

# **SUBMARINE TAILINGS DISPOSAL IN NORWAY'S FJORDS**

Is it the best option?

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## **Abstract**

The majority of worldwide mining operations use conventional, land-based containment type methods to manage their tailings. An alternative to land-based tailings storage is the disposal of tailings material at sea, in a practice known as Deep Sea Tailings Discharge or Submarine Tailings Disposal (STD). STD is undertaken in only a handful of locations worldwide, with a significant number of these in Norway's fjord regions. With the exception of Norway, STD has been largely abandoned by developed nations due to a combination of perceived environmental and reputational risk and restrictive regulatory conditions. STD is preferred over land-based tailings management options and justified in Norway due to a combination of climatic, topographical and cost issues. This study involved the use of multi-criteria analyses to compare STD and land-based methods against a range of sustainability criteria to assess if STD is really the best option for the management of tailings in this region. Results indicate that due to a combination of the prohibitive costs, impacts on aesthetics and potential for catastrophic accidents associated with land-based methods, STD does appear to be a preferable option. Further research is recommended to be shaped towards the broader question of whether mining in any sense is feasible and preferable in Norway's fjord regions, given its relatively minor importance to the Norwegian economy and its potential for deleterious effects on the fjord environment.

**Keywords:** Norway, mining, submarine tailings disposal, deep sea tailings deposition, environmental impacts

# Executive Summary

The process of mining for valuable commodities generally involves the separation of relatively minor amounts of the target mineral from its containing ore. The combination of overburden, waste rock and tailings in most instances comprises the vast majority of the total material extracted from a mine, and is greater than 99% for some precious metals. This material poses a number of environmental challenges both due to its sheer volume and potential toxicity. Accordingly, management of this material is recognised as the most significant environmental issue associated with any mining project.

In general, effective management of mine tailings aims for stabilisation, containment or otherwise minimisation of the environmental impacts that would eventuate from the direct deposition or release of raw tailings to the environment. The great majority of worldwide mining operations use some form of land-based tailings management containment method, such as a simple tailings dam, to achieve this. A much fewer number of mines undertake direct riverine discharge and a very minor number utilise a practice known as Deep Sea Tailings Deposition or Submarine Tailings Discharge (STD).

Compared to traditional, land-based, tailings management, STD has been less comprehensively studied and is not as well represented in the scientific literature. Additionally, STD has been largely abandoned in the global mining industry due to a combination of perceived environmental and reputational risk and restrictive regulatory conditions. A number of nations explicitly prohibit the practice of STD for mines operating within their borders and some of the largest mining companies in the world have standing policies to not use this method for tailings management.

A significant proportion of the total number of mines that utilise STD as a tailings management method are located in Norway's fjord regions. At the time of writing, at least five sites in Norway were undertaking STD to manage their tailings, with another three projects progressing through approvals to do the same. Norway is at present the only western nation using this method of tailings management. The prevalence of STD in Norway is thus an interesting practice given the predominant global attitude.

In addition to the general environmental concerns raised around STD, in the local Norwegian context there are also competing land uses and other stakeholders that may potentially be affected by this practice. Specifically, Norway's tourism and seafood/aquaculture industries are both heavily centered within the fjord regions. These industries are the second and third largest in Norway by percentage of GDP, and are both major 'brands' of the nation. Considering these issues, therefore, the purpose of this study was to assess if the practice of STD is really the most preferable option for tailings management in Norway's fjord regions. This research was guided by the following questions:

1. How do the costs and benefits of STD compare to those of land-based alternatives when sustainability criteria are included in the analysis?
2. Can STD still be considered a preferable option, for both industry and the Norwegian government, following such an analysis?

## **Research & Analysis Methods**

A wide range of literature was consulted for the general scope of this study, including scientific articles, journalistic pieces, consultant reports and publications prepared by governmental departments and other regulatory bodies. Deeper literature review focused upon the tailings management operations at each identified site in Norway as well as at a number of international locations. Published studies on the environmental impacts of STD operations around the world were analysed in detail to provide for a global context. Direct communications were also held with scientists at the Norwegian Institute for Water Research and the Swedish Agency for Marine and Water Management. Input from these sources contributed to the understanding of the potential environmental effects of STD in a Norway-specific context.

Multi-criteria analysis (MCA) has been used as the primary assessment tool for this study. MCA is a structured method of assessing decision alternatives against an identical range of well-defined evaluation criteria. The results of MCA indicate the extent to which decision options meet these criteria, and therefore it provides a basis for decision making or input data for further analysis. Two separate MCAs have been conducted for comparison in this study: one from the point of view of regulators or governments as decision makers and one from a perspective of mining companies as decision makers. Identifying the primary decision maker in an MCA is critically important as this influences the relative scores and weights applied to the chosen evaluation criteria, and in turn has a great bearing on the end results.

## **Justification for STD in Norway**

The case for STD over land-based solutions in Norway is most commonly justified in the literature due to a combination of the following:

Lack of suitable land - Ideally, surface storage facilities are constructed within natural depressions in land of relatively low relief. Mountainous or hilly land, of which almost the entirety of the Norwegian fjords could be described, is therefore not conducive to the economically feasible construction of surface tailings storage facilities

Minimisation of Acid Rock Drainage (ARD) – ARD is a common phenomenon resulting from the oxidation of sulphide bearing ores that are excavated and exposed to air and water during mining operations. Removing the source of oxygen or otherwise placing a physical barrier between the tailings and atmosphere is very effective in slowing or eliminating ARD. Disposal of tailings deep underwater, in an anoxic environment, is thus a very effective way to eliminate or minimise issues arising from tailings with acidic potential.

Aesthetics - Tailings management areas can often comprise up to one half of the total area of land disturbance associated with a mining operation. As most tailings storage facilities rise above the natural landscape, they can also be highly visible and interrupt views. Windblown dust can also be an issue. These aesthetic impacts of conventional tailings management facilities are largely avoided through STD, as extensive land areas are not required, the process does not result in artificially elevated (terrestrial) landscapes and dust and odour are not readily produced from material stored deep underwater.

Cost - Compared to land-based tailings management alternatives, such as tailings dams, initial capital costs for STD can be orders of magnitude cheaper. Beyond upfront costs, the long-term management costs of land-based solutions can be open-ended and may extend a liability on the mine operator for decades. By comparison, long-term STD management costs are near non-existent.

## ***Results of MCAs***

The results from both MCAs conducted for this study indicate STD is a preferred option in Norway when considering the specific range of evaluation criteria chosen. The case appears to be much stronger when considering these options from the point of view of mining companies, although the results for the MCA with regulators as primary decision makers also had the same, if less emphatic, result. Of interest are the handful of evaluation criteria which provided major contributions to the final scores. These criteria are largely similar for both MCAs conducted – specifically those relating to cost, aesthetics, long-term management considerations and the risk for catastrophic failure of land-based solutions - indicating that these are major issues for whoever is involved in the decision making.

## ***Reflections and recommendations***

As with any analysis, the end result is only as meaningful and robust as the data fed into it. While attempts were made in this study to provide relative quantifications of broad-ranging qualitative information, the figures used as input into the MCAs were open to bias and subjectivity at every step of the research. Future studies of this type would therefore be much improved by aiming to include as much robust, quantitative data as possible.

The results obtained from the MCAs do not indicate that STD is without its negative aspects. A number of cases studies around the world have identified various negative environmental impacts that must be managed. Further, the body of research on this practice is still relatively thin, and the deep waters and complex ecosystems of the Norwegian fjords provide a challenging environment to study and effectively monitor. It cannot be said yet if the practice, in an environmental sense, is inherently safe or inherently damaging. If it is to be accepted, however, that STD is the most preferred tailings management method at present the next question to be asked may be whether or not mining in this region is really a cost-effective process. Are the known and unknown risks of STD justifiably faced considering the relatively small size of the Norwegian mining industry and its contribution to country's GDP? Is it worth going against the near-blanket opposition to the practice in the western world and the potential for political fallout from doing so? These questions are recommended for the basis of further research.

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# 1 Introduction

## 1.1 Background

The process of mining for valuable commodities generally involves the separation of relatively minor amounts of the target mineral from its containing ore. The combination of overburden, waste rock and tailings in most instances comprises the vast majority of the total material extracted from a mine, and is greater than 99% for some precious metals. This material poses a number of environmental challenges both due to its sheer volume and potential toxicity. The safe and effective processing and/or containment of this material is therefore a major environmental management challenge for mining operations worldwide.

Tailings management refers to the further processing, containment and/or stabilisation of tailings materials as to prevent their direct and uncontrolled discharge to the surrounding environment (Department of Industry, Resources and Tourism, 2007). A number of different methods exist for this purpose, with the most suitable method for each application chosen based upon geology, geography, climate, local laws and cost. The majority of mines worldwide use conventional, land-based containment type methods to manage their tailings. These methods generally involve minimal processing but do require greater land areas and long-term management strategies. An alternative to land-based tailings storage is the disposal of tailings material at sea, in a practice referred to as Submarine Tailings Disposal (STD) or sometimes Deep Sea Tailings Placement (DSTP). STD is undertaken in only a handful of locations worldwide, with a significant number of these located within Norway's fjord regions (Figure 1).

Compared to traditional, land-based, tailings management, STD has been less comprehensively studied and is not as well represented in the scientific literature (Hammer, 2011). Additionally, STD has been largely abandoned in the global mining industry due to a combination of perceived environmental and reputational risk and restrictive regulatory conditions. A number of nations explicitly prohibit the practice of STD for mines operating within their borders and some of the largest mining companies in the world have standing policies to not use this method for tailings management (e.g. BHP Billiton, 2013).

The use of STD in Norway is thus an interesting practice given the predominant global attitude. In the local context, there are also a number of competing land uses and other stakeholders that may potentially be affected by STD. For example, Norway's massive aquaculture and seafood export industry is largely focused around the fjord areas, as too are a great proportion of its tourism 'hot-spots' (iGlobeTrotter, 2013). Therefore, given the combination of a) the relative global isolation of Norway with regards to this practice; b) the substantial knowledge gaps with regards to the environmental effects of this practice; and c) the existence of valuable industries within the same region that may be affected by STD, questions arise as to whether or not this method of tailings disposal is desirable for this region and if alternatives may provide for more sustainable outcomes.



Figure 1. Global STD locations.

## 1.2 Research questions

While questions of the type mentioned above have undoubtedly been considered previously by mine operators and regulators in Norway, this paper seeks to approach this issue from a broader perspective by considering a wide range of sustainability criteria inclusive of environmental, social and economic parameters. The following research questions thus guided the study:

1. How do the costs and benefits of STD compare to those of land-based alternatives when sustainability criteria are included in the analysis?
2. Can STD still be considered a preferable option, for both industry and the Norwegian government, following such an analysis?

## 1.3 Audience

This paper is intended to be useful for policy makers in Norway and other nations where STD may be considered as a management alternative for mining operations. This paper seeks to provide additional information on a number of sustainability issues which can often be overlooked or underrepresented in decision making. It is hoped that the findings presented in this paper will contribute to the debate on STD and stimulate further research into what is a largely underexplored issue.

## 1.4 Disposition

The outline of this paper is as follows:

- Section 1 introduces the topic, provides background on STD and poses the research questions which have guided this study.
- Section 2 details the research methods used to acquire the information used in the study.
- Section 3 provides a run-through of what tailings management is and outlines a number of commonly employed methods. This chapter also provides further detail on what exactly the practice of STD entails and some of common justifications cited by its proponents.

- Section 4 outlines the sustainability aspects associated with STD. Emphasis is placed upon environmental aspects and a number of case studies of environmental impacts attributed to STD are presented.
- Section 5 presents a summary of the Norwegian mining industry and the practice of STD as carried out at mines in Norway. This chapter also looks at how STD is rationalised in the Norwegian context, what other land uses compete with mining and STD practices and how STD in Norway fits within the local legal context.
- Section 6 briefly details the expressed views and policies on STD from a number of western nations and large international bodies. This chapter serves to provide the global context within which the Norwegian situation can be viewed and assessed.
- Section 7 comprises the core analysis for which this study was conducted. The alternatives of land-based tailings management and STD are compared and contrasted against a range of sustainability criteria by way of two multi-criteria analyses. The results of these analyses provide the data for discussion and analysis in Chapter 9.
- Section 8 presents an analysis and discussion of the results obtained from the multi-criteria analyses outlined in Chapter 8.
- Section 9 concludes this paper and poses additional questions for further research on the viability and cost-effectiveness of STD in Norway.

## **2 Research Methods**

### **2.1 Data collection**

Data collection for this study relied primarily on reviews of the existing literature and also some direct communication with stakeholders.

#### **2.1.1 Literature review**

Initial research was conducted through broad-based online searches with search terms including *submarine tailings discharge*, *deep sea tailings placement*, *STD*, *DSTP*, *Norway + mining*, and *Norway + fjord*. A number of scientific articles, journalistic pieces, consultant reports and publications prepared by regulators and other stakeholders were discovered in this manner. Via this method, the main actors and geographic locations for STD in Norway were identified and the understanding of these guided further literature review.

Deeper literature review focused upon the tailings management operations at each identified site in Norway as well as at a number of international sites, both those previously in operation and those currently in operation. Published studies on the environmental impacts of STD operations around the world were analysed in detail to provide for a global context.

#### **2.1.2 Direct Communications**

The costs and benefits of STD were discussed in communications with Mr Morten Schaanning, Research Manager at the Norwegian Institute for Water Research (NIVA). On the issue of mining and STD, NIVA is primarily involved in modelling, predicting and/or analysing any potential impacts from such projects in Norway. Mr Schaanning provided input as to the costs and benefits to be considered when assessing STD practices and also reviewed the assessment criteria used for the multi-criteria analyses conducted in this study.

The environmental impacts of STD were also discussed with Mr Bengt Fjällborg, Senior Analyst at the Swedish Agency for Marine and Water Management (SwAM). Mr Fjällborg is an ecotoxicologist who undertakes risk assessments for mines within Sweden and also has experience in risk assessment for process chemicals used in mining. Given the similarities between the geographical and political settings of Sweden and Norway, the discussions with Mr Fjällborg provided valuable input for the types and magnitudes of potential impacts associated with STD, with a focus on the impacts of process chemicals in the fjord environment.

### **2.2 Data Analysis**

#### **2.3 Multi-criteria analysis**

Multi-criteria analysis (MCA) has been used as the primary assessment tool for this study. MCA is a structured method of assessing decision alternatives against an identical range of well-defined criteria. The results of MCA indicate the extent to which decision options meet these criteria, and therefore it provides a basis for decision making or input data for further analysis. MCAs are particularly useful for assessing a wide range of criteria of different units, and especially those for which assigning a monetary value would be difficult or too subjective (World Bank, 2013).

The construction of the MCA for this paper largely follows the guidelines presented in the multi-criteria analysis manual prepared by the UK Government for use in government and wider community decision making (Dodgson, Spackman, Pearman, & Phillips, 2009). This

manual describes the basic MCA process in eight steps (Figure 2). The first seven of these steps were followed in the preparation of the MCA for this study. A sensitivity analysis was not undertaken.

1. Establish the decision context. What are the aims of the MCA, and who are the decision makers and other key players?
2. Identify the options.
3. Identify the objectives and criteria that reflect the value associated with the consequences of each option.
4. Describe the expected performance of each option against the criteria. (If the analysis is to include steps 5 and 6, also 'score' the options, i.e. assess the value associated with the consequences of each option.)
5. 'Weighting'. Assign weights for each of the criteria to reflect their relative importance to the decision.
6. Combine the weights and scores for each of the options to derive an overall value.
7. Examine the results.
8. Conduct a sensitivity analysis of the results to changes in scores or weights.

Figure 2. Eight steps of any MCA process (Dodgson et al., 2009).

For this study a qualitative approximation of a simple form of MCA, a linear additive evaluation model, has been used. The linear additive model was chosen as it has a well-established record in decision making (Dodgson et al., 2009) and provides for a simple analysis of alternatives in situations where criteria are mutually independent. A linear additive approach describes one in which parameters are scored, weighted and then added together to produce a single value for comparison. The methods used here are also influenced by the proposed MCA planning tools contained within the report *Impact assessments in the development of marine plans: Socio-economic impact assessment as part of a sustainability assessment in marine spatial planning* (Söderqvist & Hasselström, L. & Soutukorva, A., 2013), produced by the Swedish Agency for Marine and Water Management for the purposes of sustainability assessments in marine spatial planning in Sweden.

The SwAM model was considered relevant to the present study due to two factors. Firstly, there are clear geographical, climatic, political, legislative, environmental and socioeconomic similarities between Sweden and Norway which make the transposition of a model developed for one nation to the other a somewhat straightforward affair. Secondly, and importantly, the SwAM model takes into account, and applies appropriate emphasis to, the three domains of sustainability: economic, social and ecological/environmental. These three domains are what need to be explored in detail when attempting to answer the research question of the present study.

## 2.4 Limitations

The effectiveness of this study was limited by the following:

- Language – As the author does not speak Norwegian, translations of Norwegian documents produced by the main stakeholders was time consuming and often incomplete and imprecise. On occasions this prevented a deeper understanding of the material and restricted the literature review in parts to a superficial analysis.
- Access to company reports and costings – For an ideal MCA, full and accurate costings of every parameter would be available. As company costs for tailings management are sensitive information, however, these were not attainable from the mining companies practising STD in Norway.

- Use of qualitative data- the MCAs presented here make use of a range of qualitative data sources. Many pages of information from different sources have been assessed and eventually distilled into simple values for analysis. As such, the scores and weightings assigned are inherently subjective. This subjectivity inevitably means that others could assess the exact same data sources for the same purpose and arrive at different conclusions. The results in this paper are therefore to be considered with this in mind.
- Absence of a sensitivity analysis – A sensitivity analysis would usually be the final step of any MCA process, serving to test the robustness of the model and the sensitivity of the end results to changes in the input scores and weightings. This is a value-adding, but non-essential, part of the MCA process and has been omitted here.
- Experience and expertise in MCA - The study presented here is the author's first attempt at a structured multi-criteria analysis. Additionally, the MCAs presented here were undertaken solely by the author, and not by a group of people as is recommended in most of the literature. Accordingly, these MCAs are more subjective and not as robust as those that would be conducted by experienced people working in a group.

## 2.5 Scope

The scope of this study is limited in the following ways:

- Geographically - The primary focus is on mining operations which discharge tailings into fjords within the borders of Norway. These operations are then set within and compared to the international context of mining operations in other parts of the world
- Time - As the primary research questions of this study regard whether or not STD is a sustainable choice for Norway *at present*, the scope is limited to Norwegian mines that are either currently undertaking STD or have proposed to undertake STD and are currently progressing through the approvals stage. Again, former disposal locations and practices are also discussed to provide for context and comparison.



## 3 Tailings Management

### 3.1 Goals of tailings management

Management of mine tailings and waste rock is recognised as the most significant environmental issue associated with any mining project (Department of Industry, Resources and Tourism, 2007). In general, effective management of tailings aims to stabilise, contain or otherwise minimise the environmental impacts that would eventuate from the direct deposition or release of raw tailings to the environment. (Franks, Boger, Claire M. Côte, & Mulligan, 2011) outlined a number of principles for the management of mining and mineral processing wastes, succinctly describing the general aims or ideal results from tailings management as follows:

#### 3.1.1 Physical principles

The four physical principles or goals for which tailings management should aim for as identified by Franks *et al.* (2011) are:

- Stability - in the sense that tailings should remain physically stable and not eroded or otherwise degraded at an excessive rate.
- Inert - in the sense of ensuring tailings remain chemically inert and do not react excessively to produce undesired chemical compounds.
- Isolation - where tailings are effectively isolated from the surrounding environment, rather than integrated with it.
- Containment - similar to isolation, tailings are effectively contained within a designated area and do not migrate beyond designated containment boundaries.

#### 3.1.2 Local context and continuous improvement

Additional to the four physical principles described above, Franks *et al.* (2011) also identified a number of general management principles that are dynamic as according to the local situation where the tailings management will occur:

- Mine wastes should be managed within the specific social and environmental context of each location – this includes adapting management methods to be consistent with local regulations, climate, geography and social/community considerations.
- Mine wastes should be managed to minimise post-closure management.
- Techniques which provide for improved environmental / performance or minimised surface footprint should be preferred.
- Waste management should seek to minimise inputs such as water and energy.

### 3.2 Conventional & Historical Tailings Management Methods

To provide context against which to assess and compare the practice of STD, a selection of other methods and technologies used in tailings management are outlined briefly here.

#### 3.2.1 Tailings Dam

Conventional tailings dams are the most widely tailings management technique used in the mining industry. Dams are designed to contain waste material and isolate it from the surrounding environment. The basic structure of tailings dams consists of an earthen barrier, sometimes built of the tailings material itself, constructed across a natural or formed depression. Tailings from a mineral processing plant are turned into slurry of the required density through the addition or removal of water and then piped into the dam, with solids

fractions usually ranging from 25 to 50% (Department of Industry, Resources and Tourism, 2007). Once contained within the dam structure, tailings may be concentrated through natural evaporation of the water portion of the slurry and may also undergo chemical changes that result in stabilisation of the solid and aqueous components.

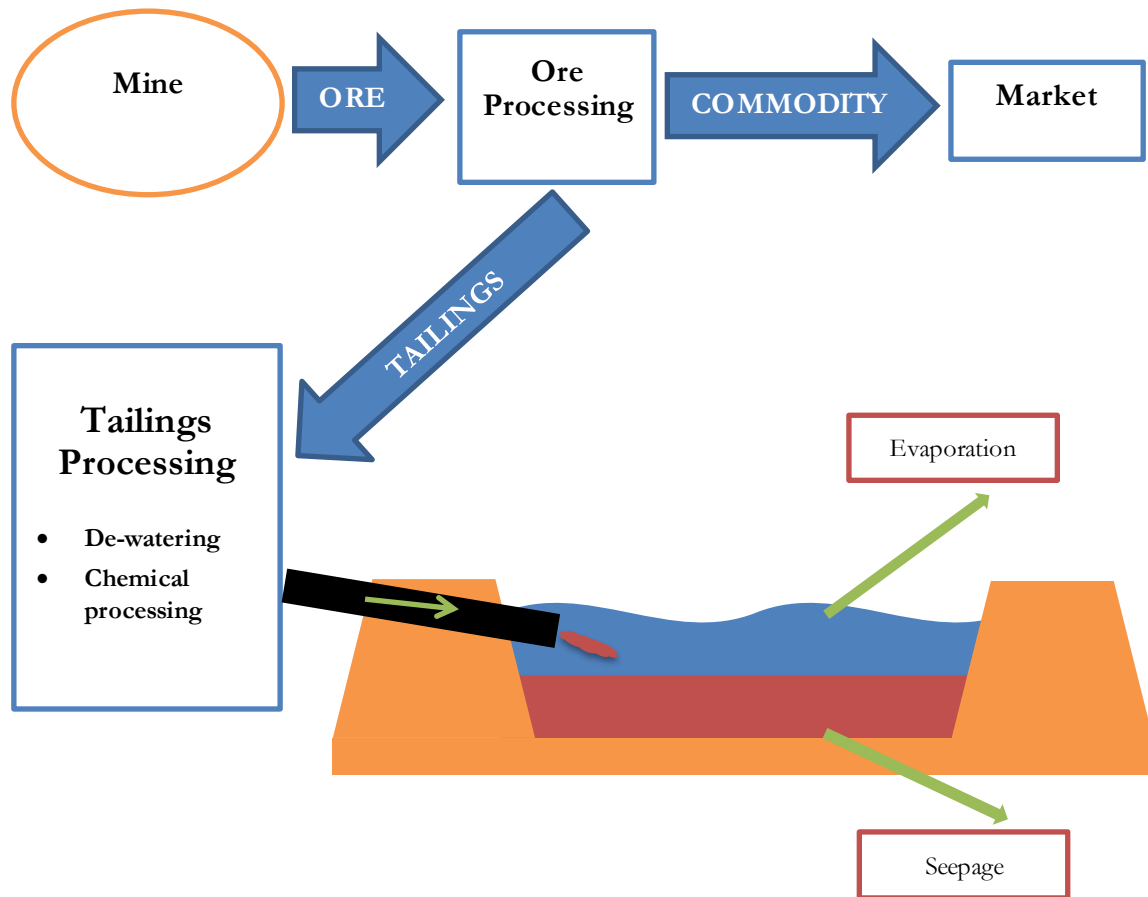


Figure 3. Simplified diagram of a typical tailings dam. Tailings are processed to slurries of varying consistencies and pumped to a containment pond. The pond largely contains the tailings although seepage outside of the structure is possible.

Erosion, leaching and the possibility of major dam wall failure are all serious management issues for conventional tailings dams. Each of these could potentially result in the uncontrolled release of tailings material directly to the surrounding environment. For these reasons, dams are most commonly employed in more arid environments, where rainfall volumes and intensity do not pose such a great risk (US Environmental Protection Agency, 1994).

### 3.2.2 Paste or thickened tailings

Paste or thickened tailings refers to tailings where a greater proportion of water has been removed prior to deposition in a tailings storage facility. Dewatering of tailings to a paste can more than double the solid fraction of a slurry, thereby improving tailings stability and greatly reducing volume and consequently the area of land required for disposal. Thickening tailings also reduces the risks of loss of tailings water and process chemicals through evaporation, leaching and overflow of a tailings storage facility (Department of Industry, Resources and Tourism, 2007). Thickened tailings can be disposed of in a conventional surface facility (i.e.

dam) or be returned to mine voids in-pit or underground. The return to mine option can improve long-term mine void stability and reduce or eliminate the need for additional land disturbance for a surface storage facility.

### **3.2.3 Riverine**

The earliest methods for managing tailings were largely characterised by the *absence* of real management – material was generally discharged directly into the surrounding environment. A common method was to flush material downstream from a mining site via a river or other waterway. Riverine disposal is very cheap to undertake and effectively removes tailings material from site, leaving little management concerns in the long-term. However, this method is largely out of favour on environmental grounds due to the resultant sedimentation and potential chemical contamination of downstream water bodies. Riverine tailings disposal is currently only undertaken at a handful of sites worldwide, although notably at the Grasberg mine in Indonesia, the largest gold mine in the world (Vogt, 2012).

## **3.3 Submarine Tailings Disposal (STD)**

Like riverine disposal, ocean disposal of tailings has been practiced for as long as mining has existed, with the most rudimentary methods (shallow disposal) involving the direct dumping of tailings and other wastes in a near shore environment. Shallow dumping methods have been largely phased out in recent times and have been replaced by more sophisticated disposal of tailings at depth. This type of managed deep water disposal is what is most accurately characterised as STD or DSTP (Vogt, 2012). Modern STD practices aim to deposit tailings at a sufficient depth as to prevent mixing with the water column above. Most commonly, this involves discharging material below a thermocline (temperature boundary), halocline (salinity boundary), pycnocline (density boundary) or other cline that represents distinct stratification.

STD practices typically involve the processing of tailings material into a de-aerated slurry which is then piped to the disposal site. Additional processing steps may include the use of chemicals to improve particle flocculation and flotation and the mixing with seawater to increase density and increase the rate of settlement at the deposition location. The exact type of processing methods used will depend upon the nature of the ore and tailings being managed, local geographical/climatic conditions and the local regulatory environment.

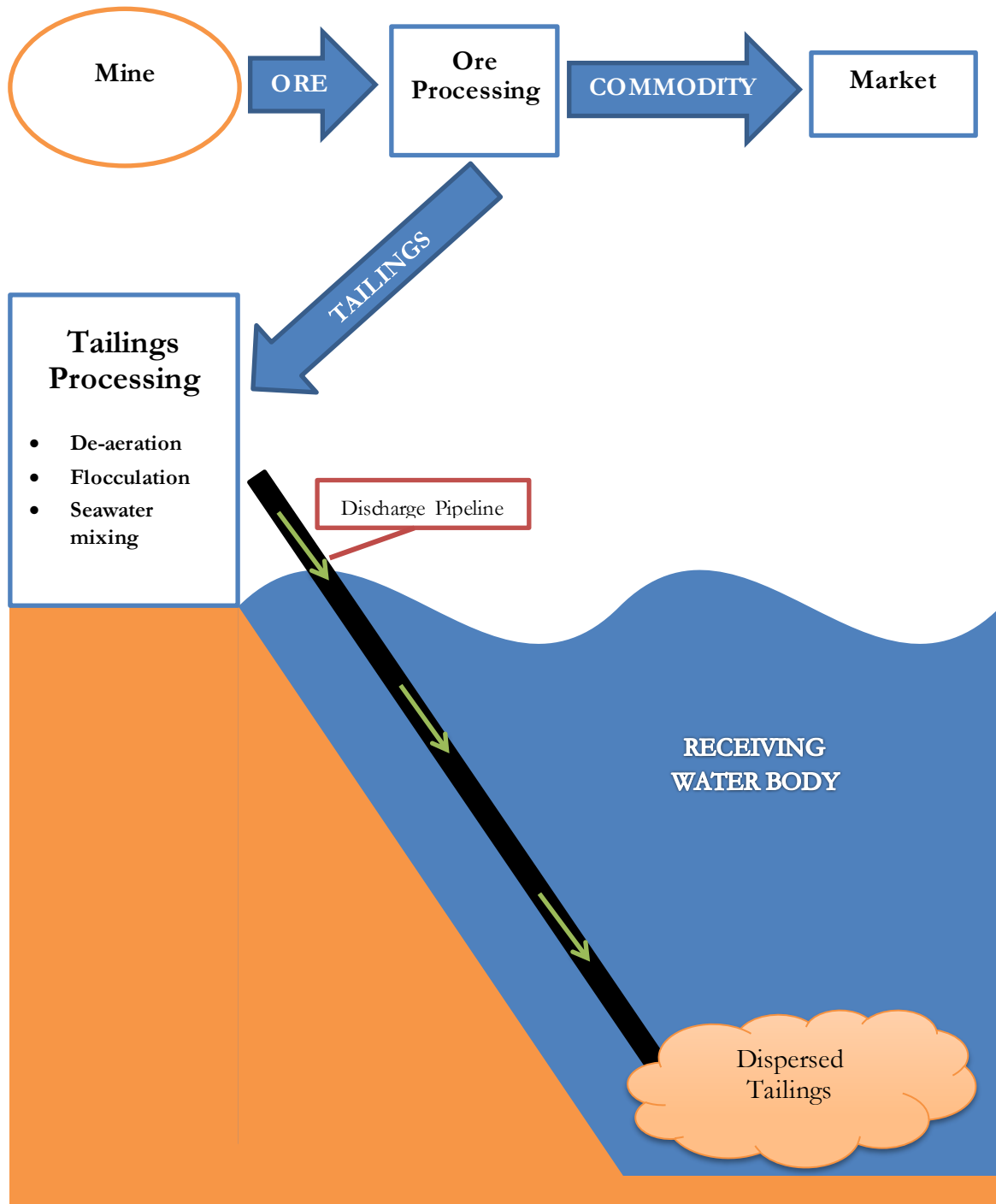


Figure 4. Simplified diagram of submarine tailings disposal. Once the target commodity is separated from the mined ore, tailings are further processed and piped below the sea surface for disposal.

### **3.3.1 Justification for STD**

Other than on an economic basis, where STD is generally considered a cheaper option than land-based tailings management in many instances, the practice of submarine discharge is commonly justified on a combination of physical management principles. The four most important of these are described below.

#### ***Seismic concerns***

In areas of high seismic activity, the integrity of land-based tailings storage facilities is less sure. Seismic events can result in the failure of containment structures and the subsequent catastrophic uncontrolled release of tailings material. Regions such as Indonesia and Papua New Guinea are particularly seismically active and this is cited by mine operators as a primary reason for undertaking STD (or riverine discharge) in this area (e.g. Newcrest Mining Limited [2013]; PT Newmont Nusa Tenggara [n.d.]).

#### ***Lack of suitable land areas***

Construction of a surface tailings storage facility can require a large amount of available land, which may often be a larger area of land disturbance than the mine for which it is constructed (Department of Industry, Resources and Tourism, 2007). Ideally, surface storage facilities are constructed within natural depressions in land of relatively low relief. In the absence of natural depressions, containment areas can be excavated and/or surrounded by earthen barriers. Regardless, relatively flat land is required for this purpose. Mountainous or hilly land is therefore not conducive to the economically feasible construction of surface tailings storage facilities as doing so would likely require extreme amounts of earthworks to create a suitable site.

#### ***Acid Rock Drainage***

Acid Rock Drainage (ARD), sometimes referred to as Acid Mine Drainage, is a common phenomenon resulting from the oxidation of sulphide bearing ores that are excavated and exposed to air and water during mining operations. Whereas these sulphide minerals exist in a non-reactive state prior to excavation, the exposure to oxygen and water during mining activities results in rapid oxidation and production of sulphuric acid, with these reactions often catalysed by acidophilic bacteria (Western Australia Department of Mines and Petroleum, 2009). The resulting acidic runoff or leachate has direct impacts on surrounding biota and ecosystem processes due to its low pH. Additionally, heavy metals may be more readily mobilised from the surrounding rock and transported to a receiving body (lake, ocean, groundwater) where their increased concentrations can induce negative environmental impacts (European Commission, 2009)

As the primary cause of ARD is the exposure of sulphide ores to oxygen, removing the source of oxygen or otherwise placing a physical barrier between the ore and atmosphere is very effective in slowing or eliminating ARD. Disposal of tailings deep underwater, in an anoxic environment, is thus a very effective way to eliminate or minimise issues arising from tailings with acidic potential. In addition to the exclusion of oxygen in this environment, sulphate-reducing bacteria present in the ocean also immobilise metals present in the tailings (Kvassnes, Sweetman, Iversen, and Skei, 2009).

#### ***Aesthetics***

Tailings management areas can often comprise up to one half of the total area of land disturbance associated with a mining operation (Department of Industry, Resources and Tourism, 2007). As most tailings storage facilities rise above the natural landscape, they can also be highly visible and interrupt views. Tailings facilities are also prone to producing dust

and odours. These aesthetic impacts of conventional tailings management facilities are largely avoided through STD, as extensive land areas are not required, the process does not result in artificially elevated (terrestrial) landscapes and dust and odour are not produced from material stored deep underwater. The relative importance of aesthetics for tailings management decisions depends upon the location of the mine and local context: aesthetics are more important where mines are situated in proximity to populated centres or wilderness areas where maintaining a natural environmental state is desired and less important in unpopulated or seldom visited areas.

## 4 Sustainability Aspects of STD

Society is dependent upon mining for the extraction of raw materials that are used in the production of goods and infrastructure for almost all sectors of a modern economy. Mining also provides employment and sustains local communities, with many examples existing of mining being the sole or primary employer of a region (World Bank, 2003). As an extractive process, however, mining can also contribute to environmental degradation and other alterations to natural systems that can have negative social consequences. Effective management of a mining operation therefore needs to balance all sides of the sustainability equation – economic, social and environmental – in order to facilitate the production of these essential resources with due regard to all of its intertwined sustainability aspects. STD, as a component of mining therefore has its own set of sustainability aspects that must be considered.

This chapter outlines the main sustainability aspects associated with STD. As environmental issues comprise the majority of sustainability-related concerns highlighted in the literature with regards to STD, this realm is covered more extensively here than economic and social aspects. Additionally, as environmental considerations are such a widespread and major part of the STD sustainability equation, they are dealt with here in a generic sense. Economic and social aspects are described as they pertain to the specific Norwegian situation. The sustainability issues discussed herein form the basis of the evaluation criteria used for the MCAs in the analysis section of this paper.

### 4.1 Economic

Mining can be a highly profitable industry. In most cases, profitable industries are favoured by governments and communities for the employment and revenues they provide. In order to maximise profitability, costs must be kept as low as possible and therefore regulatory environments are commonly engineered to facilitate this. Considering STD in Norway's fjords therefore, it can be seen that there is a direct incentive for support to be given to the practice as it has been shown to be many times cheaper than alternative methods of tailings management (see 5.3). Taking a simplistic economic approach to the issue would therefore understandably show STD as a clear choice; providing better outcomes for companies, governments and communities.

However, as economic issues are rarely this simplistic, other impacts must be considered here. The primary issue of importance is the need to consider other land uses in the area which may be affected by a choice of STD as a management method, and how those effects translate into economic costs or benefits. Norway's fjord regions also support the country's second and third largest export industries – tourism and fisheries/aquaculture – and these industries must be considered as part of any decision making process regarding mining practices that may impact on them. One clear example is the impact mining and tailings management may have on the visual amenity and other aesthetic values of an area of fjord also used for tourism purposes. Would these industrial processes detract from the natural-tourism experience to an extent that tourism revenues would be affected? Such questions, which go beyond the immediate appraisal of direct economic costs and benefits, form the core of assessments focusing on the full suite of sustainability aspects.

### 4.2 Social

The social aspects of STD can be linked to both the economic and environmental issues also described here. Community perceptions of an industrial practice, such as mining with associated STD, are directly linked to the actual or perceived environmental and economic

effects of such an operation. The development of a mine can bring economic benefits to a local community, which may in turn assist the funding of other community infrastructure, but it can also lead to cultural and environmental degradation. If such negative impacts are perceived by a community this can lead to social tension (International Institute for Energy and Development, 2002).

Mining has a long history in Norway's fjord regions, with some sites operating near continuously for over 100 years (e.g. the Sydvaranger iron ore mine). The practice of STD has a similarly long history. It could be argued therefore that local communities in these regions are already accustomed to the practice and are accepting or at least not strenuously opposed to this form of industry. The potential for social impacts in Norway exists mainly in association with possible land use conflicts, which in turn influence economic and environmental outcomes. The concept of net-community benefit is an important consideration here, as referred to by the IIED (2002):

*"...for mining to contribute to the goals of sustainable development at the community level, it must provide a net benefit to the affected community",*

Put simply, a community may be willing to accept some form of environmental degradation or impact on culture if net benefits are perceived to be positive overall. It can be deduced from this that once a community perceives that a net benefit is not being reached, and negative consequences (e.g. environmental and social) are outweighing positive consequences (i.e. economic) social tension is bound to rise. For the Norwegian context, effects on net community benefits are primarily linked to aesthetics and to the other main competing land uses: nature-based tourism and fisheries/aquaculture. If a mining operation's tailings management method has a real or perceived impact on aesthetics or on these other industries the social impacts on the region begin to increase.

### 4.3 Environmental

A review conducted by Vogt (2012) analysed the existing literature on the environmental impacts of STD and summarised the most likely potential impacts as follows:

1. Smothering benthic organisms and physical alteration of bottom habitat
2. Reduction in species composition/abundance and biodiversity of marine communities
3. Direct toxicity of trace metals mobilized from mine tailings
4. Bioaccumulation of metals through food webs and ultimately into human fish-consuming communities, and corresponding increases in risk to human health.

These environmental impacts of STD are relatively less well understood than the impacts of terrestrial or riverine tailings management methods. This is partly attributable to the understanding of benthic ecosystems and deep ocean processes, which are themselves comparatively less known to science than pelagic, near-shore or terrestrial systems. Additionally, the abundance of conventional tailings storage facilities in past or present operation has provided an immense amount of data for the understanding of the environmental impacts of tailings disposal on land. The relative dearth of in-depth, long-term and unbiased studies on the impacts of STD is one of the main reasons this method is considered by some to be not preferred on environmental grounds (e.g. World Bank, 2003).

In addition to the general, and possibly inevitable, effects of STD as described by Vogt there is also the potential for accidents and catastrophic movement or releases of tailings. The two greatest concerns are for discharge pipe failures, resulting in uncontrolled release, and large mass wasting events from disposal sites. Such mass wasting is characterised by sudden slips or



breakaways of large volumes of tailings material and consequential migration outside of the intended discharge zone (Kvassnes, Sweetman, Iversen, and Skei, 2009).

To discuss these identified impacts further by way of example, a selection of case studies documenting a range of experiences with STD and associated environmental impacts are presented in the following chapter. These case studies have been chosen to provide a broad overview of experiences with STD to date, and thus cover a range of geographical locations, commodities and observed impacts.

## **4.4 Case Studies of Environmental Impacts**

### **4.4.1 Amax Molybdenum – Kitsault, Canada**

#### ***Overview***

The Amax Molybdenum mine at Kitsault, located in north-west Canada, discharged mine tailings into the surrounding marine basin during the period 1981-1982. Tailings were discharged at the head of a body of water known as Alice Arm, a drowned glacial valley similar to many other coastal features in the region. Over the period STD was undertaken, approximately 12000 t of tailings were discharged via pipe at a depth of 50 m. Prior to 1981, tailings from the mine were disposed of in rivers or onto intertidal areas.

#### ***Observed Impacts***

A study by Odhiambo, Macdonald, OBrien, Harper, & Yunker (1996) focused on the analysis of sediment cores from within Alice Arm and surrounding and interconnected inlets. Findings from the study indicated that sediment impacts, measured via heavy metal concentrations (cadmium, lead, zinc), were observable throughout the entirety of the Alice Arm inlet, though decreased from head to mouth. These findings were compared to other non-STD tailings disposal sites in the vicinity of Alice Arm, where sediment and metals migration was much more dispersed. The study concluded that the STD technology used by the Amax mine “...appears to have been effective in containing most of the tailings and their associated metals within Alice Arm.” The majority of tailings were found to be contained within 10-15km of the disposal site.

### **4.4.2 Cayeli Bakir copper-zinc mine - Rize, Turkey**

#### ***Overview***

The currently operating Cayeli Bakir copper-zinc mine located at Rize, in north-eastern Turkey, discharges mine tailings to the Black Sea at a depth of 350 m at approximately 3.5 km offshore. A study by Berkun (2005) focused on the potential for tailings plume separation and upwelling above the disposal depth. Berkun used oceanographic sampling combined with laboratory experimentation in a water tank to determine plume dispersal characteristics. The findings indicated a worst-case potential for plume separation and upward movement of fine particles up to 89 m above the 350 m discharge depth. This was considered to be acceptable as this region was within the deep anoxic zone and still deeper than the permanent pycnocline existing at ~ 150 m.

### **4.4.3 Lihir Gold Mine – Papua New Guinea**

#### ***Overview***

The Lihir Gold Mine, located on Lihir Island in Papua New Guinea, has deposited overburden and tailings slurry into the ocean around the island since 1997. Overburden is

deposited in near shore ravines by barge while tailings are piped offshore at a depth of 128m. Being part of a volcanic island group, the seafloor slopes steeply away from the island and reaches depths of a few kilometres a short distance offshore. This gradient is thus exploited as tailings are deposited with the expectation of downhill migration towards stable zones on the seafloor. Approximately 100 000 ML per year of tailings are disposed of in this manner (Brewer *et al.*, 2007).

### **Impacts**

Brewer *et al.* (2007) studied the impacts of tailings deposition around Lihir island on several species of deep-water fish. Species abundance and concentrations of trace metals in tissue were compared between fish in proximity to the tailings disposal areas and fish populations from control (unaffected) areas. The study concluded that there appeared to be impacts on the populations of fish close to the mine, with significantly fewer fish captured close to Lihir, compared with the control areas. Studies of trace metal concentrations in fish tissue did not indicate significant contamination that could be linked to the tailings.

#### **4.4.4 Tellnes titanium mine - Jøssingfjord, Norway**

##### **Overview**

Jøssingfjord, situated in southern Norway, was used as a disposal site for tailings from the nearby Tellnes titanium mine from 1960 to 1994. Initially, mine tailings were dumped in shallow water (~85m) and then later at an alternative site with depth of greater than 100m (Olsgard, & Hasle, 1993)

The volume of waste dumped at the initial site resulted in a reduction in average water depth from 85m to 30-40m, and this coupled with observations of tailings spreading beyond the immediate disposal site precluded the decision to seek an alternate location. Tailings disposed of at Jøssingfjord were composed of fine mineral particles of feldspar, pyroxene and limonite, and small amounts of flotation chemicals in a seawater slurry (Olsgard, & Hasle, 1993).

##### **Impacts**

(Olsgard, & Hasle, (1993) researched the effects of tailings discharged into Jøssingfjord during 1983-1988 on the health and abundance of benthic fauna at varying distances from the disposal site. The study found that the biological impact of tailings varied over time and distance. Significant reductions in species diversity in highly disturbed sites were observed during the study period, while monitoring sites 2-3km from the primary deposition area did not exhibit significant species diversity reductions. Within one year of the conclusion of tailings deposition at the site, recolonisation of benthic fauna was observed, and within four years all of the primary or indicator benthic organism groups were represented.

#### **4.4.5 Black Angel lead-zinc mine - Maarmorilik, West Greenland**

##### **Overview**

The Black Angel lead-zinc mine located in Maarmorilik, West Greenland, operated between 1973 and 1990. During this period mine tailings were disposed of directly into the fjord areas adjacent to the mine. The fjord system into which the tailings were dumped is part of the greater Ummannaq fjord complex. Tailings were disposed of directly into the Affarlikassaa fjord, which is partly enclosed and originally had an average depth of 30 m. The Affarlikassaa fjord is connected to the larger Qaamarujuk fjord, which although was not used for direct tailings disposal, did experience spill-over impacts from the Affarlikassaa fjord (Søndergaard,

Asmund, Johansen, & Rigét, 2011). Approximately 600 000t of tailings were deposited into the fjords each year during the mine's operating phase (Perner *et al.*, 2010).

### **Impacts**

Tailings deposition from the Black Angel mine resulted in significant increases in metals concentration in the receiving water bodies. In particular, lead and zinc concentrations were hugely elevated during the mine's operational period and remained so for some time afterward (Søndergaard *et al.*, 2011). The concentration of metals in seawater decreased significantly after the closure of the mine; however, concentrations of lead and zinc in sediments and biota remained high for decades following closure. Søndergaard *et al.* (2011) studied populations of mussels located up to 12km from the tailings disposal site in 2009 (20 years after closure) and detected highly elevated tissue concentrations of lead and slightly elevated levels of zinc. Elevated metals concentrations were also detected in algae. The authors concluded that these results indicated a slow response and recovery rate of arctic fjord systems to contamination from mine tailings. The example of the Black Angel mine is commonly cited in literature in demonstration of the potential long-term environmental impacts of STD (e.g. Josefson, Hansen, Asmund, & Johansen, [2008]; Perner *et al.* [2010]; Elberling, Karen, Peter, & Asmund [2003]).

## **4.4.6 Alaska-Juneau gold mine: Alaska, United States**

### **Overview**

The Alaska-Juneau gold mine in the north-western United States considered STD as an option when the mine was to be reopened in 1996, following a period of inactivity. A special exemption was given to the operators of the mine to consider this alternative, as the policy of the United States EPA was and is to not permit STD. Given the special exemptions surrounding this case a number of intensive studies were undertaken to attempt to characterise and predict the effect of STD from the Alaska-Juneau mine on the receiving water bodies.

### **Laboratory Studies**

One such study by Johnson, Rice, & Moles (1998) focused upon the effects of STD on benthic fishes, particular the yellowfin sole. Johnson *et al.* carried out tank experiments in the laboratory to test the behavioural and health (survival, growth and metals accumulation) effects of different bottom substrates (fresh tailings, weathered tailings and natural sediment) on juvenile sole which had been wild captured and transferred to the experiment tanks. Fresh natural sediment (the reference sediment) was collected from an undisturbed control location within the vicinity of the mine, simulated fresh tailings were created within a pilot plant and weathered tailings were gathered from the tailings disposal site of another nearby gold mine that had operated 75 years prior.

The results from the study by Johnson *et al.* showed that juvenile sole consistently avoided the fresh, un-weathered tailings. The weathered (75+ years) tailings were preferred over the fresh tailings and the natural sediment was preferred most overall. Fish held over fresh tailings substrates did not exhibit significant increases in metal concentrations in tissues, with the exception of lead and chromium. Lead and chromium tissue concentrations for fish held in tanks over fresh tailings were two to six times higher than background levels. Fish held over fresh tailings were also observed to grow at a slower rate than fish over natural sediment. This, however, was observed only for the first half of the observation period; growth rates equalised

during the rest of the experiment. The authors concluded that tailings deposited in the marine environment from the Alaska-Juneau mine were likely to result in short term avoidance (local population reduction) and short term growth rate reduction in yellowfin sole. The results associated with the weathered tailings indicated that effects of STD on benthic fishes should decline over time as the tailings are gradually weathered, diluted and covered by natural sediments.

In another study, Kline & Stekoll (2001) tested the probable colonisation response of benthic invertebrates following STD. The study involved the underwater placement (at 21 m depth) of trays of natural, defaunated sediments and tray of simulated tailings from the Alaska-Juneau mine for the purpose of observing the recolonisation of these substrates by invertebrates. The trays were removed, and core samples of the surrounding natural sediment were taken at 9, 17 and 22 months and the abundance, biomass, and biodiversity of the invertebrates present was determined.

Kline & Stekoll's (2001) study on the recolonisation of tailings found no statistically significant differences in biomass and biodiversity between the simulated gold tailings substrate and the reference sediment, however, both were observed to be different from the ambient substrate. The authors concluded that the recolonisation of sediments by benthic invertebrates should not be inhibited by the presence of tailings from STD, following the conclusion of active deposition.

#### **4.4.7 What do these case studies demonstrate?**

The case studies presented here have been deliberately chosen to represent a wide range of geographies, climates, resource-types and political/regulatory situations. One thing that can be observed from this mixed collection of studies is that experiences with STD and the magnitude of any potential associated environmental impacts are locally determined. What occurs in one part of the world at one particular mine and STD site is likely to not be 100% analogous to another site in another location, regardless of how superficially similar they may seem. Geology, topography, bathymetry (underwater topography) and other oceanic characteristics influence the fate of underwater tailings, and countless other variables also come into play on-land and in the ocean.

These case studies also show that STD has been successfully undertaken in some instances with minimal adverse environmental effects and then conversely in other instances with extensive environmental impacts. Relating these cases to the Norwegian context must therefore be done with this in mind; these examples do illuminate a range of possible outcomes from undertaking STD but are unlikely to accurately describe any potential impacts in Norway in totality.

## **5 Mining and STD in Norway**

### **5.1 Mining Industry Overview**

The Norwegian mining industry is a comparatively small part of Norway's economy. The metals and mining industry is valued at EUR 2.2 billion, representing 0.6 % of GDP (MarketLine, 2012). Aluminium extraction and processing accounts for more than 70 % of the industry's total value, with iron, coal, base metals and aggregates representing the remainder. Substantial growth is forecast for the next few years in this sector, following a recent period of contraction.

### **5.2 STD in Norway**

#### **5.2.1 Overview**

As of 2013 there are five mine sites in Norway undertaking marine disposal of tailings and other geological wastes such as overburden and waste rock (Figure 5). At least three further sites have been proposed and are under consideration. More than 20 other sites in Norway have been used for STD in the past but have since either ceased the practice or have been decommissioned. Unlike many other contemporary examples of STD, marine tailings deposition in Norway occurs at relatively shallow locations, with disposal depths in the fjords ranging from as shallow as 30 m to over 400 m. Deposition in Papua New Guinea, Indonesia and Turkey, by comparison, occurs at depths greater than 1 km.

This section describes a number of currently operating and proposed STD sites in Norway. Where available and relevant, selected summaries of observed environmental impacts and/or similar studies are presented. It should be noted that this is not an exhaustive list of all current or proposed mines with associated STD. A number of other projects were researched but are not included here due to either their relative small size and consequently potential impacts, a lack of sufficient data, difficulties with language translation or a combination of these factors.



Figure 5. Locations of Norwegian STD operations discussed here.

## 5.2.2 Currently Operating STD Locations

### **Bøkfjorden**

The Sydvaranger iron mine, located nearby Bjørnevatn and Kirkenes the far north of Norway, is operated by Sydvaranger Gruve AS, which is itself a subsidiary of the Australian listed Northern Iron Ltd. In 2009, production of iron concentrate was restarted after being halted in 1997 after near-continuous operation since 1907. Sydvaranger Gruve dispose of up to 4 million tonnes of tailings per annum (this figure being the licensed maximum) into the nearby Bøkfjorden. Along with these tailings, the company is permitted to dispose of 35 tonnes of flocculation agents used in processing. Tailings are deposited at a depth of 28m and approximately 450 m offshore. Tailings are first thickened, mixed with seawater and de-aerated (Vogt, 2012).

The Norwegian Institute for Water Research (NIVA) conducted a study in 2010 on the effects of these tailings on the marine environment in Bøkfjorden. These studies analysed turbidity, toxicity of the flocculant chemicals (Magnafloc), and the impact of changing sediments on benthic fauna. The study found that there were discernible environmental impacts from tailings up to 10km from the discharge point. Effects on organisms were mixed depending upon soft- or hard-bottom adaptations, depth and distance from the disposal site. An identified toxic component of the flocculation chemicals used at the mine, acrylamide, was not detected in samples (Skotte, 2011).

Sydvaranger Gruve AS currently have an application lodged with the Norwegian Climate and Pollution Control Directorate (KLIF) to double production capacity at the Sydvaranger mine. Doubling of production will result in a similar increase in tailings volumes disposed of in Bøkfjorden. Additionally, the increase in production is to require the use of a new flocculation chemical identified as Lilaflot, which was previously used at the mine prior to 1997 (Sydvaranger Gruve AS, 2010). Fosså et al. (2009) have advised the Norwegian government

against approving the application for Sydvaranger on the grounds that Lilafloet is a known toxic chemical with potential for bioaccumulation. Additionally, they describe Bøkfjorden as already being a strongly modified water mass that has been impacted by the previous deposition of mine tailings and process chemicals.

### ***Ranafjorden***

Ranafjorden, located in northern-central Norway, is a deep fjord of 540m which has had a long association with mining and mine tailings. Mining has occurred in the vicinity of Ranafjorden since the beginning of the twentieth century, with tailings deposited into the fjord for the majority of this time (Skei & Paus, 1979). Currently, Rana Gruber AS operate the Kvannevaan iron ore mine and associated satellite mines in the Dunderland valley, near Mo i Rana. Until 1999, the deposits were mined via open-pit extraction, though now underground methods are also used (Rana Gruber AS, 2013). Approximately two million tonnes of tailings are currently disposed of into the adjacent Ranafjorden each year at a depth of about 80m (Vogt, 2012).

### ***Frænfjorden***

Omya Hustadmarmor operates a number of marble (calcium carbonate) mines in the region around Elnesvågen, on Norway's mid-west coast. A processing plant at Elnesvågen grinds and sieves the marble resource and produces a product ready for direct shipping (Hustadmarmor AS, 2013). The resulting calcite tailings (approximately 500 000 tonnes per annum) are disposed of via STD into the nearby Frænfjorden. Tailings have been deposited here since the start of the 1980s, and monitoring of environmental impacts has been conducted for a similar amount of time (Amundsen, 2009). Monitoring results indicate that marine sediments in the area are able to self-restore to a similar condition within short periods of time following cessation of tailings disposal (Vogt, 2012).

## **5.2.3 Proposed STD Locations**

### ***Repparfjorden***

Nussir ASA control a large and as-yet undeveloped copper deposit in northern Norway, close to the town of Hammerfest. Although discovered in the 1970s, the mineral deposit has not yet been commercialised. Current activities include further exploration drilling and the development of mine scheduling and management plans, with a view to commence production operations in 2015/2016 (Nussir ASA, 2012). The company has applied to the Norwegian Climate and Pollution Agency for a permit to discharge tailings into the adjacent Repparfjorden. Tailings volume would be in the region of 2.1 million tonnes per annum and would be mixed with seawater and de-aerated prior to disposal at a depth of 50-60 m. The tailings would contain a number of processing chemicals, including Magnafloc (Nussir ASA, 2012). According to Vogt (2012), previous mines operating in the region have disposed of tailings to Repparfjorden in the past.

### ***Førdefjorden***

Nordic Mining ASA are in the late development stages for what would be one of the world's largest rutile (a titanium bearing ore) mines when operational. The proposed mine will be centred around the Engebø deposit, located near Førdefjorden on the south-west coast of Norway. The proposal outlines plans for a 50 year mine life, with the initial 15 years consisting of open-pit production and the following period characterised by underground mining. Nordic Mining has applied for approval to dispose of 3 million tonnes of tailings per annum during the open-pit period and 6 million tonnes of tailings per annum during the underground period. Flocculants and process chemicals will also be discharged with the tailings. Over the

life of the mine, approximately 250 million tonnes of tailings, 150 000 tonnes of process chemicals and 500 tonnes of flocculants will be discharged (Vogt, 2012). The proposed disposal site is a location within Førdefjorden at a depth of 300m. Modelling conducted by Nordic Mining has indicated that impacts from the tailings deposition should not extend beyond 100m depth (Fossum, 2009).

### **Sandsfjorden**

Norsk Stein have applied for approval to dispose of mine tailings into Sandsfjorden near Jelga in south-west Norway. No further information as to the status of this application was found during the research period.

## **5.3 Rationalisation of STD in the Norwegian context**

A number of grounds are commonly cited for the justification or rationalisation of STD over other forms of tailings management. These were referred to in the generic sense in 0 and are again presented here as they specifically pertain to the Norwegian context.

### **5.3.1 Available land**

Lack of suitable land areas in Norway's mountainous fjord region is most often identified as the single most important driver for the use of STD in this area. The region is almost exclusively of high and varied relief, making the construction and management of a land-based tailings facility extraordinarily difficult and costly.

### **5.3.2 Cost**

Cost is perhaps the most obvious justification for the use of STD in Norway. Compared to land-based tailings management alternatives, such as tailings dams, initial capital costs for STD can be orders of magnitude cheaper. By way of example, it is estimated that the cost to construct a tailings impoundment facility at the Nussir mine would approach EUR 182 million, compared to EUR 1.8 million for the proposed submarine discharge (Nussir ASA, 2011). As mentioned previously, even within non-mountainous areas with suitable land available for conventional tailings management, which facilitates fewer upfront capital costs, STD is usually still a cheaper alternative. This is mainly due to the ongoing management costs associated with ensuring tailings storage facilities are operating as designed and are stable. This ongoing management can be required beyond the life of mine, leaving operators with a financial burden.

### **5.3.3 Environmental considerations**

Fewer and/or less damaging environmental impacts are sometimes cited as a reason for undertaking STD in preference to land-based tailings management. A quote from (Amundsen, 2009) demonstrates one such argument:

*“Why do we then have the feeling that borrowing the sea bed for some years are of much grater (sic) importance then destroying the land areas forever? The marine environment offers a grate (sic) potential of recolonisation and recovering.”*

Unlike the other factors discussed here, this environmental argument is not one that is widely apparent in the literature pertaining to STD around the world, being a specific rationalisation used in the Norwegian context.



## 5.4 Competing Land Uses

The primary alternate land uses in Norway's fjord regions that may be affected by STD are fisheries (both wild and cultured) and tourism. Both of these industries are growing and are very important to the Norwegian economy, providing for diversification beyond petroleum. Some agricultural land exists around the fjords though the area covered is relatively minor and is in decline, as more of the rural population migrates to the cities and agricultural land is allowed to return to a wilderness state (Science Nordic, 2013).

### 5.4.1 Wild fisheries and aquaculture

Norway's fishing and aquaculture industry is one of its most important export industries, with a value of EUR 7 billion (2011) making it the world's second biggest seafood exporter and making seafood the nation's third most valuable export sector (FAO, 2005). Norway is the world's largest producer of Atlantic salmon, with salmon and trout produced through aquaculture accounting for more than half of the entire value of Norway's seafood exports (Norwegian Seafood Council, 2012). Salmon farming is conducted along the entirety of Norway's coastline and is an important provider of employment for many regions (Ministry of Fisheries and Coastal Affairs, 2013).

Atlantic salmon are an anadromous species, meaning part of their life cycle is spent in freshwater and part in saltwater. Salmon hatch in coastal rivers and migrate as juveniles out into the fjords. Following sexual maturation, adults migrate in the reverse way from the fjords and upstream again for reproduction. Navigation is theorised to be accomplished via smell and responses to chemical stimuli in the surrounding water, which makes any anthropogenic disturbance in near shore areas where fish are likely to migrate through a concern (Davidsen et al., 2013). Aquacultural practices mimic these life stages, with juveniles reared on land in freshwater tanks and adults grown out to harvest size in sea cages. Typically, these growing out cages are situated within sheltered fjords, where land-use conflicts may occur.

In 2003 the Norwegian parliament passed measures aimed at ensuring the long-term viability of national salmon stocks (Norwegian Ministry of the Environment, 2003). These measures included the establishment of 21 national salmon fjords, designated as areas for the protection of wild salmon. No new (in addition to existing) aquaculture is allowed within any of the designated fjords. Further, 13 of the fjords were classified as aquaculture-free zones. Although these laws restrict aquaculture within some fjords as a means of ensuring wild salmon population survival, other activities are not excluded from the fjords. For example, mining and associated STD is currently undertaken at Ranafjorden and is proposed for Repparfjorden – both designated national salmon fjords.

### 5.4.2 Tourism

Tourism is an important part of Norway's economy, accounting for 3.3 % of GDP and 6.3 % of national employment (Statistics Norway, 2012), making it Norway's third largest industry after petroleum and seafood products. The tourism market is heavily skewed towards nature-based tourism, with the coastal fjords and mountains of Norway's coasts accounting for many of the most visited attractions. Surveys indicate the main reasons for tourists holidaying in Norway include 'sightseeing', 'nature' and 'the fjords' (Innovasjon Norge, 2012). Fishing-based tourism is also popular, and thus exhibits the potential to also be affected by aesthetic and physicochemical impacts.

Although mining occurs in many fjord locations, no operations and/or associated STD are currently undertaken in the vicinities of the most popular tourist fjords of Geirangerfjord,

Romsdalsfjord, Aurlandsfjord, Nærøyfjord, Sognefjord, Hardangerfjord and Lysefjord (Fjords.com, 2013).

## 5.5 Recent Review of Norwegian STD practices

Fosså et al. (2009) of the Institute of Marine Research in Bergen conducted a review of the environmental impacts of STD on the biodiversity and ecosystems in Norway's fjords. The review looked at both current and proposed STD cases via an assessment of the impact on local fish and crustacean populations within STD locations. The review concluded that STD within the fjord system altered the biodiversity within the fjords through the smothering of the benthos. This smothering contributed to the direct loss of habitat for demersal fish and crustaceans, with flow-on effects throughout the food-webs of the fjords. These flow-on effects were characterised as a break-down of the "eternal cycle" of production and nutrient transfer, resulting in alteration to the baseline biodiversity. This recent study, from a reputable research body, adds some weight to the concerns raised over STD within Norway's fjord systems.

## 5.6 STD in Norway: Legal context

### 5.6.1 International Law

The *Convention on the Prevention of Marine Pollution by Dumping of Waste and Other Matter, 1972 (London Convention)* and its update and more modern version, the *1996 Protocol to the Convention on the Prevention of Marine Pollution by Dumping of Waste and Other Matter, 1972 (London Protocol)* exist for the objectives of preserving the marine environment and protecting it from sources of pollution. Under the Protocol, the dumping of all wastes, other than those on a permitted list, is prohibited. The permitted list allows for the disposal of 'inert, inorganic geological material', which could potentially apply to some forms of tailings and wastes rock. It is more likely, however, for tailings to not be inert, as they are commonly reactive, such as demonstrated by their acid-generating capacity. This definition is therefore in contention where the permissibility of STD under the Protocol is questioned. A further point of contention under the protocol is the definition of dumping at sea, and if this also covers disposal of wastes from land via a pipeline, as in STD.

### 5.6.2 European Union Law

Two EU directives relate directly to tailings management: The Mineral Waste Directive (2006/21/EC), which applies to the management of mine wastes on land (as for conventional tailings management techniques) and the Water Framework Directive (WFD) (2006/60/EC), which covers discharge of pollutants into fresh and marine water bodies (Kvassnes et al. 2009). The WFD does not come into effect until 2015, and it is from that time that STD is likely to be regulated under its conditions. A third directive, the Marine Strategy Framework 2008/56/EU also indirectly relates to STD through its applicability to marine environmental management.

Kvassnes *et al.* (2009) conducted an assessment for the Norwegian Institute for Water Research on the potential future implications for STD in Norway following the implementation of the WFD. The authors concluded that STD may *possibly* be permitted under the WFD, and, if so, this would be under a classification as a Heavily Modified Water Body, defined as "...a body of surface water which as a result of physical alterations by human activity is substantially changed in character...". This conclusion was reached due to the WFD providing for much more stringent environmental impact parameters than previous regulatory tools. The

WFD allows for only *minor* deviations from the natural ecological and chemical states of a water body; STD contributes to substantial alternations to ecosystems and water chemistry and would thus not likely be considered 'minor'. Being a practice that causes more than minor impacts, STD would effectively be disallowed without the receiving fjords being classified as heavily modified.

## **6 Global practices and views on STD**

As mentioned previously, Norway is somewhat of an anomaly within the mining world with regards to its views on STD. Some nations have explicitly banned the practice, while others have effectively prohibited it through regulation and permitting structures. Some mining companies have publicly stated they will not undertake STD in any circumstances, while others do not explicitly rule it out. Major international institutions have expressed a range of positions on the issue. To provide global context to the Norwegian situation, a summary of the legal situations and views on the practice of STD expressed by a number of western nations, the European Union and the World Bank is presented below

### **6.1.1 Australia**

The dumping of wastes at sea is regulated in Australia under the Environmental Protection (Sea Dumping) Act 1981 and its associated regulations. This Act prohibits the disposal of wastes considered too detrimental to the marine environment and regulates the disposal of less-harmful, permitted wastes to minimise impacts (Commonwealth of Australia, 2011). Australia is also a signatory to the London Convention and Protocol, and thus abides under the directions regarding dumping at sea. It can be argued, however, that there is no explicit prohibition of STD in Australia. The Australian Government's handbook on tailings management (Department of Industry, Resources and Tourism, 2007) makes only a brief reference to the legality of STD: "*Such methods (riverine and marine tailings discharge) are not supported by the Australian regulatory environment...*". (Shimmiel, 2013) further alludes to the not-so-certain status of STD when she refers to the Australian situation: "*...government authorities must themselves evaluate tailings management alternatives, setting-out the terms of any permits to discharge tailings into the marine environment...*". Such interpretations indicate that although STD is not explicitly illegal in Australia, designs for implementation of this method of tailings disposal would be subject to robust scrutiny and a very thorough approvals process.

### **6.1.2 Canada**

Canada's Metal Mining and Effluent Regulations explicitly prohibit the dumping of tailings in the marine environment. Prior to the ascension of these regulations in 2002, marine disposal of tailings was legally possible, but was only undertaken following an extensive review and approvals process (Vogt, 2012).

### **6.1.3 USA**

Environmental regulations in the USA are such that dumping of mine wastes in marine waters is effectively prohibited. The Clean Water Act specifies a 'no discharge' threshold for marine waters, meaning there is no acceptable volume or composition for mine wastes in the marine environment (Vogt, 2012). This effectively prohibits the practice of STD and no mines within the USA are currently undertaking this practice for tailings management.

### **6.1.4 EU**

The European Commission's Best Available Technique (BAT) guidance document for the *Management of Tailings and Waste Rock in Mining Activities* states that STD may be an acceptable method of tailings management in areas of ARD generating potential (European Commission, 2009). As ARD can be a potential management issue at the majority of mine sites around the world, however, the same document notes that it is usually the lack of suitable areas for land-based management that is the main incentive behind the employment of marine discharge practices.

Also to be considered in addition to the BAT, however, are European Directive 2006/21/EC on the Management of Wastes from Extractive Industries and the Water Framework Directive (WFD) (2006/60/EC), as discussed in Section 6.6. As previously mentioned, it is possible that STD may be permitted following the introduction of the WFD, though it is likely only to be permissible for ‘highly modified water bodies’ (Kvassnes, Sweetman, Iversen, and Skei, 2009).

### **6.1.5 World Bank (International Finance Corporation)**

The World Bank’s Extractive Industries Review (EIR) of 2003 (World Bank, 2003) was undertaken to assess the current and future involvement of the World Bank in mining and other extractive industries. The review concluded the following regarding STD:

*“Almost all STD operations worldwide ...have had problems, including pipe breaks, wider than expected dispersal of tailings in the sea, smothering of the benthic organism ...and loss of biodiversity, increased turbidity, introduction to the sea and marine biota of metals and milling agents ...and loss of potentially re-mine-able metals from tailings in the deep sea.”*

Regarding funding of mining projects that involve STD, the recommendation from the EIR was as follows:

*“The WBG [World Bank Group] should apply the precautionary principle and not fund projects that would require submarine tailings disposal until balanced and unbiased research ...demonstrates the safety of such technology.”*

Further to this, the EIR made the explicit recommendation that STD should not be used in areas that have “...important ecological functions or cultural significance or in coastal waters used for subsistence purposes”. Tropical islands and associated coral reef habitats, such as those in the Indo-Pacific region, were used by way of example to demonstrate areas of important ecological function, cultural significance and valuable subsistence fisheries.

The International Finance Corporation’s (IFC) Environmental, Health and Safety Guidelines for Mining (International Finance Corporation, 2007) contains the following two passages regarding STD:

*“Riverine (e.g. rivers, lakes, and lagoons) or shallow marine tailings disposal is not considered good international industry practice.”*

*“Deep sea tailings placement (DSTP) may be considered as an alternative only in the absence of an environmentally and socially sound land-based alternative and based on an independent scientific impact assessment.”*

These views expressed by the World Bank and IFC do not indicate explicit opposition to the practice of STD but do indicate an approach based upon caution and insistence on robust scientific support for any proposals involving STD.

## 7 Multi-criteria Analyses of STD in Norway

Two multi-criteria analyses have been conducted for this study: one which positions the Norwegian government and other regulators as the primary decision makers and one which positions the involved mining companies themselves as decision makers. It is clear that the relative priorities in any decision making will vary greatly depending upon the characteristics of the decision making party, especially when corporate and non-corporate views are contrasted.

As mentioned in Section 2.3, the process of conducting an MCA can be considered over 8 steps, which are again presented below:

1. Establish the decision context. What are the aims of the MCA, and who are the decision makers and other key players?
2. Identify the options.
3. Identify the objectives and criteria that reflect the value associated with the consequences of each option.
4. Describe the expected performance of each option against the criteria. (If the analysis is to include steps 5 and 6, also 'score' the options, i.e. assess the value associated with the consequences of each option.)
5. 'Weighting'. Assign weights for each of the criteria to reflect their relative importance to the decision.
6. Combine the weights and scores for each of the options to derive an overall value.
7. Examine the results.
8. Conduct a sensitivity analysis of the results to changes in scores or weights.

This section describes the MCAs that have been undertaken for this study in the step-wise manner as described above.

### 7.1 MCA Step 1 – Establish the decision context

The decision context surrounding a consideration of STD in Norway is primarily dependent upon the characteristics of the decision maker. It is clear that the relative priorities in any form of decision making will vary greatly depending upon the goals and values of the decision making party, especially when corporate and non-corporate views are contrasted. In view of this, *two* multi-criteria analyses have been conducted for the present study: one which positions the Norwegian government and other regulators as the primary decision makers and one which positions the involved mining companies themselves as decision makers. The decision context for each MCA, although assessing the same options, is thus quite different.

### 7.2 MCA Step 2 – Identify options

The main aim of this study is to provide more information to decision makers as to whether STD is the more preferred option in Norway or not. Therefore, a simple approach has been taken here when identifying options: the two options to be compared are “STD” and “Land-based tailings management”. Land-based options cover the range of technologies discussed in Section 3.2 though have been considered with a focus more on conventional dam storage methods. The comparison of only two options provides for a clear and concise assessment as to the preferability of STD in Norway.

### 7.3 MCA Step 3 - Identify objectives and criteria

Decision criteria for the MCAs naturally need to cover the full spectrum of sustainability objectives – that being the three domains of economic, social and environmental

considerations. Evaluation criteria were compiled and refined through the utilisation of the following sources:

- Environmental Law Alliance Worldwide document *Guidebook for Evaluating Mining Project ELAs* (Environmental Law Alliance Worldwide, 2010),
- The *BAT for Management of Tailings and Waste-Rock in Mining Activities* (European Commission, 2009),
- Annex 1 of European Directive 2008/56/EU (Marine Strategy Framework Directive),
- Discussions with scientists at NIVA and SwAM, and
- Author's previous experience in environmental management in the resources industry.

All criteria were chosen through a process that began with brainstorming ideas, consulting the literature mentioned and then applying the test question: *Are these criteria measurable or in another way able to be judged so as to provide meaningful input to the analysis?* Criteria for which the answer to this question was 'no' were deleted, and only those criteria that were determined to be readily measurable or reasonably able to be estimated were retained. The finalised criteria were reviewed by researchers at NIVA and SwAM and were refined further on account of their feedback.

#### 7.4 MCA Steps 4, 5, 6 – Scoring and weighting

The scoring and weighting of the decision options against the criteria identified in Step 3 was guided by the wide range of literature reviewed for this study, direct communications with relevant parties and the author's experience. It is accepted and understood that these steps of the MCA process are those which are most subjective and open to bias (Dodgson *et al.*, 2009). It should therefore be cautioned that the figures presented within the following MCAs are not absolute, but rather reflect a best-attempt at distillation of all of the considered qualitative material into a numerical form with which to conduct a simple form of quantitative analysis.

Scores were determined through a process similar to generic risk assessment, wherein the expected performances of the decision options against each decision criteria were assessed. The expected (negative) consequences and the probability of these consequences were then estimated. Scores for each criterion were assigned from 0-10, with 0 indicating nil or negligible impact and 10 indicating high impact. Proportional weights were assigned to each criterion from a total of 100, with greater weights indicating criteria of higher importance and lower weights vice-versa.

To describe the weighting system used by way of example, environmental effects such as negative impacts on groundwater, air emissions and loss of biodiversity are, for the purposes of these MCAs, assigned lower weights for the analysis from a corporate point of view than from a regulatory/government point of view. These weightings are assigned in this manner due to the fact that (non-catastrophic) negative environmental outcomes are usually of a low commercial impact, and are thus treated as comparatively minor issues in a business environment. Conversely, governments are most likely to place more weight on negative environmental impacts as these can result in community dissatisfaction and knock-on effects to other industries such as tourism, with these having direct political consequences.

#### 7.5 MCA Steps 7 & 8 – Examination of results and sensitivity analysis

Using the simple linear additive method, the score and weighting for each criterion is multiplied and the resulting weighted scores are summed to provide a total figure representing a weighted average of all decision criteria for each decision option. Assessment of these resultant totals thus allows for direct comparison between decision options. Further and

deeper analysis can then be undertaken by comparing criteria which have contributed relatively major or minor amounts to the totals. The examination of results for the two MCAs conducted for this study is presented in Section 8.

A sensitivity analysis was not undertaken for this project due to its minimal scope and time limitations.



## 7.6 MCA 1 – Regulators as primary decision makers

CRITERIA	SCORING		WEIGHTING	WEIGHTED SCORES	
	STD	LAND-BASED	GOV'T	STD	LAND-BASED
Dust emissions	0	3	2	0	6
Odour emissions	0	1	2	0	2
Noise emissions	1	1	2	2	2
Add Rock Drainage	1	5	4	4	20
Heavy metals	3	2	2	6	4
Process chemicals	2	2	2	4	4
Suspended solids	5	2	2	10	4
Rehabilitation	2	7	4	8	28
Catastrophe	5	10	10	50	100
Groundwater contamination	0	3	5	0	15
Impact on aesthetics	4	7	5	20	35
Impact on tourism	2	4	5	10	20
Impact on fisheries and aquaculture	3	0	5	15	0
Ground disturbance	4	5	2	8	10
Energy use	1	1	2	2	2
Water use	0	1	2	0	2
Reputational impacts	4	4	0	0	0
Biodiversity impacts	6	6	2	12	12
Safety	0	4	4	0	16
Impacts on local communities	2	3	5	10	15
Land contamination	0	1	5	0	5
Long-term management and monitoring	2	7	4	8	28
Cost	4	10	4	16	40
<b>Derived from Marine Strategy Framework Directive</b>					
Biological diversity maintained	7	0	2	14	0
Non-indigenous species	0	0	2	0	0
Populations of commercial fish species within safe limits	3	0	2	6	0
Marine food webs occurring at normal abundance and diversity	3	0	2	6	0
Eutrophication minimised	0	0	2	0	0
Seafloor integrity retained. Benthic ecosystems not affected	10	0	2	20	0
Contaminant concentrations do not produce pollutant effects	3	0	2	6	0
Contaminants in fish and seafood not above thresholds	2	0	2	4	0
Marine litter does not cause harm to marine environment	0	0	2	0	0
Energy including noise does not affect underwater environment	1	0	2	2	0
		<b>TOTALS</b>	100	<b>243</b>	<b>370</b>

The above MCA, undertaken from the perspective of government or other regulators as the primary decision makers, indicates a moderate preference for STD over land-based tailings management methods, as indicated by the total scores of 243 (for STD) vs. 370 for land-based measures. These results are discussed in detail in Section 8.

## 7.7 MCA 2 – Mining companies as primary decision makers

CRITERIA	SCORING		WEIGHTING	WEIGHTED SCORES	
	STD	LAND-BASED	CORPORATE	STD	LAND-BASED
General					
Dust emissions	0	3	1	0	3
Odour emissions	0	1	1	0	1
Noise emissions	1	1	1	1	1
Add Rock Drainage	1	5	5	5	25
Heavy metals	3	2	2	6	4
Process chemicals	2	2	2	4	4
Suspended solids	5	2	2	10	4
Rehabilitation	2	7	5	10	35
Catastrophe	5	10	15	75	150
Groundwater contamination	0	3	2	0	6
Impact on aesthetics	4	7	1	4	7
Impact on tourism	2	4	1	2	4
Impact on fisheries and aquaculture	3	0	1	3	0
Ground disturbance	4	5	1	4	5
Energy use	1	1	2	2	2
Water use	0	1	2	0	2
Reputational impacts	4	4	5	20	20
Biodiversity impacts	6	6	1	6	6
Safety	0	4	5	0	20
Impacts on local communities	2	3	3	6	9
Land contamination	0	1	2	0	2
Long-term management and monitoring	2	7	10	20	70
Cost	4	10	20	80	200
<b>Derived from Marine Strategy Framework Directive</b>					
Biological diversity maintained	7	0	1	7	0
Non-indigenous species	0	0	1	0	0
Populations of commercial fish species within safe limits	3	0	1	3	0
Marine food webs occurring at normal abundance and diversity	3	0	1	3	0
Eutrophication minimised	0	0	1	0	0
Seafloor integrity retained. Benthic ecosystems not affected	10	0	1	10	0
Contaminant concentrations do not produce pollutant effects	3	0	1	3	0
Contaminants in fish and seafood not above thresholds	2	0	1	2	0
Marine litter does not cause harm to marine environment	0	0	1	0	0
Energy including noise does not affect underwater environment	1	0	1	1	0
	<b>TOTALS</b>		100	<b>287</b>	<b>580</b>

The above MCA, undertaken from the perspective of mining companies as the primary decision makers, indicates a high preference for STD over land-based tailings management methods, as indicated by the total scores of 287 (for STD) vs. 580 for land-based measures. These results are discussed in detail in Section 8.

## 8 Discussion

### 8.1 MCA 1 – Regulators as primary decision makers

This MCA revealed a moderate preference for STD over land-based tailings management. Important contributors to the final scores were:

**Catastrophe** – The risks associated with a large scale failure of a tailings dam structure are immense. Importantly, when considering such risks from a regulatory/governmental point of view is that these risks and potential damages are not contained within a mine's footprint or lease area. The potential for large scale impacts can spread well beyond a mine site and affect the surrounding environment and communities. As such, this is a major consideration for regulators assessing tailings management options.

**Aesthetics** – The impact of a land-based tailings containment structure on the visual amenity and overall aesthetics of a region that is heavily marketed in the tourism sector on the basis of its unspoilt nature can be massive. In addition to the tourism sector, negative consequences on aesthetics can also impact on local residents.

**Rehabilitation** – Any land-based structure designed to manage tailings will usually need to be rehabilitated to some form of 'more-natural' or at least more aesthetically and environmentally acceptable state at a future point. The potential exists for rehabilitation to be undertaken in an incomplete or undesirable fashion, or for rehabilitation to be successful for a short period of time before a site becomes degraded and regresses to a pre-rehabilitated state. This uncertainty in the restoration of visual amenity and other aesthetic values positions rehabilitation as a key evaluation criterion for governments.

**Long term management** – The long term management of a tailings storage area is primarily a responsibility for the owner or operator of the mine it serves. There is, however, also some burden of responsibility on the responsible government to ensure that this management is carried out (e.g. via inspections) and, further, the potential for a shift of economic responsibility to government in the event of the operator reaching a state of bankruptcy and therefore unable to fund this continued management. These long-term considerations are thus also a potentially important evaluation criterion for governments to be concerned with.

**Cost** – While not as big a factor as for businesses considering options, cost does weigh into a government's perspective in this case in more of an indirect way. While not being directly impacted one way or the other by the cost of a project, governments are inclined to help foster the economies of the regions they manage. Therefore, the economic feasibility of projects is a concern to governments. In the case of STD vs. land-based methods, the much lower costs associated with STD translate to much better economic feasibility for the projects that undertake this method and are therefore more likely to be looked upon favourably by governments with a focus on supporting local economies.

### 8.2 MCA 2 – Mining companies as primary decision makers

This MCA revealed a very obvious preference for STD over land-based tailings management. Important contributors to the final scores were:

Catastrophe – Failures such as these can cause huge environmental damages, be dangerous to surrounding and downstream workers and communities and be prohibitively expensive to repair. The high score assigned to this risk resulted from a consideration of the direct costs and reputational damage to a mining company that would likely result, as well as the probability of its occurrence – this being somewhat higher in the fjord regions of Norway than other places due to the difficult topography and high rainfall.

Long term management of tailings storage areas – For the life of a mine and beyond, tailings storage areas must be continuously monitored and maintained to ensure their integrity. This requirement to manage can be indefinite and can result in significant costs to the operator.

Rehabilitation of land-based tailings management areas – Similarly to long-term management commitment, the costs of rehabilitation of these facilities can be large, and can potentially continue for many years after the end of a mine's life.

Cost – in an overall sense, cost is *the* critical factor when comparing tailings management options. As mentioned previously, there can be orders of magnitude difference between the costs of STD and the costs of constructing, maintaining and rehabilitating a land-based solution. Such differences can mean the difference between the overall feasibility or otherwise of a project and are therefore the primary driver in this area of decision making.

### 8.3 Discussion of overall results

The results from both MCAs conducted here indicate STD is a preferred option in Norway when considering the specific range of evaluation criteria chosen for this particular study. The case appears to be much stronger when considering these options from the point of view of mining companies, although the results for the MCA with regulators as primary decision makers also had the same, if less emphatic, result. Of interest are the handful of evaluation criteria which provided major contributions to the final scores. These criteria are largely similar for both MCAs conducted, indicating that these are major issues for whoever is involved in the decision making.

An important observation to make from the types of evaluation criteria which have been identified via the MCAs here as major is that they, in general, can all be related to large, often ongoing, and potentially open-ended costs. This applies for both governments and mining companies. From a business perspective this is easy to grasp, as costs are the primary driver for any decision making. From a government perspective, this can be attributed to the potential economic risks faced by governments forced into a position of absorbing these costs in the event of mining companies going in to administration or bankruptcy, or simply due to community pressure forcing governmental intervention if management of these facilities is not considered to be at an acceptable level.

### 8.4 Suitability of MCA for this analysis

MCA, and the linear-additive method of MCA in particular was chosen for this study as it provided a well-established, simple, partially quantitative method of going some way towards answering the research questions posed. MCA by definition provides only for subjective results, as the criteria used, scores and weightings applied and biases of the assessor all influence the analysis. However, when an analysis clearly outlines the processes of data gathering, scoring, weighting and the end assessment of the resultant scores, this subjectivity is balanced by becoming transparent. In effect, the results gained from a typical MCA could be referred to as *transparently* subjective, as the reader should be able to determine precisely

how the end result was achieved. It is intended that this paper has achieved this goal of transparent subjectivity.

Regarding how effective a subjective and qualitative tool is for answering the research questions posed in this study, MCA appears to be a useful tool. Fitting with the small scope and the intended audience of this paper, these analyses should provide some further information to the debate on STD in Norway, as is the intention. The lack of robust data in some areas, however, means that use of these results for actual decision making should be cautioned. This is in keeping with a general characteristic of all MCAs, that being that they are sometimes, but rarely, used as decision-making tools on their own and are most commonly used to provide extra input into another decision making process.

## 8.5 Recommendations for further research

Both of the MCAs conducted for this study point to STD being the preferred option for tailings management in Norway's fjord regions. As with any analysis, however, the end result is only as meaningful and robust as the data fed into it. While attempts were made in this study to provide relative quantifications of broad-ranging qualitative information, the figures used as input into the MCAs was open to bias and subjectivity at every step of the research. Additionally, the lack of a sensitivity analysis precluded an assessment as to the robustness of the chosen model and the sensitivity of the scores and weighting as assigned.

Future studies of this type would therefore be much improved by aiming to include as much robust, quantitative data as possible, and by subjecting the resultant analyses of this data to a sensitivity analysis. The obtainment of higher-value data could be achieved by undertaking more in-depth discussions with the relevant stakeholders, gathering more people together to assess the evaluation criteria and by accessing real cost figures from governments and industry. The more work put into sourcing accurate data in this way should ideally provide for more accurate results from the analyses.

It is important to note that the conclusion that STD is a preferable method has been reached via the testing of only two decision options: to manage tailings on-land or to undertake STD. What has not been considered here is a broader question of the viability of the mining industry in these regions of Norway with high relief and difficult climatic conditions. Is it worth the cost, effort and potential environmental problems of mining in these areas to provide for only a relatively small industry that contributes less than one percent of Norway's GDP? Questions such as this should be included in any future research that looks at a broader picture than the quite narrow scope that this study has focused on.

## 9 Conclusion

Both MCAs conducted in this study indicate that STD could be considered a more preferable option to land-based tailings management when assessed against the wide range of sustainability criteria proposed. It is evident from both MCAs that the factors of cost, impacts on aesthetics and the associated knock-on effects to the tourism industry, risk of catastrophic failure and subsequent uncontrolled discharge of tailings and the requirement for long term monitoring and management all favour underwater tailings management solutions.

Difficulties posed by climate, geology and topography are commonly cited by proponents of STD as justification for the practice. It is evident from the results of the MCAs conducted in this study that these factors also weigh heavily in the Norwegian context. Simply put, the very steep terrain around Norway's fjords almost prohibits the economically viable construction and management of conventional tailings dams. This coupled with the high rainfall experienced in the region and the major importance of unblemished natural scenery to Norway's tourism industry further pushes the case for STD over land-based measures.

This is not to say by any means that STD is without its negative aspects. A number of the cases studies cited here point to various negative environmental impacts that must be managed. Further, the body of research on this practice is still relatively thin, and the deep waters and complex ecosystems of the Norwegian fjords provide a challenging environment to study and effectively monitor. It cannot be said yet if the practice, in an environmental sense, is inherently safe or inherently damaging. If it is to be accepted, however, that STD is the preferred tailings management method at present the next question to be asked may be whether or not mining in this region is really a cost-effective process. Are the known and unknown risks of STD justifiably faced considering the relatively small size of the fjord mining industry and its contribution to Norway's GDP? Is it worth going against the near-blanket opposition to the practice in the western world?

These questions are recommended for the basis of further research. As the world is becoming ever-more environmentally conscious and Norway's tourism sector continues to see strong growth, there may be a break-even point where the benefits of mining in the fjord regions are outweighed by the negative consequences of political backlash and degradation of highly regarded tourism assets. These factors coupled with the imminent changes in European water management policy as the Water Framework Directive comes into effect should push the case for a much more detailed, quantitative and costed look at the pros and cons of STD in Norway. It is hoped that this present study provokes some thought on this matter and encourages this type of future research.



# Bibliography

## References

- A.B. Josefson, J.L.S. Hansen, Asmund, G., & Johansen, P. (2008). *Threshold response of benthic macrofauna integrity to metal contamination in west greenland* Elsevier Ltd. doi:10.1016/j.marpolbul.2008.04.028
- Amundsen, A. (2009). Marine calcite tailing deposition - the best environmental solution. *Marine and Lake Disposal of Mine Tailings and Waste Rock September 7-10 2009*, Egersund, Norway.
- Berkun, M. (2005). Submarine tailings placement by a copper mine in the deep anoxic zone of the black sea. *Water Research*, 39(20), 5005-5016.
- BHP Billiton. (2013). *We value sustainability: Sustainability report 2012*. ().
- Brewer, D. T., Milton, D. A., Fry, G. C., Dennis, D. M., Heales, D. S., & Venables, W. N. (2007). Impacts of gold mine waste disposal on deepwater fish in a pristine tropical marine system. *Marine Pollution Bulletin*, 54(3), 309-321. doi:10.1016/j.marpolbul.2006.10.011
- Environmental protection (sea dumping) act 1981, (2011).
- Davidson, J. G., Rikardsen, A. H., Thorstad, E. B., Halttunen, E., Mitamura, H., Præbel, K., . . . Naesje, T. F. (2013). *Homing behaviour of atlantic salmon (salmo salar) during final phase of marine migration and river entry*
- Department of Industry, Resources and Tourism. (2007). *Leading practice sustainable development program for the mining industry: Tailings management*
- Dodgson, J. S., Spackman, M., Pearman, A., & Phillips, L. D. (2009). *Multi-criteria analysis: A manual*. (). London: Department for Communities and Local Government.
- Elberling, B., Karen, L. K., Peter, H. K., & Asmund, G. (2003). Applying foraminiferal stratigraphy as a biomarker for heavy metal contamination and mining impact in a fiord in west greenland. *Marine Environmental Research*, 55, 235-256. doi:10.1016/S0141-1136(02)00219-2
- Environmental Law Alliance Worldwide. (2010). *Guidebook for evaluating mining project EIAs*. Oregon, USA.: Environmental Law Alliance Worldwide.
- European Commission. (2009). *Reference document on best available techniques for management of tailings and waste-rock in mining activities*. Brussels: European Commission.
- FAO. (2005). National aquaculture sector overview: Norway. Retrieved June 18, 2013, from [http://www.fao.org/fishery/countrysector/naso\\_norway/en](http://www.fao.org/fishery/countrysector/naso_norway/en)
- Fjords.com. (2013). The fjords in western norway. Retrieved July 5, 2013, from <http://www.fjords.com/fjords.shtml>
- Fosså, J. H., Aure, J., & Meier Sonnich, W. (2009). In Egersund Conference (Ed.), *Effects of mine tailings disposal on the ecosystem and biodiversity in the marine environment - a critical view*. Bergen: Institute of Marine Research.
- Fossum, I. (2009). Planned marine disposal of tailings from a rutile mine. *Marine and Lake Disposal of Mine Tailings and Waste Rock September 7-10*, Egersund, Norway.

- Franks, D. M., Boger, D. V., Claire M. Côte, & Mulligan, D. R. (2011). *Sustainable development principles for the disposal of mining and mineral processing wastes* Elsevier Ltd. doi:10.1016/j.resourpol.2010.12.001
- Hammer, A. (2011). Dilemmas of mining. Retrieved August 26, 2013, from <http://sciencenordic.com/dilemmas-mining>
- Hustadmarmor AS. (2013). Omya norway hustadmarmor. Retrieved July 2, 2013, from <http://www.hustadmarmor.no/>
- iGlobeTrotter. (2013). The top 10 sights of norway. Retrieved August 26, 2013, from <http://www.iglobetrotter.com/norway/activities-and-attractions/top-10-sights-of-norway>
- Innovasjon Norge. (2012). *Basert på turistundersøkelsen til innovasjon norge og tall fra SSB* <br />. ().
- International Finance Corporation. (2007). *Environmental, health and safety guidelines for mining*
- International Institute for Energy and Development. (2002). ***Breaking new ground: Mining, minerals and sustainable development.*** (). IIED.
- Johnson, S. W., Rice, S. D., & Moles, D. A. (1998). Effects of submarine mine tailings disposal on juvenile yellowfin sole (pleuronectes asper): A laboratory study. *Marine Pollution Bulletin*, 36(4), 278-287. doi:10.1016/S0025-326X(97)00181-1
- Kline, E. R., & Stekoll, M. S. (2001). Colonization of mine tailings by marine invertebrates. *Marine Environmental Research*, 51(4), 301-325. doi:10.1016/S0141-1136(00)00105-7
- Kvassnes, A. J. S., Sweetman, A. K., Iversen, E. R. and Skei, J. (2009). Sustainable use and future of submarine tailings placements in the norwegian extractive industry. *Securing the Future and 8th ICARD*, Skellefteå, Sweden.
- MarketLine. (2012). Metals & mining industry profile: Norway. *Metals & Mining Industry Profile: Norway*, , 1-43.
- Ministry of Fisheries and Coastal Affairs. (2013). Farmed salmon. Retrieved July 7, 2013, from <http://www.regjeringen.no/en/dep/fkd/samlesider/farmed-salmon.html?id=610368>
- Newcrest Mining Limited. (2013). Lihir. Retrieved July 8, 2013, from [http://www.newcrest.com.au/media/our\\_business/2375\\_Newcrest\\_FS\\_Lihir\\_LR.pdf](http://www.newcrest.com.au/media/our_business/2375_Newcrest_FS_Lihir_LR.pdf)
- Norwegian Ministry of the Environment. (2003). Proposition no. 79 to the storting (2001-2002): National salmon rivers and national salmon fjords. Retrieved July 9, 2013, from <http://www.regjeringen.no/en/dep/md/documents-and-publications/government-propositions-and-reports-/Reports-to-the-Storting-white-papers/20012002/Proposition-No-79-to-the-Storting-2001-2/1.html?id=455018>
- Norwegian Seafood Council. (2012). Key figures. Retrieved July 8, 2013, from <http://en.seafood.no/News-and-media/Key-figures>
- Nussir ASA. (2011). In Sweco Norge AS (Ed.), *Reguleringsplan med konsekvensutredning for planlagt gruvedrift i nussir og ulveryggen i kvalsund kommune*
- Nussir ASA. (2012). *Søknad om utslippstillatelse: Søknads skjema for industribedrifter*

- Odhiambo, B. K., Macdonald, R. W., O'Brien, M. C., Harper, J. R., & Yunker, M. B. (1996). *Transport and fate of mine tailings in a coastal fjord of british columbia as inferred from the sediment record*
- Olsgard, F. & Hasle, J.R. (1993). *Impact of waste from titanium mining on benthic fauna*
- Perner, K., Th. Leipe, Dellwig, O., Kuijpers, A., Mikkelsen, N., T.J. Andersen, & Harff, J. (2010). *Contamination of arctic fjord sediments by Pb–Zn mining at maarmorilik in central west greenland* Elsevier Ltd. doi:10.1016/j.marpolbul.2010.01.019
- PT Newmont Nusa Tenggara. (n.d.). Fact sheet. Retrieved July 8, 2013, from [http://www.newmont.com/sites/default/files/fact\\_sheet\\_tailing\\_eng.pdf](http://www.newmont.com/sites/default/files/fact_sheet_tailing_eng.pdf)
- Rana Gruber AS. (2013). Rana gruber AS. Retrieved July 26, 2013, from <http://www.ranagruber.no/>
- Science Nordic. (2013). Tourists split on norway's changing landscape. Retrieved July 6, 2013, from <http://scienordic.com/tourists-split-norway%E2%80%99s-changing-landscape>
- Shimmiel, T. (2013). An alternative: Deep-sea tailings placement. Retrieved July 20, 2013, from <http://www.miningaustralia.com.au/features/an-alternative-deep-sea-tailings-placement>
- Skei, J., & Paus, P. E. (1979). Surface metal enrichment and partitioning of metals in a dated sediment core from a norwegian fjord. *Geochimica Et Cosmochimica Acta*, 43(2), 239-246. doi:[http://dx.doi.org/10.1016/0016-7037\(79\)90242-4](http://dx.doi.org/10.1016/0016-7037(79)90242-4)
- Skotte, G. (2011). Submarine mine tailings disposal in norway. Retrieved July 30, 2013, from [http://www.imo.org/blast/blastDataHelper.asp?data\\_id=30570&filename=Presentation-SubmarinetailingdisposalLC-SGApril2011.pdf](http://www.imo.org/blast/blastDataHelper.asp?data_id=30570&filename=Presentation-SubmarinetailingdisposalLC-SGApril2011.pdf)
- Söderqvist, T., & Hasselström, L. & Soutukorva, A. (2013). *Konsekvensbedömningar vid framtagande av bavsplaner*. ()
- Søndergaard, J., Asmund, G., Johansen, P., & Rigét, F. (2011). Long-term response of an arctic fiord system to lead-zinc mining and submarine disposal of mine waste (maarmorilik, west greenland). *Marine Environmental Research*, 71(5), 331-341. doi:10.1016/j.marenvres.2011.03.001
- Statistics Norway. (2012). *Tourism statistics 1999-2011*. (). Oslo: Statistics Norway.
- Sydvaranger Gruve AS. (2010). KLIF-application. Retrieved July 15, 2013, from <http://www.sydvarangergruve.no/klif-application.4805931.html>
- US Environmental Protection Agency. (1994). *Design and evaluation of tailings dams*. (). Washington: US EPA.
- Vogt, C. (2012). *International assessment of marine and riverine disposal of mine tailings*. ().International Maritime Organisation.
- Western Australia Department of Mines and Petroleum. (2009). Acid mine drainage. Retrieved July 4, 2013, from <http://www.dmp.wa.gov.au/documents/ENV-MEB-220.pdf>
- World Bank. (2003). *Striking a better balance: The world bank and extractive industries*. ().World Bank.
- World Bank. (2013). Multi-criteria analysis (MCA). Retrieved July 26, 2013, from <http://go.worldbank.org/XUQHLEFVQ0>