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# Guidelines and best available techniques for submarine tailings disposal in Norwegian fjords:

## Recommendations from the NYKOS project.

Foto: NIVA

Norwegian Institute for Water Research

# REPORT

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Summary

The NYKOS project aimed at addressing some of the main knowledge gaps on the environmental impacts of submarine tailing disposal (STD) to facilitate the development of techniques, practices and management measures that will minimize such impact. Here, we report on the main issues addressed by the different research groups within NYKOS, the results obtained during the project and how this new knowledge can be used by the authorities to develop guidelines for best available techniques related to STDs in Norwegian fjords.

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# Guidelines and Best Available Techniques for Submarine Tailings Disposal in Norwegian fjords: Recommendations from the NYKOS project

# Preface

This report has been compiled as one of the synthesis products of the NYKOS (New Knowledge on Sea Deposits; https://www.sintef.no/projectweb/nykos/) project (2014-2019) funded under the Norwegian Research Council BIA programme (contract 236658), which is gratefully acknowledged. The project aimed at increasing the knowledge base around the impact of submarine tailings disposals on the marine environment in Norway, to facilitate the development of new environmentally-sound criteria and monitoring technologies that would allow for a more sustainable mining industry in Norway. The NYKOS project was coordinated by Dr Per Helge Høgaas form SINTEF. The project included partners from SINTEF (particle distribution modeling), NGU (geology), NTNU (chemistry of process chemicals) and NIVA (environmental chemistry, biogeochemistry, ecology, ecotoxicology and habitat mapping and statistics). NYKOS included also seven industrial partners: Sydvaranger Gruve, Nussir ASA, Sibelco Nordic, Rana Gruber, Omya Hustadmarmor, Nordic Mining and Titania. An External Advisory Board composed by 6 members (Dr. Jens Skei – Skei Mining Conultant; Dr. Tor Jensen – DNV-GL; Dr. Tracy Shimmield – SAMS UK; Adm. dir Espen Lillebrygfjeld – OMYA; Gen. sekr. Elisabeth Gammelsæter – Norsk Bergindustri; Dr. Paul F Wassmann – UIT) provided continuous advice to the project. Dr Laura Ferrando-Climent, from the Institute for Energy Technology (IFE), has contributed in the development of the advanced analytical tools and characterization of the samples in NYKOS.

This report presents the main results of the project as well as the outcomes of a synthesis and best available techniques workshop organized in Oslo in March 2019 and with participation of all NYKOS research and industrial partners, as well as members of the Advisory Board, the FIMITA and DiTAIL research projects and the Norwegian Environmental Agency.

Oslo, 20 November 2019

Dr Eva Ramirez-Llodra
NIVA

# Table of contents

# Summary

Mining in Norway is currently in a phase of increased growth and subject to new environmental regulations. Many mines are particularly challenged by waste management, as they often produce large quantities of mineral tailings from processing. To overcome problems associated with deposition of mineral waste produced, many mines place their tailings at the seafloor of fjords as submarine tailings disposal (STDs). The NYKOS project aimed at addressing some of the main knowledge gaps on the environmental impacts of STDs to facilitate the development of techniques, practices and management measures that will minimize such impact. Here, we report on the main issues addressed by the different research groups within NYKOS, the results obtained during the project and how this new knowledge can be used by the authorities to develop guidelines for best available techniques related to STDs in Norwegian fjords.

The physiochemical properties of the tailings are governed by the preceding comminution and separation processes in the process plant, but they are not necessarily optimized for the reactions that take place in a system where the tailings are disposed to the marine environment and fresh process water meets seawater. WP2 (NTNU) focused on the considerable potential for improving properties of the tailings through novel approaches to study on adsorption/desorption characteristics of chemicals in order to prevent over dosage or recycle them prior to submarine tailings disposal. A rapid, simple and low-cost UV-spectrophotometric methods for quantitative analysis of the flotation collectors was developed and validated. Optimal selection of the disposal site as well as the assessment of long-term fate of tailings require detailed seafloor geological maps (marine base maps) that integrate substrate information with bathymetric data. Geological mapping and acquisition of full spatial coverage acoustic datasets should be undertaken during both planning and operational phases of submarine disposal. These issues were addressed in WP3 (NGU). Mine tailings contain micrometer-sized particles, which can be spread with currents in the ocean. The particles will also tend to stick together in saltwater, potentially forming large, complex flocs, which will sink at a different speed from the original particles. WP5 (SINTEF) developed and deployed new particle imaging systems to directly observe mine tailings flocs in the ocean. Numerical models that can simulate the spreading and flocculation of tailings particles were also developed. The mine tailings discharged in the marine environment usually contain a variety of chemicals employed to separate the minerals. WP4 (NIVA) developed an analytical methodology based on chromatography coupled to high resolution mass spectrometry to identify the presence of these chemicals at the low levels usually found in environmental samples. The methodology allows resolving the complexity of the analysis of technical products (that regularly consists of complex mixtures of chemicals) and track their fate and behavior in the fjord. Mine tailings can have toxic/harmful effects in marine organisms through both the physical impact of the particles as well as the chemicals present on the tailings. Studies in WP4 (NIVA) were able to differentiate between chemical and particle effects (shape/ size) using a combination of sediment elutriate and whole sediment toxicity bioassays in a range of marine organisms. Furthermore, by using mussels exposed to the mine tailings within a fjord recipient, the impact of environmentally relevant concentrations of mine tailings with distance from the discharge point can be determined. The seafloor is the ecosystem compartment that is most affected by submarine disposal of mine tailings. WP4 (NIVA) investigated the effects of tailings on the fauna at the seafloor *in situ* and through experimental studies, to better understand the role played by sedimentation rate at the border of the impact area. Alsothe recovery potential of tailings-impacted sediments was studied. After submarine tailings disposal is ended, the deposition sites are rapidly recolonized by a number of different species. However, the biological condition does not necessarily respond to the potential presence of contaminants such as flotation chemicals or trace metals. WP4 (NIVA) investigated the mobilization of metals from ilmenite tailings deposited on a seabed site more than 20 years ago. The study was done in undisturbed sediment cores transferred to a soft bottom mesocosm. During the

synthesis phase of NYKOS, WP6 (NIVA) conducted a spatio-temporal modelling exercise that integrated geological, physical, chemical and ecological data with the aim to assess if faunal composition seemed to be affected by the STD and if the pattern changed through time. Based on all the scientific results and discussions during the synthesis phase in WP6 (NIVA), NYKOS highly recommends the development of best available technologies (BATs) for submarine tailing disposal in Norwegian fjords.

# Sammendrag

Tittel: Veileder og best tilgjengelige teknologier for sjødeponering av gruveavgang i norske fjorder: Anbefalinger fra NYKOS-prosjektet.
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Forfatter(e): Eva Ramirez-Llodra, Guri S. Andersen, Trine Bekkby, Steve Brooks, Carlos Escudero-Oñate, Hege Gundersen, Morten Schaanning, Hilde C. Trannum & Evgeniy Yakushev (NIVA), Nicole J. Baeten & Aivo Lepland (NGU), Olga Ibragimova & Rolf Kleiv (NTNU), Raymond Nepstad & Per Helge Høgaas (SINTEF), Roar Sandøy (Sibelco)
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Gruvedrift i Norge er for tiden i en fase med økt vekst og nye miljøbestemmelser. For mange gruver er håndtering av store mengder mineralske avgangsmasser fra oppredningsverket en betydelig utfordring. En måte å løse dette på er å deponere avgangen på bunnen av fjorder i såkalte sjødeponier (STD). En målsetting for NYKOS-prosjektet har vært å håndtere noen av de viktigste kunnskapshullene knyttet til miljøpåvirkningene av STD og derigjennom bidra til utvikling av teknikker, praksis og styringstiltak som vil minimere slik påvirkning. I denne rapporten gjennomgås hovedspørsmålene som er adressert av de forskjellige forskningsgruppene i NYKOS, resultatene som er oppnådd i løpet av prosjektet og hvordan denne nye kunnskapen kan brukes av myndighetene til å utvikle retningslinjer for best tilgjengelige teknikker relatert til STD i norske fjorder.

De fysiokjemiske egenskapene til avgangen styres av de foregående knuse- og separasjons-prosessene i oppredningsverket, men de er ikke nødvendigvis optimalisert for reaksjonene som finner sted i et system hvor avgangen slippes ut i det marine miljøet og prosessvann med lav saltholdighet møter sjøvann. WP2 (NTNU) fokuserte på det betydelige potensialet for å forbedre egenskapene til avgangen gjennom nye metoder for å studere adsorpsjon / desorpsjons egenskapene for kjemikalier for å forhindre overdosering eller øke resirkulering før plassering i sjødeponiet. Raske, enkle og rimelige UV-spektrofotometriske metoder for kvantitativ analyse av flotasjonskjemikalier ble utviklet og validert.
Best mulig valg av deponeringssted samt vurdering av langsiktige effekter av avgangen krever detaljerte geologiske kart over havbunnen (marine basiskart) som integrerer underlagsinformasjon med batymetriske data. Geologisk kartlegging og anskaffelse av høyoppløselige datasett bør utføres i både planleggings- og driftsfaser for STD. Dette ble adressert i WP3 (NGU). Gruveavgang inneholder ofte små partikler (mikrometer-skala), som kan spres med vannstrømmene i fjorden. Partiklene vil også ha en tendens til å feste seg sammen i saltvann, og potensielt danne store, komplekse fnokker, som vil synke med en annen hastighet enn de opprinnelige partiklene. WP5 (SINTEF) har utviklet og anvendt nye teknikker for direkte (in situ) observasjon av avgangsfnokker etter utslipp i fjorden. Numeriske modeller som kan simulere spredning og flokkulering av avgangspartikler ble også utviklet. Gruveavgang som slippes ut i det marine miljøet inneholder ofte en rekke kjemikalier som brukes til å skille mineralene. WP4 (NIVA) utviklet en analytisk metode basert på kromatografi koblet til massespektrometri med høy oppløsning for å identifisere tilstedeværelsen av disse kjemikaliene på de lave nivåene som vanligvis finnes i miljøprøver. Metodikken gjør det mulig å løse kompleksiteten i analysen av kjemikaliene, som ofte består av komplekse blandinger av flere komponenter, og spore deres skjebne og oppførsel i fjorden. Avgangen kan ha skadelige effekter i marine organismer som følge både av den fysiske påvirkningen av partiklene (form / størrelse) så vel som av kjemikaliene som er til stede på avgangen. Studier i WP4 (NIVA) var i stand til å differensiere disse effektene ved å kombinere diverse biologiske tester med marine organismer eksponert i vannuttrekk og sedimenter med avgang fra pågående gruvevirksomheter i Norge. Ved å bruke blåskjell eksponert i en fjord påvirket av gruveavgang, kunne påvirkningen fra miljørelevante konsentrasjoner i økende avstand fra

utslippspunktet også bestemmes. Sjøbunnen er det økosystemrommet som blir mest påvirket ved utslipp av gruveavgang i en fjord. Gjennom eksperimentelle studier og feltstudier undersøkte WP4 (NIVA) effekten av avgang på bunnfaunaen, og det ble oppnådd en bedre forståelse for hvordan sedimentasjonsraten vil påvirke influensområdet rundt utslippspunktet. Etter avsluttet deponering, rekoloniseres deponeringsområdet raskt av en rekke forskjellige arter. Den biologiske tilstanden reagerer imidlertid ikke nødvendigvis på den potensielle tilstedeværelsen av forurensninger som flotasjonskjemikalier eller spormetaller. WP4 (NIVA) undersøkte mobiliseringen av metaller fra ilmenittavgang i sjødeponier som ble avsluttet for mer enn 20 år siden. Studien ble gjort i uforstyrrede sedimentkjerner overført til en sjøbunn-mesokosmos. I syntesedelen av NYKOS gjennomførte WP6 (NIVA) en rom-tids modelleringsøvelse som integrerte geologiske, fysiske, kjemiske og økologiske data. Målet var å vurdere om faunasammensetningen syntes å være påvirket av STD og om mønsteret endret seg gjennom tiden. Basert på alle vitenskapelige resultater og diskusjoner under syntesefasen i WP6 (NIVA), er det en klar anbefaling fra NYKOS at det etableres retningslinjer for best tilgjengelige teknologier (BAT) for deponering av gruveavgang i norske fjorder.

# 1 Introduction: submarine tailings disposal

Global demands for mineral resources are rapidly increasing, not only to sustain traditional needs of minerals and metals, but also for the development of new, green energy technology such as wind turbines or electric-car batteries (Vogt, 2013; Dold, 2014). Discussions based on robust scientific and engineering knowledge need to take place to find the necessary balance between exploration for and exploitation of known and new resources, and the development of new technologies and re-cycling of existing resources. However, the United Nations Environment Programme (UNEP) has predicted that the amount of minerals, ores, fossil fuels, and biomass consumed globally per year could triple between current day and 2050 (NCIR, 2013). Mining activities produce vast amounts of waste, and the environmentally-sound management of such waste, at all stages of mining (production, closure and post-closure) is one of the major issues faced by the mining industry, and a major concern for civil society. Mining waste includes rocks from overburden and tailings representing the waste produced after the target mineral has been extracted from the ore, and accounts for a high proportion of extracted ore (e.g. up to 99% for copper, 99.99% for gold (MMSD, 2002)). Tailings are usually in the form of a fine-particle slurry that can include process chemicals (flocculation and flotation). The tailing particles can have variable mineral composition and different shapes and sizes. Most mines world-wide dispose tailings in land-based dams, which, however, can be prone to failure in areas subjected to certain environmental conditions (e.g. seismicity, heavy precipitation, topography). Hence, in some countries, submarine tailings disposal (STD) or deep-sea tailings disposal (DSTD) are preferred as tailings management approach (reviewed in Dold et al., 2014; Reichelt-Brushett, 2012; Ramirez-Llodra et al., 2015; Vare et al., 2018). In Norway, the submarine tailings disposal in fjords is prioritized because many mineral deposits are adjacent to fjords with natural sedimentation basins that can make dispositioning in these environments a preferred solution over land management of tailings (Norwegian Environment Agency, 2019).

STD management is a major source of conflict between the mining industry and local and national stakeholders. If mining is to continue and prosper in Norway, it must be done using techniques that ensure that the environmental impacts from STDs are reduced to an absolute minimum (i.e. by applying the best available technologies (BAT)), and ecosystems are given every chance to recover as quickly as possible following the closure of mines. However, we still have only a basic understanding of how best to dispose mine tailings in the marine environment, how to monitor the deposits through time, what ecosystem impacts do they have and how to ensure that fjord systems recover as quickly as possible after a mine closes down. To address some of these knowledge gaps, the NYKOS project (New Knowledge on Sea Deposits, Norwegian Research Council BIA programme (project 236658) aimed at increasing the knowledge base around the impact of STDs on the marine environment in Norway, to facilitate the development of new environmentally-sound criteria and monitoring technologies that would allow for a more sustainable mining industry in Norway. The NYKOS project included four scientific work packages addressing specific questions (Figure 1): 1) solutions to improve tailings characteristics prior to their deposition in the marine environment; 2) marine geological mapping to improve location selection and monitoring of STDs; 3) improved methods to assess the effects of STDs and associated chemicals on marine benthic ecosystems; and 4) oceanographic modelling to assess the distribution and dynamics of tailing particles in the marine environment. All NYKOS results and data have been integrated and synthesized during the project's synthesis phase through a synthesis workshop with a focus on BATs and environmental guidelines. The conclusions of this exercise are reported here.

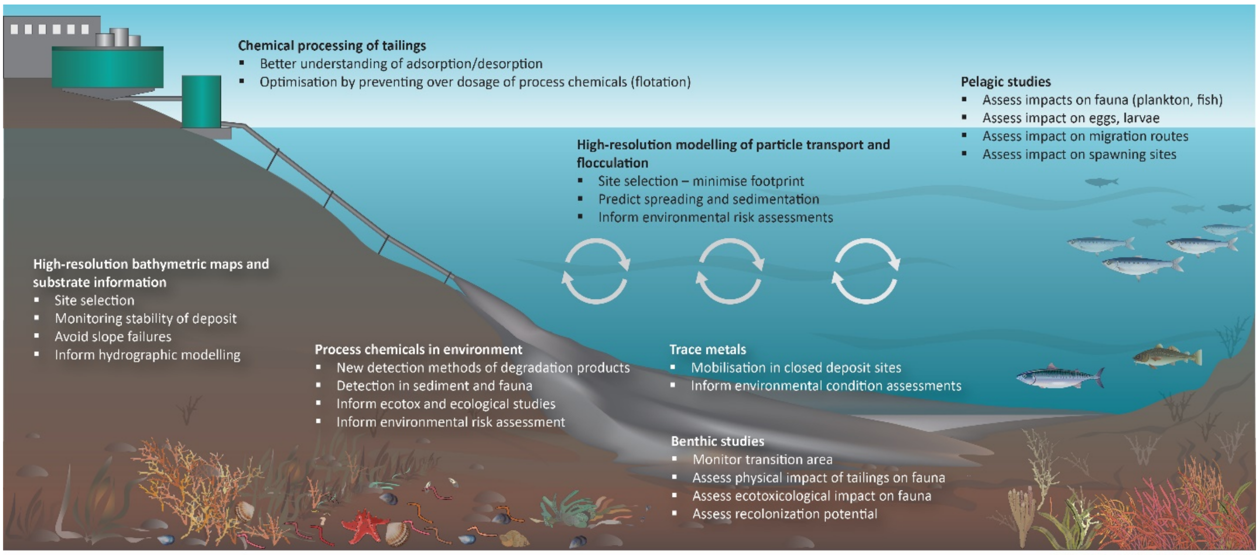


*Figure 1. Schematic diagram showing a submarine tailing disposal in a fjord and the main processes studies during the NYKOS project (excluding pelagic studies). SINTEF/NYKOS.*

# 2 Main results from the NYKOS project

The NYKOS project has conducted scientific investigations and multi-stakeholder discussions with industry and authorities for 5 years (2014-2019), to increase the knowledge base around the impact of STDs on the marine environment and facilitate the development of new environmentally-sound criteria and monitoring technologies to allow for a more environmentally-sustainable mining industry in Norway. NYKOS was a multidisciplinary and multi-sectoral project that included research in geology, physical oceanography and modelling, environmental chemistry, ecotoxicology, marine ecology and spatial modelling. Below, we provide a description of the main results obtained in each of the different topics addressed. The results are then synthesised and discussed in the framework of best environmental guidelines and best available techniques for submarine tailings disposal management in Norwegian fjords.

## 2.1 Bathymetry and geology

Disposal of tailings causes disturbance of the seafloor environment, but the dispersal, distribution, and stability of disposed materials are ultimately linked to the natural physical processes operating in the water column and on the seafloor. Hence, detailed seafloor geological maps (marine base maps) based on multibeam echosounder data (bathymetry and backscatter), sub-bottom profiler data and ground truth information (bottom type/sediment grain size) are required for reliable predictions of the fate of submarine tailings. Modern multibeam echosounder technology allows to obtain high-resolution bathymetry and backscatter datasets, which, combined with the results of seafloor sediment characterization (seabed samples) and visual observations (video footages of seafloor) can be used for producing detailed, full spatial coverage geological maps. Such maps provide information on sediment dynamics and can outline areas where erosion or accumulation processes are prevailing. The maps help also to uncover areas that can be sensitive to slope failures and allow to identify seafloor pockmarks representing fluid flow conduits where fluid expulsion currently occurs or has occurred in the recent past.

The geological datasets obtained in the frame of the NYKOS project from the studied fjords Bøkfjorden, Stjernsundet, Ranfjorden and Frænfjorden have allowed to make a clear distinction between tailings and natural sediments, identify the extent of the tailings on the seafloor (that can extend >10 km from the discharge point (Bøkfjorden)), and assess processes governing their dispersal as suspended particles, resuspension of tailings, slope failures and bedload forming migrating sand waves (e.g. Baeten et al., submitted; Bøe et al., 2018). Comparison of several bathymetric datasets demonstrated the usefulness of repeated surveys to evaluate the accumulation dynamics. Studies of sediment cores from Ranfjorden demonstrated that tailings in some areas have effectively capped seafloor sediments significantly contaminated by toxic metals and thereby isolated the metals from the environment. In Frænfjorden, pockmark formation in the natural seafloor along the edge of the tailings reflects the loading triggered dynamic compaction regime in natural sediments and tailings causing fluid expulsion (Figure 2).

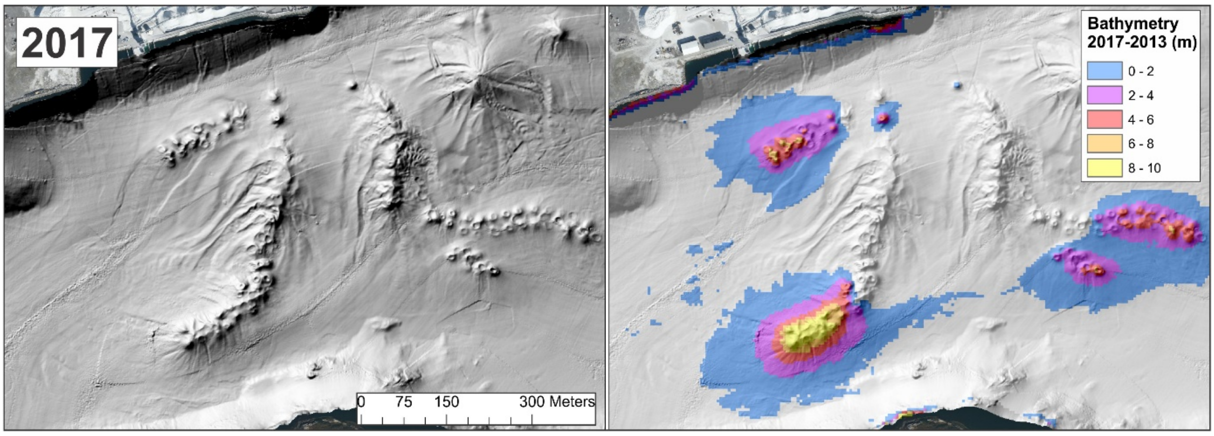


*Figure 2: Shaded relief images of the seafloor at the disposal site in Frænfjorden. Left panel shows a shaded relief image in 2017 with three chains of cone-like features marking positions of discharge pipes that have been extended into in the fjord. Right panel shows bathymetric difference between the 2013 and 2017 data visualized on the 2017 shaded relief image.*

Given the crucial importance of a variety of geological processes operating on the seafloor, the optimal selection of the disposal site as well as the assessment of the stability of tailings is tightly linked to the results of geological mapping/monitoring that needs to be undertaken during both planning and operational phases of submarine disposal.

## 2.2 Assessing and modelling particle distribution

Particulates from tailings discharged into the sea tend to settle in the water column due to their higher density compared to the ambient water. The settling speed depends on the size of the particles; smaller particles settle slower than large particles and may be transported with ocean currents further from the discharge site. Small particles in enough concentration tend to aggregate in the presence of saline water, and such aggregates (or flocs) can settle more rapidly than their individual constituents. The underlying *flocculation processes* are complex, depending on many variables, including salinity and particle concentrations, particle size distribution, turbulence and background concentrations of organic matter. To understand, predict and ultimately control tailings transport and fate in the ocean, flocculation, currents and other relevant oceanic processes and particle properties must be sufficiently understood.

Through the NYKOS project, we have used a suite of imaging instruments (including the LISST-100X and the SINTEF SilCam) to study the distribution, concentrations, shape and sizes of tailing particles and flocs. Data obtained with these instruments in Frænfjorden have enabled us to determine the size distribution of suspended particles/flocs and their concentration, as well as the distribution of suspended tailings in the fjord. These data show a shift in the smallest particle sizes towards larger flocs, and also presence of complex structured flocs several millimeters in length (Figure 3). Over time in suspension, small and dense tailings-based flocs can interact with background concentration of organic material, which can result in larger flocs composed of different materials, with a relatively low bulk density. These larger flocs can remain in suspension for some time, and were hypothesized to explain some of the observations in Frænfjorden (Davies and Nepstad, 2017). The application of these instruments to other tailings disposal sites could reveal important information about the site-specific tailings transport dynamics.

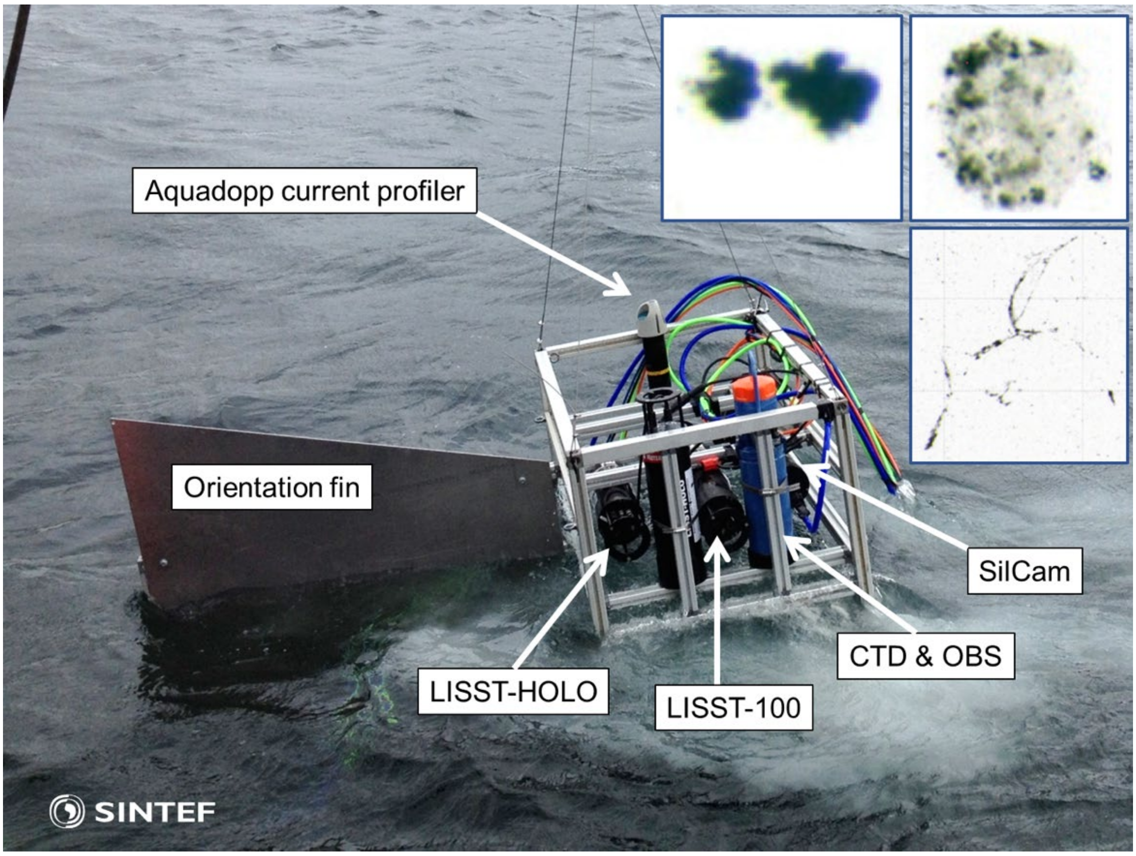


*Figure 3: The instrument package used to measure tailings concentrations in the water column and particle size distribution. Inserts shows examples of flocs imaged in suspensions in Frænfjorden.*

Numerical models (DREAM[1] and SINMOD[2]) for predicting tailings transport and fate have also been improved and used in NYKOS to study the disposal in Frænfjorden. Models are important parts of the toolbox for understanding tailings transport, partly complementary to observational tools. The DREAM model predicts the sedimentation rate and suspended tailings concentration in the entire study domain, which can be used to infer the environmental impact of the discharge, variations in time and space, and the effect of changing upstream conditions of the discharge itself (position, composition, rate, etc.).

A remaining challenge is the accurate quantification of in situ settling speed of tailings flocs, which together with the floc size (and shape) can be used to infer densities, and thus mass concentrations.

[1] www.sintef.no/DREAM
[2] www.sinmod.no

These types of data are also important input to numerical models, and for further development and improvement of such tools. Moreover, different concentration or concentration proxy measurements from commonly used instruments require further study. For instance, the relationship between turbidity, a much-used concentration proxy, and particle concentration is known to depend on particle size distribution and concentration, in addition to the instrument type and settings.

## 2.3 Tailings post-processing

The potential environmental impacts of STPs are directly dependent of the oceanographic, biochemical, and ecological conditions of the site, as well as the specific mineral processing solution employed by the processing plant. The physiochemical properties of the tailings are governed by the preceding comminution and separation processes, but they are not necessarily optimized for the reactions that take place in a system where the tailings are disposed to the marine environment and fresh process water meets seawater. A range of experiments were conducted to evaluate the potential for improving the properties of the tailings with respect to the amount and state of flotation chemicals adsorbed to their surfaces. This was done by investigating the adsorption/desorption characteristics of the chemicals/minerals-systems. The results could be used in order to prevent over dosage or to recycle, remove or destroy the residual chemicals prior to submarine tailings disposal. As part of this work, a rapid, robust, sensitive and low-cost UV-spectrophotometric methods for quantitative analysis of the flotation collectors were developed and validated. The result showed that flotation chemicals desorb to a lesser extent than expected provided that the original chemical dosage is not too high. This seems to be true not only for the collectors that are chemically adsorbed, but also when physical/electrostatic adsorption is the main mechanism. However, the desorption of flotation collectors was highly affected by the duration of exposure to seawater and the initial concentration of chemicals. In the case of the amine/calcite marble-system, the results indicated that less than 4% of the adsorbed flotation collector was desorbed when the initial concentration was equal to the industrial dosage. At concentration levels higher than those required for efficient flotation multilayer adsorption was present, and significant desorption occurred.

The results suggested that exposure to seawater could accelerate the chemical degradation or decomposition of the flotation collectors within a timeframe of 18-24 hours. Furthermore, there could be a potential for accelerating of the breakdown within time frame from mineral separation to the release of tailings. In practice, this could amount to several hours. Accelerated breakdown could possibly be achieved by manipulating temperature, solution chemistry or the addition of reactive mineral surfaces. Such mechanisms would be highly dependent on the specific mineral/collector-systems.

The results show how easily accessible low-cost analytical methodology can be developed and employed to determine the extent of desorption of flotation chemicals when the tailings are mixed with sea water. This would facilitate the establishment of simple test protocols that could be integrated in future BAP guidelines. It is important to note that such tests must be tailored to the mineral/collector-systems in question, but it is possible to propose general guidelines to aid the establishment of new test protocols. While we are able to follow the kinetics of desorption of flotation collectors by seawater in a simplified synthetic system, the studies of more mineral/collector systems and decomposition mechanisms in both fresh process water and seawater are necessary. Combined with techniques for the direct characterization of surface-adsorbed species, these selective and specific methods can be applied efficiently in aqueous mineral processing systems and offers new insight into the fate of flotation chemicals when the tailings are exposed to seawater.

## 2.4 Chemicals in the ecosystem

Large amounts of chemicals are discharged with tailings from certain mining industries. However, there's still a very scarce knowledge about their environmental fate and the effects that the different families of chemicals employed may produce in the ecosystems. Currently, very little is known about the transformation routes that these chemicals undergo (both, chemical and biological) once disposed into the environment, raising a large uncertainty on the structure, activity and potential environmental toxicity of these transformation products. Their hydrolytic behaviour, mass transport rates and distribution between solid-liquid as well as the potential biotransformation remain almost unexplored for most of the technical products employed nowadays.

This knowledge gap is partly due to the complexity of the technical mixtures employed in the different mining operations and the lack of appropriate methods for studying the distribution of the chemicals in various environmental compartments such as sediment, pore water and biota. In the NYKOS project, appropriate methods have been developed and successfully implemented in the analysis of samples collected during one season in one specific fjord.

Tensioactives are among the most widely employed chemicals in mining operations. However, these substances regularly consist of very complex mixtures of different structures that become even more difficult to resolve considering that when discharged into water bodies, they may undergo a series of reactions that lead to the formation of new products.

In the NYKOS project, an analytical procedure based on extraction followed by separation through Ultra HighPerformance Liquid Chromatography (UPLC) and coupled to High Resolution Mass Spectrometry (HRMS) has been developed for one particular chemical, a cationic flotation collector that belongs to the family of the esterquats (FLOT2015). Based on the description provided by the supplier of the technical product and the expected reactivity of this type of esterquat in the marine environment, it was developed a list of suspected esterquat-based compounds and their accurate masses were calculated. These masses where employed to tentatively identify the presence of these compounds in environmental samples. This method was successfully applied to characterize the composition of the technical product employed in the flotation operations of the mining company and to track the presence of the different components in different compartments: sediments, water and biota.

From the different transformation products of the technical product FLOT2015, one of them, the methyltriethanolammonium (Figure 4) was commercially available and therefore its qualification and quantification in the different samples from the fjord was possible.

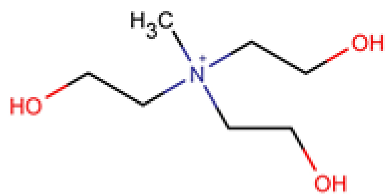


*Figure 4. Structure of the cation methyltriethanolammonium (MTOA).*

The MTOA moiety was monitored along the fjord in sediment samples at different locations and depths (0-10 cm). Valid samples for analysis were retrieved from the locations NY1, NY3, NY4 and NY5 indicated in the map of Frænfjorden below (Figure 5). A general decreasing trend in the concentration of this chemical in both sediments and pore water was observed along the fjord at increasing distances from the discharge point. MTOA concentration was also found to decrease with the depth of the sediment. These results indicate a preliminary desorption process from the mineral particle followed by its release into the pore water. This chemical once released into the fluid phase can be transported to the surface of the seabed to be further diluted in the large water mass. Concentrations of MTOA in the range of few mg/kg dry sediment and in the range of µg/L in the case of pore water were observed in all the sampled locations and depths.

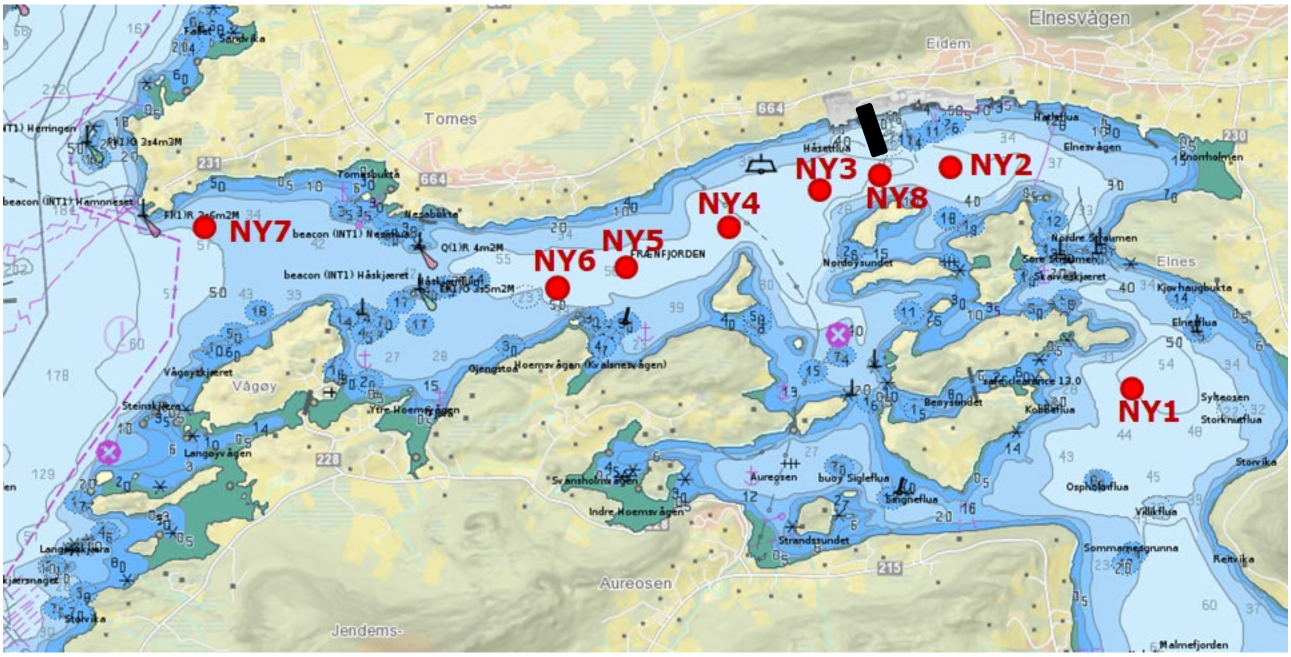


*Figure 5. NYKOS sampling stations in Frænfjorden (red dots) in relation to the STD pipeline location (black rectangle).*

The development of methods for other types of process chemicals has great potential to produce new knowledge relevant to develop the best available techniques (BAT) to manage the future sea deposits for mine tailings. Advanced analytical techniques such as these employed in the NYKOS project based on UPLC-HRMS are ready to be deployed in routine monitoring and control programs of sites affected by STDs. Close cooperation of industries responsible for STD is essential in the tune-up of the analytical methods and to establish the list of suspected chemical structures to be tracked in the environment.

## 2.5 Trace metals distribution and geochemical fluxes

Sea deposit sites for ilmenite tailings abandoned more than 20 years ago were surveyed to assess the distribution and fluxes of trace metals at the sediment-water interface (Schaanning et al., 2019). Sediments with viable macrobenthic communities were sampled from 12 stations using a 0.1 $m^2$ box corer with internal liners. The liners were carefully transferred to and maintained in a benthic mesocosm facility for *in situ* measurements and subsampling. Metals were analysed in sediments and pore water extracted by centrifugation. High-resolution, vertical profiles were obtained by 24h exposure of 12 cm long DGT-probes (Diffusion Gradient in Thin films) sectioned at 2-10 mm depth intervals. Metal fluxes were measured in a flow-through system set up on each core sample.

Consistent maxima on the DGT-profiles, revealed oxidation of metal sulfides and dissolution of nickel (Ni), copper (Cu) and cobalt (Co) 5-20 mm below the sediment-water interface (Figure 6). The distribution of Co revealed a second production zone at about 25 mm depth produced by a more complex redox cycling of this metal. The DGT profiles provided no evidence for diffusive transport of trace metals from deep deposit layers, but the near-surface oxidation of metal sulfides appeared to be maintained by an upward transport of tailings within the bioturbated top layer. Thus, the upward transport of tailings by bioturbation and subsequent reaction with $O_2$ supplied from the overlying seawater, sustained enhanced leakage of metals from the sediments to the overlying water. A daily leakage of 391 g Ni, 89 g Cu and 50 g Co was estimated for the entire 3 $km^2$ area of seabed affected by ilmenite tailings. For comparison, the current leakage of nickel from the land-deposit established after sea deposition was finalized is 7900 g Ni/day.

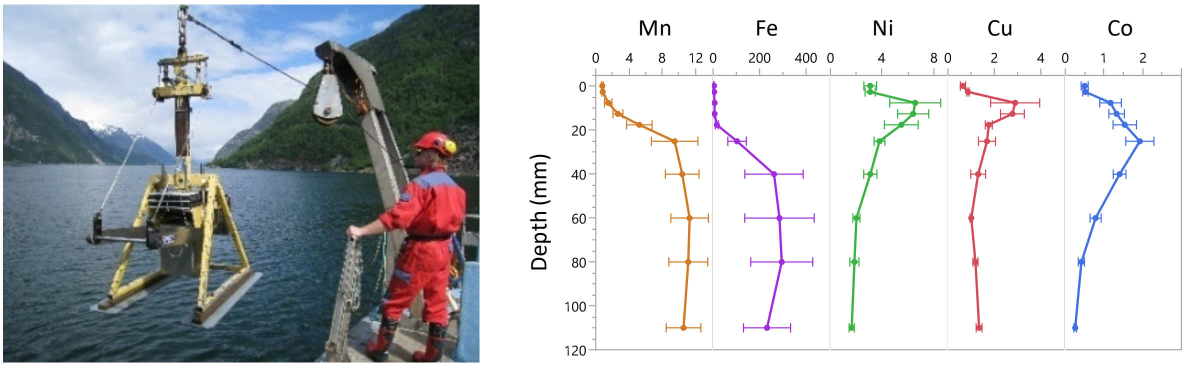


*Figure 6: Vertical profiles of metals in pore water measured with DGT-probes in box core sediment samples from an abandoned sea deposit for ilmenite tailings. The profiles show near-surface mobilisation of nickel, copper and cobalt, but no upwards diffusion of nickel, copper and cobalt from deep deposit layers. The depth scale on the profiles indicates depth in sediment.*

Metal transformations are primarily controlled by pH and redox conditions. High resolution (mm-scale) vertical variations of these parameters and metals dissolved in the pore water were applied to understand metal cycling at the sediment-water interface of the submarine deposit with sulphide tailings. Bioturbation is an important process which acts to slow down natural burial of tailings and provides vertical mixing of mineral particles across the biogeochemical gradient causing minerals which are stable at one location to dissolve in another location. These processes are restricted to the upper, bioturbated layer. The time required post deposition for depletion of mine tailings within the bioturbated layer may be considered the time required to restore natural levels of metal fluxes and metal bioavailability. Local rates of sedimentation and bioturbation are the two essential parameters for prediction of this time of recovery of the deposit site.

## 2.6 Biogeochemical model for metal transformation at the sediment-water interface

Transformation at the sediment water interface (SWI) of metals as an example of nickel was studied with a 1D benthic-pelagic coupled biogeochemical model, BROM (Yakushev et al., 2017) supplemented by a Ni module specifically developed for this study (Figure 7).

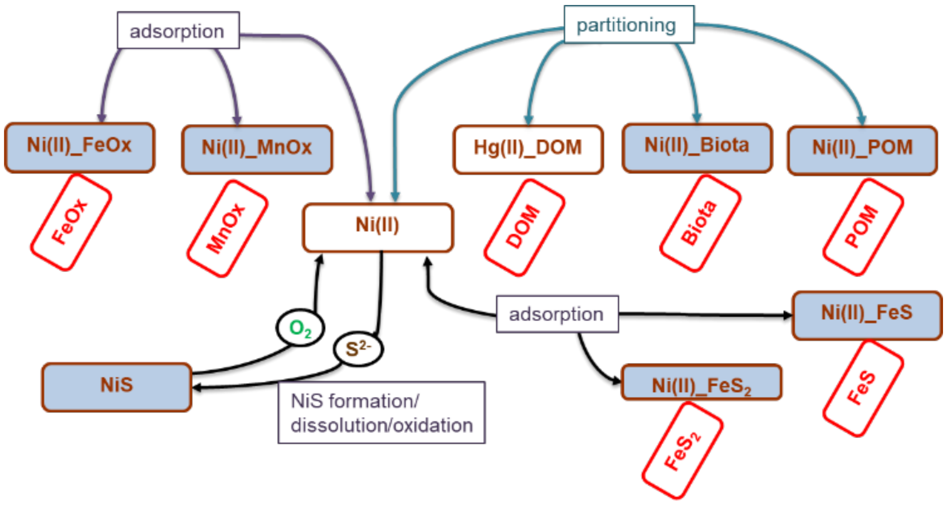


*Figure 7. Nickel transformations in aquatic ecosystems parametrized in the brom_ni module. Brown rectangles correspond to the state variables in the brom_ni module, red rectangles correspond to the state variables of BROM, whose concentrations are used in calculations of Ni transformations. Uni-directional arrows reflect the processes considered in the model. Open brom_ni rectangles represent dissolved species and shaded ones represent particulate species. The processes occur both in the pelagic and benthic parts of the model.*

BROM considers interconnected transformations of species (N, P, Si, C, O, S, Mn, Fe). Organic matter (OM) dynamics include parameterizations of OM production (via photosynthesis and chemosynthesis) and OM decay. To provide a detailed representation of changing redox conditions, OM in BROM is mineralized by several different electron acceptors and dissolved oxygen is consumed during both mineralization of OM and oxidation of various reduced compounds. Transformations of variables are considered both in the water column and in the upper sediment layer, as well as exchange with the atmosphere for gases (e.g., $O_2$, $CO_2$). The Ni module considers Ni species transformations interconnected with other chemical compounds involved in the Ni cycle: $O_2$, S, Fe, Mn, dissolved and particulate OM and biota. Simulation of redox-dependent changes is a convenient way of studying Ni fate under variable redox conditions. The model was optimized using field data collected in Jøssingfjord. The fjord baseline water column and sediment biogeochemistry and nickel cycling were simulated for the period before tailings disposal, during the intensive disposal and during the post-closure restoration period.

The model allowed to simulate the principal features of distributions and seasonal variability of biogeochemical parameters and Ni compounds in the water column and the SWI before (1950-1960) during (1960-1984) and after (1984-2020) the tailings (Figure 8). On the base of this it was possible to calculate an interannual variability of benthic flux of total dissolved Ni and demonstrate that the sediments of the disposal site can be considered as a significant source of nickel about 10 years after closure. Modelled estimates of the Ni fluxes for the present time are in a good agreement with the observed fluxes (Schaanning et al., 2019). In the future, such a model can be extended to other important substances, i.e. compounds of Cu.

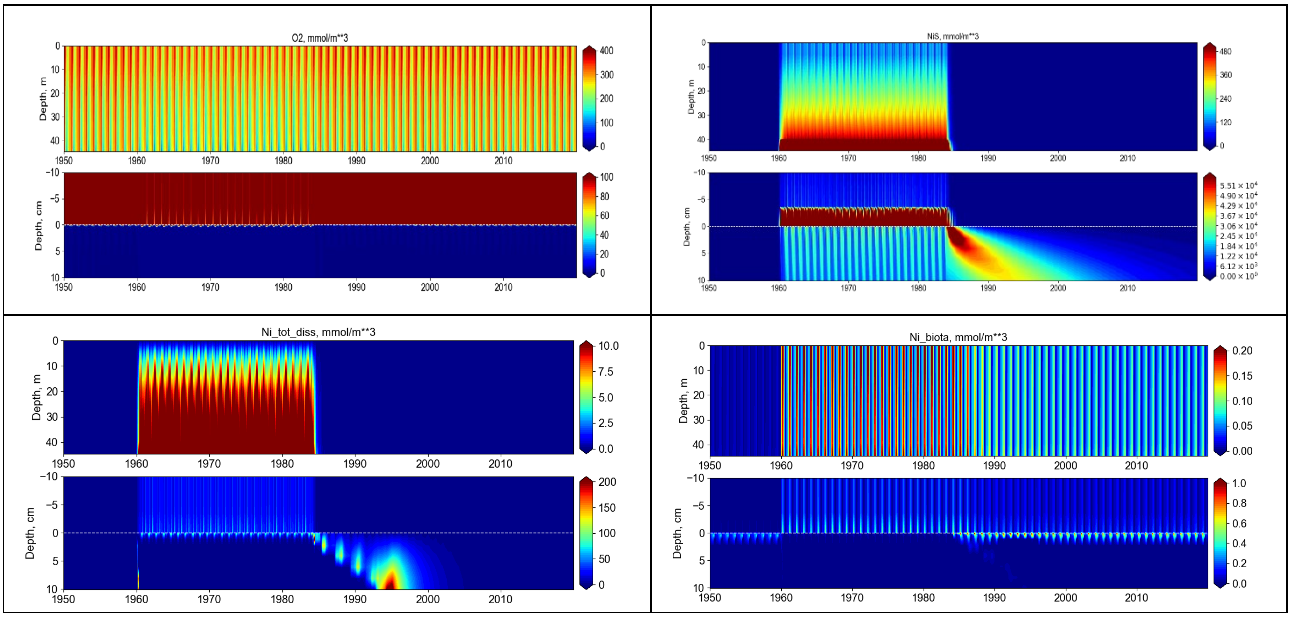


*Figure 8. Modelled interannual variability of concentrations of dissolved $O_2$, Ni, total dissolved Ni and Ni bioaccumulated by biota in the water column and at the SWI before (1950-1960) during (1960-1984) and after (1984-2020) the tailings.*

## 2.7 Ecotoxicology

Experiments were performed to determine the effects of Norwegian mine tailings to marine organisms. The work was split into two parts: 1) determining the comparative toxicity of three Norwegian mine tailings using sediment elutriates and whole sediment toxicity bioassays; and 2) a field investigation to determine the chronic effects of exposure to mine tailings within a fjord recipient.

**Comparative toxicity of three Norwegian mine tailings** (Brooks et al., 2019). The study assessed the environmental toxicity of three Norwegian mine tailings from Omya Hustadmarmor, Sydvaranger, and Sibelco, which are all released into a seawater recipient. Ecotoxicity assessments were performed on the overlying water extracted from the mine tailings, the transformation/ dissolution waters obtained from the mine tailings, and whole sediment assessment using a suite of marine organisms including algae, Crustacea, and Mollusca. Overall, based on the toxicity evaluation of the transformation/ dissolution data, Sibelco tailings resulted in the highest toxicity, followed by Sydvaranger and Hustadmarmor. Sibelco was the only mine where process chemicals were not used, but elevated metal concentrations in the tailings were assumed to have been responsible for the toxicity. The *Corophium* sediment contact assay revealed a significantly higher toxicity exerted by Hustadmarmor tailings, which was thought to indicate a physical impact of the fine tailings. The study showed different biological responses to chemical and particle exposure.

**Biological effects assessment of a mine discharge into a Norwegian fjord** (Brooks et al., 2018). The blue mussel (*Mytilus edulis*) was used to assess the potential biological effects of the Omya Hustadmarmor discharge effluent, which is released into the Frænfjord near Molde, Norway. Chemical body burden and a suite of biological effects markers were measured in mussels positioned for 8 weeks at known distances from the discharge outlet. The biomarkers used included: condition index (CI); stress on stress (SoS); micronuclei formation (MN); acetylcholine esterase (AChE) inhibition, lipid peroxidation (LPO) and Neutral lipid (NL) accumulation. Methyl triethanol ammonium (MTA), a chemical marker for the esterquat based flotation chemical (FLOT2015), known to be used at the mine, was detected in mussels positioned 1500 m and 2000 m downstream from the discharge outlet. Overall the biological responses indicated an increased level of stress in mussels located closest to the discharge outlet. The same biomarkers (MN, SoS, NL) were responsible for the integrated biological response (IBR/n) of the two closest stations and indicates a response to a common point source. The integrated biological response index (IBR/n) reflected the expected level of exposure to the mine effluent, with the highest IBR/n calculated in mussels positioned closest to the discharge. Principal component analysis (PCA) also showed a clear separation between the mussel groups, with the most stressed mussels located closest to the mine tailings outlet. Although not one chemical factor could explain the increased stress on the mussels, highest metal (As, Co, Ni, Cd, Zn, Ag, Cu, Fe) and MTA concentrations were detected in the mussel group located closest to the mine discharge.

The ecotoxicological studies have highlighted the importance of particle size and shape, in addition to chemical interactions, when investigating the effects of tailings on marine organisms. It was initially assumed that the angular and sharp-edged tailings would have an increased physical impact on external membranes leading to increased adverse effects. However, the laboratory studies showed that the finer rounded particles had more detrimental impact. Although the mechanism was not fully understood, interference of the fine particles at high densities with the gill epithelia of marine organisms was thought to be a contributing factor. The field study at Hustadmarmor supported the laboratory findings with clear impacts on the health status of mussels that were exposed to high densities of fine tailing particles. This highlights the importance of understanding particle interactions with biological membranes and studies investigating the interactions between fine mineral particles and gill epithelial cells are recommended.

## 2.8 Ecology

In addition to the ecotoxicological experiments, a field study and various experiments were performed to determine the effects of tailings on the marine seafloor communities, based on the same test tailings and fjord as described above. The work focused on the border of the impact area, as this is the area where the effects will vary most according to the particular tailings discharged. Both structural and functional responses were assessed. We also worked with communities and species in different stages; from effects on short-term recovery to effects on adult, intact communities.

**Mesocosm experiment** (Trannum et al., 2018). A mesocosm experiment was conducted to assess how thin layers of mine tailings affect mature benthic communities using tailings from Sibelco (no chemicals), Sydvaranger (flocculation chemicals) and Omya Hustadmarmor (flotation chemicals) (Figure 9). The results show a significant effect of all tailings with a threshold at 2 cm sedimentation, with the strongest effect of Hustadmarmor, followed by Sibelco, and the weakest of Sydvaranger. Deposit feeders (both surface deposit feeders and deep deposit feeders), which are directly exposed to tailings particles, were found to be more vulnerable than carnivorous and omnivorous species. Both toxicity, altered grain size as well as particle angularity were assumed to have contributed to the observed effects on the soft bottom fauna.


*Figure 9. Deployment of the box core (left) to collect benthic communities for experimental studies (right) in NIVA's Solbergstrand mesocosm facility.*

**Benthic community analyses** (Trannum et al., 2019). Analyses of benthic fauna samples collected in Frænfjorden were conducted to assess how tailings impact community structure and function of both infauna and epifauna in a fjord with a STP. The epifauna was collected with an Agassiz trawl. The infauna was collected with a grab, and the data also included previously sampled data from DNV-GL (Figure 10). In terms of both total abundance and species richness, the epifauna showed a much stronger decrease than infauna in the stations closer to the outflow pipe. The infauna community in the deposit area was dominated by typically opportunistic species, and mainly a highly tolerant mollusk. In the most impacted area functional responses included an increase in mobile carnivores/omnivores and species utilizing symbiotic bacteria. Sessile and tube-living taxa as well as deposit and suspension feeders decreased within the STP, probably due to smothering in combination with tailings-associated changes of the substrate. Functional diversity decreased for both infauna and epifauna, but relatively less than the structural diversity.

*Figure 10. A Van Veen Grab (left) and Agassiz trawl (right) used to collect infauna and epifauna respectively in Frænfjorden.*

**Recolonisation experiment** (Trannum et al., in press). A colonization experiment was conducted to assess the effect of thin layers of mine tailings on benthic recolonisation. Frames with defaunated sediments and 2 cm of different tailings (the same as in mesocosm experiment) were deployed in the Oslofjord (Figure 11). All tailings showed a fast, initial recolonization, but with a community composition differing slightly from the control. Particularly tube-building annelids had a lower recruitment success in the tailings-treatments. At the same time, abundance of other, presumably more tolerant species, including mollusks, increased, similarly to the fjord gradient described above. As in the mesocosm-experiment, the tailings from Hustadmarmor initiated the strongest response. No negative effects were recorded for the Sydvaranger-tailings. In general, there were larger difference in the abundance patterns between the controls and tailings after 6 than 12 months, probably due to coverage by natural sedimentation as well as mixing of the thin tailings layer with the sediment underneath which will dilute the tailings throughout the experiment.

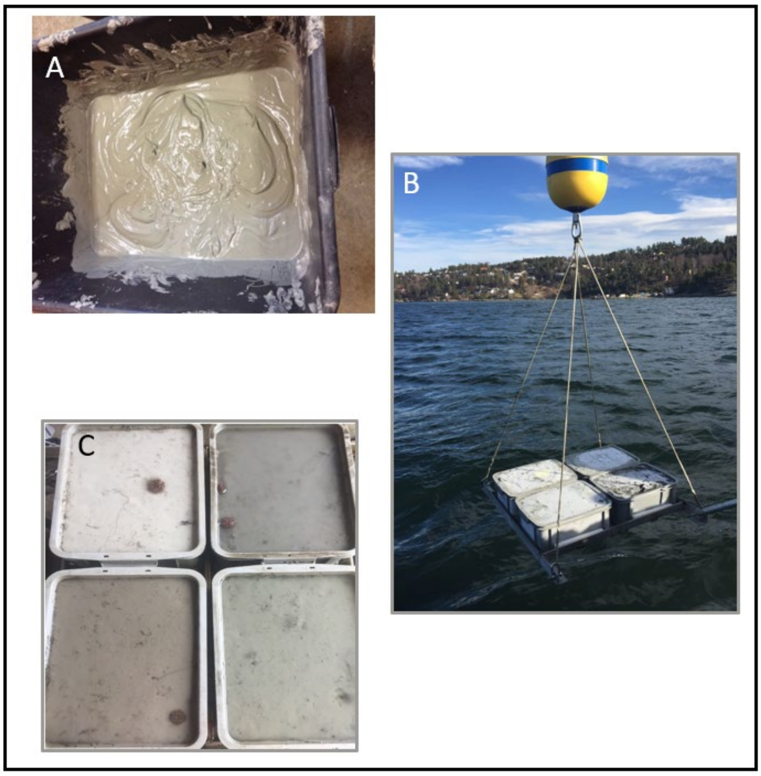

*Figure 11. Preparation (A), deployment (B) and recovered (C) boxes in the recolonization experiment.*

**Next steps.** While new data on the effect of “bulk” tailings on benthic community has been acquired, there is still a need of knowledge on the underlying mechanisms of processes affecting the fauna. Additional studies are required to elucidate the role of process chemicals and particle size and angularity at various stages of the life cycle of benthic fauna. Studies on the long-term recovery of the ecosystem when disposal ceases completely are also necessary, also with regard to restauration of ecosystem functioning. Lastly, investigations in the pelagic ecosystem and vulnerable ecosystems such as corals are essential.

## 2.9 Spatiotemporal modelling (GIS)

The benthic fauna community has been monitored by DNV-GL and NIVA in Frænfjorden back to 1993. Despite not fully balanced in space and time, this dataset, supplied with NYKOS grab samples from 2015, represented an opportunity to investigate the spatiotemporal dynamics in benthic community assemblages in this fjord. In particular, we wanted to assess if species composition seemed to be affected by the discharge, and if this changed through time.

Fauna samples were collected with a 0.1 $m^2$ van Veen grab and then identified to species or lowest possible taxonomic level. Four diversity and/or sensitivity indices (H’, $ES_{100}$, $ISI_{2012}$ and NQI1) were calculated and subjected to statistical analyses (Generalized Linear Models in R) and spatial mapping

(ArcGIS and QGIS). Since full cover predictive maps requires full cover predictors, only variables available as GIS layers could be used in the analyses. Preferably, we wanted to relate the indices to the mapped sedimentation rates (Section 2.1), but that did not cover all the fauna stations. Instead, the highly correlated (r=-0.84) distance to point source was used as a proxy. Since species composition also varies naturally with environmental and geophysical factors, the variables bathymetry, slope, curvature and wave exposure (all at a 25 m resolution), were also included in the modelling to improve predictive power. Year of sampling was included in the models to test for temporal effects.

The analyses revealed that all indices, although NQI1 not significantly, increased by distance to point source, indicating that both diversity and sensitive species might be negatively affected by the tailings ($p<0.05$). The proportion of sensitive species in the sediments, represented by NQI1 and $ISI_{2012}$, also increased over time ($p<0.001$), indicating improved conditions in the area. Here it should be noted that in autumn 2014, the previously used flotation chemical, Lilaflot, was substituted with FLOT2015, assumed to be less environmentally harmful. This may have contributed to the improvement in the latest period. The predicted spatial pattern of the fauna community indices is shown in Figure 12, whereas the spatiotemporal pattern of the two sensitivity indices can be viewed in online dynamic figures (NQI1 and ISI2012).

It is important to be aware that the fauna and data subject to this study were not sampled specifically to answer questions of spatiotemporal nature, and therefore not perfectly balanced in time and space. Thus, we must be careful to draw conclusions about causative relationships between the mining activity and responses in the benthic fauna community. However, the benthic community analyses presented in Section 2.7 (Trannum et al., in prep.) indeed support that there is an effect of tailings on community structure and function, which also accords with a previously published study on Frænfjorden (Brooks et al., 2015).

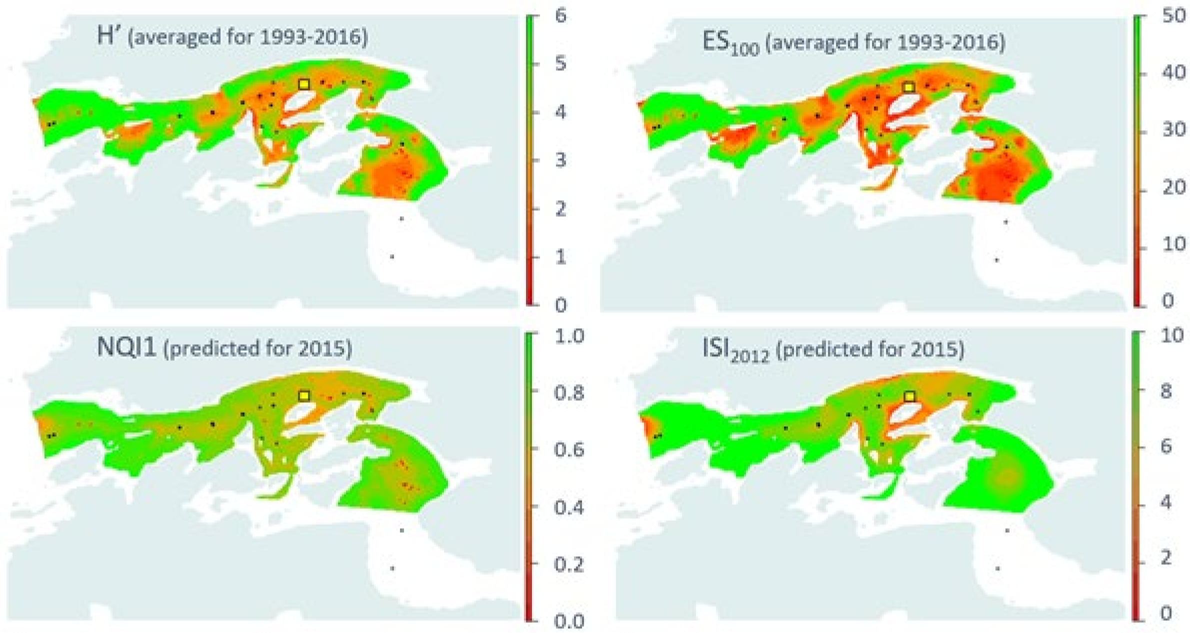


*Figure 12. Predicted maps based on GLM analyzes of fauna community indices' responses to geophysical variables (bathymetry, slope, curvature and wave exposure) and distance to point source (yellow square). Black dots show the position of fauna stations, whereof many have been visited on several occasions in the period 1993-2015. The two sensitivity indices (NQI1 and $ISI_{2012}$) are predicted for the last year in the series (2015) and show relatively high values, as the analyses revealed an improvement through the monitoring period.*

# 3 HOW CAN NYKOS RESULTS BE USED IN BAT PROPOSALS FOR STDs?

## 3.1 Main NYKOS results and developments

Norwegian fjords have variable relief and complex sedimentation regime with alternating erosion and accumulation areas. Stability and lateral distribution of STDs is ultimately linked to the optimal selection of the disposal site. The high-resolution bathymetry and seafloor geological maps (including sediment grain size and definition of erosion and accumulation areas) produced during NYKOS provide such representative baseline information on physical processes operating on the seafloor where STDs are active or planned. These maps facilitate a better assessment of the fate of tailings such as dispersal with currents or sensitivity to slope failures. The seafloor maps form an important framework for the high-resolution modelling of particle distribution, allowing to better predict where tailings particles may be dispersed to and deposited. They also allow for improved planning and delimitation of the impact area during the planning phase, as well as for an improved sampling design during the baseline study and EIA phases and improved monitoring-design during activities and post-closure.

The high-resolution modelling of particle transport developed in NYKOS provides a better database on particle and process-chemical distributions in time and space. The outcomes of the models provide an improved understanding of seasonal and inter-annual variations, as well as refined predictions on the effects of sporadic events such as storms on tailings shearing and re-suspension. NYKOS has also been pioneer in using a Silhouette Camera system (Davies, Brandvik et al., 2017) to image particles in situ, providing a better understanding of particle concentrations and flocculation processes in the environment. In combination with other optical instruments such as the LISST-100X and turbidity meters, a large range of relevant concentrations and particle sizes can be quantified, from the micrometer to the centimeter scale. The numerical models used in NYKOS have also been improved by including flocculation processes, which provides a better description of the sinking velocity of particles. As for high-resolution bathymetric maps, these particle transport models provide an improved tool to better predict the impact area of the STD during the planning phase and monitor any deviations to the permitted STD site during STD activities.

The chemical component of NYKOS has provided major improvements of our capacity to understand and measure the processes (adsorption, desorption and transformation) of process chemicals both in the processing plant and in the environment. New time-effective and cost-effective techniques have been developed to quantify flotation chemicals in tailings-seawater systems prior to submarine tailings disposal. The results show how easily accessible low-cost analytical methodology can be developed and employed to determine the behaviour of flotation chemicals when the tailings are mixed with seawater. Such tests could help to prevent over dosage of flotation chemicals and facilitate the establishment of simple test protocol that could be integrated in future BATs guidelines.

The tailings entering the marine environment carry part of the flotation chemicals added during the processing adsorbed to the tailing particles. Once in the marine environment, the chemicals will follow the tailings particles and may inflict with organisms exposed in the plume. However, the residence time in the water column will be short compared to the residence time at the sediment surface. In the sediments a small fraction of the chemicals will dissolve in the pore water and become available to sediment-dwelling organisms. The partitioning of the chemical between the solid tailings phase and pore water and biota is determined by so-called partition coefficients, which depend on the physicochemical properties of the chemical, as well as on environmental conditions such as organic matter, salinity, temperature and, in case of biota, content of lipids. Some of the chemicals employed may also serve as food for bacteria. This implies that all or some of the substructures of the chemicals will enter the metabolic apparatus of bacteria and undergo biodegradation. A complete biodegradation process would ideally transform the chemicals to harmless inorganic species such as $CO_2$ and water but the process may affect the redox conditions in sediment environments where oxygen is not always sufficiently available. Incomplete biodegradation may leave metabolites with different properties than the mother compound and that might not be detectable in chemical analyses that target the parent compound. The Ultra High Performance Liquid Chromatography coupled to High Resolution Mass Spectrometry detection methods developed in the NYKOS project are based on a general knowledge of: 1) the chemical structure of the parent compounds present in the technical mixtures employed and 2) the metabolites/transformation products suspected to be produced. Furthermore, these methods are applicable for different matrixes such as sediments, water and biological tissues.

Leaching of metal sulfides is a major problem in land-deposits producing acidic, metal laden drainage water which needs to be handled to reduce risks for plants and animals living in downstream waters. Sea water is well buffered and slightly alkaline, and tailings placed on the seabed are less exposed to advective flows of water seeping through the deposit. $O_2$ penetration is limited to the upper, bioturbated layer and metal sulfides are stable in the anoxic layers below. In NYKOS new techniques have been applied to confirm this hypothesis and to quantify metal mobilization within the bioturbated layer at old deposit sites for ilmenite tailings. The study provided new understanding of metal cycling at the sediment water interface with important implications for planning and monitoring of STD-sites, as well as more precise mitigating actions when deposition is ended.

The benthic community is one of the main recipient systems of the tailings, and potential effects have been studied in NYKOS through several approaches. The other main impacted ecosystem is the pelagic system, not studied here but under current investigations in the project DiTAIL (Disposal of mine tailings in Norwegian fjords and impacts on key ecosystem species, RCN #281093). As such, the new knowledge on the response of benthic communities to mine tailings disposal is interpreted based on available and new knowledge of relevant tailings and environmental variables and processes. NYKOS has provided a better understanding of the hypersedimentation thresholds in the transition areas between the STD impacted and non-impacted areas. This information is important to set relevant and realistic thresholds to acceptable hypersedimentation outside the STD area. NYKOS has also used novel analytical methods to assess community response to tailings, by including functional trait analyses to the traditional biodiversity indices. These functional analyses provide a better ecological understanding of the response of a community to a stressor, both with regard to the diversity in functional attributes and functional composition of the benthic community. Such analysis will address whether there are particular ecological properties that respond to the tailings, for example related to sediment dwelling depth, bioturbation, food intake, reproduction, size and age. Particularly bioturbation is very important for leaching of metals and chemicals from the sediment to the overlying water. The spatio-temporal changes in benthic communities can be modelled in relation to predictor variables that include time (years) and geophysical/chemical variables (i.e. high-resolution bathymetry, slope, seafloor curvature, particle sedimentation rates, wave exposure, distance to source of tailings, process-chemical distribution). This provides highly integrated and visual maps of community changes in time and space. These methods need robust datasets for all variables, to ensure that the model results can be interpreted correctly, emphasizing the benefits of long-term datasets.

The use of standardized ecotoxicological testing methods to assess the toxicity of tailings on flora and fauna provides results that are comparable with those of other systems and other stressors. However, in discussion with the industry partners, we recommend the use of local species whenever possible in future ecotoxicological analyses, in parallel with the use of standard species. Also, the bioassay methods generally used in ecotoxicological analyses, such as the one conducted in NYKOS, provide a measure of general toxicity that is often acute (mortality). This may be adequate to assess the effects from exposure to chemicals present naturally from the mined rock (i.e. metals), where the toxicity mechanisms are somewhat known. However, these methods may not be suitable to analyze the toxicological effect of process chemicals that are added to the tailings, since potential sub-lethal effects such as estrogenic/androgenic and neurotoxic/ genotoxic effects could be missed. In such instances, an additional level of toxicity screening may be required.

In addition to the potential toxic effects of process chemicals in the tailings, the tailings properties (size, shape and mineralogy) are also very important when assessing impact on fauna. The characterization of particles with electron microscopy can provide essential information on the shape of the particles (from rounded to sharp needles), which can help interpret results of faunal response at different life stages (e.g. larvae, settling juveniles, adults) as well as different functions and may provide guidance on mitigation actions. Metals bound as sulfides in tailings exposed in an oxidizing environment will dissolve and become available for uptake in marine organisms living at the seabed. Metals such as copper, chromium, nickel, zinc and lead are frequently present in metal sulfides mine in Norway, while mercury and cadmium can also be present in other mines, all of which are toxic above defined levels. Reducing the recycling of these metals from the sea deposit should be a major criterium for planning, management and mitigating actions taken to reduce the environmental impact of sea deposits. Appropriate understanding of the geochemical cycling of these metals are fundamental and their distribution in sediments and pore water needs to be addressed in monitoring programmes for sites where metal sulfides are present in tailings.

High-resolution models for fluxes of nickel in the sediment and benthic boundary layer have been developed for STD sites within NYKOS. These models simulate the natural changes of biogeochemical parameters and redox conditions connected with the seasonality of production and destruction of OM, that is used as a baseline for studying the impacts on environment connected with the tailings. Application of these models allows to analyze the potential consequences and predict changes resulting from the tailings of different intensities. Such models can be used for planning of the STDs and optimizations of their functioning. For example, it is possible to simulate how a discharge of certain amount of chemical in the tailings will affect the concentrations of this chemical in the environment, as well as violations in the biogeochemical regime (i.e. changes in oxygen concentrations). These changes can be analyzed from point of view of the present legislation documents (i.e. Direktoratsguppen vanndirektivet 2018) and then it can be possible to make a decision about a potential impact on the environment. Numerical experiments with different amount of chemicals will allow to find a threshold value that should not be exceeded during the planning or exploitation of the mine.

## 3.2 THE NYKOS CONCEPTUAL MODEL

A conceptual model (Figure 13) has been developed to highlight the main processes taking place in an active STD that may have an effect on the ecosystem, both pelagic and benthic. The model was developed based on the new scientific knowledge produced by NYKOS and discussions during a 3-day synthesis workshop with participation of scientists (both from NYKOS and external), industry and authorities (Norwegian Environmental Agency). The conceptual model was used to define a series of processes where Best Available Techniques (BAT) can be developed to minimize environmental impact (Figure 14). Based on the model, the NYKOS project started a table of potential BATs to be further defined and detailed (Table 1) that can guide authorities to develop a full set of BATs for submarine tailings disposal.

### 3.2.1 STD conceptual model

This model does not pretend to be an exhaustive description of an STD activity discharging in a fjord environment. It highlights, however, the main processes where BATs can be developed to minimize environmental impact. The model includes the processing plant, before the tailings are discharged in the fjord, and two main recipient systems: the water column and the seafloor. The processing plant discharges the *core tailings plume* that is deposited on the *seafloor* and should be contained in the permitted impact area. Occasionally, *shear plumes* and *positive buoyant plumes* can affect the water column and its ecosystem. The water column and seafloor environments are linked through the sediment-water column interaction processes such as *deposition* of particles, *resuspension* and *biotic processes* taking place in the benthic boundary layer. *Physical processes* in the water column can provide tailings particles (including process chemicals and metals) to the pelagic and benthic ecosystems. And the pelagic and benthic ecosystems are linked through *biological process* taking place in the trophic web. Below, we briefly discuss each of the processes taking place in the processing plant and the two recipient systems for which BATs can be developed, based on the main potential impacts that have been identified.

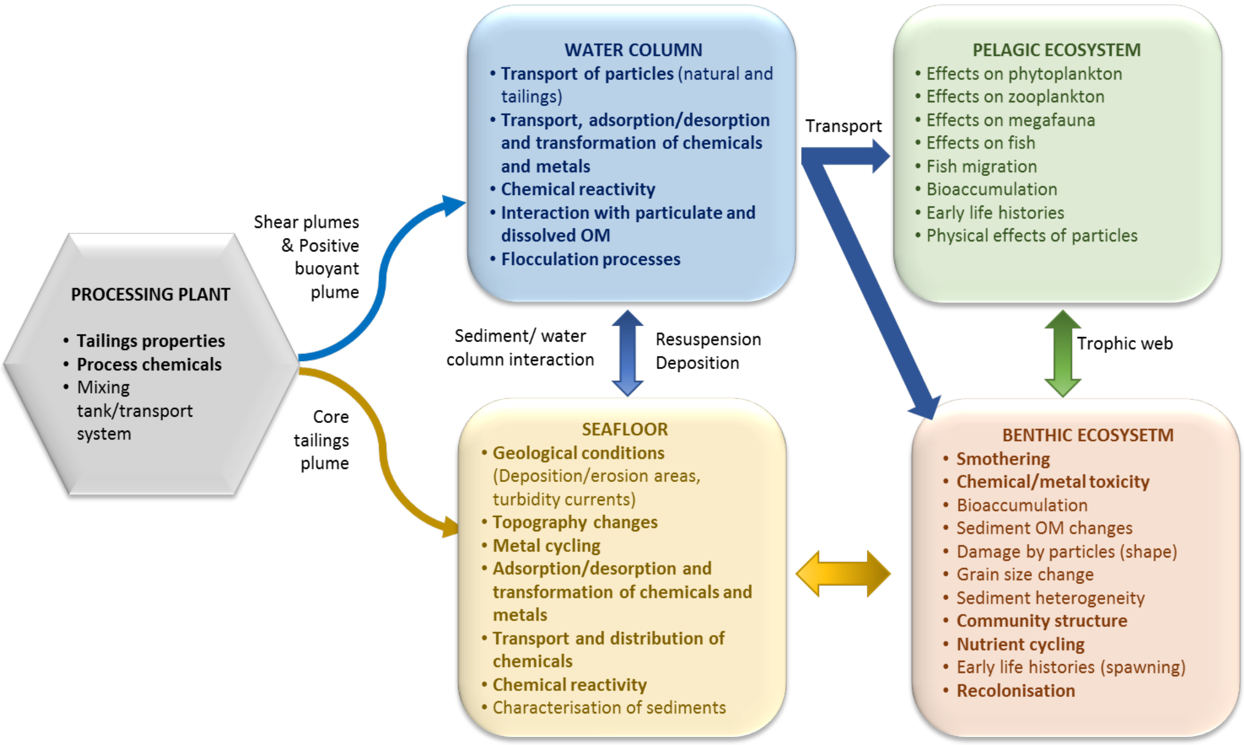


*Figure 13. The NYKOS conceptual model for the processes (arrows) and impacts (boxes) related to submarine tailings disposal in Norwegian fjords. Bold text indicates processes addressed during NYKOS.*

### 3.2.2 The processes and potential impacts

**Processing plant**

Understanding *tailings properties*, including shape, size, mineralogy and chemical reactivity, is essential to understand their relationship with added process chemicals, as well as the changes on the seafloor environment and potential impacts on the fauna. For example, some tailings produce sharp, needle-like particles with yet unknown effects on fauna, particularly on detritus feeders or early-life history stages (e.g. planktotrophic larvae and settling juveniles). The chemical stability of tailings is ultimately linked to their mineralogy and redox conditions at the fjord bottom. Tailings containing sulfide minerals are prone to oxidative dissolution and release of metals (some of which can be toxic) into the pore and bottom waters under well oxygenated fjord bottom conditions. Such oxidative dissolution is hindered in natural anoxic basins; hence such basins should be preferred for disposal of tailings rich in sulfide minerals. Given the redox dependence on chemical stability of tailings, the fjord bottom redox conditions need to be accounted for in the STD management.

An appropriate and well-designed system for tailings handling and discharge (i.e. the infrastructure of the tailings disposal) is a prerequisite for good operation. The description of these systems represents critical information when developing guidelines. The flow dynamics in pipes; i.e. the optimal plume velocity, the optimal ratio of fresh water, saline water and solids in the discharge pipe, is essential to obtain a plume density higher than the density of the receiving sea water. The outfall should be designed to create a homogenous density current which follows the bottom topography to limit the influence on the bottom water quality. This will reduce the occurrence of shear plumes. Additionally, an infrastructure which removes air from the plume is critical to avoid fine particles being transported upwards in the water column.

The ability of detecting and quantifying *process chemicals* prior to their discharge in the fjord can help prevent over dosage of flotation collectors and simple test protocols could be integrated in BATs. However, such tests must be adapted to the mineral/collector-system in question. Accelerated breakdown of adsorbed or dissolved collector molecules prior to discharge of the tailings could offer an additional opportunity to lower the environmental impact of the flotation chemicals.

**Water column**

The dispersal of tailings in the water column can potentially have effects on the phytoplankton and zooplankton communities, through increased turbidity, toxicity of chemicals and/or damage from particles. The pelagic macro- and megafauna, including fish, can also be affected and migration routes or spawning areas can be altered. Understanding these effects on the early life-history phases of key organisms is particularly important, to assess potential sub-lethal effects in the population. Although NYKOS did not study the pelagic system, the new Norwegian Research Council project DiTail is studying how exposure to fine tailings will affect marine copepods, fish eggs and fish larvae by integrating data from physical, physiological and molecular measurements into dynamic energy budget models (www.ditail.no). Below, we describe key processes that will need to be assessed in order to understand the impacts of STDs in the pelagic ecosystem.

Understanding the processes that shape patterns of *particle transport* (both of natural particles and from tailings) is important for several phases of an STD. High-resolution modelling of particle transport will allow for an accurate selection of the impact area. It will also highlight potential sporadic events, such as re-suspension, deep-water exchange and particle dispersal during storms, or specific particle transport based on detailed topography of the seafloor that may affect the water column and its ecosystem. Understanding the dispersal of natural particles, for example from river outflows, will provide basic information from which to differentiate between natural and STD particle processes.
Analytical methods to better understand the transformation, transport and accumulation of *process chemicals* once they enter the sea-water environment are essential to assess the potential ecotoxicological effects in the ecosystem.

The residence time of the tailings in the water column is small compared to the residence time in sediments. In contrast to fast flocculation/deflocculation processes, adsorption/desorption of flotation chemicals and dissolution of metal sulphides are generally slow processes and likely to be more important in the sediment-porewater system than in the water column.

**Seafloor**

The seafloor is the main recipient of the tailings, including the associated process chemicals. The main impact of an STD is smothering, and thus the affected area should be contained within the permit area. It is therefore important to ensure that this impact area is well delimited, and the hydrodynamic, topographic and ecological processes in relation to the region are well understood prior to the STD activity.

*High-resolution bathymetry and seabed sediment maps* (marine base maps) provide information for different phases of an active STD. During planning, they will allow for an accurate selection of the deposition and impact area based on robust baseline data. This will minimize geohazards such as landslides or turbidity currents. It will also provide the necessary seafloor topographic detail for the development of high-resolution modelling of particle transport in the water column. During production, regular monitoring will provide information on the formation of tailings piles that can inform pipe positioning.

*Sediment fluxes of chemicals (redox):* Pollutants bottom fluxes can be predicted with mathematical models. These models will analyze how the dumping pollutants interact with the environmental features (redox conditions, presence of organic matter, bioturbation and bioirrigation) and simulate the distributions and fluxes of all the model parameters. Therefore, modeling can help to analyze planning STD regimes (amount, timing and frequency of dumping) and potential consequences for the environment.

*Process chemicals in environment:* Analytical methods to evaluate the transport, adsorption/desorption and transformation of process chemicals and metals once they enter the marine environment are essential to understand changes in chemical toxicity from the chemical by-products and metals in the recipient environment, including the water column, sediment and biotas. Detection of process chemical degradation products in biota will also help explain ecotoxicity as well as to identify sub-lethal effects that may, potentially, affect population maintenance in the long term.

*Chemical reactivity*: the bulk of the tailings is non-reactive rock material. Sulfide minerals will be stable after burial to depths below the oxic surface, but near the sediment surface dissolution and release of more bioavailable species such as metal ions or complexes will occur. Mineral oxidation is slow at the pH of marine environments and the process will only affect a fraction of the total amount of sulfides. Nevertheless, the process may enhance metal fluxes significantly above background levels and concentrations in pore water may increase to exceed environmental quality standards (EQS). The fraction released will depend on the residence time of the tailings within the oxic environment. After deposition is ended or in areas with low sedimentation rate of tailings, residence times may be extensive (decades) and enhanced by bioturbation which may transport significant amounts of buried tailings particles upwards to the sediment surface.

*Characterization of sediments*: the tailings particles often have a different size and shape than the natural sediment. Characterizing both the tailings and natural sediment (shape, size and mineralogy of particles, OM changes and sediment heterogeneity will provide necessary information to assess potential impacts on the benthic fauna. For example, sharp particles can cause physical damage and clogging to the feeding apparatus, epithelium and internal organs of deposit-feeders and filter-feeders. The particle size would also affect oxygen penetration and diffusion of metal and nutrients such as silicate and phosphate across the SWI and in the upper sediments. Understanding sediment composition in the impact area and its evolution (in time and space) as STD activities cease and the area is covered with natural sediments will provide important information to assess recovery potential by recolonisation.

## 3.3 PROPOSED AREAS IN NEED FOR BATs

### 3.3.1 What are BATs?

Best Available Techniques are defined in article 2 (11) of the EU Council Directive 96/61/EC of 24 September 1996 concerning integrated pollution prevention and control as:

"The most effective and advanced stage in the development of activities and their methods of operation which indicate the practical suitability of particular techniques for providing in principle the basis for emission limit values designed to prevent and, where that is not practicable, generally to reduce emissions and the impact on the environment as a whole." The main terms in this definition are subsequently defined as:

- **Best** shall mean most effective in achieving a high general level of protection of the environment as a whole.
- **Available techniques** shall mean those developed on a scale which allows implementation in the relevant industrial sector, under economically and technically viable conditions, taking into consideration the costs and advantages, whether or not the techniques are used or produced inside the Member State in question, as long as they are reasonably accessible to the operator.
- **Techniques** shall include both the technology used and the way in which the installation is designed, built, maintained, operated and decommissioned.

EU BATs can be legally binding (e.g. BATs based on IED/IPPC Directive (Industriutslippsdirektivet)) and non-legally binding (BATs based on other directives, such as the Extractive Waste Directive (Mineralavfallsdirektivet)).

**BAT for waste from extractive industries**
The role and proper use of BATs for extractive mineral waste is explained in the Extractive Waste Directive (2006/21/EC), included as chapter 17 in "Avfallsforskriften" and the BAT Reference Document for the Management of Waste from Extractive Industries (MWEI BREF).

The Extractive Waste Directive state that "Member States shall ensure that operators responsible (Driftsansvarlig) for the management of extractive waste take all measures necessary to prevent or reduce as far as possible any adverse effects on the environment and human health brought about as a result of the management of extractive waste. These measures shall be based, inter alia, on the concept of best available techniques as defined in Directive 96/61/EC, without prescribing the use of any technique or specific technology, but taking into account the technical characteristics of the waste facility, its geographical location and the local environmental conditions."

The MWEI BREF, and more specifically the BAT Conclusions, should therefore be seen as a reference aiming at:

- Enhancing the consistent application of the Extractive Waste Directive
- Supporting decision makers by providing a list of identified BAT to prevent or reduce as far as possible any adverse effects on the environment and human health brought about as a result of the management of extractive waste, duly taking into account that the listed techniques are neither prescriptive nor exhaustive and that other techniques may be used that ensure at least an equivalent level of environmental protection.

EU BAT for the Management of Waste from Extractive Industries provide a non-legally binding Reference «tool box» for management of waste from the extractive industry.

### 3.3.2 NYKOS recommendations on BATs for STDs

Developing an exhaustive set of BATs for submarine tailings disposal in Norwegian fjords was not one of the goals of the NYKOS project. Developing BATs is a long and complex process that should be led by relevant authorities (in Norway, Norwegian Environmental Agency), with the participation of natural and social scientists and industry. Here, we report on initial discussions within the NYKOS project on what is the best way of reducing the environmental risk of sea tailings disposal of mineral waste and what practices and techniques can be used or further developed to minimize impacts on the environment. The list of BATs should neither be prescriptive, nor exhaustive and other techniques may be used that ensure at least an equivalent level of environmental protection. Thus, in addition to the BAT proposal, it is equally important to clearly define the improved environmental performance that we would like to achieve with the BAT. To ensure that this is captured in the BAT description, the following format should be used:

*"In order to [achieve an environmental performance],*
*BAT is to [BAT proposal]",*

The BAT proposal generally uses one, all or a combination of techniques from a given list. The techniques or use of the techniques may vary depending on the phase of the STD (planning, operational or closure phase)

A concrete example for a BAT definition would be:

*"In order to obtain stakeholder and regulatory acceptance for siting a new sea tailings disposal, BAT is to conduct an Environmental and Social Impact Assessment (ESIA), to identify, predict, evaluate and mitigate environmental and social effects of the sea tailings disposal, and to establish what is acceptable impact. When sea tailings disposal is considered, a comparison with a land deposit alternative should be made. BAT is to choose the realistic alternative that best combines a high level of physical safety with an acceptable environmental and social impact."*

**NYKOS recommendations**

Based on the conceptual model, we proposed several areas that would benefit from clearly defined BATs. These BATs address issues in the process plant, the water column and the seafloor, as well as shared processes/methods that can be applied to the discharging system as well as to the two recipient systems (Figure 14).

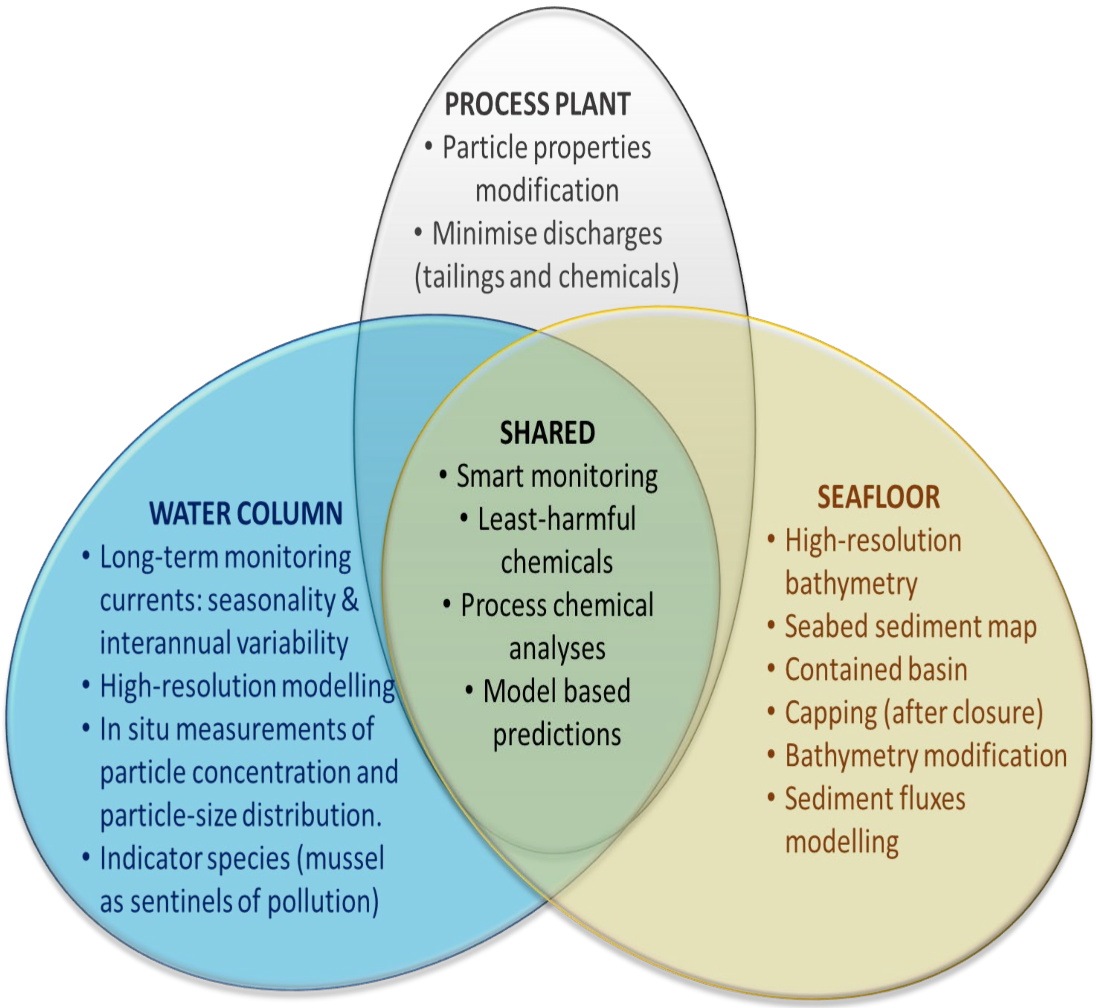


*Figure 14. Initial processes and methods proposed for consideration for BATs on submarine tailings disposal of mineral waste.*

Based on this preliminary selection of key issues, we briefly described BATs that could be further developed and adopted by the relevant authorities (Table 1). In this table, we provide a brief description of the aim of the BAT and the processes to be investigated, and we indicate what type of methods are available for each of the different phases of an STD, from planning to closure. We include also some information on potential mitigation actions and what new tools and methods NYKOS has developed to address the issues.

*Table 1. Initial set of BATs for submarine tailings disposal proposed for consideration and further development.*

| Aim | Processes | Planning | Operation | Closure | Mitigation | NYKOS tools |
|---|---|---|---|---|---|---|
| Site selection to reduce environmental impact | Hydrography<br>Topography<br>Seasonal variability<br>Natural sedimentation<br>Ecology | High-resolution tailings transport model<br><br>High-resolution marine geological mapping<br><br>Benthic and pelagic community structure, species diversity, functional diversity<br><br>Recolonisation potential<br><br>Minimize deposit area | Monitoring that the tailings are contained in the designated area. | Monitoring recolonization and re-establishment of a functional ecosystem | | High resolution maps (bathymetry and seabed sediments) and models (circulation)<br><br>Mesocosm experiments with tailings<br><br>Recolonisation experiments<br><br>Functional trait analyses |
| Reduce dispersal of particles | Seasonality;<br>Inter-annual Oceanography;<br>Particle properties;<br>Bathymetry | High-resolution tailings transport model | Monitoring Validation of model<br><br>Re-education of model<br><br>Bathymetric engineering | Monitoring particle concentration in water column | Flocculation agents<br><br>Pipe positioning<br><br>Increase plume salinity<br><br>Optimize particulate fraction | High-resolution modelling |
| Reduce environmental impact of process chemicals | Adsorption<br>Desorption<br>Transformation<br>Transport | Documentation of process chemical<br><br>Characterization of mass transfer rate and equilibrium between sediment-water.<br><br>Transformation dynamics and products<br><br>Effects of transformation products in the environment | Monitor (e.g. core samples on seafloor; mussels as pollution indicator and of biological stress) | Long-term monitoring | Substitution<br><br>Capping | New detection methods for process chemicals and their transformation products based on LC-HRMS and/or GC-HRMS |

| Aim | Processes | Planning | Operation | Closure | Mitigation | NYKOS tools |
|---|---|---|---|---|---|---|
| Reduce instability | Tailings accumulation<br><br>Natural system (river outflows, canyons, natural landslides) | Assess natural areas of potential hazard<br><br>Mapping: bathymetry and subsurface | Control tailings Monitoring in this phase is very important | N/A: cannot do anything in closure phase | Pipeline control | High-res bathymetry |
| Reduce changes in currents | Local hydrographic changes caused by changes in topography | Modelling of potential changes based on deposition planning | Regular monitoring | | Selection of pipe placement | High resolution oceanographic modelling based on high-resolution maps |
| Reduce environmental effects from metal leakage | Redox systems<br><br>Conditions that allow or limit remobilisation | Documentation Mineralogy Laboratory and mesocosm tests Site selection | Monitoring bioavailable metals | Capping | Area Selection<br><br>Capping | Biogeochemical modelling, pore water analyses, DGT-probes, flux measurements |
| Reduce smothering effect | Tailings properties | Analyse tailings properties Size and shape | Monitoring of border area | Recolonisation | | Mesocosm experiments |
| Assess toxicity | Screening Chemicals and Metals<br><br>Changes of combinations in time and space<br><br>If there is a toxic effect: identify the component responsible | Laboratory and mesocosm tests on several species | Continuous monitoring and evaluation<br><br>Measure chemicals and metals in sediment and biota | | Capping | Mesocosm studies<br><br>Ecotoxicological tests |

# 4 FORWARD LOOK

Submarine tailings disposal is a major activity in Norway with 7 current STDs actively disposing tailings in fjords, and 2 new permits awarded in 2018-2019 to Nussir and Nordic Rutile. However, in the current political agenda, no new STDs will be permitted in the period 2017-2021 and existing permits to operate STDs will be revised in accordance to the current understanding of site-specific BATs by the authorities (Miljødirektoratet). This said, no general BATs for STDs exist in Norway, and the EU MWEI BREF does not include specific BATs for submarine disposal of tailings, although some of the general MWEI BREF BATs are applicable to STDs.

## 4.1 Guidelines

The specific guidelines for each operation are determined by the authorities based on the baseline studies and environmental impact assessment initiated by the mining company. However, NYKOS recommends that the authorities initiate a process of defining a set of overarching guidelines to assist industry in the different processes and studies that need to be undertaken to ensure that environmental impact would be minimized. These guidelines should be developed in collaboration with the scientific community and industry, to ensure that they are based on robust scientific knowledge and the latest analytical tools and methods available. The guidelines should follow an adaptive management system, allowing for adjustment as new knowledge and new techniques become available. For example, monitoring capacity and accuracy is greatly and rapidly developing in parallel of technological developments such as autonomous underwater vehicles, molecular methods and modelling. A wealth of guidelines and criteria are already available from similar actives, in land-based tailings management, deep-sea tailings disposal in Papua New Guinea and Indonesia (Shimmield et al., 2010; Hughes et a., 2015; Vare et al., 2017) and the currently developing regulations for deep-sea mining (Jones et al., 2019; Durden et al., 2018; ISA Mining Code). The guidelines should include specific information for the following activities:

- Baselines studies
- Environmental Impact Assessment
- Monitoring during operations
- Closing plans
- Post-closure monitoring

## 4.2 Best Available Techniques

Similarly, we recommend that the authorities create a set of clear, overarching BATs for submarine disposal of mine tailings in Norwegian fjords. NYKOS has started this discussion, but it is beyond the scope of the project to provide a full set of BAT recommendations, as this is a major endeavor that needs dedicated time and funding, involving the authorities, scientists, industry and civil society.

The scientific, industrial and policy making community in Norway should also expand from the momentum created by NYKOS and related projects (e.g. FIMITA, EMWA, DiTail) and engage from the start in the next revision of the EU BREF MWEI, to ensure that the issues related to the impact of submarine mine tailings from mineral extraction are included.

## 4.3 Steps forward in BAT and guidelines development: addressing knowledge gaps

NYKOS has provided robust scientific data to fill in some important knowledge gaps related to the characteristics, dynamics and impacts of submarine tailings disposal in Norwegian fjords. Several of these knowledge gaps were outlined in the report published by Norwegian Environmental Agency in 2010 and now translated to English in 2019. This new information can greatly assist the relevant authorities to develop sound guidelines and BATs that will greatly assist industry in ensuring that all necessary measures are taking to minimize and mitigate environmental impact at all stages of an STD. The continuous improvement of our understanding of marine ecosystems functioning, as well as the development of new analytical methods and technologies, allow address remaining knowledge gaps, thus providing new scientific data to further improve guidelines and BATs, after these have been established. An example at the European level is the regular (every 8-10 years approximately) revision of the Best Available Techniques Reference Documents (BREF), such as the BREF MWEI mentioned above for the management of waste from extractive industries.

Several processes and issues still need additional data and improved understanding to ensure that the right management decisions are made. At the same time improved methodological developments and practices can be used to conduct robust EIAs and minimize environmental impact. These knowledge gaps and methods are briefly described below.

**Main knowledge gaps**

- *In situ* measurements of tailings floc settling speeds, essential for understanding and accurate prediction of the tailings' deposition area and suspended mass concentrations.
- Better understanding of the *composition, characteristics and transformation of the materials* being disposed: including tailings particles size, shape and mineralogy, and process chemicals.
- Development of *analytical methods* for flotation chemicals and metabolites in sediments, water and biota.
- Better understanding of the *geochemical and biogeochemical processes* in the sediment.
- Better understanding of the *composition and functioning of the pelagic community*, including migrations, trophic structure, embryos and larvae that disperse in the water column). This is essential to understand the impact of potential increased particle, metal and/or chemical concentrations in the water column caused by plume shearing or resuspension events.
- Effect of tailings on *early life history phases* of key species, including embryos and larvae. Lethal or sub-lethal effects on this vulnerable phase of benthic and pelagic species can have important consequences in the maintenance of the population.
- Better understanding of the effects of *particle shape and size* on the local fauna.
- Better understanding of potential for *accumulation and trophic transfer* of tailings-associated contaminants (metals and chemicals) in biota.
- Better understanding of the *ecological indicators and thresholds* to identify serious harm. This would provide early-warning systems if the impact of the operations deviated from the predicted processes.
- Evaluate *cumulative impacts with climate change*.

**Improve methods and practices**

- Improved *high-resolution bathymetry* will help minimize geological-related hazards and risks and will improve area planning. It will also provide essential information for the high-resolution modeling of particle dispersal.
- Further development of *high-resolution modelling* of tailings dispersal in the water column. Improved high-resolution spatio-temporal data on oceanographic and bathymetric parameters is needed to re-fine existing models. Data to ground-truth and educate the models is also essential.
- Quantify the effect of *turbidity currents* and *resuspension* on tailings transport and (re)distribution, in particular accounting for the highly dynamic character of these processes.
- Analyses of sediment and biological samples to improve understanding of *fate and effects* of flotation chemicals.
- Analyses of long sediment cores to improve understanding of *anaerobic degradation* of historically used chemicals
- Better understanding of the *lethal and sub-lethal ecotoxicological effects* of process chemicals and their transformed products in the local fauna at different life stages (embryos, larvae, juveniles and adults).

- Better understanding of the *biodegradation* of process chemicals in marine sediment environments.
- Better understanding of the toxicity of process chemicals to *benthic communities.*
- Better understanding on the effects of tailings in *hard substratum sessile fauna* (e.g. sponges, corals). These animals are mostly filter feeders and thus usually highly vulnerable to high levels or particle concentrations in the water column.
- Investigations on potential for *technological improvement* of tailings processing prior it is discharged in the fjords, to minimize re-suspension and toxicity.
- Better knowledge on *conflicts of interest*, for example with fishing practices. Tailings disposal can affect migration routes of commercially valuable species, or spawning grounds.
- Better address *social acceptance*. This is a key aspect for a controversial activity that affects the political agenda. Better communication with society, based on robust scientific data and transparency is essential.

# 5 Conclusions

Disposing mine tailings in the marine system has important environmental, social and economic implications. A better integrative work between natural and socio-economic academics, industry, authorities and NGOs is necessary to ensure that STDs, when approved, are conducted under the best available techniques and practices available at the time, and that these techniques and practices are further improved and changed as new knowledge is acquired. NYKOS has greatly contributed to this knowledge in Norway for a series of important topics related to STDs. New NYKOS data is available on assessing and modelling particle distribution (Davies and Nepstad, 2017; Davies et al., 2017; Nepstad et al., 2019 (in prep)); marine base maps including high-resolution bathymetry and sediment grain-size maps (Bøe et al., 2018; Baeten et al., in review; www.mareano.no); assessment of process chemicals in the plant (Ibragimova & Kleiv, 2018 a,b,c,d; 2019) and their behavior once they enter the marine system (Escudero-Oñate & Ferrando-Climent, in prep a & b); effects of tailings on benthic fauna (Trannum et al., 2018; Trannum et al., 2019) and recolonization potential (Trannum et al., in press.); ecotoxicological effects of tailings (Brooks et al., 2018); recycling of metals from sulfide minerals and the potential effects on the ecosystem (Schaanning et al., 2019); and modelling of geochemical fluxes (Pakhomova et al., in prep). Other projects, national and international, are providing new data and knowledge on other key components, including impacts on the pelagic system, early-life history phases and impacts on deep-sea ecosystems. This wealth of new information (Table 2) is essential for the authorities to develop robust management systems under the ecosystem approach for the management of submarine tailings disposal in the current situation of our changing oceans (Dold, 2014; Hughes et al., 2015; Ramirez-Llodra et al., 2015; Vare et al., 2018).

*Table 2. Main results and key messages from NYKOS research.*

| Topic | Main results |
|---|---|
| Seafloor geology and tailings | • The dispersal of tailings is linked to fjord-specific processes and particle transport of >10 km can occur.<br>• In fjords that have experienced discharges of contaminants, uncontaminated STDs on top of affected seafloor sediments can confine the contamination.<br>• Geological and acoustic methods are well suited for monitoring volume changes and lateral spreading of STDs. |

| | |
|---|---|
| | • Marine base maps, including detailed bathymetry, geological seabed maps and results of sub-bottom profiling, are needed for planning and monitoring of STDs. |
| Modelling and measuring spreading of tailings particles | • Floc sizes and concentrations can be determined using automated image analysis software.<br>• Numerical models can be used to predict the spreading and sedimentation of tailings particles.<br>• Model simulations combined with knowledge on biological impacts of tailings can be used to determine environmental risk.<br>• Model simulations can be used to minimize environmental footprint through optimization of the discharge. |
| Chemistry in the processing plant | • Desorption of the flotation collectors is highly affected by seawater washing time and the initial concentration of chemicals.<br>• Less than 4% of the adsorbed flotation collector has been desorbed when the initial concentration is equal to the industrial dosage and monolayer adsorption has been established.<br>• At concentration levels higher than those required for efficient flotation, multilayer adsorption is present and significant desorption will occur.<br>• The results suggest that exposure to seawater could accelerate the chemical degradation or decomposition of the flotation collectors within a timeframe of 18-24 hours. |
| Process chemicals and their transformation products | • Process chemicals from the flotation technical product FLOT2015 have been identified in sediments, water and biota from Frænfjorden.<br>• The main chemicals found are esterquat-type structures that break-down in water and form a mixture of degradation products.<br>• The main degradation products of the technical product FLOT2015 are fatty acids and methyltriethanolammonium (MTOA).<br>• An equilibrium between the chemicals adsorbed to the particles and the water surrounding them is stablished in a way that allows the chemicals getting dissolved and mobilized.<br>• The concentration of the transformation product MTOA in mussels exposed to the tailings shows a decreasing trend along the distance from the tailings' discharge point. |
| Trace metal mobilization at old sea deposits | • Metal concentrations are maintained at high levels in the top layer due to vertical mixing driven by the activity of the benthic fauna (bioturbation).<br>• Tailings mixed into the oxic surface layer reacted with $O_2$ to release copper, nickel and cobalt to the pore water and the overlying seawater.<br>• Cobalt behaves different from copper and nickel due to its redox sensitivity.<br>• Release of nickel from the sea deposit to the overlying water was large compared to reference locations in the sea (15:1), but small (1:20) compared to the release via drainage water from a land deposit with the same tailings. |

| | |
|---|---|
| | • Metal concentrations at the sediment surface (0-1 cm depth) exceeded environmental quality standards (EQS) for copper and nickel both in sediments and pore water. |
| Ecotoxicology | • The detection of process chemicals used by the mine, in the tissue of mussels position up to 2 km from the discharge outlet.<br>• A suite of biomarkers measured in the mussels indicated a clear stress response, which was correlated with chemical bioaccumulation and proximity to the discharge outlet. |
| Effects on tailings on benthic fauna | • Significant effect of all tailings tested with a threshold of 2 cm of added sediment.<br>• The abundance of epifauna (larger organisms on the seafloor) shows a stronger reduction close to the tailing outflow than the infauna (smaller animals living in the sediment).<br>• The infauna close to the tailings outflow is dominated by tolerant species, i.e. indicating a community shift.<br>• A recolonization experiment showed evidence of fast initial colonization of sediments capped with thin layers of tailings, but with a community differing slightly from sediments without tailings.<br>• Detritus feeders are more sensitive than carnivorous and omnivorous species, and non-mobile and tube-building species are more sensitive than mobile, free-living species. |
| Spatio-temporal modelling | • In an active STD-site, most bioindices increased with the distance to the point source, indicating that both diversity and sensitive species might be negatively affected by the tailings.<br>• Also, the proportion of sensitive species in the sediments at the station closest to the outlet increased over time, possibly favoured by the replacement of the flotation chemical with a new, less environmentally harmful chemical in 2014. |

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