Environmental adaptive management: application on submarine mine tailings disposal

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ABSTACT

Marine tailings disposal from mineral production is expected to have an environmental impact. In this case study we use a discharge of limestone processing tailings to a Norwegian fjord to describe an adaptive management process. The aim of the paper is to describe the development of an environmental adaptive management system, contrasted with management simply by the quantity of the discharge. The main driver for developing a new management system for the submarine tailings deposits was a desire to establish a system based on what was perceived as important to all stakeholders, i.e. environmental impact. Involvement of stakeholders is essential, and a resource group with members from fisheries, local interest organizations, scientists, independent experts and managers from the mining company jointly defined common sets of acceptance criteria to evaluate impact. Introduction of an environmental adaptive management system have resulted in a change in the company's view of the impact their activity has on the environment and an increased willingness to initiate monitoring and research to reduce knowledge gaps and uncertainty. Environmental adaptive management has facilitated the development of a more ecologically relevant, integrated and focused submarine tailings deposits management.

Keywords:

Submarine tailing; Mining; Adaptive management; Acceptance criteria; ecological impact; turbidity

INTRODUCTION

Disposal of tailings (waste) from mineral production is expected to have an impact on the environment, whether it is disposed on land or discharged into freshwater or the sea (Ellis and Ellis 1994; Ellis 2008; Kvassnes and Iversen 2013; Vogt 2013). Ramirez-Llodra et al. (2015) list the major categories of impact from submarine tailings deposits (STD) as hyper-sedimentation, metal toxicity, toxicity of process chemicals, change in organic content, changed grain size and angularity, sediment plumes and turbidity, re-suspension of materials, upwelling and slope failure. Morello et al. (2016) reviews the ecological impacts that have been associated with STDs and concludes that the consequences of mine waste disposal on the seafloor is poorly understood, given the extent of its implementation. Trannum et al. (2018) studied specifically the effects tailings have on macrobenthic community structure with case studies from Norway. Other reviews have focused on the ecological impacts of submarine tailings placement (STP) (e.g. Dold 2014; Hughes et al. 2015; Liefmann 2018). The examples given in these reviews are mainly based on historical and inactive STDs. The current paper presents lessons learnt from the management of an active STD at Frænfjorden, north-western Norway. The plant, Omya Hustadmarmor, produces fine particle calcium carbonate ($CaCO_3$), predominantly used in paper industry. The processing plant has been licensed to deposit tailings into Frænfjorden by the Norwegian Environment Agency since 1980.

Frænfjorden is a narrow and shallow fjord in north-western Norway (Figure 1). The main part of the fjord extends east–west about 7 km and is about 1 km wide. Depths are mostly less than ~70 m (75% of the fjord has a depth shallower than 50 m). Tailings from limestone (liquid marble) processing have been discharged into a designated impact area (deposit area) in Frænfjord (Figure 1). The solid phase of the discharge consists of inert milled natural minerals with traces of flotation chemicals, which are thought to be strongly associated with particles.

Approximately 50% of the discharge is limestone ($CaCO_3$), predominantly particles smaller than 20 μm in diameter. The remaining 50% is composed of particles up to 400 μm in diameter, mainly quartz, feldspar, mica and iron sulphides, as well as traces of graphite. In total, 80-85% of the solid phase of the discharge consists of particles <63 μm (silt) (DNV 2001a; DNV 2001b; Brooks et al. 2015). The total quantity of tailings discharged as a waterborne slurry increased from 3.5 x 10^5 to 5 x 10^5 tons (dry weight) per year between 1993 and 2011. Following process improvements, the discharges were reduced to 3.5 x 10^5 tons/year from 2012 (see Supplemental Data, Figure 1).

From 1980 to 2003, the discharge permit regulated the quantity of tailings deposited per hour, starting at 1 ton of tailings deposit/hour in 1980, increasing to 55 tons/hour from 1997 to 2003. As the production increased, the quantity of tailings also increased, and updated discharge permits were granted, but under the requirement of monitoring programmes to document potential environmental consequences of the tailings discharge.

The regulation based on tons/hour did however lead to a focus by the company to meet quantity requirements rather than addressing environmental impacts from the tailings. An alternative way to manage the STD was introduced by the company in 2003 based on using ecological and social acceptance criteria. This meant moving from a management by discharge quantity (tons/hour) to manage the STD on the basis of environmental monitoring results and social feedback, the latter involving stakeholders, i.e. an environmental adaptive management as described by Holling (1978) and Allan and Stankey (2009).

Adaptive management is a process with a "learning by doing" approach (Holling 1978; Walters 1986) and has been comprehensively discussed elsewhere (Allan and Stankey 2009; Williams et al. 2009; Doremus et al. 2011). Williams and Brown (2012; 2016) provided examples as to how adaptive management can be used in practice, and Dover et al. (2016)

described adaptive management as an iterative cycle of predictive modelling, monitoring, assessment and feedback, i.e. as a tool managers may use to continually integrate new knowledge into existing plans to improve management, which would typically comprise a "plan-act-monitoring-evaluate-mitigate" cycle. Craig et al. (2017) discuss how federal agencies use adaptive management and the contexts in which adaptive management will be applicable and useful. According to Craig et al (2017) this is where management actions occurs periodically over time, there is substantial uncertainty about resource behaviours and the influence of management on them, and learning can be used to influence decision making.

An early version of adaptive management system established at Omya Hustadmarmor was based on experience from the Øresund Link construction (Gray and Jensen 1993; Gray 1999; Jensen and Lyngby 1999). These authors coined the term "feedback monitoring" to describe what has later been widely termed "adaptive management". The company proposed the implementation of such a system to the regulating agency, the Norwegian Environment Agency, in 2002. The proposal was accepted in 2003 and included in a revised discharge permit from that year. This paper describes the development and implementation of an environmental adaptive management system (EAMS) specifically designed for a mining company with a discharge into a marine fjord, as well as its use for nearly 15 years. We discuss how such a management system can contribute to improve the environmental focus for a mining company and reduce environmental impact.

AN ADAPTIVE MANAGEMENT SYSTEM

A conceptual model was designed based on the adaptive management approach and on knowledge gained from the Øresund Link feedback monitoring management system. It was further developed to a "plan-act-monitoring-evaluate-mitigate" cycle as described by Allen and Stankey (2009) and illustrated by Rist et al. (2013) (Figure 2).

Assessing impacts of the STD

Three components are required to assess the impact of an STD on marine ecosystems: (1) environmental resources, (2) the composition of the tailings and (3) the discharge process. The first step in developing the adaptive management system was to assess impacts of the STD on Frænfjord, using available knowledge from previous monitoring activities and environmental impact assessments (EIAs), a comprehensive literature review and input from stakeholders.

Since 1989, environmental resources have been mapped through regular monitoring programmes. The monitoring programmes has comprised a range of activities, some done annually, others in selected years (see Supplementary information for details): quantity of tailings on the seafloor, sediment mapping and tailings thickness, seafloor depth, macrofauna community composition, rocky shore/hard bottom diversity, water quality (including turbidity), measurement of flocculation chemicals in water and sediments.

The resource group

Regardless of permission from national authorities, most mining companies would desire to have an acceptance from society, i.e. a societal “license”, to operate. This is particularly important when the company is a part of a local community and their activities have an impact on the local environment. One way to achieve this is the to use a reference group, including all relevant stakeholders. In this case the same interest groups that was involved in the public hearings for the initial permit in 1997 were invited to participate in a resource group. The resource group had members from fisheries organisations, local interest organisations, scientists, independent experts and managers and was established in 2003. The resource group was set up to incorporate feedback from local, regional and national stakeholders. It has been crucial for development of the management process that the company has facilitated a framework based on trust and transparency. This has been achieved over time as members of the group can see their concerns being acted upon. This particular resource group has been active for nearly 15 years. The group has been a channel for communication from stakeholders to the company and vice-versa, as well as a forum for voicing concerns and providing advice to the company to increase monitoring or carry out focused studies to reduce knowledge gaps. The resource group has been led by professors from the University of Oslo. A total of 25 resource meetings have been held. In addition to regular members, experts or other stakeholders have been invited for meetings.

Development of acceptance criteria and feedback loops

The key element in this management system was establishing acceptance criteria specifically developed for this fjord and STD. All member of the resource group contributed input on what they believe could impact the ecosystem in the fjord or unacceptable impacts. Acceptance criteria were then selected based on the following: it should be feasible to monitor, it should be ecologically and socially relevant, and it should be possible for the company to mitigate to meet acceptance criteria. Guided by the scientific members of the group, the resource group has determined acceptance criteria, has discussed whether predicted effects would be acceptable or not, and has set quantifiable limits for the acceptance criteria. Specific monitoring programmes were established, based on the acceptance criteria.

A protocol was developed for each acceptance criterion with a feedback loop leading to predefined actions or requirements for mitigation (Figure 3). Hence, the monitoring and associated acceptance criteria were normative for acceptable amounts of STD.

In addition to the monitoring studies required both to fulfil the obligations stated in the discharge permit and to evaluate whether acceptance criteria were complied with, several focused studies have been carried out to reduce knowledge gaps identified by the resource group or by Norwegian authorities.

Based on results from previous monitoring activities in Frænfjord, scientific literature and input from stakeholders, the following candidate acceptance criteria were considered: (1) particle concentration in the water, (2) quantity of tailings on the sea floor, and (3) ecological impact of tailings.

Acceptance criteria were then defined as follows:

1. Particles in the water column (measured as turbidity) should be <10 FTU outside the defined STD area (FTU=formazine turbidity unit) (Downing 2004). The turbidity limit was initially set to 10 FTU. Since there were no generally established turbidity guideline values this was based on experience from dredging operations and is comparable to the U.S Environmental Protection Agency (US EPA) water quality criteria for turbidity.

EPA (1988) gave values from 5 NTU (nephelometric turbidity unit (1 FTU = 1 NTU) over background level and up to 10 or 25 NTU depending on the type of waterbody.

2. Quantity of tailings on the sea bed should be less than 10 cm outside the defined STD area. This is defined by the particle sedimentation that was found to cause no effects on the macrofauna in previous studies. This was later changed to include a time factor and the acceptance criteria was modified to an annual sedimentation, which should be less than 6 mm/year at the border and outside the STD area. This is in accordance with Smit et al. (2008), who used 6 mm/year as a general effect limit for effects on macrofauna exposed to fine particle sedimentation.

3. Soft bottom macro fauna community diversity should be class II or better according to the Norwegian Environmental Agency classification system (SFT 1997) outside the defined STD area. Class I is defined as "background" level and class II as "Good" in the classification for environmental quality in fjords. The classification system is based on the diversity of macrofauna and expressed by Hurlberts index (ESn=100) (Hulbert 1971) and Shannon-Wiener index (H') (Shannon and Weaver 1963). The range for the classification is I (background) – V (strongly affected).

A feedback loop was established for each of the three acceptance criteria; turbidity is used below to illustrate a typical decision tree (Figure 4).

Monitoring

Not surprisingly, the main impact was found to be associated with sedimentation and the largest impact potential was seen for sessile organisms such as macrofauna and benthic algae.

A monitoring program was designed to provide turbidity measurements from 14 stations at least six times a year. Turbidity was measured by turbidity sensors, deployed throughout the water column at regular intervals both outside and inside the tailing deposit border (sampling sites in Figure 1). If turbidity was observed to be below 10 FTU at the border of the deposit area, then the acceptance criteria were met, and the monitoring continued as before. If the turbidity was found to be higher than 10 FTU, the company would be expected to identify the reason and carry out corrective actions. If these actions did not reduce the turbidity in the water column, the company should then discontinue their discharges until they could find a solution so that the turbidity could be kept below the acceptance criterion.

A time series of turbidity from 20-30 m depth during 2001 to 2017 from the deposit area (representing by site S4, S10, S12 and S27), from outside the deposit area (site S15, S40 and S17) and from the site closes to the outlet, site SB7, can be found in Figure 5. The depth was chosen to be the same depth as the outlet for the STD. Even at sampling sites inside the deposit area, where the acceptance criteria limits are not applicable, nearly all measurements were below the acceptance criterion at 10 FTU (average turbidity was 2.7 FTU). Outside the limit of the deposit area the turbidity was lower, typically around 1-2 FTU (average 1.3 FTU), and close to the outlet the turbidity was found to be periodically high and could exceed 160 FTU, with an average 5.0.

Quantity of tailings were measured using a gravity corer. Sediments were sampled at many sites each year and a combination of a visual inspection of the core samples and acid residue analysis gave a good estimation of the quantity of tailings on the seafloor. In addition to measure the amount of tailings in sediment traps gave a good estimate of the sedimentations amount and rates. If the quantity of tailings was observed to increase less than 6mm outside the deposit area, then the acceptance criteria were met, and the monitoring continued as before. If the quantity of tailings was found to increase more than 6mm the company would be expected to identify the reason and carry out corrective actions as described for the turbidity above. Impacts on the macrofauna in Frænfjorden was reviewed by Brooks et al. (2015). There were significant effects on the macrofauna within the deposit area, but the effects were reduced towards the border of the area. There were no apparent effects on the macrofauna at the border of the deposit area or outside the border (Brooks et al. 2015). In cases where an increased quantity of tailings has been measured at the border of the deposit area, the thickness of the tailings was found to be less than 10 cm (DNV GL 2015a). Both acceptance criteria have thus been met.

The acceptance criterion was set to 10 cm of tailings on the seafloor, but this criterion lacked a temporal property. The effect on the macrofauna would clearly be different if 10 cm tailings would be deposited over a period of weeks or months rather than years. By combining measurements of thickness data of the tailings deposited annually with the diversity of the macrofauna for the same period, an annual increase of tailings without reducing the diversity was estimated. From 2000 to 2010, the diversity expressed as Shannon-Wiener diversity index (H') did not change significantly (stable around 4.8) and at the same time the thickness of the tailings increased from 1 cm to 9 cm (Figure 5). Based on these findings the acceptance criterion was modified from the original 10 cm to an annual increase of 6 mm tailings per year (or 3 cm over 5 years). This is also in accordance with other studies, e.g. Smit et al. (2008), who used 6 mm/year as a general effect limit for effects on macrofauna exposed to fine particle sedimentation.

Inside the deposit area the macrofauna was highly affected, class V (strongly affected) close to the outlet, class II near the border. Outside the deposit area the macrofauna could be classified as "background" (class I).

Focused studies

Throughout the process, additional studies were required to address specific challenges or knowledge gaps. A series of focused studies were therefore carried out (Table 1).

ROV (Remote Operating Vehicle) was deployed for visual mapping of the seabed throughout the fjord (Det Norske Veritas 2003, DNV GL 2015a). Water column studies have included plankton distribution (DNV 2013) as well as the presence and numbers of fish and fish eggs/larvae (DNV GL 2017). A sediment profile image camera system was used to increase the knowledge about the distribution of macrofauna within sediment with different quantity of tailings (NIVA 2009). Re-colonization of macrofauna has been studied to understand how long it will it take to re-establish a healthy community after ceasing inputs to the STD (Det Norske Veritas 2009). The tailings have been characterized and specific studies have been carried out to assess effects of process chemicals on resources, both in the field and in the laboratory (DNV GL 2017, Sverdrup and Sjursen 2006). To understand how tailings are transported and distributed in the fjord, currents have been measured and modelled (DNV 2005, DNV GL 2014), sediment traps deployed to quantify sedimentation and turbidity measured extensively in the water column (DNV 2005, DNV GL 2014, DNV GL 2015a). The latter included specific studies to measure the particle distribution and sedimentation rates (DNV GL 2015b).

The focus studies provided valuable insight into how the tailings effect the fjord. But the focus studies also provided a basis by which to evaluate the acceptance criteria. As described above there was an increase in the depth of the deposit (from 1 cm to 9 cm) near the border, but at the same time the turbidity in the water in the same area was found to be too low to explain such an increase. The turbidity was measured only four times a year and the results did not probably explain the potential transport of particles as was registered e.g. by fisherman using the fjord (deposit material on fish gear near the deposit border) and the increase of tailings on the seafloor in the same areas. A focused study with continuous measurements was then initiated, including the use of a lander equipped with sensors to measure turbidity, current and temperature. The lander was deployed at the border of the deposit area (close to S14 in Figure 1). The results of the continuous measurements at 30 m depth from March to December 2013 are shown in Figure 6. During this period the turbidity was found to be between 1 and 2 FTU with a peak period in August and October (maximum 26 FTU). Continuous monitoring revealed that the concentration of tailing particles in the water column can periodically be sufficiently high to explain the observed increase in deposited tailings near the border area.

The acceptance criterion for turbidity was initially set to 10 FTU. However, routine monitoring data as well as increased knowledge about particle distribution from extended monitoring programs recombined with a literature review concerning particle impacts on fish eggs and larvae (DNV GL 2014; Messieh et al. 1981 and FeBEC 2013), suggesting that there could be effects on cod eggs and herring larvae down to 5 mg/L, led to a revision of the acceptance limit for turbidity from 10 FTU to 5 FTU as a daily average. The new acceptance criterion for turbidity was introduced in 2015.

DISCUSSION

Results from the focus studies described above led to modification of the acceptance criteria for two endpoints (turbidity and quantity of tailings). The acceptance criteria were modified as a result of data collected, an indication of the dynamic nature of an adapted management system.

A management system such as that described here is based on a protocol including a feedback loop, developed specifically for each acceptance criterion. The protocols do not have a legal standing, but are a practical way to establish a mutual understanding of environmental issues by stakeholders and how they can be evaluated. There is a clear expectation by the resource group that the company will fulfil their responsibility according to the agreed protocols.

The results from the monitoring programme are presented to the resource group once or twice a year. The resource group are encouraged to present any concerns they may have related to a real or perceived impact of the tailings in the recipient, and to suggest new endpoints or needs to increase the extent or scope of monitoring activities.

What has been developed at Omya Hustadmarmor is a structured decision-making process inspired by adaptive management which focuses on natural resources and the possibility of reducing ecological uncertainty by management (Rist et al. 2013). In this case the focus is on management of the effluent and tailings deposit that affects resources in the ecosystem, and then through mitigation actions reduce the impact. The purpose of monitoring resources and increasing knowledge through focus studies was to understand how the tailings impact the ecosystem. An essential part of the adapted management is how the company can reduce the uncertainty of environmental impacts. A substantial part of Frænfjord has been defined as a deposit area, and ecosystem impacts are expected within this designated area. Although the defined acceptance criteria only apply for the area outside this deposit area, it has also been possible to track how ecosystem components respond to different discharge solutions inside the deposit area. This has given the company valuable insight into how they can reduce effects in the ecosystem through modifying discharges.

Two examples can be used to illustrate the above: The outlet was initially close to the plant at 10 m depth, and consequently the tailings whitened the fjord and blanketed seaweed on the shore with fine material. The company tested out two mitigation actions, one to move the outlet further from the shore and submerged it to 20 m depth. As a result, the whitening of the fjord stopped, and the impact on the seaweed was reduced. Impact on the seaweed has since been a part of the regular monitoring (DNV GL 2018). In the second example, a re-colonization study indicated that process chemicals may impact macrofauna. The company responded by substituting the process chemicals with other chemicals which were thought to be more environmentally friendly (due to their chemical-physical properties and low acute toxicity). A re-colonization study is currently underway to clarify whether the new chemicals have less impact than the previously used chemicals. Other mitigation actions have been to alternate between different outlets to reduce the particle distribution in relevant areas at times with potential cod (*Gadus morhua*) spawning. A monitoring study is running to clarify whether this mitigation action has led to less particles in the water near the spawning area.

The management system is based on "learning by doing", which results in a dynamic approach to acceptance criteria limits. To change set values such as acceptance criteria is challenging to communicate since it questions the quality of earlier activities. An example is the acceptance criterion set for turbidity. It was originally set based on the available knowledge in 2003, and then revised based on new data in 2015. Consequently, the stricter acceptance criteria established in 2015 will be followed by a revised monitoring activity that could have economic consequences for the company because a more complex monitoring program may be required, notwithstanding new potential mitigation actions. These types of consequences should be agreed in the protocol established for each acceptance criterion. This is also one of the challenges using EAMS when inviting stakeholders to discuss knowledge gaps and uncertainty to assess the impact tailing has on the environment. The answer is often more monitoring and new research, rather than to do structural changes in the discharge/discharge arrangement as optimizing the discharge placement of the outlet, move the outlet, reduce the discharge permanent or occasionally, or substitute of the process chemicals. Many of these mitigation actions have been included in the management of the STP in this case as collaboration with local fishermen to reduce the deposition of tailings during spawning periods, moving the outlet to reduce the particle distributions, periodically using two outlets and testing new, less toxic, process chemicals.

Rist et al. (2013) discussed three stages to evaluate whether a management system can be described as an adaptive management system. The first stage is whether adaptive management is appropriate? In the current case this appears to be affirmative, because the company has moved towards decreasing the uncertainty in understanding the impact the tailings have on the marine ecosystem. This has also included assessing impacts beyond regular monitoring to address predicted challenges. The second stage is whether adaptive management is feasible? For the current case the answer is again affirmative, based on the predefined feedback protocol that was established for each acceptance criteria with mitigation actions. Finally, the third stage is whether adaptive management was successful? Again, the response is affirmative, in the sense of changing a system that focused more on ton discharged of tailings towards a system that has caused reduced environmental impacts, have an open dialog with stakeholders, is willing to carry out mitigations actions if the acceptance criteria were not met, or willingness to change the limits defined for each acceptance criterion.

One of the challenges with the EAMS as described here is that it has been driven by the company itself. The authorities require companies with a discharge permit to have good management systems and a regulatory agency will by necessity include parameters in the discharge permit that can be controlled. Today the company has a discharge permit that includes limits to the quantity of production chemicals used, in addition to requirements saying there should not be any negative effects in the environment outside the impact zone. If there is no demand to include an EAMS, the company must see benefits, e.g. a license to operate, but even more importantly, a motivation to reduce their impact as much as possible and to be aligned with other users of the recipient.

Another challenge is to establish a relevant stakeholder group, the resource group in this case, that can work together and focus on what can be achieved. Stakeholders may have widely varying views on specific issues, sometimes contradictory, but as a resource group they will have to adopt the common aim to reduce the impact of the tailings as much as possible. In this case the resource group has been in operation for 15 years. It can be a challenge that such a group can be become dormant and will not be the "watch dog" it should be as well as less innovative when comes solve new challenges and possibilities.

Introduction of EAMS has been a prolonged process but has resulted in higher environmental engagement from the company and an improved understanding of impacts on the environment. The EAMS that involve stakeholders, using feedback loops to address learning by doing has established a good communication between the company and the stakeholders. The stakeholders can raise their concerns on specific issues and the company will then initiate new studies to reduce the relevant knowledge gap.

One of the main challenges introducing EAMS has been to define accept criteria that are both feasible to monitor and includes mitigation actions that can be activated if the acceptance criteria are not met. In this case, mitigation actions as periodical alteration in the design, composition and outlet placement has been found to work according to the intention.

CONCLUSIONS

Introduction of an EAMS for Omya Hustadmarmor has resulted in a change in the company's focus on the impact they have on the environment, and a willingness to initiate monitoring, research and effectuate mitigation actions to reduce knowledge gaps and uncertainty in the environmental impacts of their activity.

This case study demonstrates the usefulness of a dynamic management system where acceptance limits may change based on updated knowledge. The introduction of EAMS for the company has facilitated the development of a more ecologically relevant, integrated and focused STD management.

The main success factor for the environmental adaptive management system at Omya Hustadmarmor was the introduction of resource group, with focus on involvement and collaboration between local stakeholders and the company itself.

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Data Accessibility

Data for turbidity versus time is available in supplemental files.

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Focus studies	**Studies includes**	**References**
Particles in the water column and sedimentation	Current/water exchange Sedimentation *In situ* particle distribution	DNV 2005; DNV GL 2014 DNV 2005; DNV GL 2014; DNV GL 2015a DNV GL 2015b
Effects of particles and chemicals	Distribution of plankton Distribution of fish eggs Chemicals in biota Ecotoxicity testing	DNV 2013 DNV GL 2017 DNV GL 2017 Sverdrup and Sjursen 2006
Biodiversity and potential effects on benthic fauna	Visual mapping using ROV Distribution of indicator species Sediment profile imaging Re-colonization of macro fauna	Det Norske Veritas 2003; DNV GL 2015a Det Norske Veritas 2012 NIVA 2009 Det Norske Veritas 2009
Other environmental factors	Nutrients	DNV 2013

Table 1. Overview of focus studies addressing specific issues.