore and partly in the inter-tidal area. These problems resulted in unexpected environmental issues. The Black Angel Lead/Zinc mine was operational from 1973 to 1986. Mine tailings were disposed of at 25 metres depth in a shallow threshold fjord. When the fjord was cover by a layer of ice, special hydrographic conditions occurred so that the metalliferous water from mining discharge was transported unintentionally up to the surface and over the threshold. The other unexpected environmental problem occurred in connection with the disposal of waste rock in the inter-tidal area. As the waste rock contained metals, theses metals were flushed out by seawater and caused significant contamination of organisms in the upper water layers. This problem became particularly evident when the disposal of tailings was terminated, while the level of metals in organisms remained high due to the flushing of metals out of the waste rock heap. See also chapter 4.5.4.

5.2.9 Summary - sea disposal

The review of the most important experience-based material regarding sea disposal of tailings created nationally and internationally, indicates that a useful base of data has been established on the technical solutions and physical conditions related to transport, dispersal and sedimentation of mine tailings in a marine environment. The experience base related to ecological consequences is much less comprehensive, particularly regarding long term effects as data collection has only taken place over the past 20-30 years.

The main data base relates to sea depths of < 100 m in areas close the coast (mainly fjords, estuaries and bays) with some experience relating to deep-sea disposal (disposal in shallow water close to the coast and dispersal via turbidity current to deep basins of > 1,000 metres depth).

The prerequisites that should be taken into account for sea disposal, the impontant issues that require clarification during planning of sea disposal for mine tailings and what is considered best practice in relation to outfall design, summarised.

The most important prerequisites required for sea disposal projects are:

1. **Understand the significance of having knowledge of the environmental conditions in the discharge area (seabed geology including bottom substrates, sedimentation rates, appearence of gas in the sediments, natural geochemical background values in the bottom sediments and hydro-physical status such as salinity, temperature and currents , oxygen levels, ecological status etc.)**
2. **Understand the significance of the selection of disposal depth with respect to density stratification in the water mass**
3. **Understand the significance of grain size, water content and shear strength in order to e.g. evaluate stability to avoid slope failure**
4. **Ensure that the tailings including chemicals do not contain toxic components that are water-soluble**
5. **Ensure that the actual ore processing does not generate secondary toxic substances that are transported with the tailings**
6. **Ensure that the content of sulphides in the tailings is low**
7. **Ensure that the disposal site is stable (geotechnically)**
8. **Understand the need for suitability criteria and acceptance criteria**
9. **Understand the need for environmental impact assessments and monitoring**

Subsequently, be aware of the following critical issues that require clarification when planning sea disposal of mine tailings:

8. How far the mine tailings are dispersed from the discharge pipe?
9. Can the tailings be transported upwards in the water mass towards the surface?
10. What are the consequences of increased turbidity in the water mass?
11. What are the consequences of smothering due to tailings on the bottom and when is smothering causing damage to benthic fauna?
12. Will smothering affect the marine resources (fish and shellfish)?
13. How high is the risk of accidents in relation to the disposal of tailings and what are the potential consequences of different types of accidents?
14. How long will it take for the environmental conditions in a disposal site to return to normal after a mine is closed, and what is the environmental risk represented by an underwater disposal site?

In order to succeed with sea disposal, the following principles for best practice regarding outfall design are necessary:

1 The tailings should be mixed with seawater to achieve a density of the suspension exceeding the density of the seawater where the tailings are disposed. Accordingly, the tailings plume will sink towards the bottom. It is a supposition that the fine particles in the tailings move as a density current along the sea floor instead of being dispersed higher up in the water column. The tailing slurry should have a high content of solids (>30 %).
2 The tailing suspension should not contain air bubbles. Such air bubbles would rise in the water masses from the discharge pipe and will carry small particles up to the surface. A system to reduce entrainment of air into the tailings pipe should be installed to avoid air bubbles bringing fine particles to the surface.

6. Status regarding the use of chemicals

In this context, chemicals are defined as chemical substances added during processing and enrichment of metals or minerals and which, to a small or large extent, follow tailings when discharged to the recipient. There are two main types of chemicals used in the mining industry:

1. Flotation chemicals, used to enrich the metal or mineral to be extracted.
2. Flocculation chemicals, used to recover water in the thickener and to reduce the water content in the tailings, helping increase flocculation of the fine fraction.

In addition to the above-mentioned substances, which are active ingredients, we should also mention nitrogen compounds used in explosives, from which nitrogen residue is found in waste rock and tailings.

The classification of chemicals is based on experiments on animals – where the animal/organism is exposed to the chemicals in controlled conditions – epidemiological data and field observations. The tests are standardised, and a limited number of species used. The species used in such tests are not relevant for all recipients to which the chemicals are discharged.

It may therefore be necessary to carry out trials using relevant species in order to identify how a specific recipient is affected by a specific chemical.

There may also be physical-chemical issues (e.g. pH, oxygen and light) that affect the toxic properties of the chemicals in the recipient.

Classification of chemicals provides important information on hazard properties, but should also be studied in conditions that are as similar as possible to those in the recipient.

6.1 Flotation chemicals

Flotation chemicals are necessary for efficient operation of a flotation plant for enrichment of ores and minerals. The flotation process was introduced in Norway as early as 1909 (Wathne, 1990). The flotation process is used to separate minerals, thereby achieving an enrichment. In principle, all minerals can be separated when they have different surface properties.

There are mainly three types of flotation chemicals used, all with different functions:

1. Skimmers (allows simpler formation of air bubbles).
2. Collectors (adsorbed to the surface and makes hydrophilic (attracts water) particles hydrophobic (rejects water)).
3. Regulatory substances (added to achieve full effect of skimmers and collectors).

Organic flotation chemicals will mainly be skimmed off with the mineral particles and will follow these particles, while inorganic chemicals follow the tailings. As a result, the organic flotation chemicals shall in principle not be discharged to the recipient. However, as it is common practice to add an excess volume of flotation chemicals, some of these will be discharged with the tailings. In cases where reversed flotation is applied, the skimming process will determine the content in the tailings, and these will contain flotation chemicals (so that only excess chemicals follow the product).

Typical skimmers are terpene-based compounds (e.g. Flotol B), ethers and alcohols (e.g. various Flotanol products). Chemicals that have been used as collectors are various types of xanthates (effective sulphide collectors), tall oil and cation collectors (e.g. quaternary ammonium salts such as “Lilaflot”). The regulatory substances that are most commonly used are pH regulating substances (lime, sodium hydroxide or sulphuric acid), activators or pressurisers (hydrofluoric acid, ferric chloride, sodium or potassium silicate etc.) and organic compounds such as dextrin (potato starch).

Flotol B, a production of pine tar distillation, mainly comprises terpene alcohols, and toxicity is considered low at moderate concentrations. The product is also categorised as easily degradable. The alcohol ethers (e.g. Flotanol) are water-soluble and are only toxic at concentrations far above those expected in recipients. They are also relatively easily degradable.

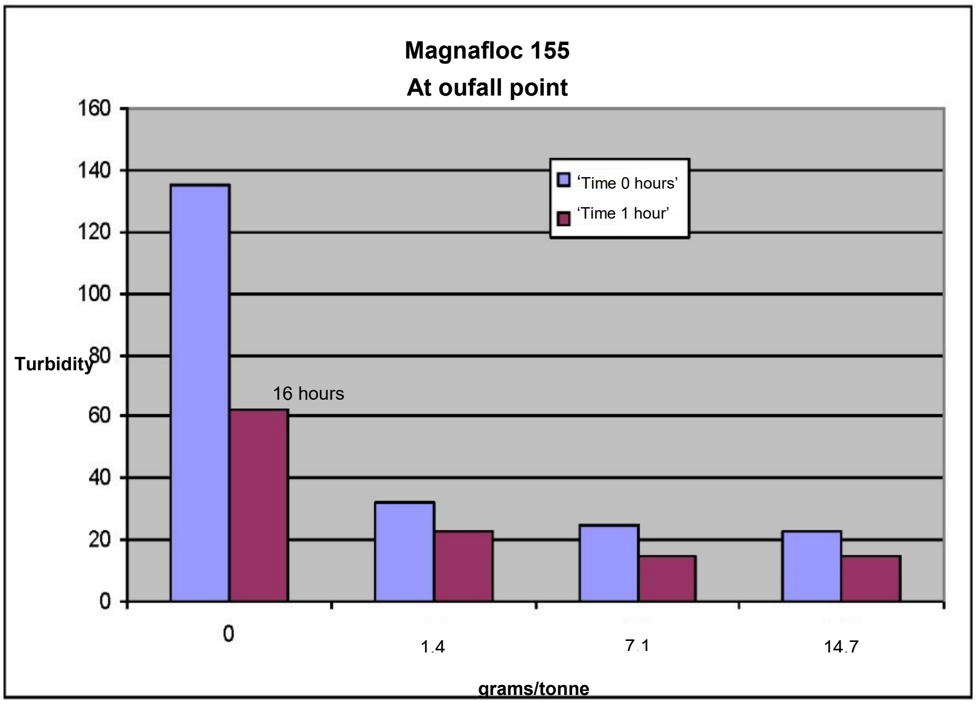
Collectors, which also comprise Lilaflot (cation collectors) have attracted negative attention in the Norwegian mining industry because they contain amines that are documented as toxic for aquatic organisms. Amines are primarily used for silicate flotation.

The regulatory substances that are inorganic are not problematic assuming they are not introduced to the environment at high concentrations. Both acid and lye are easily buffered by seawater and the negative impact will only be locally near the discharge pipe. When seawater is added to the tailings pipeline, some of the buffering process will take place inside the pipeline. The discharge of organic compounds such as dextrin will only affect the recipient as an organic impact (oxygen consumption). In summary, there are various chemicals used by the mining industry, with different product names, but that can be classified according to a few chemical groups. Their chemical composition and properties are specified in datasheets, but it may be difficult to find relevant documentation for certain chemicals relating to environmental impact in a marine environment.

6.2 Flocculation chemicals

Flocculation chemicals are used by the mining industry to increase sedimentation of fine-particulate material in the thickener. They are used in thickeners for tailings in order to recover fresh water during the enrichment process. Flocculation of the fine fraction produces a secondary effect related to the dispersal of fine material in the recipients (fjords or lakes). Flocculated fine material sediments much more rapidly than individual particles due to the Van der Waals force between individual particles that helps the formation of large flocs with a high sedimentation rate (Syvitski et al., 1987). In seawater, natural particles with a diameter of less than 10 µm will sediment as flocs. At a water depth of 5 metres, the settling rate may be 30 metres/24 hours, increasing vertically in the water column. At a water depth of 30 metres, the settling rate may be 100 metres/24 hours (Syvitski et al., 2006). By comparison, and according to Stokes' law, a single particle of 10 µm has a rate of descent of 8 cm/24 hours. This illustrates that natural flocculation of mineral particles in seawater is very efficient due to the ionic strength of seawater. This implies that the discharge of mine tailings containing fine material will sediment much more easily in seawater than in fresh water, irrespective of whether flocculation chemicals are used.

There are various types of chemical flocculation agents. The most commonly used are Magnafloc, where the effective agent is polyacrylamide. There are many different types of Magnafloc, but Magnafloc 155 is perhaps the most commonly used product. NIVA has carried out laboratory tests of the flocculation effect of Magnafloc 155 on fine-particulate mine tailings at different dosages. Material from crushed and grinded eclogite was used in the tests. The figure below illustrates the effect of adding various volumes of Magnafloc to mine tailings compared with the effect of natural settling in seawater. A flocculation efficiency of 76-81 % is achieved when adding 1.4 - 7.1 grams Magnafloc per tonne of tailings. The flocculation is spontaneous. It can be emphasised that the tests were small in scale and it is uncertain whether they provide a fully correct illustration of full-scale flocculation effect. The flocculation effect may also vary according to the type of tailings.



6.3 Explosive residue

Explosives commonly used in the mining industry contain ammonium nitrate and calcium nitrate. ANFO anolyte is an explosive comprising approximately 90 % ammonium nitrate and 5-6 % oil mixture. Slurry explosive has e.g. calcium nitrate as an active agent. One common property for all explosives used is that they contain nitrates. During blasting, large parts of the nitrogen is transformed into nitrous gases, but there will also be a large amount of nitrate residue. The residue from explosives that contain nitrates may be discharged along with tailings and waste rock. If the nitrates follow the tailings, they may cause increased levels of nitrogen in the deep water. This is unlikely to have a negative impact. Seepage water from waste rock may have a high content of nitrogen compounds and this can cause increased algae growth in the upper layers of the water body. Provided that seepage water from waste rock piles is treated and recycled, this is unlikely to be deemed a major environmental problem.

6.4 Environmental challenges

Significant volumes of chemicals, in particular flotation chemicals, are used and it is therefore important to ensure these are degradable, not toxic (acute or chronic), or can be bioaccumulated. Irrespective of the above, it is always preferable to minimise the discharge of chemicals to water and, when unavoidable, use chemicals with low toxic potential and are easily degradable in nature.

Given that there is such a large range of chemicals in use, it is important to obtain information on each substance and the known environmental impact in a marine environment. This information may be lacking. This applies in particular to tests on organisms that are relevant for Norwegian conditions and that comprise tests of organisms at different levels in the marine ecosystem. This does not only apply to toxicity testing, but also tests that involve decomposition of chemicals in relevant conditions, e.g. in a fjord (salinity, temperature, oxygen etc.).

A number of industries use large volumes of chemicals (e.g. textile industry and oil industry). It is therefore important to have access to experience from other industries when evaluating environmental challenges related to chemicals used in the mining industry.
The effects of chemical discharges from the mining industry to an aqueous environment insufficiently known.

It is expected that most chemicals, based on chemical composition, will not represent a major problem, but there are exceptions. One of these is the use of Lilaflot.

Lilaflot D817M
Lilaflot belongs to a group of chemicals known as “long-chained alcyloxy diamines”, and all available documentation indicates that these substances are toxic for aquatic organisms, and that fish, zooplankton and phytoplankton will die at water concentrations of 0.75-170 µg/L (EPA, 2003).

Given that Lilaflot also takes a very long time to biologically degrade (< 20 %, OECD standard test) and has high fat-solubility (Log_{Kow} > 5), and therefore the potential for bioaccumulation, the chemical meets all criteria for inclusion on the list of substances prohibited for use or discharge to nature in Norway. Corresponding substances such as quaternary ammonium compounds that have been used as cationic detergents (e.g. DODMAC) have already been included on the list of prohibited environmental toxins.

Lilaflot therefore meets several of the requirements mentioned below for priority environmental toxins defined by the Norwegian Parliament (Stortinget) in their White Paper: **Report No. 14 to the Storting (2006-2007) Working together towards a non-toxic environment and a safer future – Norway's chemicals policy.** Criteria for identifying priority ecological toxins whose releases are to be substantially reduced by 2010 and eliminated by 2020:

- Substances that are persistent and bioaccumulative, and that either
  - a) have serious long-term health effects, or
  - b) show high ecotoxicity
- Substances that are very persistent and very bioaccumulative (no requirement for known toxic effects).
- Substances found in the food chain in levels that give rise to an equivalent level of concern.
- Other substances that give rise to an equivalent level of concern, such as endocrine disruptors and heavy metals.

New analyses from NIVA show that Lilaflot can still be measured in the sediments in the Bøkfjord, and estimates indicate that approximately 1 % of the total discharge still remains in the fjord, 13 years after discharges ended (Berge, 2009). This shows that Lilaflot has a long lifetime in nature (even though the values are now very low and most likely not hazardous).

Lilaflot has a low water-solubility (estimated as 2.6 mg/L => factor x 20 over toxicity) and will therefore accumulate in the sediments. This may imply that the substance has low bioavailability for organisms in the water column (may be bioavailable for sediment-dwelling organisms). Documentation of the effect of Lilaflot in Norwegian fjords is very limited, and there is an obvious knowledge gap related to this chemical.

If we apply the evaluation regulations from the offshore industry (see PLONOR figure in chapter 6.4.1), Lilaflot will be defined as belonging to the red or black category, most probably black. Chemicals with similar properties to Lilaflot D817M were used by the offshore industry in the mid-1990s, but have now been phased out.

6.4.1 Experience from associated activities on the Norwegian continental shelf

Some of the activities on the Norwegian continental shelf can be compared to the activities involving disposal of masses from mining operations close to the sea. Both industries extract resources from the ground. The mining industry uses chemicals to separate the resources from masses. This results in large volumes of residual substances (tailings) that have to be disposed of, together with disposal of waste rock. The petroleum industry uses chemicals during the actual drilling process and to separate oil from water when extracted from the reservoir. The drilled cuttings are either released to the seabed, injected into the ground or transported on shore for disposal in a suitable landfill.

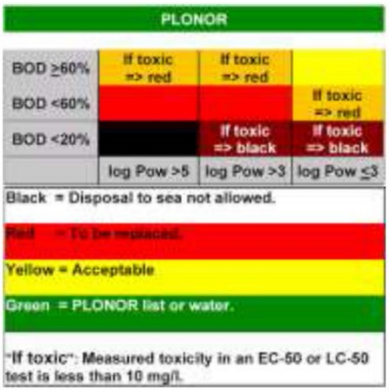
Moreover, the administrative regimes are different. The Norwegian Planning and Building Act does not apply on the continental shelf. Activities offshore are governed by the OSPAR Convention and the Framework Regulations (Regulations relating to health, safety and the environment in the petroleum activities).

One fact that is also worth mentioning is that offshore activities in Norwegian waters are relatively new (from the end of the 1960s) while mining in Norway has been carried out for many centuries. This may provide one explanation as to the relative differences between the practice related to evaluation of environmental status between mining (close to the sea) and offshore operations.

Below is a review of factors and experience relating to the petroleum industry that may be relevant for mining operations close to the sea.

Use of chemicals offshore
As with mining, the petroleum industry uses chemicals. The most important chemical groups are those used during drilling (drilling chemicals) and during production (production chemicals). In 2008, the total consumption of chemicals offshore was 452,000 tonnes, of which 130,000 tonnes were discharged to sea. The majority of those chemicals discharged to sea are related to drilling operations. In 2008, these amounted to 72 % of all discharges.

All the chemicals planned for use in the petroleum industry shall be tested with a view to inherent properties such as biodegradability, bioaccumulation and acute toxicity. In accordance with the Framework Regulations for the petroleum industry, the chemicals are defined on the basis of these properties into four categories; black, red, yellow and green. Chemicals in the black category are the most environmentally hazardous and chemicals in the red category are specially prioritised with a view to substitution. The chemicals in the green category are those included on OSPAR's PLONOR list (OSPAR list of substances /preparations used and discharged offshore which are considered to Pose Little or No Risk to the Environment). The regulations specify that the operators are responsible for testing, categorisation and environmental assessments of the chemicals. The operators are obliged to select those chemicals which, according to the environmental assessments, represent the lowest risk of environmental damage. Chemicals in the red and black categories shall only be selected if necessary, for technical or safety-related reasons.



PLONOR

BOD ≥60%	If toxic => red	If toxic => red	🟨
BOD <60%	🟥	🟥	If toxic => red
BOD <20%	⬛	If toxic => black	If toxic => black
	log Pow >5	log Pow >3	log Pow ≤3

Black = Disposal to sea not allowed.

Red = To be replaced.

Yellow = Acceptable

Green = PLONOR list or water.

"If toxic": Measured toxicity in an EC-50 or LC-50 test is less than 10 mg/l.

All fields on the Norwegian continental shelf have had a high focus on substitution of chemicals, and good results have been achieved. As a result, the industry is seen as having fulfilled the zero emissions goal for environmentally hazardous added chemicals for several years now. In 2008, discharges of black category substances totalled 2,450 kg, a reduction of 93 % when compared with 2002. The total discharges of substances in the red category on the Norwegian continental shelf is down 98.5 % since 2002. Discharges of red category substances totalled 15 tonnes in 2008. A further reduction in the discharge of substances in the black category and red category is expected, as a high focus remains on substitution. For safety and technical reasons, there will still be some discharges of these substances to the sea in the years to come. Some substances in the red and black categories that have been phased out to yellow category have proven to have unsatisfactory function over time, and in such cases the operators have been forced to resort to environmentally hazardous substances.

Drill cuttings and drilling fluid
The best possible analogy for the mining industry must be the management of drill waste. Drilling operations offshore produce two types of drill waste, drill cuttings that are drilled stone masses and used drilling fluid. Drill cuttings will always contain drilling fluid when released or otherwise treated. Requirements laid down by the authorities in 1991 regarding oil attached to drill cuttings when discharged have in practice resulted in the termination of discharges of drill cuttings related to drilling with oil-based drilling fluid. This requirement, which prohibits discharge of cuttings with oil exceeding one weight percentage, has resulted in e.g. the development and use of water-based drilling liquids. These drilling liquids now mainly contain only chemicals in the yellow or green categories. The discharge of drill cuttings with such water-based drilling liquids is in principle permitted and is not specifically regulated in the discharge permits for oil fields. The one exception is drilling operations in the Barents Sea and in areas with a sensitive benthic fauna. Water-based drilling liquids often contain clay, various salts and growth substances such as barite when drilling in sections below the hole section. These substances are classified in Klif's yellow and/or green category. Mineral-based chemicals such as barite also contain small volumes of heavy metals that are pollutants.

Monitoring offshore sediment
Few seabed areas have been subject to such close studies as those surrounding Norwegian petroleum installations. According to requirements from the authorities, the operators have monitored the chemical content and biodiversity in sediments since the early 1980s. There has been considerable focus on those installations that have discharged cuttings and oil-based, synthetic drilling liquid. The fine-grained cuttings part, accompanied by the oil-based drilling mud, was seen to disperse at some distance from the platforms. Increased concentrations of barium (Ba) and total hydrocarbons (THC) were found several kilometres from the platforms. A combination of chemical and physical (mud particles) impact resulted in disturbance of the soft-bottom fauna. After it became prohibited to discharge oil-based/synthetic drilling liquids, sediment monitoring offshore has shown an improvement in the environmental status in several of the regions monitored. The report entitled “Offshore sediment monitoring on the Norwegian continental shelf 1996-2006” concludes that less than 0.1 % of the continental shelf area is contaminated, and the areas where benthic fauna are affected are even smaller.

The discharge of cuttings accompanied by water-based drilling liquids does not have a corresponding environmental impact on the bottom sediments as the former oil-based liquids. The water-based drilling liquid systems have a high salt content and contain easily degradable organic components. The chemicals used therefore have a minimal impact on the marine environment. The risk of impact related to discharges of water-based drilling liquids is unlikely. Former studies found a slight disturbance of organism communities in a radius of around 50 metres from the drilling hole. This implies that biodiversity differs between areas close to the installation and areas assumed to have no disturbance. It is thought that this is caused by physical smothering. Experience from monitoring studies after drilling show, however, that smothered areas are quickly re-colonised once drilling ends.

The traditional sediment monitoring process shows that there is a general trend for slightly increased THC concentrations around fields that started at the end of the 1990s and after 2000. These are fields that only discharge cuttings with water-based drilling liquids. The higher concentrations are, however, only observed at the closest stations (500-250 metres), and several of the fields with start-up during the same period have shown a rapid fall in concentrations several years after drilling stopped. No impact on benthic fauna has been observed around new fields and neither at the innermost stations within a radius of 250 metres.

7. Minimising waste

The extraction of metals and minerals results in large volumes of residual waste containing solids (waste rock and fine-grained tailings) in addition to chemical residue. The mining industry, environmental authorities and the general public all wish to reduce to a minimum the volume of residual products, which to date have mainly been defined as waste. This requires that the vast volumes of solid waste generated are, to the greatest extent possible, utilised for a valuable purpose or product. However, it should be noted that the volumes of solid waste generated are so high that it is unrealistic to believe that it all can be utilised as above. Attempts should however be made to utilise as much as possible of the residual substances, even though this is hardly profitable from a corporate perspective.

Possible alternatives for utilisation are most realistic for the coarse masses (waste rock). Waste rock is stone masses produced when extracting ore from mining. This is not defined as ore due to the low content of minerals or metals, but as a residual product that requires disposal. Tailings are a residual product of the actual enrichment process, and are non-economic minerals separated from the commercial minerals via a number of separation processes. One traditional utilisation for waste rock is the production of aggregates for road building, airports etc. The utility value of the aggregates depends on mineralogy (breakability/wear resistance, hardness, specific weight etc.). When using aggregates to cover pipelines at sea, specific weight is a major factor. Some types of fine-particulate residual substances may be utilised as soil improvement agents, as additives to concrete (provided the minerals are not alkali-reactive) and for ceramic products. Experience has shown that it is easier to utilise aggregates and tailings from non-sulphidic rock with a low heavy metal content and where utilisation does not generate a new environmental problem.

A new area of application for certain types of tailings may be in connection with storage of CO_2. It may also be possible to use tailings to cover polluted sediments. Klif has prepared a requirement and approval specification for the types of tailing masses that are suitable as capping material for polluted sediments.

In addition to the potential applications mentioned above, it is important to identify by-products extracted and that help reduce the volume of residual substances. This will most often be economically beneficial for the industry.

In addition to the above-mentioned methods to stimulate minimising waste, refilling of waste rock and tailings to a mine will provide a reduction in the dispersal of pollution to the surrounding environment. Successful backfilling requires a number of factors (e.g. plans for how to take action if the mine fills with water in the future). Purification of mine water and recycling of metals are also part of the concept of minimising waste.

8. Need for research

We now have around 30 years of experience, both at home and abroad, of the environmental consequences of disposing of mine tailings in the sea, and around 50 years of experience of disposal in fresh water. Experience gained in Norway is principally documented in various types of research and consultancy reports. However, a main body of experience from foreign mining projects involving disposal of tailings in water has been published in peer reviewed international journals (see chapter 9, References and bibliography). A lot of the expertise related to handling tailings is found in the individual mining company and the consultants who work for the industry. As such, the situation is somewhat complex. It is difficult to achieve an overview over knowledge status, and therefore even more difficult to specify the knowledge we lack but should have, i.e. knowledge gaps.

Research conducted on mining and the environment in Norway has been financed by the individual mining company and, to a certain extent, the Directorate of Mining (Bergvesenet, now renamed Direktoratet for mineralforvaltning). As such, the results of the research remain with the customer, and the national research community will not necessarily benefit from the work conducted. For this reason, a public research programme organised by the Research Council of Norway has been lacking for some time now. Such a programme would focus on the most important knowledge gaps and help ensure environmentally acceptable operations within the mining industry.

The Geological Survey of Norway (NGU) has compiled a geochemical atlas of Norway containing data based on overbank deposits, i.e. the most weathered and washed-out part of the soil types. However, with the exception of the northernmost parts of North Norway, there is no data on the heavy metal content of moraines and marine clay. We therefore lack the data to "extrapolate” geochemical conditions in sediments on the fjord bottoms. Chemical analyses of e.g. marine clay in connection with pollution mapping for building projects etc. has shown that the NGU's “background values” from overbank deposits are frequently exceeded. The same applies to Klif’s standard values, which also lack a basis in natural background values.

In areas with mineralisation of e.g. copper, there is reason to believe that the fjord sediments are affected by the same metals that are commercially of interest to extract. Without knowledge of “local background levels”, it is impossible to evaluate the consequences of discharges.

8.1 Disposal in fresh water – research needed

Over the years, we have accumulated experience relating to disposal of tailings in fresh water. However, we still lack theoretical knowledge of a number of factors. These are summarised in brief below:

Physical properties
Sedimentation properties of tailings and action to delimit particle dispersal.

Weathering processes under water
Experience shows that the geochemical conditions in tailings disposal sites are complex. The properties of the tailings change over short distances in the disposed tailings, most probably due to heterogeneous conditions. It is therefore difficult to estimate the weathering processes and the chemical balances that apply.

International research into this subject is under way but, in many cases, the terms and natural conditions for this research are of little relevance for Norway. A number of theoretical models are in use to estimate the sequence of weathering under water. NIVA has established a disposal model that is still being improved. The goal would be to establish a model that can be utilised from as early as the planning stage and where theoretical values from the planned enrichment process can be input. To date, the data gained from the Bjønndalsdammen dam in Løkken has been utilised. By utilising so-called DGT samplers (passive samplers for metals), we can produce metal and sulphur profiles in pore water. The purpose of this has been to allow for calibration of the model to provide an improved prognosis of what occurs in a disposal site and how conditions develop over time. The actual technique is simple and helps save time in comparison with former practice, involving storage of samples over a number of days.

Flotation chemicals
We still lack knowledge of a number of flotation chemicals in terms of decomposition and biological effects.

Tolerance limits and salmon
There is a need to clarify the tolerance limits for metal seepage in relation to particularly vulnerable life stages for anadromous salmon, and especially the smolt stage for Atlantic salmon. Established chemical speciation techniques and biological endpoints can be applied, and studies should preferably be conducted in site specific water qualities.

Disposal in lakes and rehabilitation
It is important to document the length of time it takes for a lake to be rehabilitated after mining stops. There are numerous lakes in Norway where the disposal of tailings was terminated many years ago and that are suitable study objects.

There are also numerous disposal sites, and it is important to collate the experience available from each disposal site into a larger context. The observations made at each disposal site may be difficult to interpret as the disposal sites are affected by a number of external factors, such as the flow of polluted seepage water from other sources, regulation effects etc. However, there are two disposal sites where conditions are so unambiguous that they are suitable for further studies of the effects of tailings disposal under water in fresh water; Bjønndalsdammen dam in Løkken and Huddingsvatn lake.

8.2 Disposal in sea – research needed

In this context, we lack knowledge of two principal subjects:

1. **How to prepare *suitability criteria* with which to judge whether a marine recipient is suitable for sea disposal of mine tailings? The basic information on local conditions required to make such an assessment (critical information).**
2. **How to establish *acceptance criteria* for tailings disposal? What is the acceptable negative environmental impact? How to document fulfilment of the criteria?**

Mine tailings mainly comprise mineral particles with a grain size fraction corresponding to clay, silt and sand. A slurry made up of fresh water, seawater and solids is transported at relatively high speeds through a pipe and continues as a heavy flow of mud down to the seabed. The tailings plume transforms into a turbidity current that moves along the seabed, transported away from the outfall point by gravitation. At the same time, particles settle – first the coarser particles and then the finer ones. The distance over which particles are transported depends on current in the bottom water layer, the slope of the bottom, the grain size distribution and the level of flocculation in the fine material. A good modelling tool is required to describe how this slurry is transported and the extent to which the mud plume is split so that the finest particles are stored in the water mass above the actual turbidity current. A combination of modelling and large-scale experiments will provide new knowledge of this phenomenon. Research is required to contribute to requirement specifications on the outfall design, so that slurry exiting the tailings pipeline disperses in a predictable and optimal manner with a respect to environmental impact.

The most important source of knowledge of sea disposal of tailings is found in the environmental impact assessment report prepared in connection with the plans for the Quartz Hill molybdenum mine in Alaska in 1993, with a tailings discharge of 25 million tonnes per year at 50 metres depth in a fjord (Hesse and Reim, 1993), and experience-based material from 25 years of sea disposal at Island Copper Mine in British Columbia (discharge of 12 million tonnes of tailings per year to a fjord at 50 metres depth) (Pedersen et al., 1995). When identifying knowledge gaps, these documents will be important sources.

Critical questions on knowledge gaps are still made in three areas. Firstly, physical factors related to dispersal and sedimentation of fine material. Secondly chemical and toxicological factors. Thirdly, the ecological effects of mine tailings smothering the seabed in the short and long term. The latter applies particularly in the disposal site border areas, where smothering is moderate.

Prediction of dispersal and sedimentation of fine material can be based on modelling (near-field and far-field modelling, circulation models) and/or experiments in large tanks (simulation trials). Important knowledge gaps relate to how the plume behaves after leaving the discharge pipe. Will it behave as a homogeneous plume flowing down to the bottom or will the plume split, with the parts of the plume containing the finest particles forming a separate plume stored higher up in the water mass? According to the environmental impact assessment for Quartz Hill, such a split would only occur if the tailings pipeline is not fitted with a de-aeration unit to prevent air bubbles in the plume that would transport the fine fraction upwards in the water mass (Hesse and Reim, 1993).

Another subject related to dispersal of fine material is the importance of small changes in density in the water mass that prevents the dispersal of fine material upwards in the water column from the discharge depth. We lack knowledge of the required strength of these density barriers to effectively stop vertical transport. Moreover, there is a need to study in detail the mechanisms related to deep water exchange in fjords and the extent to which this contributes to the transport of fine material out of the area defined as the disposal site. The residence time of the basin water and water at mean water depths will have a major significance for the sedimentation of fine material. We therefore need to model deep-water exchange and particle dispersal.

It may also be necessary to carry out field studies of deep-water exchange in a typical threshold fjord where there are no discharges from point sources, and to measure turbidity profiles throughout the entire water mass during water exchange. Normally, there is a water layer close to the bottom in marine areas that always has a high natural content of particles (a nepheloid layer) and to date there are no studies as to the extent to which this turbid water layer affects turbidity in mean water layers when the bottom water is pressed upwards and flows out of the fjord above threshold level. When tailings are discharged to deep waters in a fjord, the plume will spread as a turbidity current along the bottom, and there will be a water layer close to the bottom with high turbidity. It is therefore important to be able to document whether a deep-water exchange will result in concentrations of fine material at intermediate water depths that represents an environmental risk for aquatic organisms (fish, zooplankton). We now have a solid base of new knowledge on the concentrations of mineral particles that are acceptable in seawater in relation to negative impact on fish and plankton (Smit et al., 2009). This shows that the lowest concentration for negative impact appears to be approximately 50 mg/l, while the major negative effects emerge at a concentration that is at least 10 times this limit. It should be noted that negative effects depend not only on concentration, but also exposure time. A situation where a high particle content in the water lasts for years may differ considerably from an episodic impact.

Smothering by mine tailings and impact on benthic fauna are most probably the most commonly mentioned environmental impacts of sea disposal of tailings. Given that the annual discharge of tailings from major mining operations can often be in the range of several million tonnes per year, the sedimentation rate in the areas close to the discharge point is often several metres per year, as opposed to a natural sediment growth of several millimetres per year. In addition to the physical smothering that buries existing benthic fauna, the mine tailings contain mineral material that is almost free of organic carbon (with the exception of organic flotation chemicals that follow the tailings, e.g. potato starch or dextrin). This implies that benthic fauna is covered by a material with zero nutritional value. There is therefore widespread agreement that in the area close to the discharge point where smothering is at its highest and where the main product that settles is sand, the benthic fauna will practically be exterminated during the production period. There may be knowledge gaps relating to how the border area of the actual disposal site is affected by smothering.

Tolerance limits for sediment growth will depend on the organisms existing in the bottom sediments and their capacity to move vertically through sediment.

Another key issue that also has knowledge gaps is the re-establishment of fauna once tailings disposal is terminated. National and international experience gained of sea disposal shows that it can take from two to ten years to re-establish a new benthic fauna in those areas where the sediment growth is greatest (close to the discharge point). There may be a difference of opinion on how the re-established fauna differs from the original fauna, and the extent to which a change in species distribution necessarily has a negative impact. In some circumstances, the depth conditions close to the outfall point will be substantially different due to high rates of sedimentation. When water depths are reduced, the biodiversity and biomass may increase as natural sedimentation takes over. In some cases, the substrata will change in that the sediment becomes coarser than the original sediment, providing habitats for different types of organisms. In many situations, the bottom substrata exposed to smothering will become hard and compact, giving rise to the increased establishment of animals that live on the surface of the sediment rather than buried in the sediment. In total, there is a knowledge gap regarding the long-term ecological impact of sea disposal of mine tailings.

More specifically, we lack knowledge on the following issues related to physiochemical factors:

- Establishment of modelling tools related to dispersal of fine material from tailings and that also include descent of particles (sedimentation) (near-field and far-field modelling).
- Studies of flocculation processes, with and without chemical flocculation agents. The stability of flocs formed by fine material in the tailings and how the mineralogy of the tailings affects flocculation, and the interaction between mineral particles and natural organic particles.
- Geochemical, mineralogical and geotechnical processes in underwater tailings disposal sites (background values, pore-water chemistry, leaching of metals, compaction, geotechnical stability)
- Studies of re-suspension phenomena (ratio between current velocity and particle sizes). A graph established in the 1930s (Hjulström curve) is mainly used today and this was in fact established for particle transport and erosion in rivers.
- Studies of natural nepheloid layers (bottom layers with high particle concentration) in fjords (how they are formed and what they contain)
- Studies of the natural vertical particle distribution in fjords and the significance of minor changes in stratification
- Studies of natural particle transport in different water layers in fjords (link between current data and turbidity) and seasonal variation
- Large-scale model experiments (tank trials) with build-up of tailings cones and documentation of angles of repose for tailings with different grain size and grain size distribution
- Study how the use of organic chemicals in the enrichment process affects oxygen consumption in sedimented tailings.

Specific problems involving biological/ecological impact of tailings disposal in fjords, where there is a knowledge gap, include:

- The effects of increased concentrations of mineral particles in seawater on phytoplankton and zooplankton
- Mineral particles in seawater and their impact on behaviour of fish
- Smothering of benthic fauna and the effect of thin layers of mineral material

- Re-colonisation trials of mine tailings re-establishment of fauna with natural sedimentation of organic material
- Bioturbation studies in mine tailings disposed on fjord sediments
- Effects on demersal fish (primarily); loss of habitat, spawning area, high turbidity close to seabed
- Effects of chemicals (decomposition conversion in the marine environment)

As the main problem related to tailings and disposal is the vast volumes, minimising waste is a key issue for research in an environmental technology context.

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ANNEX: Status update

New knowledge, environmental challenges and knowledge gaps.

2010-2018

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Background.
The current report on mining and waste management was accomplished in 2010. It was published in Norwegian, and due to a demand for an English version, it was decided to translate the report. The Norwegian version was published 8 years ago, and contained a chapter 8 on knowledge gaps and research options. To give an updated version, we decided to add an annex to the English version to reflect this chapter.

Objectives.
The objectives of adding an annex to the translated English version are to

- present an updated status of sea tailing disposal practice in countries where implementation of sea disposal is considered as an alternative to land disposal of mine waste and
- to discuss the environmental challenges which still remain and
- how knowledge gaps have been handled the last decade to increase the level of understanding and documentation of what may be considered as best practice to minimize environmental impact.

To accomplish this task, it has been necessary to summarize new knowledge presented in peer review publications, reports and EIAs. Additionally, it is referred to international agreements and directives, prerequisites for permits related to sea disposal, monitoring requirements and ongoing research.
The annex is completed with a list of publications and bibliography for the period 2010 – 2018.

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[1] www.skeimining.com

The present situation in Norway regarding sea disposal of mine tailings.

Governmental documents

In **2010**, the Government presented a new Minerals Act[2] which replaced five other Acts. The Act was an important step in simplifying earlier regulations in the minerals sector, and in creating transparent and predictable framework conditions for the minerals industry.

In **2013** the Norwegian Ministry of Trade and Industry presented a Strategy for the Mineral Industry[3]. The strategic priorities also include research and development and environmental concerns. Challenges related to tailings disposal were emphasized with less use of chemicals and possibilities for the reduction of waste rock and its alternative uses. The Strategy underlines that the Government will strengthen expertise and knowledge related to the environment and to the environmental impact of minerals operations. It emphasizes that handling of tailings will therefore be a key challenge in planning mineral extraction.

The Strategy for the Mineral Industry says that *"historically, gangue has been deposited on land, while tailings have been deposited in the sea or in a lake where the mine or quarry has been close to such areas. Landfills should preferably be in natural depressions in nature so that artificial barriers and dams that need to be serviced and maintained over long time periods are not needed. With mineral extraction in coastal areas, marine disposal can be a viable alternative. Disposal on land and in the sea can both have environmental consequences. It is not possible to establish, on a general basis, what type of disposal solution is most environmentally responsible. The disposal solution must be assessed specifically, in each individual case"*. Additionally, "*The choice of disposal solution must be determined on the basis of a thorough, fact-based assessment of the effects on the natural environment, costs and possible consequences for other industry and other interests.*"

Norway has played an active role to achieve recognition for the fact that sea disposal of mine tailings in some cases may be considered at Best Available Technique (BAT). A review of the Reference document on Best Available Techniques (BREF) for the Management of Tailings and Waste-Rock in Mining Activities in Europe has included discussions on sea disposal of tailings in fjords and near shore environments. It has particularly been a focus on whether sea disposal is an acceptable alternative to land disposal and if sea disposal in some cases may be considered as BAT. A meeting in Sevilla, Spain in November 2017 concluded with respect to the BAT discussions. The EU Joint Research Centre (JRC) has finalised the BREF document. The Norwegian

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[2] https://www.regjeringen.no/no/dokumenter/mineralloven/id597815/

[3] https://www.regjeringen.no/contentassets/3fe548d142cd496ebb7230a54e71ae1a/strategyforthemineralindustry_2013.pdf

ambition was to include BATs on sea tailings disposal in the document. The Norwegian goals before the meeting were:

- A recognition of STD as a possible BAT option, for cases where this has been fully evaluated by a socio-environmental impact assessment. Following that, work with the more specific BATs for sea tailings disposal within the Norwegian Environment Agency and within the Norwegian R&D project NYKOS[4].

A compromise text from the BREF-document reads as follows:

"The Technical Working Group (TWG) acknowledges that progress has been made in improving the knowledge base on sea tailings disposal (STD) but following the exchange of information, no consensus has been reached, neither on the inclusion, nor on the exclusion of BAT for STD in this document. The TWG encourages the technoscientific community to further expand the knowledge base on impacts and benefits of STD. Finally, the TWG acknowledges that Norway continues to acquire experience in this field and has shared experience to this extent."

The process of Environmental Impact Assessments (EIA) in the mining industry in Norway.

1. EIA is mandatory depending on the size of mining project (size of the area and/or volume of ore extraction).
2. The local government where the mine is situated, and where the management of the waste will take place, is the owner of the EIA process. This implies that the EIA-process is politically ruled (The Planning and Building Act). In some cases, it may be overruled by the government, depending on to what extent the outcome of the EIA is of national importance.
3. The EIA-process starts with a public announcement saying that an EIA will be initiated. Secondly, a scoping process is initiated where the mining company, politicians, NGOs, scientific experts and varies stakeholders participate to discuss what are critical investigations to be included in the EIA-programme. The outcome of the scoping discussions is presented in the Planning programme, outlining the scope of the investigations necessary on land and in the sea where impact is expected.
4. Based on the agreed Planning program the mining company is now the operator of the EIA-project and hires independent consultants, academics etc. to carry out field studies on land and in the sea and desktop work which address the issues outlined in the planning programme. All costs are covered by the mining company.

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[4] https://www.sintef.no/projectweb/nykos/

5. During the EIA-process several hearings and public meetings where stakeholders are invited are carried out. In some cases, additional investigations are incorporated in the Planning programme, based on the outcome of hearings and public meetings.
6. An EIA shall describe the present environmental setting, consequences for natural resources and the society in the area expected to be influenced by the mining project. The positive and negative effects are weighed and compared. If the overall outcome of the comparison is positive, the project is recommended. The EIA should make sure that the impact on the environment, resources and society is acceptable and what terms the project should be operating on and to what extent remedial actions should be implemented.
7. An EIA shall cover a minimum of two alternative waste facilities for mine waste (for example one land disposal alternative and one sea disposal alternative).

Permits to operate sea disposal of mine tailings in Norway.
In addition to test programs and investigations carried out in connection with EIAs, the discharge permit issued by the Norwegian Environment Agency also triggers mandatory tests and investigations (not already included in the EIA), as well as a monitoring programme.

Below, the conditions related to discharge permits are summarized for the two mining companies (Nordic Mining and Nussir) included as cases. These conditions include technical infrastructure, regulatory frameworks and standards:

Infrastructure and waste management plan

- Description of the mining process and waste disposal infrastructure (dimension of pipelines, mixing tank for tailings, seawater and freshwater, de-aeration system for tailing pipe).
- Design of infrastructure of sea disposal which limit dispersal of tailings and to avoid formation of tailing cones close to end of the pipe.
- Obligatory preventive maintenance of equipment and installations of DSTP/STP infrastructure to avoid accidental discharges.
- The company must present an overall “Waste Management Plan” which also includes a monitoring programme and control of disposal sites, alternative use of the waste and plan for remediation after termination of the mining activity.
- The Waste management plan should include the following issues:
    - Characterization of the waste
    - Describe how the waste may be harmful for humans and the environment due to the disposal
    - Describe how to minimize negative effects

  - Describe backfilling of waste in the mine (both tailings and waste rock)
  - Alternative usage of the waste
  - Monitoring plan (prior to production start, during operation and after closure)
  - An environmental risk analysis for the whole operation.
  - Plan for rehabilitation of the mining area after termination of the activity
- Use of processing chemicals (flotation chemicals and flocculation agents). Brand names, chemical composition and annual use of chemicals (tonnage). It is well known in the mining industry that the majority of the flotation agents used ends up in the products and a minor fraction is associated with the tailings
- A maximum amount of chemicals the mining company is permitted to use per year (specified by products)
- The company is asked to phase out chemicals which are shown harmful to the environment and use substitutes which cause fewer problems, if available.

Regulatory framework and standards

- The company is obliged to present a monitoring programme including, water, biota (including fish) and sediments as well as a test program for investigating short and long-term effects of process chemicals in the disposal site as well as degradation of the chemicals in the marine environment. Additionally, if the degradation products cause an environmental concern, investigations should include chronicle effects on marine organisms including the early stages of fish and the potential for bioaccumulation
- Duty to comply with limit values ("Norwegian Standards")[5]. This means quality standards of seawater, sediments and biota. These are documents issued by the Norwegian Environment Agency to customize the environmental conditions in Norwegian fjords
- Concentration limits (applied in the Nordic Mining discharge permit):
  - The concentration of particles in the water column should not exceed 2 mg/l 40 m above the depth of discharge The concentration limit of 2 mg/l includes the natural background concentration (< 1mg/l)
  - The concentration of particles in the water column should not exceed 3 mg/l at the boundary of the area regulated for tailing disposal (measured at the depth of discharge)

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[5] Contaminants in coastal waters of Norway 2015" in web:
http://www.miljodirektoratet.no/Documents/publikasjoner/M618/M618.pdf

  - The sediment accumulation rate should not exceed 3 mm/year at the boundary between natural sea bottom and area regulated for sea disposal (see figure below).

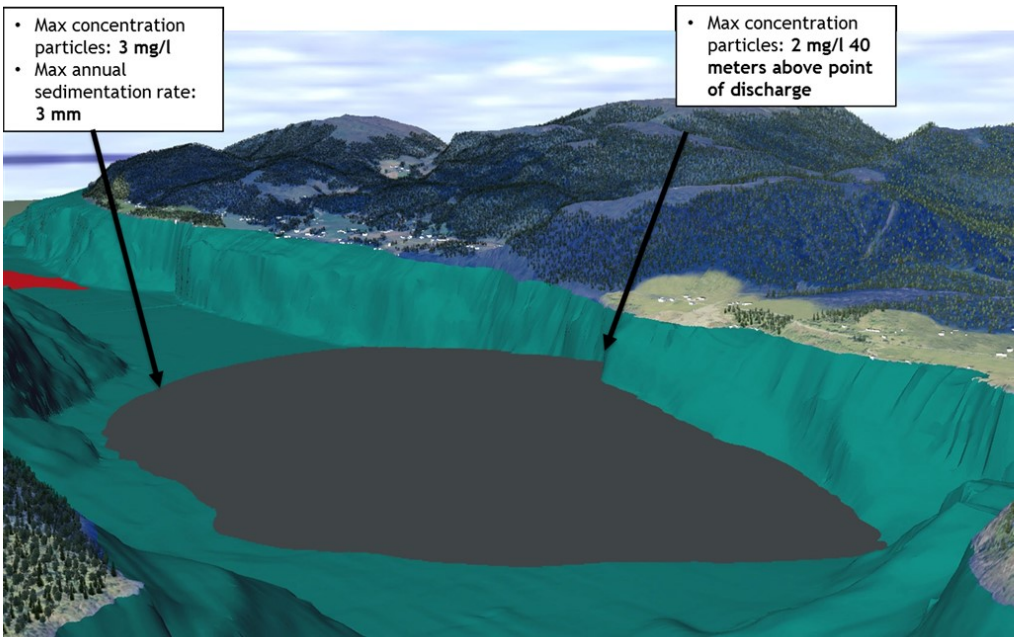

Illustration: *Asplan Viak*

Planned disposal site in Førdefjorden (Nordic Rutile AS). The illustration of the disposal site (black area) as anticipated after 50 years of disposal. The size of the disposal site will be about 4 km^2 and the deposit is expected to contain 140 mill m^3 tailings (Norwegian Environment Agency).

  - The concentration limits in the water column and the sedimentation rates should be monitored regularly (the concentrations of particles in the water column should be monitored by online instruments)
  - If the concentration limits in the water column are exceeded, the disposal should be terminated until the cause has been identified and mended.

- The company is obliged to make sure that the frequency of sampling and measurements in the sea will give representative data (taking into account seasonal variations of background). QA procedures are important to evaluate the results. The analyses of environmental samples and reporting of the data should be carried out by external accredited laboratories. The data should be stored in data bases available for the public.

The company Nordic Rutile AS (previously Nordic Mining ASA) has permission to discharge 4 million tonnes of tailings annually at 250 m depth into Førdefjorden on the west coast of Norway. Nussir ASA has a permission to discharge 2 million tonnes of tailings annually at 30-60 m depth in Repparfjorden, in Northern

Norway. All permits are approved, and they will start their production in a few years' time[6] [7].

The above terms and conditions for permitting sea disposal of mine tailings is an example of a part of the roadmap for implementing DSTP/STP in Norway. Terms and conditions are site dependent both with respect to site properties, risk of user conflicts and type of mining activity (and discharge of waste). Every type of pollution is individually classified as undesired and, in principle, is prohibited by the Pollution Control Act[8]. In the Pollution Control Act, the pollution control authorities are assigned the task of assessing which types of pollution should however be permitted, subsequent to a comprehensive assessment. When assessing whether a permit shall be granted pursuant to section 11 of the Pollution Control Act, and possibly the conditions for such a permit, the Act states that: "it shall pay particular attention to any pollution-related disadvantages arising from the project as compared with any other advantages and disadvantages so arising", cf. section 11 fifth paragraph. The pollution control authority determines whether to grant a permit on the grounds of their own assessment. The weighing up required pursuant to section 11 will principally be between the environmental damage and disadvantages on the one hand and the financial and commercial advantages provided by the project on the other. There are also requirements to plans for monitoring, which will be submitted for consultation with other authorities (Directorate of fisheries, Norwegian Food Safety Authority etc.).

The permit for disposal to sea in relation to Nordic Rutile was appealed by a NGO to the EFTA Surveillance Authority (ESA) which concluded that the process leading up to the permit was in line with rules set out in the Water Framework Directive[9], leading to the conclusion that Norway is not in conflict with the directive in granting the permit. EFTA Surveillance Authority monitors compliance with European Economic Area rules in Iceland, Liechtenstein and Norway, enabling them to participate in the European internal market. The EFTA Surveillance Authority ensures that the participating EFTA States respect their obligations under the EEA Agreement.

Finally, it may be noticed that GESAMP (of the United Nations and IMO) acknowledges the importance of sea tailings disposal issues, and consequently have created a WG on the topic (WG42: Impacts of wastes and other matters in the marine environment from mining operations, including deep-sea mining)[10]. GESAMP is a group of independent scientific experts that provides advice to the UN system on scientific aspects of marine environmental protection.

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[6] http://www.nordicmining.com/engebo-rutile/category317.html

[7] http://www.nussir.no/index.php

[8] https://www.regjeringen.no/en/dokumenter/pollution-control-act/id171893/

[9] http://www.epa.ie/water/watmg/wfd/

[10] http://www.gesamp.org/work/groups/42

Comparison of deep sea and coastal water disposal of mine tailings.

GESAMP WG42 has defined deep sea tailings placement (DSTP) as disposal at depth of 1000m and sea tailings disposal (STD) in shallow or intermediate waters (shallow 0-100m and intermediate at 100 -1000m). This working group are advocating for a change to the current term DSTP to a more precise terminology; Deep –Sea Tailings Disposal (DSTD). The argument they use is that the use of the term "disposal" is considered to be more accurate. In fjords in Norway the maximum depths often vary between 100 and 1000 m depth and at locations where mine tailings are disposed the depth of disposal take place between 20 m and 300 m. The main difference between deep sea disposal and coastal disposal is:

- The distance between depth of disposal (end of tailing pipe) and the final destination of the tailing (disposal site) is much longer when DSTP is implemented. The risk of plume sharing is greater with long distance plume transport as well as risk of pipe failure.
- The ability to do comprehensive monitoring at deep sea sites represent technical challenges and high costs.
- The disposal site with respect to fjord disposal is a confined area - a basin surrounded by sills – where the majority of the tailings particles are trapped.
- The knowledge about ecology in the deep sea is low compared to coastal ecology (Vare et al., 2018).

Research initiatives in Norway, 2010-2018.

In addition to comprehensive base line studies and monitoring programs with respect to sea disposal of mine tailings there is a significant need of research programs where the results are published in peer review international scientific journals. In the past most of the documentation of environmental impact from sea disposal has been presented in the grey literature (governmental reports and consultant reports initiated and financed by the mining industry).

In Norway a research program (**NYKOS; Developing new knowledge on submarine tailings disposal**)[11] was initiated in 2015 and will be finalized in 2019. The aim of the NYKOS program is "*to increase the understanding of how best to dispose of mine tailings in the marine environment, how to monitor the deposits through time, what ecosystem impacts do they have and how to ensure that fjord systems recover as quickly as possible after a mine closes down*".

This aim should be achieved through five scientific work packages focusing on

- tailings improvement and characteristics (desorption/readsorption kinetics of chemicals/fines and potential for recycling or immobilising chemicals/fines

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[11] https://www.sintef.no/projectweb/nykos/

- marine geological mapping - a prerequisite for location and monitoring of STPs (integrating data in selected fjords and pilot marine geology study of two STPs)

- effects of mine tailings and associated chemicals on marine, benthic ecosystems (development of analytical methods for chemicals associated with STPs, ecotoxicity, sensitivity of the benthic ecosystem to sedimentation of contaminated STPs, colonisation experiment on mine tailings disposals, state of benthic communities in STP-affected and reference fjord, trace metal speciation and processes at the sediment-water interface in seabed deposits with sulfide tailings, development of modelling of the dispersal of fine fractions and work package management)

- modelling, impact acceptance criteria and risk aspects (flocculation, impacts from use of added chemicals and validation with data from an existing fjord where STP has been implemented)

- synthesis: Best Available Techniques for STPs (data management, GIS-analyses and spatial modelling, BAT guidelines).

The program is 80 % financed by the Norwegian Research Council and 20 % by 7 mining companies. The program is carried out by five Norwegian research institutes. NYKOS will contribute to new knowledge about the environmental consequences of sea disposal as an alternative to land disposal. The outcome will be a reduction of speculations regarding environmental risk as the scientific based documentation will increase and the scaling of the effects will be facilitated. Furthermore, new knowledge will contribute to the decision making related to mine waste management and permits of tailing disposal will consequently achieve a broader knowledge base.

The NYKOS program is now in a phase where data are published in scientific journals. In 2017 a paper on in situ characterisation of complex suspended particulates surrounding an active submarine tailings placement site in a Norwegian fjord was published (Davies and Nepstad, 2017). The paper clearly indicates the complexity of flocculation of fine particles in marine waters, both natural particles and particles originating from disposal of fine tailings from the mining industry. The majority of very fine particles (< 10μM) are flocculated in sea water due to the effect of salt and the presence of colloidal organic matter. The sinking rate of flocculated particles depends on the specific weight of the flocs which depends on the content of organic matter. Consequently, the sinking rate of flocs are not dependent alone on flocs sizes. A range of sophisticated instruments are necessary to study the behaviour of fine particles in the sea and the paper mentioned has illuminated important processes and new knowledge.

Another NYKOS-paper has recently been published (2018) on effects on submarinemine tailings on macrobenthic community structure and ecosystem processes (Trannum et al., 2018). Benthic organisms are frequently scrutinized in relation to hyper sedimentation caused by disposal of solids. Use of mesocosm experiments to study benthic community structure and biogeochemical processes have shown to be useful to gain new knowledge. It is important to distinguish between negative effects from high sedimentation rates of solids and chemicals associated with the particles. The paper concludes that a couple of centimetres of mine tailings is a threshold for negative effects on the macrofauna, but points at the fact that these experiments are most suitable for distinguishing between different types of tailings rather than predicting absolute effects.

At a Sed-Net conference in 2017 a NYKOS paper on Metal fluxes from a sea deposit site was presented[12].The sea deposits of mine tailings from one of the largest producers of ilmenite in the world (Titania AS) were active during the period 1960 and 1984 (disposal site: Jøssingfjorden) and between 1984 and 1994 (disposal site: Dyngadjupet). This implies that there is a history of more than 30 years of sea disposal which is preserved in the bottom sediments at the disposal sites. It should be pointed out that during this period the areas of disposal were extensively monitored, particularly in relation to biological and ecological effects. As sea disposal was terminated 20 years ago in this case this also allows studies of the long-term behaviour of metals associated with the tailings with respect to mobilization from the deeper part of the deposits which now are covered by natural sediments during the last 20 years. However, it should be emphasized that during the period were sea disposal was ceased in 1994, for the benefit of land disposal, fine tailings have been to some extent carried by runoff from land to the sea surface to become incorporated in the surface sediments at the old tailing disposal sites and causing levels of metals (copper and nickel) above background levels.

Experimental work on box cores taken in the two disposal sites and a reference size, applying DGT probes (diffusive gradients in thin films) to measure dissolved metals in the pore water profiles indicated no significant mobilization of nickel and copper from the deeper layers in the deposits. Flux of nickel from the sea deposits corresponds to 5 % of leakage from land deposits to the sea.
Titanias landfill is estimated to be full in 2024, depending on the future production rate. Titania startet in 2016 assessment studies of four alternative tailing management solutions; land disposal, sea disposal, backfilling in the open pit and alternative use of the tailings. This study is planned to be completed by 2019 (pers. comm. Ann Heidi Nilsen, Titania).

EWMA (Environmental Waste Management) is a competence cluster focusing on research and education related to petroleum-and mineral- industry in cold environment. One of the research prioritizes is the study of effects of environmental pollution and the identification of actions that are required for preventing/minimizing the influence of potential environmental pollution. In

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[12] http://sednet.org/events/sednet-conference-2017/sednet-conference-2017-presentations/

this respect, as pointed out by the industry, it is important to pay attention towards the Best Available Technique (BAT) and Life Cycle Assessments (LCA). Improved knowledge within relevant fields for new and expanding industrial activities in cold climates will be essential to develop EWMA to a key research and knowledge centre in the High north.

One objective is to advance the knowledge of dispersal of mine tailings related contaminants after their discharge to the marine environment. This shall be achieved through:

- filling of major gaps in the knowledge of the present sea-bottom contamination
- investigation of the influence of mine tailings in the past
- improved predictions of future environmental consequences related to pollutant loadings.

The program started in 2010 and ended in 2017. EWMA carried out research on the effects on disposal of mine tailings from an iron mine situated in the far north of Norway – Sydvaranger Gruve AS and which operated sea disposal of mine tailings in Bøkfjorden for 40 years. One of the conclusions drawn related to this work was that tailings disposed by the iron mine have not caused significant environmental consequences with respect to metals because the metals are strongly bound to tailing particles[13].

Within the same research program field investigations in Repparfjord in Finnmark have been carried out to investigate environmental effects on earlier disposal from a copper mine which operated in the 1970s and to use the results to predict the environmental consequences coupled to the new operation by Nussir AS which has obtained a permit to dispose tailings in Repparfjorden.

A paper was published in 2017 on the impact of submarine copper mine tailing disposal from the 1970s on Repparfjorden (Sternal et al, 2017). They used sediment cores and they observed that the impact of tailings disposal is mainly restricted to the inner fjord where the discharge occurred. The inner fjord confined by a sill was a depo-centre for mine tailings. The mine-tailing sediments were found only in cores of the inner fjord along a ~1.5 km long transect.

Sediment cores retrieved from the inner fjord contained layers of mine tailings 9cm thick, 3–9 cm below the sediment surface. The mobility of Cu from buried contaminated sediments to the sediment-water interface in the inner fjord indicates that benthic communities have been continuously exposed to elevated Cu concentrations for nearly four decades.

The newly funded NFR project **"Disposal of mine tailings in Norwegian fjords and impacts on key ecosystem species" (DITAIL)** aims at study impacts of marine mine tailing disposal on pelagic ecosystem components in Norwegian

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[13] http://aktuelnaturvidenskab.dk/fileadmin/Aktuel_Naturvidenskab/nr-5/AN5-2017mineaffald.pdf

fjords: the copepod Calanus finmarchicus, a key species in the planktonic food web, and early live stages of Atlantic cod, a fish species of commercial interest[14]. Tailing particles, metals and processing chemicals and their impact on the pelagic ecosystem will be studied. Additionally, the plan is to develop biological models to predict to what extent mine disposal sites will have an effect on biological populations as well as developing physical models predicting tailings dispersal in fjords.

Research priorities and knowledge gaps.

As pointed out above three research programs initiated I Norway have been active during the period 2010-2018. All of them have been devoted to sea disposal of mine tailings to fjords and the ambition has been to fill gaps of knowledge and increase the general understanding of how STD works and the environmental risks and the size of footprints. Sea disposal is viewed as an alternative to land disposal where sea disposal is considered as the best technology to minimize environmental impacts. This implies that site specific conditions must be evaluated when choices of waste management alternatives are decided, and disposal permits are issued.

Results from the three research programs will enlarge the data bank and the level of knowledge which facilitates a better foundation for decision making. Additionally, the number of peer reviewed publications during the last decade has increased substantially, including several review articles on the subject which put things in perspective. During the last decade comprehensive monitoring programs, taking advantage of modern and sophisticated monitoring technology, contribute to increased knowledge and better opportunities to distinguish between natural and seasonal variations and manmade impact in the marine environment.

The knowledge gaps related to DSTP/DSTD are more obvious compared to STP/STD when it comes to the complexity of marine community structures and processes in the deep ocean (see Vare et al., 2018). The priority topics for future research have been selected based on discussions during the GESAMP/MITE-DEEP/INDEEP[15] workshop and post-workshop deliberations and include expert comments from a variety of scientific disciplines, industry and policy makers from broad geographical regions. Detailed consideration should be given to the following issues:

- Tailings dispersal in the water column: there is a need for better spatio-temporal physical oceanographic data to feed into more accurate models (e.g., data on shearing currents and plume generation) and ground-truthing of models.

- Engineering developments to change tailings behaviour (turbidity currents, plume generation) to reduce impacts.

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[14] https://www.nord.no/no/aktuelt/nyheter/Sider/Stort-miljoprosjekt-om-gruveavfall.aspx

[15] http://dosi-project.org/working-groups/tailings-placement

- Post-deposition behaviour of tailings: what are the potential physical (resuspension, slope failures) and chemical (reactions in water column and sediments) processes affecting deposited tailings and their components?

- Inventories of the materials being deposited: what is the nature of processing chemicals and what is their behaviour in different environments?

- Detailed faunal community studies: what is the composition and structure of benthic and pelagic fauna (using morphological and molecular tools)?

- Ecosystem function: what are the trophic relationships in the ecosystem? What benthic-pelagic coupling processes are found? What are the reproductive patterns of the key species and are they affected by tailings deposition? What microbial processes take place in the sediment? What ecosystem services derive from these functions and how can they be impacted by DSTDs?

- Effects on pelagic early life-history stages: what is the effect of plumes (particles and toxicity) on eggs, larvae and juveniles?

- Effect on recolonization and settlement: what are the different effects of varying grain size, organic matter content and grain shape/sharpness? What are the sensitivities of early life stages to mine-derived chemical contaminants?

- Ecotoxicity: although most EIAs include ecotoxicity tests, these are conducted on standard, shallow-water species, and the results may not be relevant to deep-sea species. There is an urgent need to develop similar analyses for deep-sea species, but the difficulty of collecting and maintaining deep-sea fauna alive in laboratory conditions continues to limit these studies.

- Evaluate cumulative impacts from different direct and indirect stressors.

- Identify thresholds to evaluate serious harm.

- Assess long-term fate of tailings in deep-sea ecosystems.

- Value deep-sea ecosystem services to provide the necessary information to managers assessing the cost-benefit of DSTD applications and deciding upon required compensation for lost services.

- Circular economy: further research is necessary in the reprocessing of tailings to extract value and minimize waste volume.

- Legislation and standard rules/guidelines for Good Practice: further rollout of guidelines for the use of DSTD.

The list of recommendation of research priorities worked out by GESAMP and presented in Vare et. al., 2018 are connected to deep sea, but are also partly relevant for coastal disposal of mine tailings.

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