International Seabed Authority

Development of environmental threshold values

Report of the Intersessional Expert Group (IEG)

List of Contributors

This report has been compiled by the Legal and Technical Commission co-chairs of the intersessional expert group (IEG) in accordance with the terms of reference for an intersessional expert group on the development of binding environmental threshold values ((‘Terms of Reference’), included in Annex of ISBA/28/C/5[1], and subsequently modified during the second part of the 28th session[2]).

The co-chairs led the work of each of the three subgroups (toxicity (*TX*), turbidity and settling of resuspended sediments (*TS*), and underwater noise and light pollution (*NL*). This report reflects the discussions and contributions from the IEG members nominated by regional groups, member States and other relevant Stakeholders of the Authority, according to the Terms of Reference.

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[1] Report of the Chair of the Legal and Technical Commission on the work of the Commission at the first part of its twenty-eighth session (ISBA/28/C/5)

[2] The Terms of Reference are available at: https://isa.org.jm/wp-content/uploads/2026/07/ToR_Development_of_environmental_threshold_value.pdf

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The report has been prepared by the Commission co-chairs with scientific and technical contributions by the members of the IEG through their contributions at *in-person* and online meetings, written submissions and their peer review comments.

The report draws on multiple sources of information, including publicly available peer-reviewed literature, national and international regulatory documentation and environmental impact statements, as well as unpublished data and annual reports submitted by exploration Contractors to the Authority.

The report also draws heavily on the outcomes of the workshop on ecotoxicological impacts of deep-sea mining hosted by the German Federal Institute for Geosciences and Natural Resources (BGR) in April 2023 (published in Schmidt et al., 2025). In addition, a meta-analysis of biological responses to suspended sediments in the deep ocean was commissioned to Jesse van Grient, under the guidance of Malcolm Clark and Daniel Jones (see supplementary information). A comparative overview of underwater noise regulatory frameworks, guidelines and thresholds across different industries and jurisdictions was prepared by Jane Warley and Sophie Kendall under the guidance of Becky Hitchin (see supplementary information).

The production and editorial work of the report was managed by Luciana Genio under the guidance of Jose Dallo Moros of the ISA Secretariat. In addition, several Secretariat staff, consultants and trainees provided input, feedback and support to the preparation of the report, including Wanfei Qiu, Gwenaelle Le Gurun, Sheldon Carter, Kioshi Mishiro, Ansel Cadien, Camelia Campbell, Yuneeda Oozeeraully, Adam Cook, and Eleana Karachaliou.

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[3] Decision of the Council of the International Seabed Authority relating to the development of binding environmental threshold values (ISBA/27/C/42)

Abbreviations and Acronyms

ADCP: Acoustic Doppler Current Profiler

ALAN: Artificial Light at Night

ANZECC: Australian and New Zealand Environment and Conservation Council (Water Quality Guidelines)

ASV: Autonomous Surface Vehicle

AUV: Autonomous Underwater Vehicle

BBNJ Agreement: Agreement under the United Nations Convention on the Law of the Sea on the Conservation and Sustainable Use of Marine Biological Diversity of Areas beyond National Jurisdiction

BGR: Federal Institute for Geosciences and Natural Resources (Germany)

BIE: Benthic Impact Experiment

BPC: Beijing Pioneer Hi-Tech Development Corporation

CMS: Convention on Migratory Species

CCZ: Clarion-Clipperton Zone

COLREGS: Convention on the International Regulations for Preventing Collisions at Sea

DCCEEW: Department of Climate Change, Energy, the Environment and Water of Australian Government

DGV: Default Guideline Value

DORD: Deep Ocean Resources Development Co., Ltd. (Japan)

DP: Dynamic Positioning

DR: Draft Regulation of the Draft Regulations on Exploitation of Mineral Resources in the Area

DSM: Deep-Seabed Mining

DSSRS: Deep-Sea Sediment Resuspension System

ECHO: Enhancing Cetacean Habitat and Observation (Programme)

EEXI: Energy Efficiency Existing Ship Index

EIA: Environmental Impact Assessment

EIS: Environmental Impact Statement

EMMP: Environmental Management and Monitoring Plan

ENSO: El Niño-Southern Oscillation

ERP: Ecological Reference Point

FTU: Formazin Nephelometric Unit

GSR: Global Sea Mineral Resources NV

HC5: Hazardous Concentration for 5% of species

HC50: Hazardous Concentration for 50% of species

HF: High Frequency (marine mammal hearing group)

HL5: Hazardous Level for 5% of species

IEG: Intersessional Expert Group

HPS: High-Pressure Sodium

IOM: InterOceanMetal Joint Organization

ISA: International Seabed Authority

JET: Japan Deep-Sea Impact Experiment

JOGMEC: Japan Organization for Metals and Energy Security

KIOST: Korea Institute of Ocean Science and Technology

London Convention: Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter

LEDs: Light- Emitting Diodes (LEDs)

LF: Low Frequency (marine mammal hearing group)

London Convention: Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter

London Protocol: Protocol to the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter

LTC: Legal and Technical Commission

mab: meters above the seafloor

MSFD: Marine Strategy Framework Directive (EU)

NOEC: No-Observed-Effect Concentration

NORI: Nauru Ocean Resources Inc.

NTU: Nephelometric Turbidity Unit

OSPAR Convention: Convention for the Protection of the Marine Environment of the North-East Atlantic

PAF: Potentially Affected Fraction

PIANC: Permanent International Association of Navigation Congresses

PMN: Polymetallic Nodules

PTS: Permanent Threshold Shift

RNS: Reactive Nitrogen Species

ROS: Reactive Oxygen Species

ROV: Remotely Operated Vehicle

S&G: Standards and Guidelines

SCOC: Sediment Community Oxygen Consumption

SD: Standard Deviation

SEL: Sound Exposure Level

SOFAR: Sound Fixing and Ranging (Channel)

SSD: Species Sensitivity Distribution

TOC: Total Organic Carbon

TTS: Temporary Threshold Shift

UNCLOS: United Nations Convention on the Law of the Sea

VHF: Very High Frequency

WFD: Water Framework Directive (EU)

ZoHI: Zone of High Impact

ZoI: Zone of Influence

ZoMI: Zone of Moderate Impact

Note

The present report contains references to terms and measures that are applicable to the exploitation phase for which the draft regulations on exploitation of mineral resources in the Area are still under negotiation; those terms and measures may therefore need to be aligned once the regulations have been finalised.

Executive Summary

The International Seabed Authority (the "Authority") organizes and controls mineral-resources-related activities in the Area on behalf of humankind as a whole under the United Nations Convention on the Law of the Sea (the "Convention"). In so doing, it is mandated under Article 145 of the Convention to ensure the effective protection of the marine environment from harmful effects which may arise from such activities. To fulfil this mandate, the Authority is developing a comprehensive regulatory framework, known as the Mining Code, which governs all mineral-related activities, including exploration and future exploitation. The Draft Regulations on Exploitation of Mineral Resources in the Area require the establishment of legally binding "Standards" and recommendatory "guidelines", including for the management of environmental impacts.

As part of this suite of Standards and guidelines, development of environmental threshold values is expected to contribute substantially to the determination of what is required to ensure effective protection of the marine environment pursuant to article 145 of the Convention and to set measurable requirements or standards with regard to levels of harm from mining and related activities in the Area, including the maximum levels of harm that can be considered acceptable.

On 11 November 2022, the Council adopted a Decision relating to the development of binding environmental threshold values (ISBA/27/C/42[4]). For the development of these threshold values, the Council decided that the work would be led by the Legal and Technical Commission (the "Commission") and supported by the scientific and technical expertise of an intersessional expert group (IEG).

The IEG was tasked to develop proposed threshold values for three topic areas (toxicity, turbidity and settling of resuspended sediments, and underwater noise and light pollution) and compile a report to the Commission, to be published on the website of the Authority, presenting all available options discussed by the IEG and outcomes of its deliberations. The Commission will consider the report after formal stakeholder consultation and will submit its recommendations to the Council.

The IEG was established in late 2023, divided into three subgroups covering each of the topic areas to synthesize existing scientific data and guidance from other relevant regulatory frameworks, identify appropriate indicators to define threshold metrics and define threshold levels, including early warning thresholds and levels of uncertainty, and consider knowledge limitations and research priorities.

Whilst current work has focused on polymetallic nodules, as it is the resource and habitat regarded as most homogeneous and with most available information on environmental impacts, the approach proposed by the IEG is designed to be adaptive to other mineral resources. It acknowledges existing limitations, such as limited deep-water baseline data, incomplete

[4] Decision of the Council of the International Seabed Authority relating to the development of binding environmental threshold values (ISBA/27/C/42)

understanding of ecosystem functioning, and uncertainties regarding the ecological impacts and technologies used in full-scale mining.

The proposed approach

The IEG proposes a methodology that allows environmental management to reflect specific spatial and temporal pressures exerted by mining, such as sediment suspension or noise emissions, and to establish a relationship between human activity and the response of ecological receptors that is scientifically defendable. This standardized approach integrates the concept of Ecological Reference Points (ERPs) into a Zone of Impact model, as a science-based starting point, intended to evolve as more operational data become available, for the development of project-specific environmental threshold values.

The ERPs are measures or metrics that are indicative of the status or health of an ecosystem, such as a specific percentage of a population affected or a specific and measurable change in community structure and/or ecosystem functions (e.g. biogeochemical processes, microbial activity). ERPs define the transitional boundaries between different zones of impact, allowing for the identification of early warning signals should impacts exceed acceptable levels. The IEG identifies these ERPs from a variety of methods, including results from direct experimental measurements, ecological analogues from similar environments, and numerical modelling.

A three-tier Zone of Impact model is utilized to guide environmental monitoring and mitigation:

1. Zone of High Impact (ZoHI): Areas of intense, potentially irreversible damage, typically the direct footprint of resource extraction.
2. Zone of Moderate Impact (ZoMI): Transitional areas where impacts are clear but less severe and are considered reversible or sub-lethal.
3. Zone of Influence (ZoI): The outermost areas where changes in environmental quality are predicted but remain within the range of natural variability.

The approach emphasizes the importance of cumulative impacts, recognizing that deep-sea organisms are exposed to multiple interacting stressors simultaneously. The approach moves toward effect-based thresholds that can be validated by both pressure indicators (e.g., metal concentrations) and state indicators (e.g., biological health, ecosystem processes). This framework for environmental management ensures a precautionary and adaptive approach for managing the common heritage of humankind.

Toxicity

Toxicity in the context of deep-seabed mining (DSM) refers to the potential for substances released during mining activities - specifically trace metals in dissolved or particle-bound forms - to adversely affect marine organisms. Potential sources of metal exposure include sediment suspension plumes generated by seafloor disturbances from collectors, and the discharge of return water from the on-board solid-liquid separation process on the surface vessels ("discharge plumes"). Sediment resuspension under oxic conditions can cause measurable enrichment of some dissolved metals (particularly Mn, Fe, Co and occasionally Cu), but current evidence suggests that enrichment is limited to a subset of elements and the ecological significance remains uncertain. The IEG focused on assessing mobilization, speciation, and bioavailability for a subset of ten metals—arsenic (As), cadmium (Cd), cobalt (Co), copper (Cu), iron (Fe), manganese (Mn), nickel (Ni), lead (Pb), vanadium (V), and zinc

(Zn)—based on data availability in the Clarion-Clipperton Zone (CCZ) and their relevance for ecotoxicological assessment, including both essential and non-essential elements for biological functions.

Metal concentration data were evaluated across multiple environmental compartments, including the mid-water column, bottom waters, seafloor sediments, porewaters, and sediment plume samples collected during the Patania II pre-prototype nodule collector test in the BGR and GSR contract areas, as well as water-column baseline data from the NORI contract area.

Based on the currently available data from the Patania II nodule collector test, dissolved metal concentrations in benthic sediment plumes generally remain within the range of natural variability observed in mid-water and bottom-water samples under oxic conditions, with enrichment of Fe, Mn, and Co of up to approximately 4–5 times background levels. Uncertainties remain regarding data representativeness and the ecological relevance of observed effects, particularly for long-term and ecosystem-scale responses, given the limited data coverage and scarcity of deep-sea ecotoxicological studies.

Biological responses to metal exposure, as observed in previous studies on shallow-water species, include damage to protein structures and DNA, disruption of metabolic functions, and the induction of oxidative stress. Deep-sea environmental conditions, such as high hydrostatic pressure and low temperatures, may influence these responses, decreasing lethal toxicity in certain species and potentially delaying mortality in others, although available data remain limited and largely restricted to short-term experimental studies. Moreover, sensitivity is likely to differ among taxa. In abyssal polymetallic nodule fields, organisms living within sediments and pore waters, including deposit feeders that routinely ingest sediment particles, are naturally exposed to metal-rich microenvironments and may exhibit a greater tolerance to metal exposure than species that experience lower natural exposure levels. Early-life stages are considered particularly sensitive, with potential implications for population viability.

Many environmental toxicity thresholds already exist for inshore and offshore activities, such as those for the oil and gas and dredging industries, which are operational and part of existing regulatory regimes. However, environmental threshold values developed for coastal settings and/or other industries are not necessarily transferable to polymetallic nodule mining activities in abyssal environments. Nonetheless, the methodologies used to derive such thresholds, and in some cases the threshold values themselves as provisional screening benchmarks, may provide useful initial guidance for developing ERPs. The IEG evaluated two primary approaches for developing ERPs:

1. International Water Quality Standards: Using existing benchmarks (like the Australia New Zealand Guidelines) to define protection levels (e.g., 99% or 95% of species protected).
2. Background-Based Statistical Approach: Setting ERPs based on natural variability (e.g., $Mean + n \times standard\ deviation$, n being a positive integer number).

The IEG group expressed divergent views when comparing the two examples and evaluating their potential use as an interim approach for developing ERPs. Several experts favoured the background-based statistical approach, given its reliance on CCZ-specific baseline data, while others preferred to rely on existing water quality guidelines. A disadvantage of the latter approach is that these guidelines were developed for coastal waters and may therefore not be applicable to deep-sea ecosystems. With regard to the statistical approach, the main concern was that the multiplier values (*n*) can not yet be scientifically constrained; furthermore, when multiplier values from shallow-water projects were applied, the resulting differences between ERP levels were relatively small, potentially approaching analytical detection limits and sensor resolution. Several experts further suggested that site-specific ERPs and corresponding Zones of Impact should be empirically derived, drawing on field observations, monitoring data, and laboratory or *in situ* experiments, determined for each operation.

The group emphasized the value of Bulk Toxicity/Elutriate Testing during environmental impact assessments (EIA) to assess the combined impact of physical stressors (e.g. turbidity and sedimentation) and chemical stressors (e.g. increased metal bioavailability) associated with sediment plumes. Appropriate indicators for monitoring include both lethal and sublethal endpoints, including behavioral responses in sensitive taxa such as sponges, holothurians, and anemones. For initial testing, and for practical reasons, it seems likely that shallow-water proxy organisms would need to be used and this would likely result in conservative but uncertain estimates of sensitivity, given the physiological differences between shallow-water and deep-sea taxa.

Turbidity and settling of resuspended sediments

Turbidity and settling of resuspended sediments are a key pressure caused by plumes potentially generated by DSM. Turbidity is a quantitative measurement of the particle density in the sediment-laden seawater. Eventually, the sediments in the plume settle and are redeposited on the seafloor. This process is called "settling of resuspended sediments."

The IEG examined the spatial and temporal variations in turbidity and sedimentation under natural conditions. Although turbidity was variable between regions and within the CCZ, levels were typically extremely low across geographic regions, with small overall interannual variations. Even during spring blooms, turbidity levels were significantly lower than the those generated by sediment plumes during collector test operations.

Sedimentation particle flux measurements obtained from sediment traps installed < 100 m above the seafloor (to ensure direct relevance of results to benthic fauna) were compared between data from the CCZ and other regions. Significant spatial variations and relatively consistent annual patterns were observed in the western CCZ (DORD contract area), central CCZ (Government of the Republic of Korea contract area), eastern CCZ (BGR contract area), Northwest Pacific (BPC contract area), and Indian Ocean (Government of India contract area). Furthermore, in the central CCZ, long-term monitoring results conducted by the Government of the Republic of Korea revealed significant fluctuations related to climate change, such as the El Niño–Southern Oscillation.

Results from past benthic experiments and recent collector tests were examined together with shallow-water surveys and initiatives in other industries to evaluate the effects of sediment deposition on deep-sea organisms. There are limited studies on deep-sea animals, but these show impacts can vary significantly between species and depend on the extent and duration of burial by the sediment (especially epifauna such as corals), but also on the size, shape, and composition of the sediment particles. Data from oil and gas industry studies on burial depth at shallow water depths of 100-200m for various benthic organisms (molluscs, polychaetes, and crustaceans) may offer a useful insight into the potential sedimentation depth effects in the deep sea.

An extensive literature exists on the effects of turbidity on shallow-water animals, with sediment concentration, exposure time, exposure pattern (pulse or continuous), and mineral composition of suspended sediments having different effects depending on the species and the life cycle stage. Fewer studies assessed the effects of turbidity in deep water conditions. A meta-analysis study was undertaken by the IEG, compiling all available data from laboratory experiments, which primarily focussed on deep-sea sponges and corals. Models were developed to investigate firstly the overall response of deep-sea animals to suspended sediment concentrations (SSC), and secondly to identify factors that could potentially influence relationships between responses and sediment concentrations. SSC created a range of responses from feeding to survival. Increasing suspended sediments generally resulted in negative responses but this may depend on the exposure regime. A general dose-response curve was calculated for sponges and corals.

Such dose-response relationships, expressed as Species Sensitivity Distributions (SSD) plot the cumulative fraction of individuals affected by the pressure as it increases. Points along the SSD curve associated with certain changes in species or community condition, can provide ERPs to inform the specification of thresholds. Following a 5-level split of Zones of Impact adopted by the dredging industry (which splits each of the ZoMI and ZoI referred to above into two), these experimental results were used to illustrate how such SSD studies can provide an important step in developing thresholds. However, at this stage the IEG considered that more studies (both laboratory experiments and *in situ* data collection) are needed to broaden the amount and range of dose-response data across multiple taxa and to reflect the likely duration, periodicity, and spatial scale of exposure to the pressure from actual mining before this approach can produce robust generic impact levels to define ERP values.

The IEG also considered appropriate indicators to monitor thresholds. Ecological changes such as declines in the abundance and density of sensitive taxa due to feeding restrictions caused by turbidity, as well as changes of Total Organic Carbon (TOC) and Sediment Community Oxygen Consumption (SCOC) in sediments caused by settling sediment could be effective indicators.

Knowledge gaps and research priorities were identified, including measurement accuracy at low SSC levels, calibration of sensors, robustness of experimental data, and applicability of knowledge from shallow water.

Underwater noise

Underwater noise is a pervasive pressure that will be generated across all stages of DSM operations. Sound propagates efficiently in the ocean, so that noise caused by a source can potentially impact a wide range of marine receptors throughout the water column, and across considerable distances from its origin. The chapter in this report summarizes the current understanding of noise sources associated with DSM, biological sensitivities of marine mammals, fish and invertebrates, as well as existing management strategies and regulatory thresholds in place for marine mammals and fish.

The primary sources of noise include mining vessels (through propulsion systems, thrusters, engines and onboard processing of extracted minerals), ancillary ships, vertical transport systems, and seabed collectors. While acoustic characteristics for some of these components may be obtained from existing offshore industries and are relatively well understood, risers and seabed collectors represent newer technologies with less certain acoustic characteristics. Risers may act as continuous noise sources encompassing the whole water column, complicating both measurements and modelling of their radiated noise. In addition, Patania II trials documented seafloor vibrations created by the nodule collection mechanism that may affect benthic organisms, noting this was shown to dissipate within 400 m from where the collector was operating. DSM-generated noise should be considered in the context of the natural acoustic environment of ambient ocean noise, which has many contributions from geophysical and metocean phenomena such as wind and rain, from biological sources such as fish and whales, and from anthropogenic sources such as background shipping.

Potential biological impacts from anthropogenic underwater noise range from physiological to behavioural responses. Permanent or temporary hearing damage may occur at high noise exposure levels and durations. Behavioural disturbance may include changes in functional, physical and acoustic behaviour such as communication, movement, feeding, and habitat use. Marine mammals are today the best-studied group, with established quantified thresholds for noise-induced hearing loss (temporary or auditory injury) and qualitative guidance on behavioural response thresholds. Although less quantified, some thresholds also exist for fish. In contrast, noise effects on invertebrates remain poorly understood, although emerging evidence suggests impacts on behaviour and physiology, including effects on reproduction. A key concern across all groups is the cumulative effect of multiple noise sources operating over large spatial and temporal scales.

Regulatory approaches to underwater noise generally combine source-based and receptor-based strategies. Source-based controls focus on limiting noise emissions through engineering and operational design, while receptor-based approaches consider risk thresholds and spatial management (e.g., exclusion zones or periods) to protect marine organisms from injury or disturbance.

The IEG considered that if science-based guidelines are already available for a receptor group, these should be followed. The application of such guidelines, including metrics and indicators for marine mammals and fish, was illustrated following the Zone of Impact model and associated ERPs. Similar approaches should be considered to develop noise thresholds for marine invertebrates.

However, significant uncertainties remain today, mainly due to the limited amount of empirical data obtained from full-scale DSM operations, particularly regarding noise emissions from risers and seabed collectors. Baseline acoustic conditions in potential DSM environments are not well characterised, and there is a major lack of understanding of how noise affects invertebrate communities. These gaps constrain the ability to accurately assess impacts and define appropriate thresholds.

Light pollution

Artificial light represents an artificial pressure in the naturally aphotic (lightless) environment of the deep sea. While the spatial footprint of light is expected to be significantly smaller than that of sediment plumes or noise, its high intensity can cause immediate and potentially irreversible impacts on deep-sea organisms adapted to extreme darkness in the benthic environment. Artificial Light at Night (ALAN), which refers to any human-made illumination during nighttime, disrupting natural dark cycles, is also important to be considered for assessing impacts throughout the overall water column ecosystems.

Primary sources of artificial light in the context of DSM include:

- Surface: Lights from mining and support vessels.
- Seafloor: High-intensity LED lighting on seabed collectors (possibly), ROVs, and AUVs used for navigation and monitoring.

Biological responses primarily involve visual impairment and behavioural and physiological changes. Many deep-sea organisms possess highly sensitive visual systems that can be permanently blinded by exposure to high-intensity artificial light. Light pollution has also shown to affect reproduction and physiology of many species. Furthermore, light can act as an attractant or a repellent, disrupting natural predator-prey dynamics and daily migrations.

Currently, there are no established thresholds specifically for light in the deep sea. Recent scientific studies proposed a depth/distance-based metric that can serve to estimate risk exposure to light. While this approach uses an indicative value of light sensitivity from a shallow water species, it provides a useful starting point for applying the zone of impact model to DSM context. The IEG suggests that management may initially rely on operational guidelines—such as, where possible, minimizing light intensity, using specific wavelengths (e.g., red light), and limiting the duration of exposure.

General remarks

Developing environmental threshold values is an iterative and adaptive process. Establishing environmental threshold values as regulatory tools requires consideration of scientific as well as economic, technological, societal and political values and/or constraints, linked to environmental objectives and the acceptable levels of environmental impacts to society. The work of the IEG focused on the ecological aspects of threshold development as a basis to inform project-specific operational thresholds during exploitation activities.

Progress in this study is characterized by the development of a unified management framework that can be used for each of the pressures considered in the report, as well as for future work on other pressures. The proposed Zones of Impact model provides a structured way to translate impacts along a gradient of pressures into operational management zones, based on identification of ecological reference points. This allows the more sensitive ecological receptors or spatially extensive pressure to drive regulatory boundaries.

The IEG emphasizes that while pressures such as toxicity, turbidity, noise, and light were treated separately in the present report, *in situ* ecological responses arise from their combined and potentially synergistic effects. Chemical and physical stressors act simultaneously within sediment plumes, with potentially additive impacts. Hence, for example, impacts of turbidity/settling sediments and ecotoxicity could best be considered together.

The IEG identified critical knowledge gaps and priorities for future research to refine environmental thresholds. A primary recommendation is to undertake laboratory studies using shallow-water proxies to assess biological responses that can serve as initial guidance for *in situ* experiments and monitoring involving actual deep-sea fauna. The group advises, in general, prioritizing research on the long-term, chronic, and sub-lethal effects of mining pressures—such as changes in reproduction, growth, and behaviour—which may serve as the most effective early warning signals of ecosystem-level change. In addition, data sampling and analysis standardisation is critical to allow for direct comparisons across different contractor areas and oceanic regions.

Specific research priorities include:

- Toxicity: Investigating the role of environmental conditions (pressure, temperature, pH) on metal bioavailability and the wider application of bulk toxicity testing.
- Turbidity and settling of sediment: Experimental work with deep-sea taxa, exposed to realistic mining plume scenarios, and carried out for a sufficient time to detect sub-lethal long-term impacts on animal health.
- Noise: Characterizing the acoustic signatures of specific DSM equipment, investigating sensitivity of understudied receptors (fishes and deep-sea invertebrates), investigating sensitivity to the full range of noise effects including particle motion.
- Light: Quantifying light intensities that elicit biological responses for key indicator species in the aphotic zone.
- Standardization: Establishing global protocols for sampling and analytical techniques.

The IEG notes that close cooperation between the Authority, ISA contractors, and wider scientific community is essential to increase data confidence and refine the methods during equipment trials, test mining and exploitation phases. Standardized baseline surveys and monitoring are required to integrate available datasets into a coherent global framework for contributing to effective environmental protection.

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1 Background

The International Seabed Authority (ISA, herein referred as the Authority), an autonomous international organization established under the 1982 United Nations Convention on the Law of the Sea (UNCLOS, herein referred as the Convention) and the 1994 Agreement relating to the Implementation of Part XI, is the organization through which States Parties to the Convention organize and control all mineral-resources-related activities in the Area for the benefit of humankind as a whole. In doing so, the Authority has the mandate to ensure the effective protection of the marine environment from harmful effects that may arise from activities in the Area according to Article 145 of the Convention.

To fulfill this mandate, the Authority is currently developing Draft Regulations on Exploitation of Mineral Resources in the Area (the "Draft Regulations"). In adopting and implementing the regulations, the Authority must, for the exercise of its functions under Part XI of the Convention, incorporate "mining standards and practices, including those relating to operational safety, conservation of the resources and the protection of the marine environment" (Annex III, article 17(1)(b)(xii) of the Convention). The appropriate mix of prescriptive measures in the regulations, process and performance Standards and guidelines remain a core part of the ongoing negotiations, in accordance with the needs of the Authority, the industry and relevant stakeholders.

The Convention links different levels of environmental impacts from seabed mining with specific legal and environmental management consequences. Necessary measures must be taken with respect to activities in the Area to ensure an effective protection of the marine environment from the harmful effects of activities in the Area as set out in Article 145 of the Convention. Disapproval of an application is decided in cases where substantial evidence indicates the risk of serious harm to the marine environment (arts. 162(2)(x) and 165(2)(l) of the Convention). In addition, the Convention provides for emergency orders, including the suspension or adjustment of activities to prevent serious harm of the environment (arts. 162(2)(w) and 165(2)(k) of the Convention). Finally, the Convention foresees liability and compensation for environmental damage (arts. 139 (2) and 235 (2) of the Convention).

The Authority has a preference for a regulatory framework, including Standards and guidelines to be developed on the basis of an outcome or results-based approach to regulations, in particular in connection with environmental regulations, and drawing on existing best practices in regulatory frameworks for other industries, such as the offshore oil and gas industry. An outcome-based approach provides for rigorous and contractually binding outcomes, while affording flexibility in the processes used to achieve those outcomes (ISBA/25/C/19/Add.1[5], Annex). In this approach, defining appropriate environmental standards, including quantitative environmental thresholds and trigger points for environmental effects, will inform management measures to achieve the different requirements set out in the Convention. Yet, allowing a level of flexibility for contractors to decide how to deliver these requirements will encourage technological innovation and contribute to the development of best practices for activities in the Area.

[5] Report of the Chair of the Legal and Technical Commission on the work of the Commission at the second part of its twenty-fifth session (ISBA/25/C/19/Add.1)

The following sections describe current progress on the development of the Draft Regulations and associated Standards and guidelines, as a context in which the initial steps towards the development of environmental threshold values have been considered, following the Council decision ISBA/27/C/42[6]. This chapter then includes an overview of the scope, purpose and structure of this report relating to this initial work.

1.1 Development of Regulatory Framework

1.1.1 Draft Regulations on Exploitation of Mineral Resources in the Area

The Draft Regulations currently under negotiation form the concluding cornerstone of ISA's regulatory framework that governs all aspects of seabed mining operations, from prospection and exploration to exploitation (the Mining Code). Part IV of the Draft Regulations (ISBA/31/C/CRP.1/Rev.3[7]) focuses on environmental protection, incorporating provisions aimed at minimizing the adverse impacts of seabed mining activities on marine ecosystems. Key elements include requirements for environmental impact assessments, the establishment of environmental management and monitoring plans, and the implementation of monitoring and reporting mechanisms to ensure compliance with environmental standards. By establishing clear norms and procedures, the Authority aims to promote transparency, accountability, and responsible stewardship of the common heritage of humankind.

1.1.2 Draft Standards and guidelines

The Draft Regulations require that the organs of the Authority develop specific Standards and guidelines to support their implementation. The Standards will be legally binding (i.e. mandatory) for both contractors and the Authority, whereas the guidelines will be recommendatory in nature (ISBA/25/C/19/Add.1[8], section IV.A and Annex). A first set of Standards and guidelines were drafted in 2022 (from ISBA/27/C/3 to and including ISBA/27/C/12).

An expanded list of anticipated Standards and guidelines based on the ongoing negotiations of the Further Revised Consolidated Text (ISBA/31/C/CRP.1/Rev.3[7]) and Further Revised Suspense Document (ISBA/31/C/CRP.3[9]) is currently under consideration by the Legal and Technical Commission (the "Commission"), who is expected to revise the list of Standards and guidelines, including those that had been drafted in 2022, in light of the current state of negotiations.

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[6] Decision of the Council of the International Seabed Authority relating to the development of binding environmental threshold values (ISBA/27/C/42)

[7] Draft regulations on exploitation of Mineral resources in the Area - Further Revised Consolidated Text (Revision 3) ((ISBA/31/C/CRP.1/Rev.3)

[8] Report of the Chair of the Legal and Technical Commission on the work of the Commission at the second part of its twenty-fifth session (ISBA/25/C/19/Add.1)

[9] Elements to be relocated from the draft regulations on exploitation of mineral resources in the Area to the Standard and Guidelines and other rules, regulations and procedures of the Authority - Further Revised Suspense Document (ISBA/31/C/CRP.3)

1.1.2.1 Environmental threshold values

As part of this suite of Standards and guidelines, and following the submission by the delegation of Germany as contained in the document ISBA/27/C/30[10], the Council decided that binding environmental threshold values, including early warning thresholds, would be developed to contribute substantially to the determination of what is required to ensure effective protection of the marine environment pursuant to article 145 of the Convention, and to set measurable requirements with levels of harm from activities in the Area, including the maximum level of harm from activities in the Area that can be considered acceptable (see ISBA/27/C/42[11]).

According to the Council's decision (ISBA/27/C/4[12]), the initial steps towards the development of environmental threshold values are led by the Commission and supported by scientific and technical expertise of an intersessional expert group (IEG). The IEG was established in November 2023, following the nomination and selection process described in the Terms of Reference specified in the Annex to the document ISBA/28/C/5[13], and subsequently modified during the second part of the 28th session[14]. It worked as three subgroups, focusing on the following specific topic areas:

- Toxicity
- Turbidity and settling of resuspended sediments
- Underwater noise and light pollution

Experts nominated by regional groups were selected to fill in up to five seats of each subgroup. The remaining seats, to a maximum of ten per subgroup, took into account nominations by other stakeholders of the Authority. Geographic and gender balance were considered, and, in all cases, IEG members were selected based on technical expertise and experience. Additional experts with experience in light pollution were nominated by the IEG co-chairs, in line with paragraph 14 of the Terms of Reference, to complement the range of expertise necessary to support the IEG deliberations (see List of Contributors).

1.2 Scope, purpose and structure of the report

This report summarises the outcomes of the IEG work, addressing the following objectives set out in the Terms of Reference:

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[10] Normative environmental thresholds for deep-seabed mining submitted by the delegation of Germany (ISBA/27/C/30)

[11] Decision of the Council of the International Seabed Authority relating to the development of binding environmental threshold values (ISBA/27/C/42)

[12] Ibid.

[13] Report of the Chair of the Legal and Technical Commission on the work of the Commission at the first part of its twenty-eighth session (ISBA/28/C/5)

[14] The Terms of Reference are available at: https://isa.org.jm/wp-content/uploads/2026/07/ToR_Development_of_environmental_threshold_value.pdf

- Synthesis and review of existing information on thresholds;
- Identification of appropriate indicators to define threshold metrics;
- Definition of threshold levels, including early warning thresholds and levels of uncertainty and confidence;
- Evaluation of critical gaps in knowledge related to threshold determination and future required work.

Establishing environmental threshold values as management tools requires several procedural steps, considering scientific as well as economic, societal and political values, linked to environmental objectives and the acceptable levels of environmental impacts to society (see chapter 2). The work of the IEG focused on the ecological aspects of threshold development as a basis to inform project-specific operational thresholds during exploitation activities. This centred on a science-based approach that includes methodologies for defining a standardized zone of impact model and establishing ecological reference points.

According to the Terms of Reference, the IEG work focused on thresholds for polymetallic nodules, which is the resource and habitat regarded as most homogeneous and with most available information on environmental impacts. However, applicability of the methodological approach to other mineral resources was kept in mind as it is expected that thresholds will be similarly developed for cobalt-rich ferromanganese crusts and polymetallic sulphide resources in due course. The IEG discussions considered current understanding of mining plan concepts and technologies that have been tested so far during exploration by Contractors. It was acknowledged that other equipment may require different considerations.

The methodological approach proposed by the IEG, including steps required to develop operational environmental threshold values is introduced in chapter 2. This is followed by summaries of current knowledge of baseline and experimental data, existing thresholds and guidance developed by other industries, critical gaps in knowledge and future research priorities to develop environmental threshold values and indicators, organized respectively for each of the topic areas: toxicity (chapter 3), turbidity and settling of resuspended sediments (chapter 4), underwater noise (chapter 5) and light pollution (chapter 6). Where possible, examples on the use of methods and data to determine relevant metrics used in threshold development are provided. The report ends with general remarks on progress towards the development of environmental threshold values and future research priorities (chapter 7).

This report will be published on the website of the Authority for formal stakeholder consultation. The Commission will consider the report after public consultation and submit its recommendations to the Council, in accordance with paragraph (f) of Council decision ISBA/27/C/42[15].

[15] Decision of the Council of the International Seabed Authority relating to the development of binding environmental threshold values (ISBA/27/C/42)

2 Methodological approach for the development of environmental threshold values

In the context of environmental management, a threshold is often seen as a point that, when reached, results in a change in the characteristics of the ecosystem, often in an abrupt and discontinuous way. Some of these changes may be reversible, but many are not, and ecological responses to reaching a threshold may vary, depending on, not least, the local environment and the type, magnitude and extent of disturbance, over space and time.

Environmental thresholds should be based on readily measurable and cost-effective indicators that have a straight-forward and well-understood link to an ecosystem response (Johnson and Ray 2021). While defining limits of ecological change - beyond which continued disturbance will have adverse effects on the ecosystems - play an important role in environmental assessment, they are not always a solution to complex socioecological decisions. Therefore, threshold values that are used as management tools often relate to a continuum of risk that is weighed against socioeconomic interests as well as environmental change.

Recent reviews of approaches for setting thresholds of "good" environmental status highlight this role of value judgements around acceptability of impacts and management objectives (Hilton et al. 2022, Hiddink et al. 2023, Hiddink et al. 2025). Establishing environmental threshold values as management tools must be based on both scientific understanding as well as political, economic, social and practical considerations (Hitchin et al 2023). In order to be acceptable to the wide range of deep-seabed mining stakeholders, thresholds need to strike a balance among levels of harm acceptable by society, levels of environmental precaution justifiable by governments, scientific robustness, and operational practicality.

The work of the IEG focused on ecological aspects of threshold development, centred on a science-based approach to inform operational project-specific thresholds during exploitation activities. The initial steps considered by the IEG included i) the identification of pressure, receptor and impact gradients, ii) application of ecological reference points, iii) zone-of-impact models, iv) identification of indicators, and v) cumulative effects.

2.1 Pressure, receptor and impact gradients

Pressures are natural or anthropogenic (human-induced) forces that cause stress in an individual organism, population, community, or ecosystem, potentially altering fundamental population, community or ecosystem characteristics such as composition, structure, and function.

Mining systems typically present a gradient of decreasing pressure away from a source (in time and/or in space). However, how these gradients produce impact are not all the same for all pressures and all receptors. An ecological receptor is any individual organism, population, community, or ecosystem that can be affected—positively or negatively—by exposure to an environmental pressure.

A pressure - receptor relationship can be derived in several ways to inform the development of metrics to help develop thresholds:

- Direct experimental measurements of impact on a receptor (e.g., an experiment that investigates the level of toxicity from a metal that leads to the death of 50% of organisms of interest). This can lead to identifying species that act as 'a canary in a coal mine' for other species that are sensitive, albeit less so, to the pressure in question.

- Ecological analogues from another environment where pressure – receptor relationships are better known (e.g., initially using a threshold value of suspended sediment concentration that is known not to cause significant effects on a comparable receptor). The applicability of such analogues from shallow water to the deep ocean would need to be scientifically considered prior to their operationalisation.
- Numerical modelling of impacts (e.g., modelling of cetacean noise injury thresholds instead of experimentally exposing cetaceans to potentially harmful noise levels) can provide the basis for relationships that may otherwise be too resource-intensive or ethically challenging to gain through data acquisition.

Understanding the relationship between the pressures and the species, communities, and ecosystems that may be impacted is critical for determining reference points that evidence environmental change, as well as for identifying and evaluating appropriate mitigation measures to avoid or minimize the environmental impacts.

2.2 Application of Ecological Reference Points

Ecological reference points (ERPs) are metrics or measures to indicate the status or health of the ecosystem and describe levels of environmental change at which measurable and ecologically meaningful responses occur. These could be, for example, the percentage of a population affected by a particular level of pressure.

ERPs provide measurable ecological benchmarks that allow receptor impacts to be monitored, and action taken to manage and reduce impacts before severe or irreversible change occurs. They can also provide benchmarks that allow proactive mitigation to be put in place to develop management strategies that avoid or reduce receptors being exposed to a particular pressure level. When assessed for a particular mineral resource environment and operation, they can then help determine threshold criteria and development of management actions. ERPs can correspond to severe or potentially irreversible change but can also reflect earlier shifts in condition that may still be reversible if pressures are reduced. In this way, they also can act as ‘early warning’ measures.

2.3 Zone of Impact models

A common tool used in understanding levels of impact that may lead to differing options for environmental management is a Zone of Impact model. In this model, a series of zones of impact are defined as spatially discrete areas around a source of disturbance or pollution, each characterized by a varying degree of environmental change or degradation. The model allows for the consideration of multiple pressures acting simultaneously along a single dimension and their overall combined impact. These zones can help to guide development of environmental monitoring and mitigation efforts (Johnson and Ray 2021).

Many management schemes use the following three zones:

- **Zone of High Impact (ZoHI):** Severe, potentially irreversible damage. This is the area closest to the source of disturbance, where environmental changes are most intense and often exceed natural recovery capacity, likely resulting in irreversible damage. For extractive industries, the ZoHI is usually considered to represent the footprint of the area directly targeted for extraction and the area immediately adjacent to it.

- **Zone of Medium/Moderate Impact (ZoMI):** Temporary, reversible, or sub-lethal impacts. This is a transitional area surrounding the Zone of High Impact, where impacts remain noticeable but are less severe due to dilution or dispersion of the impact with distance from the source.
- **Zone of Influence (ZoI):** Minimal or no detectable impact on biota, though the pressure remains present. This is the outermost area where pressures are noticeable. In the Zone of Influence, changes in environmental quality are expected / predicted, but typically remain within the range of natural variability, without an associated detectable impact or with minimal impact on the environment. These areas are often large in comparison to the ZoHI and the ZoMI. The relative size of each zone will relate to the pressures and receptors concerned, as well as environmental characteristics of the area.

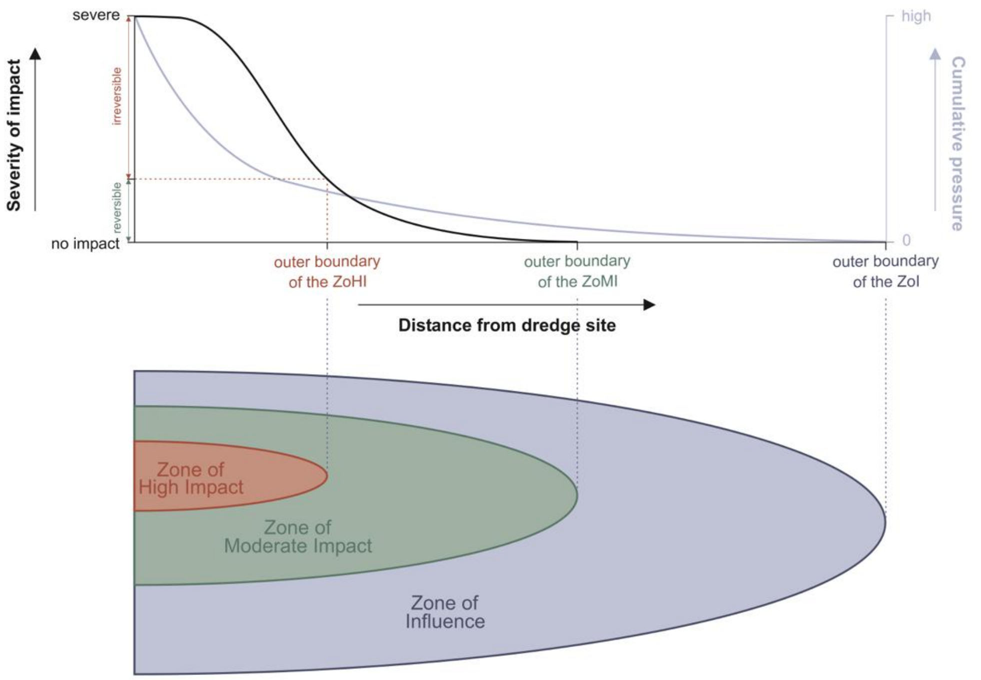

Figure 1 An example of a Zones of Impact approach used for a dredging project. In this case, the zone boundaries are based on the biological effects for corals (sedimentation thickness, suspended particulate matter, etc.) Source: Environmental Protection Authority 2016, Technical Guidance – Environmental Impact Assessment of Marine Dredging Proposals, EPA, Western Australia

Some management schemes, especially those related to sediment and turbidity levels from dredging, use subdivisions within this 3-Zone construct, with the ZoI and ZoMI being further split in two, resulting in a 5-level classification of the severity of impact (Table 1).

Table 1 The severity categories within the Zone of Impact approach, and descriptions of impact characteristics. Compiled and adapted from various sources (PIANC, 2010, 2023; ISBA/27/C/4[16])

Zone	Severity	Description
Zone of High Impact	Major Impact	Total loss or major/substantial alteration to key elements or features of the baseline conditions such that ecological/habitat character/composition/attributes will be fundamentally changed. The impact will result in complete or substantial habitat reduction over the affected area, and likely to cause localised loss of biological communities. Population-level impacts. Major change to ecosystem structure and potentially function.
Zone of Medium Impact	Minor Impact	A minor but measurable shift away from baseline conditions, not a material change. Reflected in higher levels of stress, small changes in behaviour. Detectable but localised mortalities of individuals may occur, at a localised spatial scale. The underlying character/composition/attributes of the baseline condition will be maintained.
	Moderate Impact	Loss or alteration to one or more key elements or features of the baseline conditions such that ecological/habitat character/composition/attributes will be materially changed. The impact will result in detectable mortality at a spatial scale that may affect population size or be locally significant.
Zone of Influence	No Change	Within the range of normal natural variability in baseline conditions. No change will occur to the quality or functionality of the habitat, communities, or species.
	Slight Impact	Elevated stress may occur with individuals, potentially small changes detectable in behaviour. Will be below levels that can be expected to be detectable as mortality in the field.

The IEG considered the Zone of Impact model to be an appropriate approach to use for informing the development of project-specific operational threshold values, with ERPs defining the transitional boundaries between different zones of impact. This approach can therefore provide a scientific basis to define quantitative environmental threshold values, with subsequent inclusion of political, economic and social values. Such Zone of Impact models will depend on the region, type of resource and characteristics of the mining project. The model application will need to consider the varying spatial and temporal scales of physical mining impacts and associated ecological recovery times (seasonal and inter-annual), interactions between pressures, as well as the three-dimensional nature of mining operations, with impacts and effects spanning the seabed and water column through the duration of the mining operation and post-mining monitoring plans.

2.4 Identification of indicators

An indicator is a quantitative or qualitative value or measurable parameter that can be used to provide information on, and insight into, the health or state of the environment. There are a large number of potential indicators, depending on exactly what aspect of change in the environment or ecosystem needs to be measured. Indicators can be specific to environmental characteristics, individual taxa, or communities. Indicators that can measure a broad-scale level of response in ecosystem structure or function are likely to be more appropriate for determining changes between the various categories of impact referred to above than highly specific or

[16] Draft standard and guidelines for the environmental impact assessment process (ISBA/27/C/4)

localised indicators. This is an important component to evaluate the effects of specific management measures.

Both pressure-based indicators (e.g. concentrations of dissolved metals, sedimentation rates, noise and light levels) and state-based indicators (e.g. biological responses, changes in community structure, abundance, habitat loss, change in ecosystem processes) are needed to validate thresholds. In situations where ecological data are limited, thresholds may initially rely more heavily on pressure-based indicators linked to baseline variability and precautionary assumptions. Over time, thresholds can evolve toward stronger linkages with state-based responses and improved ecological understanding that provide ecosystem-level assessment. Like in other regulatory frameworks, the development of indicators and thresholds is an ongoing process and requires periodic review as new knowledge become available.

2.5 Cumulative impacts

Cumulative impacts are the combination of multiple past, present, and reasonably foreseeable future pressures over space and time. They represent the total burden of stressors on a system and show where individually minor actions, when combined with others, can lead to significant, long-term environmental consequences. Impacts may be synergistic (where the combined impacts are greater than the sum of the individual impacts), or antagonistic (where there are opposing effects that reduce the overall total impact).

Cumulative impacts can occur within a single mining operation, between mining operations and between mining operations and other users of the sea as well as other human-induced pressures (e.g., climate change, pollution, ocean acidification, oxygen loss). All these need to be considered as part of the impact assessment of mining operations at both the local and regional levels (ISBA/27/C/4[17]).

The Zone of Impact approach considered by the IEG adopts an integrated perspective, where pressure- and state-based indicators across all stressors are ultimately evaluated within unified zones of impact, taking into consideration cumulative impacts. This ensures that management boundaries reflect the most sensitive or spatially extensive driver(s) of impact, rather than any single stressor considered in isolation. For clarity and alignment with the request made by Council, analyses and discussions of the different pressures are presented in separate sections of this report, and further remarks on cumulative impacts are included in chapter 7.

[17] Draft standard and guidelines for the environmental impact assessment process (ISBA/27/C/4)

3 Toxicity

The toxicity of a substance is defined as its capacity to cause adverse effects in a living organism (Duffus et al., 2007). In the context of deep-seabed mining, toxicity therefore refers to substances, such as dissolved or particle-bound metals and fine suspended particles, that may adversely affect marine organisms through physicochemical interactions. In addition, mining activities generate physical stressors, such as elevated suspended sediment concentrations, which can also affect biological functions. It is important to emphasize that, in the marine environment, these chemical and physical stressors do not act independently. Organisms are exposed to both simultaneously via sediment plumes, and their combined effects may be additive or synergistic.

This chapter focuses on metal-related toxicity, with particular emphasis on metal mobilization and bioavailability. Other chemical substances, such as hydraulic oils, may enter the marine environment during mining operations through accidental spills or equipment breakage. However, such incidents would be expected to be rare and are therefore not covered here. The physical effects associated with sediment suspension, turbidity, and deposition are addressed in Chapter 4. The IEG agreed that physical and chemical stressors should not be evaluated separately and therefore advocated for bulk toxicity tests investigating the physical (sedimentation/turbidity) and chemical (metal toxicity) factors simultaneously. Accordingly, while these two toxicity aspects are covered in separate chapters in the present report for clarity and ease of reference, the overall threshold framework recognizes the need for an integrated assessment. In particular, bulk toxicity testing and the Zones of Impact approach provide mechanisms through which chemical and physical stressors can be evaluated together when defining operational thresholds and management responses.

Metals may increase in concentration in the marine environment via the physical disturbance of naturally occurring metal-bearing sediments and nodules, thereby increasing the likelihood of metal exposure to biota. Potential sources of metals include the sediment plumes generated during collector operations ("seabed disturbance plumes") and return water – comprising seawater separated from mineralized material, including nodules and sediments – discharged from the surface vessel into the water column ("discharge plumes"). Whether biota is exposed to these metals, and to what extent the metals are bioavailable, are critical factors in assessing ecological risk and developing appropriate thresholds.

The work presented in this chapter focuses on polymetallic nodules in the Clarion Clipperton Zone (CCZ). It synthesizes baseline metal data provided by ISA Contractors exploring for polymetallic nodules, results from published ecotoxicological studies under laboratory and *in-situ* conditions, and comparisons with marine environmental quality thresholds applied in other industrial sectors. This work builds on a recent expert workshop organized in 2023 on "Ecotoxicological Impacts of Deep-Sea Mining" (Schmidt et al., 2025), which provided opportunities for dialogue among scientists, regulators, and other stakeholders. The aim is to inform the development of a scientifically grounded approach for defining environmental threshold values that are both operationally applicable and environmentally meaningful for marine mineral exploitation. The chapter concludes with identifying key knowledge gaps and priorities for future research and monitoring.

3.1 Variability of heavy and trace metals in the water column and sediments

The IEG subgroup focused on a subset of ten metals—arsenic (As), cadmium (Cd), cobalt (Co), copper (Cu), iron (Fe), manganese (Mn), nickel (Ni), lead (Pb), vanadium (V), and zinc (Zn)—based on data availability and their relevance for ecotoxicological assessment in abyssal polymetallic nodule bearing environments. These metals include both essential and non-essential elements. Essential trace metals (e.g. Co, Cu, Fe, Mn, Ni, and Zn) support biological processes but may become toxic at elevated concentrations. Vanadium is not universally recognised as essential but may play biological roles in certain organisms. In contrast, metals such as As, Cd, and Pb, have no known biological functions and may exert toxic effects even at relatively low concentrations. Depending on the resource type, geological setting, and operational processes (including extraction and dewatering), these metals may become enriched relative to natural background conditions.

The behavior of trace metals generated by deep-seabed mining depends not only on their concentration, but also on their chemical form and physical state – that is, whether metals are dissolved in seawater (including sediment porewater) or associated with suspended particles. Because dissolved and particle-associated phases can exhibit different transport and fate characteristics, trace-metal plumes may not necessarily overlap with sediment plumes in space and/or time. Three principal processes influence metal dynamics in these plumes: (1) adsorption of metals onto, or incorporation within, suspended particles; (2) release of metals into the dissolved phase through desorption, dissolution, or remineralisation; and (3) scavenging, whereby reactive suspended particles remove dissolved metals from the surrounding water column. The balance between these processes determines the relative proportions of dissolved, colloidal, and particulate metal fractions, and therefore their potential bioavailability.

In the CCZ, bottom seawater and porewaters within the upper sediment layers are oxygenated. Sediment resuspension under oxic conditions can cause measurable enrichment of some dissolved metals (particularly Mn, Fe, Co and, in some cases, Cu), but current evidence suggests that enrichment is limited to a subset of elements and the ecological significance remains uncertain (Schmidt et al, 2025). Furthermore, concentrations of colloidal-bound metals may increase as dissolved elements adsorb onto nanoparticles of manganese oxides and iron oxyhydroxides. Sediment resuspension also increases concentrations of particle-associated metals in the water column. The understanding of bioavailability and toxicity of these particulate metals remain limited, although filter-feeding organisms may be affected both by exposure to suspended particles and by the mobilisation of particle-bound metals during digestion. Disturbance of the sediment surface during mining may remove the upper few centimeters of the sediment column, thereby temporarily reducing the thickness of the oxic layer. Such changes in sediment oxygenation can promote the reduction of Mn- and Fe-oxide phases and the subsequent mobilisation of associated trace metals (Volz et al., 2020). Robust baseline metal datasets, together with measurements obtained during sediment plume-generating activities, are therefore essential for distinguishing natural variability from mining-induced changes in dissolved, colloidal and particle-associated metal concentrations.

In the present assessment, baseline metal concentration data were evaluated across multiple environmental compartments, including the mid-water column, bottom waters, seafloor sediments, and porewaters. Sediment plume samples collected during the Patania II seafloor nodule collector test in the BGR and GSR contract areas generally remained within the range of natural variability observed in mid-water and bottom-water samples, with only limited enrichment (typically up to a factor of 4-5) for selected elements such as Fe, Mn, and Co. These data were provided by exploration Contractors as part of their environmental baseline studies for polymetallic nodule exploration, either through the ISA DeepData database or directly by BGR based on recently analysed datasets.

To ensure comparability, only datasets derived from consistent methodologies were included in this report. These comprise data from the BGR and GSR contract areas in the CCZ, where identical sampling and analytical protocols were applied. In addition, water-column data from the NORI contract area available through DeepData were of the same order of magnitude as the BGR bottom-water data and were generated using comparable analytical methods; these data were therefore included in the assessment. Metal data from other contractors were excluded, as sampling depths varied and, in several cases, sampling and analytical methods are either insufficiently documented or not standardized, which may introduce methodological inconsistencies in the data interpretation.

The average trace metal concentrations in bottom water from the BGR and GSR (both sampled 5 m above the seafloor) and the NORI contract area (50-200 m above the seafloor) are very similar (see Figure 14), despite large distances between sampling sites (930 km between BGR and GSR and ~150 km between BGR and NORI) and differences in water depth (BGR: ~4100 m; GSR: ~4500 m; NORI: ~4200 m, see Figure 13). Whether this consistency extends across the eastern CCZ remains to be tested. If confirmed, it would support the use of data from multiple contract areas to constrain a robust regional baseline for environmental assessments. This interpretation is consistent with findings by Schmidt et al. (2022), who showed that trace metal concentrations from the BGR contract area generally fall within the range of observations reported by the GEOTRACES programme for the Central Pacific Ocean.

Table 2 summarizes trace metal concentration data across key environmental compartments in the BGR, GSR, and NORI contract areas, covering baseline conditions in (1) the mid-water column, (2) ambient bottom water, (3) surficial seafloor sediments, and (4) sediment porewaters, as well as impact conditions in (5) seawater from a benthic sediment plume generated during the Patania II nodule collector test in the BGR and GSR contract areas. This dataset enables comparison between the mid-water column and bottom waters, across baseline and disturbance conditions, and among contract areas, while also providing insight into the partitioning of metals between the dissolved and particulate phases.

Dissolved metal concentrations in the mid-water column (Table 2 , column a) and bottom waters (Table 2, column b) are generally low and comparable in magnitude for most elements (with the exception of Pb and Cd, which are typically an order of magnitude lower), reflecting relatively homogenous background conditions in the deep waters across these three contract areas. Whether this pattern applies to the entire CCZ or beyond, remains to be validated. In contrast, metal concentrations in seafloor sediments (Table 2 ,column c) are several orders of magnitude higher, consistent with the strong association of trace metals with Mn-oxide-rich particles (Koschinsky and Halbach, 1995). Sediment porewater concentrations (Table 2 column d) exhibit variability across elements, particularly for redox-sensitive metals (i.e. elements that are sensitive to changing oxygen conditions) such as Mn and Fe, with associated variability also observed for Co and Pb, reflecting diagenetic processes within the surface sediments. Porewater metal concentrations from the BGR and GSR contract areas show broadly comparable ranges, consistent with the pattern observed for bottom waters (Figure 15).

Overall, differences in bottom-water and porewater metal concentrations between the three contract areas are small, although it remains to be investigated whether this pattern holds across the wider region. The observed variability across the environmental compartments reflects both natural heterogeneity and differences in data coverage and analytical approaches among contractor datasets.

Table 2 Environmental baseline concentrations of heavy and trace metals measured across key compartments in the Clarion-Clipperton Zone, including (a) mid-waters, (b) bottom waters, (c) surficial seafloor sediments, (d) sediment porewaters, as well as concentrations measured in (e) a benthic sediment plume (impact) generated during the Patania II nodule collector test in the BGR and GSR contract areas in 2021. Element abbreviations: As (arsenic), Cd (cadmium), Co (cobalt), Cu (copper), Fe (iron), Mn (manganese), Pb (lead), Ni (nickel), V (vanadium), Zn (zinc). NA = not available, SD = standard deviation, # = number of samples.

Metal	Environmental baseline												Impact	
	a. Mid-water (µg/kg; unfiltered)			b. Bottom water (µg/kg)			c. Seafloor sediment (mg/kg)			d. Porewater (µg/kg; < 0.2 µm)			e. Sediment plume (µg/kg; <0.2 µm)	
	Range (min - max)	mean ± SD	#	Range (min - max)	mean ± SD	#	Range (min - max)	mean ± SD	#	Range (min - max)	mean ± SD	#	Range (min - max)	#
As	1.22 - 1.77	1.45 ± 0.17	15	1.17 - 1.89	1.55 ± 0.25	26	NA	NA	NA	NA	NA	NA	NA	NA
Cd	0.083 - 0.107	0.094 ± 0.007	15	0.08 - 0.11	0.09 ± 0.01	27	NA	NA	NA	0.15 - 0.42	0.21 ± 0.07	54	0.084 - 0.093	4
Co	NA	NA	NA	NA	0.0008 ± 0.0001	7	41.0 - 72.0	59.0 ± 5.1	37	0.004 – 0.074	0.017 ± 0.015	54	0.0012 - 0.0059	4
Cu	NA	NA	NA	0.16 - 0.35	0.288 ± 0.015	7	129 - 248	172 ± 29	37	1.90 - 18.9	5.59 ± 3.67	53	0.27 - 0.46	4
Fe	NA	NA	NA	NA	0.064 ± 0.028	7	3.69 - 4.53	4.20 ± 0.17	37	0.05 - 2.83	0.42 ± 0.56	53	0.073 - 0.343	4
Mn	NA	NA	NA	NA	0.013 ± 0.003	7	0.26 - 0.76	0.55 ± 0.11	37	0.03 - 1.80	0.41 ± 0.46	54	0.019 - 0.22	4
Ni	0.54 - 0.59	0.57 ± 0.02	15	0.50 - 0.62	0.546 ± 0.031	27	97 - 213	173 ± 30	37	0.45 - 5.47	1.32 ± 1.08	53	0.55 - 0.7	4
Pb	0.020 - 0.053	0.030 ± 0.009	10	NA	0.003 ± 0.001	5	4 - 13	5.88 ± 2.8	37	0.001 - 0.017	0.002± 0.002	53	0.001 - 0.018	4
V	1.70 - 2.50	2.08 ± 0.19	16	1.56 - 2.34	2.05 ± 0.26	27	82 - 106	96.0 ± 4.4	37	2.07 - 30.7	6.37 ± 5.46	53	1.51 - 1.94	4
Zn	0.54 - 2.14	0.82 ± 0.38	15	0.54 - 2.20	0.90 ± 0.41	25	14 - 39	25.0 ± 6.1	37	0.87 - 7.40	1.55 ± 0.93	54	0.98 - 1.77	4
Source	*Mid-water column data (1750-3500 m) from the NORI contract area obtained in 2020 from seven CTD casts.*			*Data from the BGR and GSR contract areas (5 mab; filtered <0.2 µm; Schmidt et al., unpublished) and from the NORI contract area (50-200 mab; compiled from the DeepData database; unfiltered).*			*Data from boxcorer samples (0-5 cm sediment depth) collected in the BGR contract area (see Environmental Impact Statement, 2024).*			*Data from multicorer samples (0-5 cm sediment depth) collected in the BGR and GSR contract areas in 2021 and 2022 (Schmidt et al., unpublished)*			*Data obtained during the Patania II nodule collection trial in 2021 in the GSR and BGR contract areas. Mean and SD are not available (Schmidt, unpublished data).*	

Figure 2 provides a graphical comparison of the metal concentrations across environmental compartments shown in Table 2. The figure highlights the strong contrast between dissolved metal concentrations in the water column (Figure 2 a and b) and the markedly higher concentrations in sediments (Figure 2 d and e). The graphical representation further emphasizes the high variability and wide range of values in porewaters and sediments, reflecting spatial heterogeneity determined by geochemical controls.

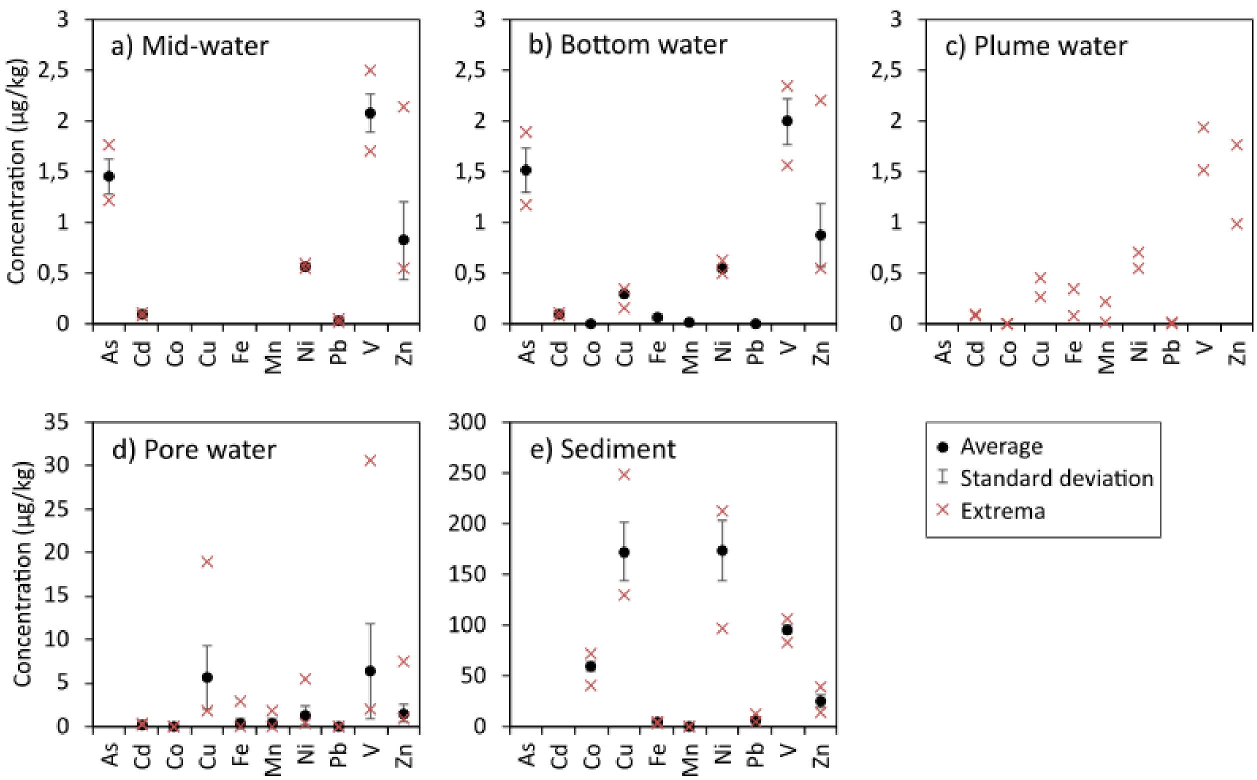

Figure 2 Graphical representation of trace metal concentrations summarized in Table 2 across the five environmental compartments in the BGR, GSR, and NORI exploration areas of the Clarion-Clipperton Zone, including (a) mid-water column, (b) bottom water, (c) plume water, (d) sediment porewater, and (e) seafloor sediments. Concentrations are shown for selected trace metals (As, Cd, Co, Cu, Fe, Mn, Ni, Pb, V, Zn). Black symbols indicate average concentrations, error bars represent standard deviations, and red crosses denote minimum and maximum values (Extrema).

3.2 Proxy and experimental studies

Measurements of metal concentrations were obtained from benthic sediment plumes generated during the Patania II nodule collector tests in the BGR and GSR contract areas. During the two tests, which lasted about 2 days, approximately 4-8 cm of the surficial sediments were removed, with penetration depths typically ranging between 4 and 6 cm, over an area of max. 0.037 km² (Gazis et al. 2025). These data are included in the section above to facilitate comparison with background bottom-water concentrations, although they should be interpreted with caution due to the limited dataset.

This comparison indicates that dissolved metal concentrations in the sediment plume (Figure 2 c) generally fall within the range of natural variability observed in mid-water and bottom-water samples, with only limited enrichment (typically up to a factor of 4-5) for selected elements such as Fe, Mn, and Co. Overall, given the relatively high metal content of nodule-bearing seafloor sediments, resuspension is expected to substantially increase concentrations of particle-associated metals in the water column affected by the sediment plume, whereas available evidence indicates that increases in dissolved metal concentrations remain limited under oxic conditions. It is noted that additional data on background seawater chemistry and metal concentrations in sediment plumes from nodule collector tests in the BGR, GSR and NORI contract areas are currently under analysis or in preparation for publication in peer-reviewed scientific journals and are expected to substantially expand the evidence base underpinning this assessment.

3.3 Biological responses to heavy and trace metals

Biological mechanisms of toxicity and detoxification pathways were reviewed in Schmidt et al, 2025. Heavy metals – both non-essential (e.g., Pb, Hg, Cd) and essential metals in excess (e.g., Fe, Cu, Zn) – can harm organisms through three major mechanisms:

- Direct interaction with proteins, lipids, carbohydrates, DNA, and membranes, leading to structural and functional impairment.
- Substitution of essential metal cofactors, disrupting enzyme activity and metabolic processes.
- Generation of reactive oxygen and nitrogen species (ROS/RNS) through redox cycling, causing oxidative stress and damage to nucleic acids, proteins, and lipids.

Metals may accumulate within organisms as bound or insoluble complexes (e.g., metallothioneins, phytochelatins), allowing toxic levels to arise even from low environmental concentrations during an organism's life span (bioaccumulation) or through trophic transfer in marine food webs (biomagnification). Thus, long-lived species and higher-trophic-level organisms are especially vulnerable. Metal levels in sediment minerals reflect historical inputs, but metal levels in biota indicate present bioavailability.

Organisms have evolved diverse detoxification strategies, including: 1) metal-binding compounds (extracellular polysaccharides in bacteria, phytochelatins in algae/plants, metallothioneins in many animals) and 2) antioxidant systems (superoxide dismutase, catalase, glutathione pathways, carotenoids). These mechanisms vary widely even among closely related species. Detoxification is energetically costly, so chronic exposure reduces growth, reproduction, and fitness, while acute exposure can overwhelm protective pathways altogether.

There are two different approaches to assess toxicity, including assessing concentrations that lead to immediate death of organisms (mortality endpoints) and assessing concentrations that cause impacts but do not lead to immediate death (sublethal endpoints). A compilation of published studies where the impacts of metals were assessed under deep-sea environmental conditions (i.e. low temperature and/or high pressure) can be found in Schmidt et al., 2025. These involved studies with shallow-water or deep-water organisms, exposed to metals in the laboratory or *in situ*, and some of them also included different temperature and high- pressure regimes (Auguste et al. 2016, Brown et al. 2017a, Brown et al. 2017b, Martins et al. 2018, Mestre et al. 2019a, Mestre et al. 2019b, Martins et al. 2022). Early larvae development, behaviour, and stress biomarkers are some of the biological responses (endpoints) presented in these studies.

The current knowledge can be synthesised as follows:

- Low temperature appears to decrease lethal and sublethal toxicity in shrimps adapted to warmer environments, probably linked to lower metabolism. This suggests toxicity effects may be delayed in shrimps, possibly like the observed delayed mortality in cold-water corals.
- Pressure seems to affect lethal and sublethal toxicity of different metals differently; it potentiates the lethal toxicity of mixtures of metals, being an environmental factor not to be ignored, although there are still difficult-to-overcome methodology/feasibility limitations in conducting ecotoxicological experiments under hyperbaric or high-pressure conditions (both *in situ* and in pressurised aquaria);
- Early-life stages are the most sensitive, and crucial for the maintenance of viable populations. The life cycles of most deep-sea species are unknown, so when establishing future thresholds, it is important to consider this limitation.
- Shallow-water proxies are apparently not possible to define for sublethal biomarkers in shrimps. For holothurians there was a broadly similar acute behavioural response between shallow and deep-water species, although replication with deep-sea species when conducting *in situ* experiments is an issue.

Among these studies, only three have investigated biological responses of deep-sea fauna from nodule-bearing or nodule-free abyssal plains (at water depths of 4000-6000 m) to chemical or particle-related stressors:

- Kwan et al., 2019 exposed deep-sea amphipods to elevated Cu concentrations under in situ conditions and observed proteomic changes indicative of physiological stress, but without clear evidence of acute toxicity
- Brown et al., 2017 applied a comparative experimental approach, examining ecotoxicological responses in shallow-water and deep-sea holothurians, and found broadly similar behavioural responses in both groups.
- Mevenkamp et al. 2019 investigated nematode responses to short-term (11 days) burial with crushed nodule particles and found no evidence of increased Cu accumulation or toxicity resulting from particle exposure.

Overall, the studies mentioned above suggest that deep-sea organisms may not exhibit strong acute responses to short-term exposure to metals or particle disturbance under experimental conditions. However, the available evidence remains sparse, taxonomically limited, and largely restricted to short-term laboratory or *in situ* experiments. Consequently, the extent to which these findings are representative of long-term or ecosystem-level responses remains uncertain.

3.4 Existing marine metal contaminant thresholds

Thresholds form an integral part in many of the existing environmental frameworks and typically include some levels of pressure that will also occur during DSM. Schmidt et al., 2025 includes a review of a variety of legal instruments, including binding international treaties, such as the United Nations Convention on the Law of the Sea (UNCLOS), the London Convention/London Protocol (LC/LP), Regional Sea Conventions, such as the Convention for the Protection of the Marine

Environment of the North-East Atlantic (OSPAR), and the Agreement under the United Nations Convention on the Law of the Sea on the Conservation and Sustainable Use of Marine Biological Diversity of Areas beyond National Jurisdiction (BBNJ Agreement) governed by international law. There are also EU directives, such as the Water Framework Directive (WFD) or the Marine Strategy Framework Directive (MSFD), along with national regulations, such as the Norwegian water regulations that implement the directives, as well as non-binding guidelines and recommendations, such as the Australia and New Zealand marine water quality guidelines, the Canadian Environmental Quality Guidelines, and the U.S. EPA Recommended Water Quality Criteria for salt water.

Although some frameworks provide thresholds in the form of a concentration (which are often restricted to a few stressors and are generic), many frameworks provide detailed guidance on approaches and concepts used to derive and implement site-specific values and assess risks and effects. The terminology differs between regulatory bodies, which often relates to differences in function and in methodology for derivation. Most information is available for pressure indicators, which are typically used for the assessment of risks for offshore activities.

Many environmental (operational) thresholds already exist for inshore and offshore activities, such as those for the oil and gas and dredging industries, and these are embedded in existing regulatory regimes. Table 9 presented in Schmidt et al. (2025) expands the initial summary of industry thresholds developed in the “Draft standard and guidelines for the environmental impact assessment process” (ISBA/27/C/4[18]).

Although environmental metal toxicity thresholds are well established in land-based and coastal industries, their applicability for deep-sea environments is currently unknown, considering the following:

- Deep-sea organisms may respond differently to contaminants than their shallow-water counterparts.
- Environmental conditions such as hydrostatic pressure, temperature, seawater chemistry (e.g. pH, alkalinity, redox conditions), and oxygen availability, most of which differ markedly from shallower settings, can influence both the behavior of metals in seawater and responses of exposed species.
- Natural background metal concentrations, typical of abyssal environments, vary across oceanic regions - some metals may occur at concentrations that exceed existing regulatory thresholds for shallow water settings.

Consequently, environmental thresholds values developed for coastal settings and/or other industries may not be directly transferable to the polymetallic nodule mining operations in the abyss, although they may provide useful regulatory analogues or interim precautionary ecological reference points during early threshold development.

[18] Draft standard and guidelines for the environmental impact assessment process (ISBA/27/C/4)

3.5 Development of threshold values, including early warning and uncertainty levels

It is common practice in other marine environments and industries to establish separate thresholds for individual metals and for distinct environmental matrices (water, sediments, biological tissues). However, this approach does not realistically reflect *in situ* environmental conditions. Organisms can be simultaneously exposed to multiple metals and compounds, which can be present both in dissolved and particulate forms. While it is acknowledged that this is standard practice for other industries and environments, relying on single-metal thresholds risks overlooking potential additive or synergistic effects, as well as the physical impacts of particulates themselves, which may interfere with feeding or respiration. Moreover, there is substantial uncertainty about how environmental parameters such as pressure and temperature modify toxicity (e.g. Brown et al., 2017a, b).

As an alternative, Hauton et al. (2017) have argued for the use of *bulk toxicity* assessments (a.k.a. elutriate testing). This approach evaluates the combined toxicity of a given mineral resource across relevant matrices, using proxy organisms. These types of assessments have been conducted in a DSM context for an environmental impact statement for a polymetallic sulphide project in national waters (Coffey, 2008;

Annex 2 – Case study: Solwara 1). Although this assessment was done for an operation in a different deep-sea ecosystem (hydrothermal vents), this case study shows the principle, methodology, and potential use of this technique for abyssal nodule environments. Applying bulk toxicity testing using the characteristics of the plume generated by extraction and those of return water from surface dewatering would provide a more realistic assessment of toxic risk.

Importantly, elutriate tests must be site- and operation-specific, reflecting local sediment composition, pH, and temperature. Although reproducing *in-situ* pressure conditions in the laboratory is currently impractical, other parameters can and should be mimicked to ensure tests are environmentally meaningful. Bulk toxicity testing should also include chemical analyses of elutriates to identify which metals or particle fractions drive toxicity. Determining which contaminants require the highest dilution to reach non-toxic concentrations will help to identify priority metals (or substances such as sediment) for monitoring.

Findings from these bulk ecotoxicity tests can then inform both the setting of ecological reference points (ERPs) that define the transitions between different zones of impact, and the prioritization of monitoring. As further data are gathered – from ecotoxicological experiments, *in-situ* plume trials, bulk elutriate tests and monitoring during operations – these ERPs will then need to be revised through an adaptive management process. In this way, the framework remains robust while still allowing for improvement as scientific knowledge advances.

At present, the state of scientific knowledge is not sufficient for deriving ERPs using methodologies that combine biological responses with associated pressure levels (i.e. metal concentrations), such as Species Sensitivity Distributions (SSD) or the Assessment Factor (AF) method (see Schmidt et al. 2025). Instead, the IEG explored alternative interim approaches that can help establishing preliminary ERPs.

3.5.1 Application of Ecological Reference Points (ERPs) and Zones of Impact

This section presents two illustrative approaches applying examples from other environmental contexts and regulatory frameworks to derive ERPs for DSM. The first approach is based on international marine water quality standards, while the second applies a statistical method using site-specific baseline metal concentration data.

Both approaches were discussed within the IEG, and key considerations are summarised below. The numerical values derived in these examples are demonstrative only and should not be interpreted as final ERPs for DSM. The IEG group experts expressed divergent views when assessing the two approaches and their potential application as interim measures in the context of DSM. Some experts preferred the background-based statistical approach due to its foundation in CCZ-specific baseline data. Others preferred the existing water quality guideline framework, highlighting its status as one of the limited internationally accepted and scientifically robust methods for establishing marine contaminant threshold values.

3.5.1.1 Example 1: Using International Marine Water Quality Standards

As one example, the Australia and New Zealand Water Quality Guidelines (ANZG) define protection levels associated with different concentrations of metals in seawater (3). The 99% protection level is used where metal concentration is expected to protect 99% of species (1% may be affected) and is used for high ecological or conservation value ecosystems (e.g., marine parks). The 95% level aims to protect 95% of species (5% may be affected; this is the default guideline for most marine waters), and the typical application of the 80% protection level is highly disturbed systems where the objective is gradual improvement rather than full ecological protection.

Table 3 Australia New Zealand Water Quality Guideline (ANZG) Values for metal concentrations in marine water.

	Concentration (ug/l)							
	As	**Pb**	**Cd**	**Co**	**Ni**	**Zn**	**Cu**	**V**
Australian and New Zealand Water Quality Guidelines - marine water								
Default Guideline Values (DGV)	n/a	4.4	5.5	1	70	8	1.3	100
>99% protection	n/a	2.2	0.7	0.005	7	3.3	0.3	50
>95% protection	n/a	4.4	5.5	1	70	8	1.3	100
>80% protection	n/a	12	36	150	560	21	8	280
DRAFT Australian and New Zealand Water Quality Guideline values - marine water[a]								
>99% protection					1.8		0.12	
>95% protection					5.8		0.4	
>90% protection					11		0.72	
>80% protection					23		1.4	

[a]ANZG 2024, including data for tropical and temperate organisms and for Australian and/or New Zealand species

The ANZG guideline values are derived using species sensitivity distributions (SSDs) based on toxicity datasets comprising fish, crustaceans, molluscs, algae, echinoderms and other aquatic organisms, predominantly from coastal and continental shelf environments. Although many of these higher taxonomic groups are also represented in abyssal ecosystems, ecotoxicological data for deep-sea species remain limited. Consequently, the guideline values were not specifically developed for abyssal environments and their direct applicability to deep-sea ecosystems remains uncertain. Nevertheless, the ANZG framework provides one of the few internationally recognised and scientifically established approaches for deriving marine contaminant thresholds and therefore offers a pragmatic basis for screening the potential significance of dissolved metal exposure associated with sediment plumes generated by marine mineral extraction.

Applying the Zones of Impact framework, water quality protection thresholds may be used to delineate spatial management zones. For example, concentrations corresponding to the ANZG 99% species protection level could define the outer boundary of the Zone of Influence (ZoI), while progressively lower protection levels (e.g. 80% species protection) could define the boundary between the ZoI and the Zone of Moderate Impact (ZoMI). Lower protection levels associated with an increasing probability of environmental effects could similarly be used to delineate the Zone of High Impact (ZoHI) (Table 4). In this context, the assignment of protection levels to the impact zones is a management convention intended to provide a consistent, transparent and reproducible framework for translating contaminant concentrations into spatially explicit zones of potential environmental impact.

Under this approach, predicted or measured dissolved metal concentrations within sediment plumes would be compared with the selected guideline values to determine the dilution required to achieve the corresponding protection thresholds. The spatial extent of sediment plume dilution would then define the boundaries of the Zones of Impact. To ensure a precautionary assessment, the metal requiring the greatest dilution could be used to determine the spatial extent of each zone.

The resulting zone boundaries should be regarded as indicators of the potential spatial extent of impact. As deep-sea-specific ecotoxicological data become available, the metal concentration thresholds corresponding to different levels of species protection can be refined and incorporated into the framework, thereby improving the environmental relevance of the resulting Zones of Impact.

Table 4 Illustrative ecological reference points (ERPs) by zone transition (µg/l) based on Australia New Zealand Water Quality Guideline Values for marine water. Values in grey are from the draft (updated) water quality guideline values. Note the updated Cu values were not included in the below table as the CCZ environmental baseline Cu concentrations exceeded the updated ERP values and thus the effect level of 1% affected would never be reached. TBD = to be determined.

Zone Transition	Effect level or ERP	Cd	Co	Cu	Fe	Mn	Ni	V
ZoHI → ZoMI	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD
ZoMI → ZoI	80% protection	36	150	8	TBD	TBD	560/23	280
Outer ZoI Limit	99% protection	0.7	0.005	0.3	TBD	TBD	7/1.8	50

3.5.1.2 Example 2: Using baseline data and a statistical approach

Another approach to derive ERPs could consist of employing a statistical method based on natural background variability in metal concentrations. Using this method, ERPs could be defined relative to baseline concentrations. One of the most widely used methods involves adding a multiple of the standard deviation to the mean baseline concentration, according to the following equation:

ERP = Mean + n × Standard Deviation (SD)

where *n* represents a precautionary, positive and integer multiplier. For an overview of other commonly used statistical approaches to define ERPs or thresholds, the reader is referred to Schmidt et al. (2025) and references therein.

This statistical approach is widely applied in environmental monitoring and assessment to distinguish natural variability from anthropogenic enrichment and provides an objective, reproducible and site-specific framework for evaluating changes in environmental conditions. Its principal limitation is that it does not directly incorporate ecological effect data and should therefore be regarded as an interim management tool rather than an ecotoxicological threshold.

Background-based ERPs are most appropriately used to identify measurable departures from natural background conditions. Exceedance of an ERP should therefore be interpreted as an increasing deviance from natural background conditions and should trigger additional management actions, such as intensified monitoring, biological assessments, toxicity investigations, or a broader weight-of-evidence evaluation, since the potential for biological or ecological effects may increase (Schmidt et al., 2025).

At the present stage of scientific knowledge, the selection of the multiplier (n) values cannot be scientifically constrained. Appropriate values will ultimately depend on the management objectives, the data distribution in the baseline dataset, analytical uncertainty, and the level of precaution adopted by the regulatory framework. Consequently, the multiplier values presented below should be regarded solely as illustrative examples and not as recommended regulatory thresholds.

ERPs derived from baseline bottom-water dissolved metal concentrations in the combined datasets of the BGR, GSR and NORI contract areas are presented in Table 5 using the equation provided above. For illustrative purposes only, multiplier values of 1, 2 and 3, which were used in the Gladstone project EIS[19] for developing turbidity thresholds in Australian coastal waters, are used in the example below to demonstrate the application of this statistical approach. It is stressed that these values are not intended as recommended regulatory thresholds.

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[19] Gladstone project EIS. Available at: https://eisdocs.dsdip.qld.gov.au/Port%20of%20Gladstone%20Gatcombe%20and%20Golding%20Cutting%20Channel%20Duplication/EIS/chapter-08-water-quality-26mar19.pdf

Table 5 Illustrative background-based Ecological Reference Points (ERPs) for dissolved metals derived from baseline bottom-water concentrations of the combined datasets of the BGR, GSR, and NORI contract areas using the equation ERP = Mean + n × SD, where n is a precautionary multiplier to be defined during future regulatory development and SD is the standard deviation of the baseline metal concentration data.

Zone Transition	ERP	As	Cd	Co	Cr	Cu	Fe	Hg	Mn	Ni	Pb	V	Zn
ZoHI → ZoMI	Mean + 3×SD	2.29	0.12	0.0012	0.28	0.33	0.72	0.75	0.022	0.64	0.006	2.83	2.11
ZoMI → ZoI	Mean + 2×SD	2.04	0.11	0.0010	0.27	0.32	0.70	0.68	0.019	0.61	0.005	2.57	1.71
Outer ZoI Limit	Mean + 1×SD	1.79	0.10	0.0009	0.26	0.30	0.67	0.61	0.016	0.58	0.004	2.31	1.30

The baseline-based ERP method provides a practical and precautionary framework for linking metal concentrations to management zones based on departures from natural background variability. Anchoring ERPs to natural variability provides an objective basis for distinguishing between background conditions and mining-induced enrichment.

Within this framework:

- Exceedance of the upper ERP (Mean + 3 x SD) indicates a substantial departure from natural background variability and should trigger an appropriate level of management response, including detailed biological assessment where appropriate.
- Intermediate exceedance (Mean + 2 x SD) indicates measurable enrichment above background conditions and should require additional monitoring and evaluation.
- The lower ERP (Mean + 1 x SD) represents the upper range of expected background variability and may serve as a precautionary criterion for delineating the outer Zone of Influence or the extent of a mixing zone.

It is important to emphasise that these interpretations are not yet supported by direct ecotoxicological evidence for deep-sea organisms. In particular, the choice of the multiplier (n) remains uncertain and preliminary comparisons with available baseline datasets indicate that, for some metals, observed background maxima exceed the illustrative Mean + 3 x SD values. This highlights the need to validate the approach using more exhaustive baseline datasets before potential regulatory implementation, or to consider other statistical approaches based on background concentrations. Despite its provisional nature, this approach allows contractors and regulators to implement objective and adaptive benchmarks until more robust, effect-based thresholds derived from toxicity tests and species sensitivity distributions become available.

Several limitations of this approach should be recognised:

- The selection of appropriate multiplier values (*n*) is not yet scientifically constrained and requires further evaluation.
- Depending on the natural variability of individual metals, differences between successive ERP levels may be small and, for some analytes, approach analytical uncertainty or sensor resolution (i.e., the differences between the zones may not be measurable).
- Statistical departures from background concentrations do not necessarily imply significant ecological effects.

- Future effect-based thresholds should be derived from ecotoxicological studies, species sensitivity distributions, and site-specific ecological information as these become available.

Some experts further suggested that background-based ERPs should primarily support the delineation of the outer Zone of Influence or the extent of a mixing zone within individual contract areas and be incorporated into Environmental Impact Assessments (EIAs), while Zones of Impact should ultimately be defined using biological evidence and integrated weight-of-evidence approaches.

3.5.2 Identification of appropriate indicators

Ecotoxicological studies can rely on two categories of indicators: lethal and sub-lethal endpoints. Sub-lethal effects, such as reduced growth or reproduction, may take longer to appear and can be influenced by natural variability (e.g. reproductive cycles), making them less reliable in early assessments. For this reason, it is recommended that initial thresholds focus on lethal effects, with *no-effect concentrations* (NOECs) serving as a precautionary metric. Species sensitivity distribution (SSD) curves are obtained by fitting a statistical distribution to species-specific NOEC levels, obtained via ecotoxicity tests. A lower percentile (referred to as HCp - hazardous concentration for p% of the species) of this distribution is selected as the basis to derive the ERP (Figure 3). The HCp is equivalent to a protective concentration PC100-p, which describes the percentage of species (p) being protected at that concentration. In most regulatory ecotoxicological frameworks, the 5th percentile of the species sensitivity distribution (SSD) (HC5), corresponding to the protection of approximately 95% of species (PC95), is used as the basis for deriving environmental quality thresholds. This protection level has been widely adopted in freshwater, marine, and sediment quality guideline development and represents a balance between ecosystem protection and the uncertainties inherent in extrapolating laboratory toxicity data to natural communities.

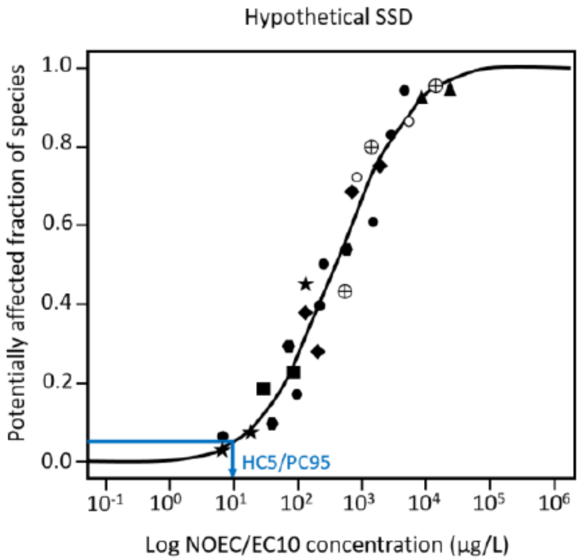

Figure 3 Illustration for deriving a hazardous concentration for 5% of species / protective concentration for 95% of species (HC5/PC95), based on a hypothetical cumulative frequency distribution of log-normal toxicity values of a substance. The different symbols represent different species. SSD = species sensitivity distribution. Figure taken from Schmidt et al. (2025).

At the same time, behavioural responses of organisms – for example, avoidance behaviour by holothurians, amphipods, or commercially relevant fish – should be systematically monitored during and after mining operations and incorporated into Environmental Management and Monitoring Plans (EMMPs). The identification of appropriate indicator taxa is central to this approach. Given current limitations (i.e., to mimic in situ deep-sea environmental conditions and/or retrieving deep-sea species alive), most lab bulk toxicity tests will likely continue to rely on shallow-water proxies that are taxonomically or functionally related to target indicator deep-sea species. While imperfect, this provides a reasonable basis for extrapolating mortality thresholds until suitable methods for deep-sea taxa are developed.

3.6 Identification of knowledge gaps and priorities for research and monitoring

Although significant progress has been made in recent years, knowledge about the ecotoxicological impacts of marine mineral exploitation from the abyssal plains remains limited. This uncertainty is one of the main reasons why a precautionary and adaptive approach to threshold development is essential. Identifying where the gaps lie, and how they can be addressed, is therefore a priority for the Authority, contractors, and the wider scientific community.

3.6.1 The responses of deep-sea organisms

Much of the current understanding is based on experiments with shallow-water proxies or with species from deep-sea environments other than abyssal nodule plains, such as hydrothermal vents or cold seeps. The responses from this fauna may be different to abyssal deep-sea fauna (and there may be differences due to different environmental conditions such as temperature, pressure, oxygen levels, and acidity [pH]). The fauna of nodule provinces lives under stable, low-energy conditions in the abyssal plains; however, they may also be naturally exposed to elevated metal concentrations compared to other environments and so may have developed adaptations / tolerances to cope with these concentrations. These factors need to be considered when making recommendations about toxicity threshold values. Chronic and sub-lethal effects also remain poorly understood. While acute toxicity thresholds provide important benchmarks, subtle, long-term changes in reproduction, growth, behaviour, or community composition may be more relevant for assessing ecosystem-level impacts and may serve as early warning signals. Developing monitoring protocols (e.g. through photo and video transects) for these effects is a pressing research need.

3.6.2 The role of environmental conditions

Other conditions such as pressure, temperature, pH, and oxygen levels represent another uncertainty. These factors can alter both the chemical behaviour of metals and the way organisms respond to exposure. At present, the ability to simulate deep-sea conditions, notably pressure, in laboratory experiments is limited, and methods to bridge the gap between lab and field studies would ideally be improved, if possible.

3.6.3 Standardization and comparability

Current datasets often differ in sampling methods, analytical techniques, and reporting standards, making direct comparisons difficult. Establishing agreed protocols for baseline surveys, toxicity testing, monitoring and data reporting will allow the integration of results from different contractors and regions into a coherent global framework.

4 Turbidity and settling of resuspended sediments

Turbidity and the settling of resuspended sediments are key pressures resulting from plumes generated by deep-sea mining (DSM), which are the subjects of this chapter. A plume is defined as the dispersion of sediment-laden seawater, and turbidity is a quantitative measurement of this state. Eventually, the plume's sediment will sink and be redeposited on the seabed - a process referred to as the settling of resuspended sediments; this process is additional to background turbulence that naturally disturbs the seabed.

DSM-plumes are primarily generated in two ways: first, by seafloor disturbances from collectors, and second, by the discharge of water from the on-board solid-liquid separation process at various depths between the seafloor and the surface. The Recommendations for the guidance of contractors for the assessment of the possible environmental impacts arising from exploration for marine minerals in the Area (ISBA/25/LTC/6/Rev.3[20]), prepared by the Commission, classify the former as "seabed-disturbance plumes" and the latter as "discharged plumes".

The consideration of environmental issues related to seabed mineral resources began in the 1970s, and early on plumes were recognized to pose a very high risk of serious impact. In the 1990s, a series of benthic impact experiments using the same disturbance device were conducted to determine the impacts of plumes on benthic organisms. These experiments revealed that the settling of resuspended sediments affects the composition and abundance of benthic organisms. Furthermore, results from shallow-water research including laboratory experiments suggest that the impact of plumes on benthic organisms is affected not only by their volume, but also by their mineral composition, organic matter content, and particle size and shape. Studies have also shown that these plumes can have various impacts, including the oral apparatus clogging of suspended-matter feeders, tissue loss and damage, reduced reproduction rates, and reduced respiration. Thus, it has become clear that the environmental effects of plumes can be complex.

In the following sections, we report on the findings of the intersessional expert group (IEG), including summarizing the status of existing knowledge on turbidity and settling of sediment; describe key studies on biological impacts; discuss progress towards developing thresholds and appropriate indicators; and highlight important gaps in our knowledge. Only seabed impacts were analysed, because the IEG considered there are currently insufficient data to progress an evaluation of impacts in pelagic communities from a midwater discharge plume.

Turbidity, as discussed in this chapter, indicates the concentration of suspended matter in the water column. In the case of turbidity near the seafloor, the suspended matter may originate from particles settling from the surface or from resuspended seafloor sediments. Because it is difficult to distinguish between particles resuspended from seafloor sediments and particles settling from

[20] Recommendations for the guidance of contractors for the assessment of the possible environmental impacts arising from exploration for marine minerals in the Area (ISBA/25/LTC/6/Rev.3)

the surface under natural conditions, in this section we will use the terms "settling rate of resuspended sediment" and "sedimentation rate" interchangeably.

4.1 Variability of turbidity and sedimentation rate

In this section, the spatial and temporal fluctuation of natural sediment concentrations and sedimentation rates are reviewed.

4.1.1 Turbidity

Turbidity is expressed as volumetric units (e.g., mg/l) or light scattering units (e.g., Nephelometric Turbidity Units, NTU, or Formazin Nephelometric Unit, FTU). The volumetric units are suitable for directly assessing the impact on deep-sea organisms and ecosystems. The light scattering units are less quantitative but indirectly infer biological impacts and allow for more continuous measurement. Ideally, the two types of units could complement each other through calibration, but they do not always exhibit a linear relationship (Figure 4). In this report, we will focus mainly on light scattering units from a practical standpoint, even though calibration challenges remain.

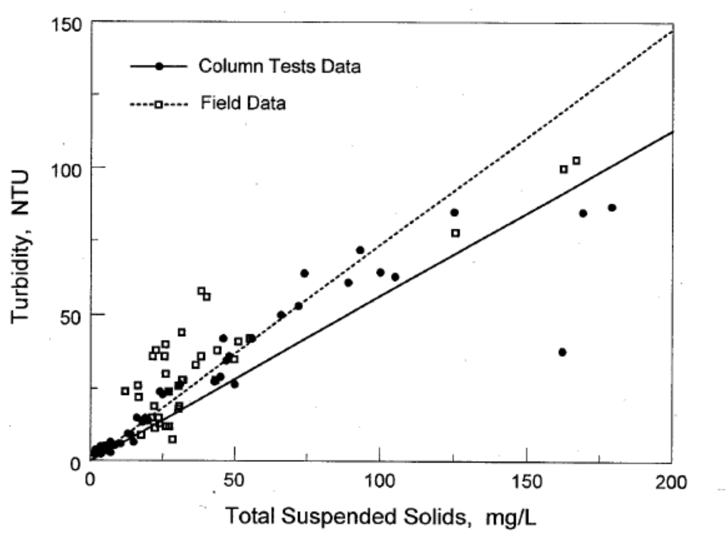

Figure 4 An example of calibration results between total suspended solids and turbidity expressed as NTU. Aster ERDC TN-DOER-E8, 2000

Most exploration Contractors have measured turbidity in their contract areas, and many have used optical sensors. Here we give several examples to demonstrate that levels can be highly variable between areas, and over time within an area (see Table 6).

In the BGR exploration area, located in the eastern region of the CCZ, turbidity levels typically fluctuate around 0.08 NTU, but temporarily can rise to 4.18 NTU during algal bloom periods. In the Belgian (GSR) exploration area, which is approximately 1000 km west of the BGR area, levels were reported to be 0.02 FTU near the seabed. In the Nauru (NORI-D) exploration area, also in the eastern CCZ and immediately south of the BGR contract area, measurements were taken at two locations: at one site, levels were 0.5–0.84 FTU at 3.5 m above the seabed and 0.46–0.72 FTU at 12.5 m; at a second site, levels ranged from 0.15 FTU to 0.84 FTU at 3.4 m and 0.42 FTU to 3.7 FTU at 9.6 m. In the Chinese (China Minmetal Corporation) exploration area, in the western region of the CCZ, turbidity is usually less than 0.4 FTU.

In addition to the CCZ, contractor data in the Northwest Pacific (Japan, JOGMEC) showed background natural turbidity values at the abyssal seafloor below 0.01 FTU. Similarly, in the Russian exploration area of the Atlantic Ocean, values were reported to range from 0.001 to 0.056 FTU at a depth of 4,100 meters.

However, care is needed interpreting these values as absolute because the detection limit of turbidity sensors varies depending on the model. Background sediment concentrations in the CCZ (20-30 µg/l) are below the detection limit for some sensor models.

Table 6 Examples of turbidity data measured in different contract areas (a.b. meters above bottom)

Region and resource	FT/NTU	Contract area
East CCZ (PMN)	0.08(N); temporarily rose to 4.18(N)	BGR
	0.02(F)	GSR
	0.05-0.84(F)	GSR (MiningImpact site)
	0.5-0.84(F)	NORI site 1; 3.5m a.b.
	0.46-0.72(F)	NORI site 1; 12.5m a.b.
	0.15-0.84(F)	NORI site 2, 3.4m a.b.
	0.42-3.7(F)	NORI site 2; 9.6m a.b.
Central CCZ (PMN)	0.006-0.47(F)	Yuzhmorgeologia; 1000 a.b.
West CCZ (PMN)	0.4(F)	China Minmetal Corporation
NWP (CFC)	0.01 (F)	JOGMEC
Northern MAR (PMS)	0.001-0.035(F)	Russia; over 4100m depth

Hence, according to current knowledge, turbidity levels in deep-seabed environments are extremely low regardless of geographic region. While occasional extreme values have been reported, the overall interannual variability is low. Processes such as algal blooms at the surface and benthic storms can elevate background levels of turbidity, although these events are not well quantified broadly across the abyssal oceans. Typically, even during algal bloom events, turbidity remains far below the plume concentrations generated at the source of disturbance by collector operations (see section below).

4.1.2 Sedimentation rate

Sediment accumulation rates have been calculated in several studies for the abyssal plains based on sediment core studies and radioisotope analyses. These indicate natural accumulation rates of several mm/kyr. However, historical data are of limited relevance to evaluating the impact of mining activities, and here we summarise several particle flux measurements obtained from sediment trap deployments within 100m of the seafloor in the Clarion-Clipperton Zone (CCZ) and other areas.

Within BGR's contract area in the eastern CCZ, three sediment trap systems were deployed 7 m above the seabed in 2019. Two of these were short-term moorings (19 and 28 days), and one was moored for 10 months. The latter had a minimum value of 12 mg/m²/day, a maximum value of 97 mg/m²/day, and an average of 36 mg/m²/day.

In the Deep Ocean Resources Development (DORD) contract area in the western CCZ, two sediment traps within 100 m of the seafloor were deployed in 2015. The two sets of data are relatively similar, with annual fluctuations ranging from a minimum of 0.3 mg/m²/day to a maximum of 37.7 mg/m²/day, with an average of 12-13 mg/m²/day.

Total mass flux measurements were conducted within the Republic of Korea contract area, located in the central section of the CCZ (at the "KOMO" site), in 1997-1998 and from 2003 to 2013. A consistent pattern of annual variation was generally observed, although the total flux in 2008, which was a La Niña year, reached approximately three times the total flux (average 58.8 mg/m²/day, range 12.8–129.9 mg/m²/day) compared with the preceding five years (average 19.1 mg/m²/day, range 3.5–36.9 mg/m²/day)Figure 5).

When comparing the values from BGR, DORD, and Korea, significant spatial variation and a relatively consistent intra-annual pattern were observed within the CCZ. However, data from the Korea contract area revealed significant interannual variability associated with climate variability such as ENSO.

Other trap data within 100m of the seafloor are available for the Northwest Pacific Ocean, where China (BPC) exploration in 2021 and 2022 observed an annual minimum of 1.7 mg/m²/day, a maximum of 41.5 mg/m²/day, and a range from 7.7 to 12.9 mg/m²/day. Measurements from the Indian Ocean by India include a 40-day period before a disturbance test, with an average of 48 mg/m²/day.

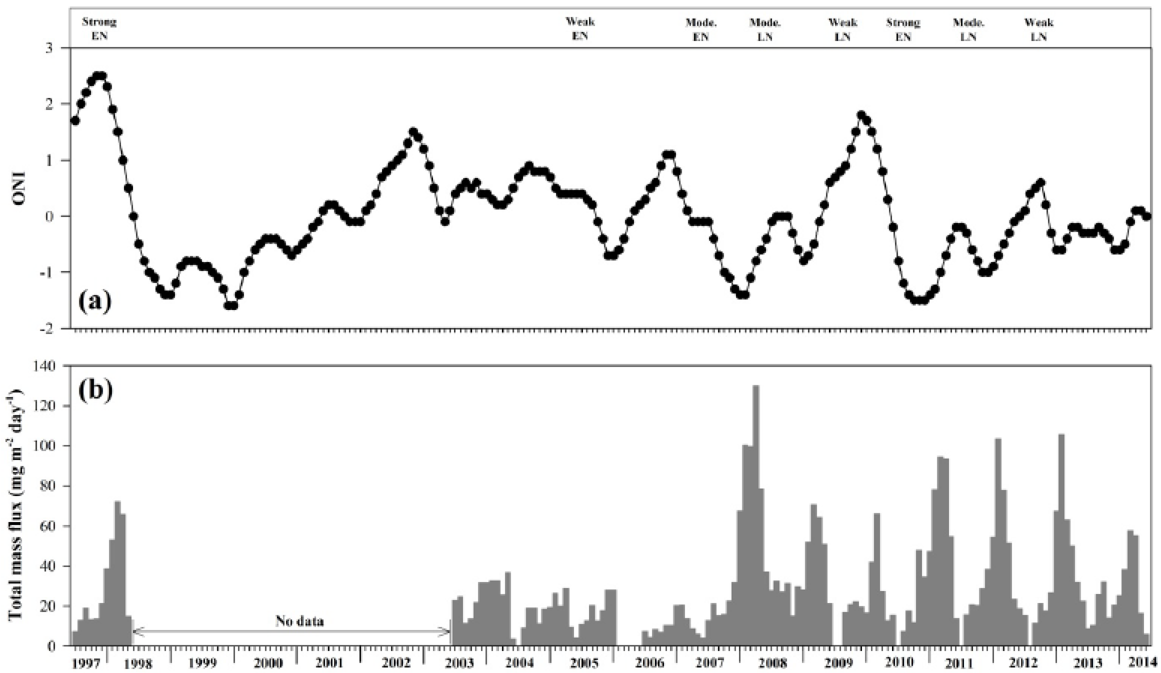

Figure 5 Fluctuations over time of total mass flux during 1997 to 2013 at the "KOMO" site (bottom panel) and sea surface temperature (top panel). After KIOST 2014

4.2 Proxy and experimental Studies

Several experimental studies, including collector tests, have been conducted from the 1970s to the present. These studies aimed to investigate the effects of sedimentation from potential seabed mining for polymetallic nodules on abyssal plains. Representative experiments are described below.

4.2.1 Benthic Impact Experiments (BIE)

BIEs were a series of experiments in the 1990s designed to measure the impact of resuspending sediment. The same disturbance device (NOAA Deep-Sea Sediment Resuspension System; DSSRS (Brockett & Richards 1994)) was used in four areas, three of which were located in the CCZ. These included BIE-I, II（USA & Russia, 1991-92, 1993), JET (Japan 1994), IOM'BIE (the InterOceanMetal Joint Organization (IOM) 1995), and INDEX (India 1997（Trueblood et al. 1997, Fukushima, 1995, Kotlinski,1995, Sharma et al. 2003. Among these, JET and IOM'BIE have been conducting long-term monitoring for over 20 years (Radziejewska et al., 2022, Fukushima et al., 2022). These early experiments suggested that rapid settling of resuspending sediment (deposition rate 1,000 times faster than natural conditions) caused statistically significant declines in the abundance of meio-, macro-, and megabenthos. The results also showed that the effects on deposit feeders lasted longer than on suspension feeders. Furthermore, monitoring of these experiments continued for over 20 years, suggesting that while the abundance of marine life returned to its original levels, species diversity remained below its initial state. These findings are well-described in Jones et al. (2017) (Figure 6). More recent assessment of the long-term impacts of the OMCO test after 44-years broadly support these patterns (Jones et al. 2025).

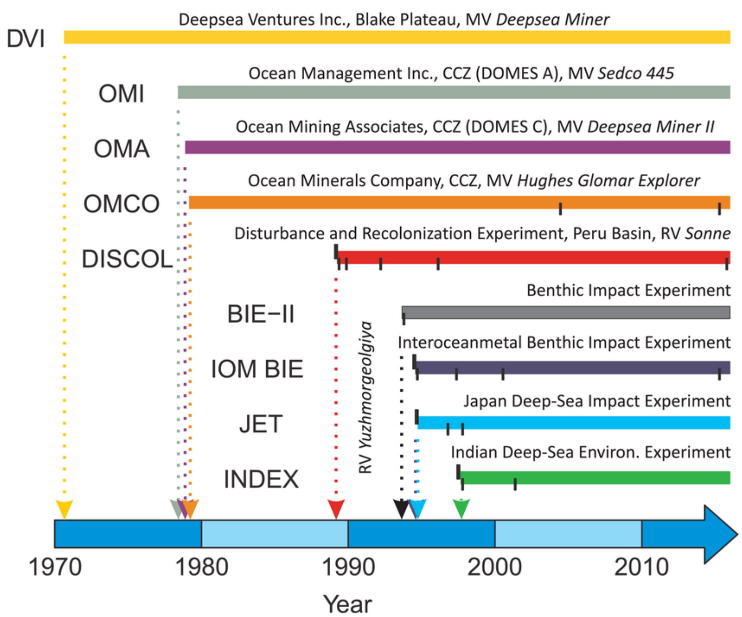

Figure 6 Timeline of deep-water seabed test mining or mining simulations. Bars represent time since initial disturbance to the seafloor. Upward ticks indicate the timing of pre-disturbance visits. Downward ticks indicate the timing of post-mining monitoring visits. Short name indicate in capitals and full name of each experiment indicated above each bar. OMI, OMA, OMCO, BIE-II, IOM BIE and JET experiments were carried out in the Clarion Clipperton Zone (also indicated as CCZ). The INDEX experiment was carried out in the Indian Ocean. Note OMCO disturbance investigated was sledge samples and not the mining vehicle test.

4.2.2 Recent nodule collector tests

Two collector tests (Patania II (GSR and BGR) and Nauru Ocean Resources Inc. (NORI)) were conducted in the northeast CCZ in 2021 and 2022. These tests measured resuspended sediment generated from prototype collectors representing smaller versions of actual mining equipment, thus providing more realistic insights than the above-mentioned DSSRS.

4.2.2.1 Patania II collector testing (GSR, BGR, MiningImpact):

During the Patania-II trials, the resuspended sediment formed a dense particle plume behind the collector vehicle. This plume initially propagated under its own turbulent dynamic and on flat seabed moved about 100m, but extended further downslope (slopes of >3°) as a gravity current for up to ~500 m. This indicated that plume dispersion was dominated by turbulence, gravity currents, and prevailing near-seabed currents. The maximum particle concentration was 260 mg/L, which was four orders of magnitude higher than the background concentration of 0.03 mg/L. However, particle concentrations and settling velocities were observed to decrease rapidly with time, distance, and height above the seabed (Gazis et al, 2025, Ouillon et al.2022) (Figure 7). Nevertheless, a low-concentration plume (concentrations <1 mg/L) travelled further than 4-5 km beyond the disturbed area. About 4-8 cm of surface sediments were removed by the collector and redeposited inside and outside the mined area, with thickest blanketing over 3 cm inside the collector test area and up to a distance of 100 m outside. Beyond 2 km distance from the collector test site, blanketing of the nodules was only very faint (see Figure 10 in Gazis et al. 2025).

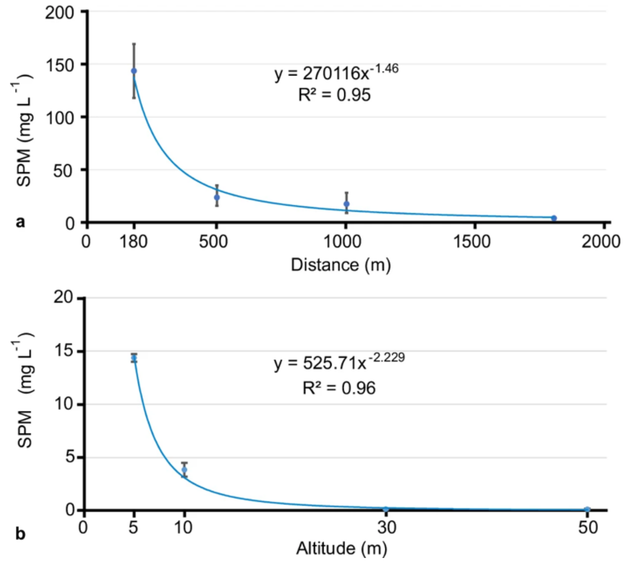

Figure 7 Changes in concentrations of suspended sediment with distance and altitude above the seabed observed in the Patania II collector test: From Gazis et al., 2025.

4.2.2.2 NORI collector testing:

NORI conducted a collector test in the central CCZ in 2022. During the experiment period, increased levels of sedimentation were observed up to 1-2 km outside the test area (where actual physical disturbance occurred) at detectable limits (0.1 mm thickness) after all NORI collector runs had been completed. The deepest sediment deposits were 5 cm thick close to the tracks. The collector discharged very high levels of suspended solids (g/L), but this fell out of suspension very quickly. Levels of suspended solids >10 mg/L were only found in the collector test area, usually <1 mg/L outside the test area.

8These recent experiments have yielded much information on the dynamics of resuspended sediment, showing that, in general, while particles discharged from collectors are initially at very high concentrations, they settle relatively quickly, and their dispersion range is limited, much more so than predicted by dispersal models in the 1980s. However, specific results vary between the two designs of collector (Patania II and NORI), and between the three areas (BGR, GSR and NORI) where environmental conditions differ somewhat. Hence care is needed drawing detailed conclusions about sediment dynamics across wider areas.

9.2.2.3 Other collector experiments

Similar dynamics were found in recent experiments using sediment from nodule areas at 5km depth in the Philippine Basin. Reductions in turbidity occurred relatively quickly with the suspended particle size dependent on the settling velocity (Zhang et al. 2026). Initially, the plume caused elevated total dissolved solids, chemical oxygen demand, and total organic carbon, which decreased as larger particles settled.

4.3 Biological responses to turbidity and sediment fluxes

Studies on the impact of turbidity and sediment deposition on surface water ecosystems are limited. Additionally, no mining plans are thought to envision discharging wastewater to the surface. While some studies have examined mesopelagic ecosystems (e.g. Stenvers et al. 2023), our current knowledge about midwater diversity and functioning is limited. Although the PLUMEX sediment discharge study in 2018 gave insights into plume dynamics in midwater (Munoz-Royo et al. 2022) very little information exists on the characteristics of sediment plumes in midwater or impacts on pelagic organisms. Given these circumstances, this report does not consider midwater environments and focuses solely on benthic ecosystems.

4.3.1 Effects of sediment deposition

Research in shallow waters has revealed that the impact of sediment flux is not just dependent on volume, but also on particle size, shape, and composition of sediment particles. The environmental conditions in deeper waters are different from those in shallow waters, with water masses moving less and sedimentation rates being lower. Therefore, research results from shallow waters cannot be directly applied to DSM, but they can be informative.

Species Sensitivity Distribution (SSD) for various fauna have been compiled. SSDs predict the potentially affected fraction of species (PAF) at a certain level of exposure to a pressure, and the curves provide reference points that are used in environmental risk assessments (Harbers et al. 2006). Smit et al (2008) reviewed data from offshore oil platforms at continental shelf depths (<200m) in the North Sea, Norwegian Sea and Barents Sea. They derived SSDs for a range of benthic species (molluscs, polychaetes, crustaceans) (Figure 9). While not directly applicable to abyssal plain environments, these results demonstrate how ecological reference points can be determined.

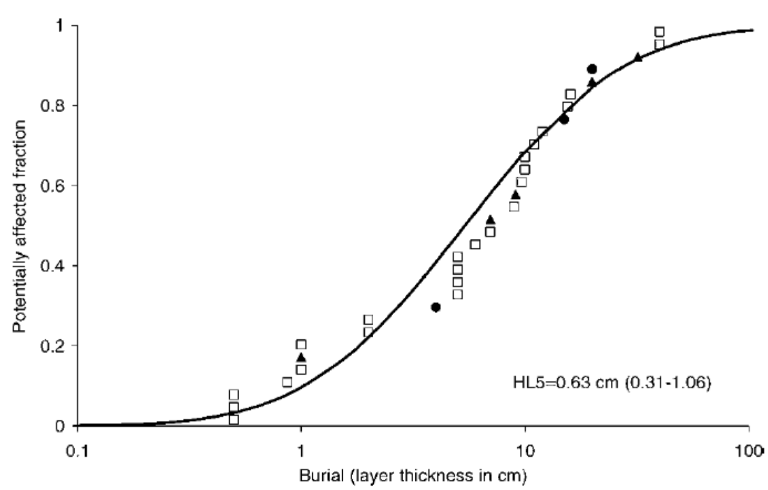

Figure 9 Species sensitivity distribution (SSD) of benthic species for burial expressed as thickness of an instantaneous burying layer and the corresponding hazardous level for 5% of the species (HL5) (median value and 5–95% confidence interval) (n _ 32). □ = mollusc; ▲ = crustacean; □ = polychaete. From Smit et al (2008)

Infaunal species may be better able to cope with sedimentation, with some species escaping >10 cm of burial (Jackson and James, 1979; Maurer et al., 1982; Bell chambers and Richardson, 1995), whereas epibenthic species are often unable to escape more than 1 cm of burial (Kranz, 1974; Hendrick et al., 2016). Importantly, different faunal groups respond differently to sedimentation, and their burial effects are often highly species-specific.

There are few examples of research on the impact of resuspended sediment deposition on deep-sea organisms. However, several studies provide useful insights into varying effects of depth of burial. These include studies on:

- The effects of sediment thickness and exposure time on coral mortality and polyp elongation (Brooke et al., 2009; Smit et al., 2008). Complete burial of the coral species *Desmophyllum pertusum* for more than 4 days led to very high/complete mortality, but if only partially buried then corals were able to survive. Survival was affected by maintenance of coenosarc tissue (Larsson and Purser, 2011)
- The physiological effects of complete burial and generation of anoxic conditions effectively suffocating corals (Allers et al., 2013).
- Repeated pressure and acclimation with an ability of corals to "reject" sediment (Larsson and Purser, 2011). Corals efficiently removed deposited material even after repeated exposures to different sediment types and duration, indicating an efficient cleaning mechanism".
- The effects of volcanic ashfall on foraminiferal diversity (Hess and Kuhnt, 1996; Hess et al., 2001). After initial burial by ash, opportunistic species dominated, even after 7 years as foraminiferan communities became broadly similar to their pre-eruption structure.
- A case where submarine volcanic ashfall limited oxygen supply to a chemosynthetic ecosystem where burial by 15cm or less of ash resulted in variable levels of mortality (Beinart et al., 2024).
- The effects of sediment on ecosystem function (seafloor respiration) where it was reduced with only 1 mm sediment deposition (Mevenkamp et al., 2017).
- Burial by mine tailing or inorganic sediment has strong negative effects on the biota and the functioning of benthic communities (Mevenkamp et al., 2019).

Analyses of recent nodule collector test data are still progressing, and specific impacts of blanketing thickness are unclear at this stage**.** Initial insights gained from 2022 studies in the NORI area Stewart et al. (2025) note that while sediment-dwelling macrofauna density was significantly reduced inside the NORI test-collector mining tracks, no change in faunal abundance was found in areas affected by the sediment plume. However, species dominance relationships were altered, with reduced biodiversity. Initial results from MiningImpact studies of the Patania II trials indicate that sediment blanketing of 0.5-3cm formed within 200m of the mining site, resulting in reduced mobile and sessile megafauna densities and altered community composition (Gazis et al., submitted) and also affecting meio- and macrofauna (Schmidt et al., 2025).

4.3.2 Effects of turbidity

Extensive studies on the effects of turbidity have been conducted in shallow waters. Among these, some studies have derived Species Sensitivity Distributions (SSDs) for individual species and used them to determine "harmful" levels based on reference points of 5% and 50% of species being affected in some way (Smit et al., 2008, van der Grient and Drazen, 2022).

Turbidity response experiments have also been conducted on deep-sea organisms, such as corals and sponges. These experiments have revealed that the effects of turbidity vary depending on several factors, including:

- Suspended sediment concentration: (Bilan et al. 2023; Mobilia et al. 2023; Jarnegren et al. 2017; Larsson et al. 2013).
- Exposure duration: (Mobilia et al. 2023; Larsson et al. 2013).
- Exposure type (pulse or continuous): (e.g., unpublished New Zealand data; Mobilia et al. 2023; Brooke et al. 2009)
- Suspended sediment mineralogy: (Carreiro-Silva et al. 2022)
- Life history stage (Jarnegren et al. 2017)

The IEG contracted a meta-analysis of the available data from these studies to derive dose-response curves for the relationship between suspended sediment concentration (in mg/L) and the percentage of affected individuals (van der Grient et al. 2025, unpublished, see supplementary information). The study collated deep-sea responses from 16 papers/data sets of mainly adult sponges (Demospongiae and Hexactinellida) and corals (Hexacorallia and Octocorallia). Responses included effects on feeding, growth, physiology, respiration, and survival. Studies included both pulsed and continuous sediment exposure experimental designs. SSDs were created (following Wenger et al., 2018, and van der Grient & Drazen, 2022), either regardless any other factor, or separated by exposure regime (pulsed or continuous exposure), duration length (acute or chronic exposures), phyla (coral or sponge) and response type (physiological or survival responses) to understand if these factors resulted in differences in SSD. Figure 10 shows the general SSD curve for corals and sponges combined, and in Table 7, we summarise the sediment concentration values at which a specific portion of animals showed significant responses to suspended sediments (indicated as percentage of individuals affected), presented separately for corals and sponges.

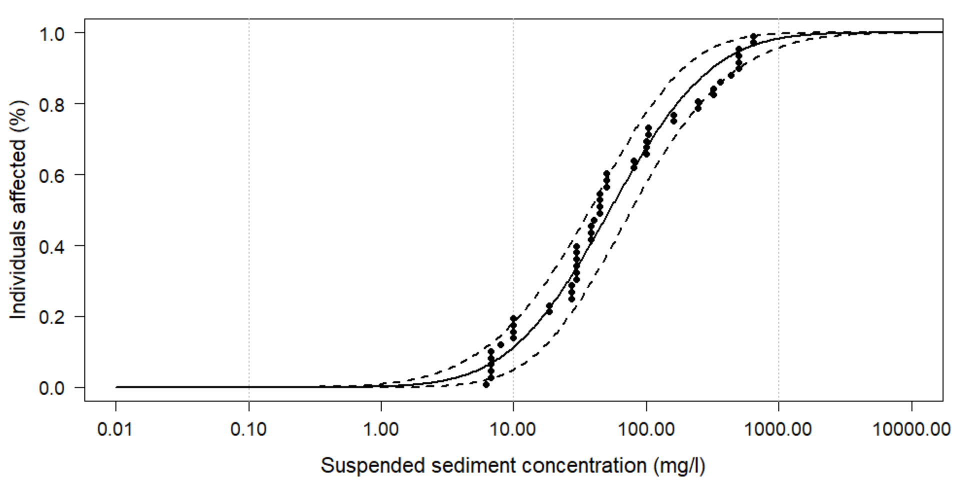

Figure 10 Modeled dose-response relationship based on deep-sea coral and sponge data. Note the logarithmic nature of the x axis. Individuals included in this analysis: n = 54.

Table 7 Dose-response values (mean and the lower and upper values of the 95% Confidence Interval (C.I.)) against different levels of individuals affected (%) split across two phyla. Sediment concentrations (mg/L) are rounded to the nearest integer.

	Phylum					
	Cnidaria			**Porifera**		
Affected (%)	**2.5% C.I.**	**Mean**	**97.5% C.I.**	**2.5% C.I.**	**Mean**	**97.5% C.I.**
99	862	2489	7904	174	372	796
95	369	872	2194	107	193	358
90	226	498	1098	86	140	234
75	104	196	367	51	78	118
50	37	68	122	28	41	61
25	13	23	44	14	22	32
10	4	9	19	7	12	20
5	2	5	12	5	8	15
1	1	2	5	2	4	9

The meta-analysis highlighted several important factors that need to be considered in evaluating dose responses. Analyses showed higher sensitivities under chronic exposures compared to acute exposures, especially under suspended sediment concentrations below 70 mg/l. A striking difference was also apparent between dose-response relationships based on continuous and pulsed exposure regimes, whereby sensitivities were much higher under pulsed regimes compared to continuous exposures at all suspended sediment concentrations. The responses can also vary along the SSD curve, as seen with the sponge or coral data. While the two taxa do not differ in their sensitivities at lower suspended sediment concentrations, sponges become rapidly more sensitive to suspended sediments at sediment concentrations higher than 50 mg/l compared to corals, indicated by a steeper slope in the dose-response relationship. There were also differences in dose-response relationships between physiological and survival responses, with physiological responses increasing more steeply and at lower suspended sediment concentrations than survival responses.

4.4 Existing thresholds and examples from other industries

Other marine-related industries that already use thresholds for environmental impact include shipping, oil and gas, dredging, fishing, and offshore wind power. Among these, fishing, particularly bottom trawling, creates pressure conditions that are relatively similar to those of DSM in that they drag heavy nets and ground gear that disturb the seabed and generate sediment plumes. A summary of information from other industries is also provided by Wang et al. (2026).

Shipping: Relevant regulations and guidelines exist, but they are not applicable to activities on the deep seafloor.

Oil and Gas: Although this industry also involves seafloor activities, the properties of the suspended particles differ from those of DSM. Specifically, particles from oil and gas operations originate from drilled deep sediment layers and can include hydrocarbons and heavy metals.

Nevertheless, some values are useful for reference.

Burial: 0.65cm depth is a threshold used in Norwegian operations as a predicted no effect concentration (NOEC). This corresponds to the Hazardous concentration/level (HC5) estimated by Smit et al. (2008). The HC50 level (see later for use in Zone of Impact model) was 5.4cm sediment thickness.

Suspended sediment: values vary based on the source and type of the suspended sediment (e.g., barite concentration, total particulate solids, drill cuttings). A discharge water value exceeding 10mg/l for a certain time period is a threshold level (Baussant et al. 2018, DNV 2019).

Dredging: The Permanent International Association of Navigation Congresses (PIANC) has established five levels of concentration standards for dredging plumes: no impact, slight impact, minor impact, moderate impact, and major impact. This impact matrix is a common approach in Environmental Impact Assessment, and with dredging forms the basis of defining values along gradients of turbidity (total suspended solids) and settling sedimentation over certain prescribed time periods (Table 8). These standards primarily target shallow-water ecosystems such as corals, eelgrass, and mangroves. Nevertheless, the concept of level categories is appropriate for deep-sea mining. A mortality value of 10% can indicate the ZoMI-ZoHI boundary.

Table 8 Threshold Matrix for Sedimentation Impact resulting from dredge sediment plume on Coral Reef Habitat (from PIANC, 2010)

Severity	**Threshold**
No impact	Sedimentation < 0.05kg/m^2/day (<1.7mm/14days)
Slight Impact	Sedimentation< 0.1kg/m^2/day(<3.5mm/14days)
Minor Impact	Sedimentation< 0.2kg/m^2/day(<7.0mm/14days)
Moderate Impact	Sedimentation< 0.5kg/m^2/day(<17.5mm/14days)
Major Impact	Sedimentation > 0.5kg/m^2/day(>17.5mm/14days)

Fisheries: Bottom trawling, which can suspend large amounts of marine sediment, shares similarities with DSM plumes. Suspended sediment concentrations measured in plumes from trawling on muddy seafloor often average around 50 mg/l but can reach levels as high as 500 mg/l (Durrieu du Madron et al. 2005, Bradshaw et al 2012). The Marine Stewardship Council

(MSC) uses an 80% recovery within 5-20 years as a threshold for assessing the sustainability of fisheries MSC 2018).

4.5 Development of threshold values, including early warning and uncertain levels

As explained previously, the magnitude of sediment redeposition pressures depends primarily on the amount of suspended particles being redeposited, as well as the mineral content, organic matter content, size, and shape of the particles. It also depends on the duration of deposition as well as the duration after deposition and type of exposure. Some organisms are immediately affected by sediment redeposition pressures, while others take time to show the effects (Gazis et al., submitted).

Furthermore, even with the same pressures, the effect on an ecosystem varies depending on the area, depth, and physicochemical environmental conditions of the target ecosystem, as well as the characteristics of its community. Therefore, understanding the relationship between pressures and impacts is crucial for effective environmental management and to develop effective environmental thresholds.

4.5.1 Application of Ecological Reference Points (ERPs) and Zones of Impact

As shown in Figure 9 and Figure 10, the relationship between turbidity or sedimentation rate and biological response often follows a sigmoid curve. When pressures exceed the first inflection point, the change in impact becomes significantly larger. When they exceed the second inflection point, the impact suddenly approaches saturation.

In practice, the relationship between pressures and impacts is likely to be continuous and cannot necessarily be divided at distinct levels. However, following the threshold matrix approach adopted for dredging, there can be categories with pressures divided into five stages (

Table 9). The pressure decays with distance, and this is reflected in the Zone of Impact approach described in Chapter 2**Error! Reference source not found.**, comprising Zone of Influence (ZoI), Zone of Medium Impact (ZoMI), and Zone of High Impact (ZoHI). Points of change along the gradient are referred to as Ecological Reference Points (ERPs) and are important considerations in the derivation of threshold values for management.

Table 9 Illustrative example showing three zones of impact and five impact categories following the threshold matrix approach adopted for dredging

ZONE	IMPACT category	EFFECT level	PRESSURE (Suspended sediment concentration)	PRESSURE (sedimentation layer thickness)
Zone of Influence	Negligible impact	Natural levels	Background	Background
	Slight impact	Upper limit of natural levels, some stress/behaviour	Background + α mg/l	Background + α cm
Zone of Medium Impact	Minor impact	Causes levels of higher stress, behaviour change, individual mortality. Recovery likely.	X mg/l	X cm
	Moderate impact	Material change in habitat-ecological characteristics. Higher levels of mortality locally significant	Y mg/l	Y cm
Zone of High Impact (equivalent to area of operation)	Major impact	May cause total mortality, change in community/ecosystem structure. Recovery unlikely	Z mg/l	Z cm

Whereas the ZoI comprising negligible or slight impact can be defined by variation from natural undisturbed levels, the ZoMI and ZoHI require specific information on levels of biological impact. Species Sensitivity Distributions (SSD), as discussed above, can inform levels of pressure that lead to the levels of effect that define potential boundaries between the three Zones of Impact. The SSD presented for corals and sponges in Table 7 combined mortality and sub-lethal responses as there were limitations to the experimental design and duration of studies, and often complex interactions between factors.

Nonetheless, these results from SSDs (Table 7) can be used to illustrate how such data informs the derivation of threshold values, following levels of species-affected (%) that are often used in risk assessment as reference points (Smit et al. 2008). A level of 5% of individuals affected (termed HC5) can indicate the beginning of causing levels of stress (hence the level at which there is a transition from the ZoI to the ZoMI,, i.e. X mg/l for suspended sediment concentration and X cm for sedimentation thickness in Table 8)). A 50% (HC50) level is transitioning from moderate impact towards major impact (and the boundary between ZoMI and ZoHI, i.e. Z mg/l for suspended sediment concentration and Z cm for sedimentation thickness in

Table 9).

- The general SSD for deep-sea corals and sponges combined from the meta-analysis presented in Table 7 (see further information in van der Grient et al 2025, supplementary information, for suspended sediment showed an HC5 value of 6 mg/l (95% confidence interval: 3-10 mg/l) and an HC50 value of 53 mg/l (95% confidence interval: 36-76 mg/l). Although these data represent only two taxa deep-sea corals and sponges that are regarded as potentially sensitive taxa - these results are relevant to deep-sea environments.
- The SSD for oil and gas burial by sediment in shallower waters included mollusc, crustacean and polychaete data (Smit et al 2008). The HC5 value was 0.6cm (95% confidence interval: 0.3-1.1cm) and the HC50 value was 5.4cm (95% confidence interval: 3.7-7.9cm). There are considerable differences between the biotic and abiotic conditions in these environments compared to those of interest for DSM. Nevertheless, these values may provide a reasonable place to start.

These SSD curves can be important to inform the specific derivation of ecological reference points in the above matrix and then translate into environmental threshold values for management. However, at this stage the IEG was not confident about applying results from shallow-water studies, or information from just a few deep-sea taxa, to develop "interim" ERPs. The IEG considered that more studies (both laboratory experiments and *in situ* from collector testing types of exercises) are needed to broaden the amount and range of dose-response data across multiple taxa and to reflect the likely duration, periodicity, and spatial scale of animal exposure to the pressure before this approach can move into a practical phase and produce robust generic impact levels to inform threshold development.

In a recent study, Wang et al. (2026) derived a set of thresholds based on a review of studies on turbidity and sedimentation, which included many of the references cited above. The authors discussed many results but did not undertake a formal analysis. Nevertheless, they proposed values of 0-1mm sediment thickness as insignificant, 1-3mm as minor, 3-1mm as moderate, and >10mm as severe. Values for turbidity were 0.5-2mg/L as insignificant, 2-5mg/L as minor, 5-10mg/L as moderate, and >10mg/L as severe. These values are appreciably lower than ones discussed by the IEG and illustrated above.

4.5.2 Identification of appropriate indicators

It is important to select indicators based on the specific characteristics of the ecosystem and ensure they are relevant to the specific pressure impacts caused by the mining disturbance. Ideally there is a clear "cause-and-effect" relationship that the indicator can quantitatively measure. While mortality can potentially be a clear signal that is quantifiable, sub-lethal effects may be less obvious and require different indicators.

The impact of suspended and settling sediment on feeding habits can be significant. For epifauna, filter- or suspension-feeders (e.g., corals, sponges) may be affected directly by clogging of their feeding mechanisms, ultimately affecting their health. Dilution of organic matter in the sediments caused by the 'blanket effect' can affect deposit feeders such as sea cucumbers. Reductions in the abundance or density of such sensitive taxa can be early indicators of likely impacts caused by sediment resuspension.

For infauna, decreased concentration of total organic carbon (TOC) in sediments could also be an indicator linked directly to a reduction in the amount of food available to animals which rely on organic matter in the sediments.

Suspended sediment and sedimentation can reduce localised productivity through changes in faunal abundance, ecological function and the dynamic interface between the seawater and sediment. Other highly sensitive indicators include the availability of labile organic carbon (e.g., Chl-a is an indicator) or the composition of fatty acids as an indicator for food quality. Sub-lethal effect indicators can include reduced metabolic rates, such as sediment Community Oxygen Consumption (SCOC)/respiration rates and microbial oxygen consumption.

4.6 Identification of knowledge gaps and research priorities

Several significant technical challenges, knowledge limitations and research needs were identified by the IEG.

4.6.1 Measurement accuracy at low SSC levels

Optical SSC sensors have limited resolution. While most modern sensors have low detection limits, this should be considered when evaluating baseline measurements, as suspended sediment values are often quite low and may be below the detection limit of some instruments in some deep-sea environments. Associated with this is the need to encourage research to focus on detecting biological impacts at lower levels of suspended sediments (e.g. <1 mg l^{-1}).

4.6.2 Calibration of turbidity measurements

Turbidity measurements are generally measured in volume (mg/l) and/or light scattering units (e.g., Nephelometric Turbidity Units, NTU). Any threshold would likely be based on the measurable suspended sediment concentration (mg/l) and hence it is necessary to ensure there is calibration from NTU/FTU to mg/l (see Gazis et al., 2025; Haalboom et al., 2022; Munoz-Royo et al., 2022)

4.6.3 Applicability of experimental data

Since *in situ* experiments in the deep sea are technically difficult (but to be encouraged where possible), laboratory experiments are needed across a wide range of common or abundant deep-sea taxa to gain a deeper understanding of variability in dose-response relationships. Many experiments to date have been of relatively short duration. Longer-term experiments are needed to determine sub-lethal impacts, as well as the ability of animals to become resilient and recover. A major uncertainty with studies to date has been how well they might mimic realistic mining scenario exposure situations (pulse versus continuous etc.). *In situ* experimentation at deep-sea mining locations as well as detailed comparisons between biological responses and sedimentation levels/depths should be done at disturbed sites.

4.6.4 9.6.4 Validation of sediment plume models

Understanding the dynamics of sediment plumes derived from seabed disturbance will be important for defining zones of impact. Plume modelling already plays an important part in developing Environmental Impact Assessments for equipment testing, and as more results of these become available, modelling will become more accurate. The validation of plume models requires measurement of the characteristics of suspended particle composition as well as understanding dynamics of particle settling velocities. This will rely on improved technology, such as submersible-ROV mounted instruments that can measure particle size, concentration, and settling velocity, and probes that can detect low turbulence shear.

4.6.5 Applicability of knowledge from shallow water studies

As knowledge about biological effects in shallow waters has been accumulating, applying these findings to deep-sea environments could improve our understanding of key impacts, help identify appropriate indicators, and clarify which taxa or ecological traits are most relevant. However, such application needs to be carefully considered, taking into account factors such as significant differences in rate of reproduction of many taxa, and differences in natural sediment dynamics. Experimental studies are often carried out on "shallow" deep-sea species and there is a need to evaluate the reliability of using such animals (often collected from <1000m) to abyssal depth fauna.

5 Underwater Noise

In this report, the term "noise" refers to all anthropogenic acoustic energy transmitted into the marine environment during DSM activities considered here by the ISA. This includes noise sources such as mining vessels, collectors and vertical transport systems, as well as supporting operations such as surveys by AUVs and support vessels. The sound field caused by these noise sources potentially affects life in the complete water column over large distances as well as in and on the seabed.

The understanding of anthropogenic noise impact on the marine environment has developed over several decades (Williams et al. 2015). Acoustic propagation in the oceans is well understood today with reliable tools for sound field modelling (Jensen et al. 2011). Extensive research has been undertaken into the impacts of noise, mainly addressing the effects on marine mammals, and to a lesser degree, on fishes and turtles. Decades of collaborative research have resulted in development of regulatory practice in various jurisdictions and industrial sectors. Some of the components expected to be used in DSM are used in other offshore industries (e.g., survey and mining vessels, sonar systems), and regulatory oversight already exists, including use of science-based guidelines for categorizing impact.

Two DSM components present novel challenges for deep-sea use, although both have industrial equivalents in more shallow water operations. These are the vertical transport system lifting the nodules from the seabed to the mining vessel, and the sea floor collector. Vertical transport systems involving riser pipes are expected to continuously emit significant noise over the whole water column when nodules are being transferred to the surface. Mining collectors are innovative systems deployed for prolonged periods on the deep seabed. Considerable uncertainty exists on technical characteristics and expected noise radiation from these components, though initial results are available from the recent tests of prototype collectors by GSR and BGR contractors (Patania II) and NORI.

Some of the anthropogenic activities that have received a lot of scrutiny for management initiatives are use of seismic airguns and impact pile driving. These both produce brief but intense pulses of noise, which may cause injury or behavioural change at close distances. Dredging and shipping produces continuous noise of lower sound pressure levels, and so, the most likely effects are behavioural disturbance and acoustic masking, although also physiological consequences including for reproduction are reported. Accumulation of noise sources is an important issue given the widespread nature of noise entering the marine environment from shipping and offshore industry.

Unlike regulatory regimes that require post-impact monitoring and comparison to predicted values for understanding whether thresholds have been crossed, most regulatory regimes for noise focus instead on proactive mitigation - minimisation of noise at source (for example the IMO guidance on limiting engineering noise in new ship designs), and, for mobile receptors, use of distances from a source in which management actions occur to prevent / minimise impact. While regulating based on auditory injury is an established and continuing process, recent scientific developments have led to some regulatory authorities altering the way they consider behavioural responses (NMFS, 2024).

5.1 Variability of ambient noise

Management of noise impacts generated by DSM operations requires characterization of operational sound emissions relative to existing ambient acoustic conditions. Ambient noise can be defined as the “sounds that would be present in the absence of a specified activity” (ISO18405:2017) and includes both natural and anthropogenic components.

Figure 11 depicts a classical model of ambient noise (Wenz, 1962), plotted as spectral density noise level (average intensity levels in 1-Hz bins) vs. frequency (from 1 Hz to 100 kHz). Although the man-made noise contributions have significantly increased since 1962, the main magnitudes of this model remain valid today. This model does not account for in-water depth and doesn’t distinguish between shallow water (especially continental shelves typically shallower than 200 m) and deep-water areas, while for a given sound source the raised noise level is usually increased by a confinement effect in shallow waters.

Baseline information for the deep-sea environments are currently limited. A 2017 – 2018 ocean sound study (Niu et al., 2021) in the western CCZ have found that the high noise levels at low frequencies are generated from distant shipping and vocalizations of whales ranging between 70 and 100 dB 1 µPa (<100 Hz) and 64–93 dB re 1 µPa (100–200 Hz), respectively. The noise levels at high frequencies (>200 Hz), typically dominated by wind, were found to be low, with spectrum levels ranging from 53 to 75 dB 1 μPa^2/ Hz. In addition, sound spectrum levels at these high frequencies were approximately 5 dB re μPa^2/Hz higher in winter than in summer, consistent with seasonal variations in wind speed.

NORI (2022) undertook a sound recording campaign in the NORI-D contract area of the eastern region of the CCZ for the purpose of creating a baseline for a seabed mining trial. The data indicated that background ranges of broadband sound pressure level were lower at 4,297 m (91–104 dB re 1 µPa rms) compared to 538 m (97–118 dB re 1 µPa rms).

Understanding ambient acoustic conditions will be important to define the zone of impact limits and associated monitoring and management plans.

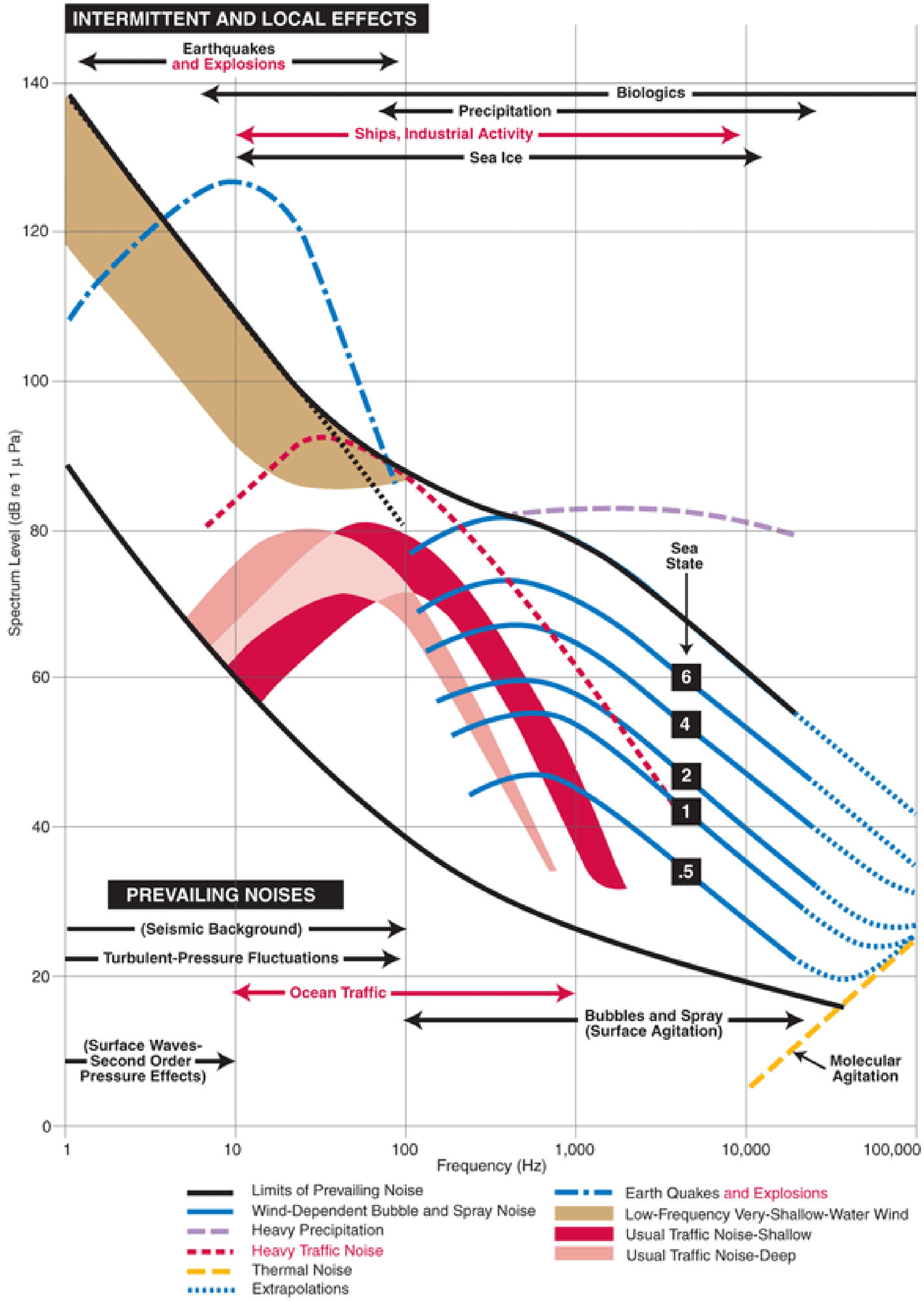

Figure 11 From https://dosits.org/science/sounds-in-the-sea/what-are-common-underwater-sounds/]: The typical sound levels of ocean ambient noise from various origins plotted vs frequency, as modelled by Wenz (1962), and therefore also referred to as the Wenz curves. The spectral levels are given in dB re 1 µPa per 1-Hz frequency bins (also written as dB re 1 µPa²/Hz). Adapted (after National Research Council, 2003) from Wenz, G. M. (1962). © Acoustical Society of America, reprinted with permission

5.2 Characteristics of noise sources

Some knowledge exists on the noise performance of several components of the DSM system either through similar systems being operated by existing industries, such as aggregate dredging vessels, or through the modelling and testing of equipment during the exploration phase, such as those undertaken by GSR (Patania II collector) and NORI. A commercial DSM system will consist of a wide range of noise sources. While some of these may occur only sporadically, many are expected to produce noise over extended periods during mining operations.

5.2.1 Mining Ships

A major component of the noise field from DSM is the mining vessel. Of particular concern are the bow thrusters used for dynamic positioning (Bretschneider et al., 2014), which can introduce high noise levels into the water column. Typical broadband source levels for these are known to be in the range of 165 -180 dB re 1 μPa m (Talisman Energy, 2006, Wyatt, 2008, Xodus, 2014, Fischer 2000). Their sound spectra contain tonal, narrowband and broadband components, with the highest source levels typically found at low frequencies. Other sound sources associated with vessels include broadband propeller cavitation, radiating over a large frequency range, and machinery sound (Smith and Rigby 2022).

Mining ships are expected to have similar acoustic characteristics to dynamically positioned, deep-water drill ships. The main noise sources are expected to be the main motorization and propulsion, thrusters used for dynamic positioning, as well as machinery dedicated to mining equipment deployment and operation; finally, the onboard operations of loading, pre-processing and storing the extracted mineral material are expected to be a significant part of their radiated noise; analogies are to be found today in the shallow-water dredging vessels e.g. Heinis et al 2013). Extrapolating from existing offshore-industry vessels a typical broadband source level of 188 dB re 1μPa at 1m has been proposed as a representative magnitude (Williams et al. 2022, Erbe et al. 2013).

GSR's Patania II tests noted that the surface dynamic positioning thrusters of the chartered vessel produced noise up to 2 kHz (MiningImpact2, 2022). NORI have indicated expected values for an offshore supply vessel using DP of 189 dB re 1 μPa at 1m during test production, at 20 Hz -2 kHz. These are comparable to surface vessel values for marine aggregates dredging (e.g., 172 -185 dB re 1 μPa at 1m (dredging) / 165 -185 dB re 1 μPa at 1m (transit) (Jones et al., 2015) at <250 Hz to 500 Hz (dredging) and 63 -1000 Hz (transit)).

5.2.2 Ancillary Ships

The mining ships will require the support of several kinds of ancillary ships, many of which will also use dynamic positioning. Tender vessels, survey vessels and bulk transport vessels for transporting the ore from the mining vessel. All of these are existing vessel types with well-established databases of ship source spectra (by vessel type and size) (e.g., the Port of Vancouver Enhancing Cetacean Habitat and Observation (ECHO) program) and published (e.g., MacGillivray & de Jong 2021; MacGillivray et al. 2022).

5.2.3 Vertical transport system

There remains considerable uncertainty about the vertical transport systems to be deployed by the DSM industry. Most current proposals have focused on the redeployment of technology developed for deep-water drilling where the drill string (or similar structure) is repurposed as a "riser". The riser is a steel tube or pipe lifting nodules to the ship carried by a flow of water which is created either by pumps located at the sea floor and along the pipe (depending on its length), or by compressed air injected part of the way up the riser.

As well as sound being created from the movement of the slurry within the pipe, local sound sources would also be produced by airlift systems or subsea slurry lift pumps, if used. NORI is intending to use an airlift system for their riser, while GSR is intending to use a series of pumps along the riser, with the shallowest pump being placed at 2000 m water depth or deeper, specifically to avoid additional noise inputs to surface waters and the Sound Fixing and Ranging (SOFAR) channel, which is a depth layer of the ocean in which sound travels farther than in other parts.

The NORI environmental impact assessment for test mining (NORI, 2022) considered expected sound output from operations in the water column. They anticipated a zone of louder sound in the upper riser as it would contain pumps that inject air into the slurry of seawater, fine sediments and nodules. This injection of air, along with the diameter of pipe increasing through the upper riser, was expected to result in a more turbulent flow and a higher frequency of nodules and nodule fragments contacting with the wall of the rigid riser steel pipe, generating non-impulsive, broadband intermittent sound in addition to slurry flow sound. In the lower riser section, an area without any air injection, there was expected to be less turbulence and sound. In addition, NORI (2022) noted that there will also be a point source of sound generated by the air lift injector nozzles, at the depth at which they are placed in the water column. NORI's predicted source levels for the riser of 150 – 155 dB re 1 μPa at 1m, with peak frequencies of 12–20 Hz, but these predictions are not yet validated from field tests, although studies are ongoing.

It should be noted that other ISA contractors exploring for polymetallic nodules in the CCZ may have different solutions for the riser and lift system, with most opting for subsea pumps over airlift. This results in a depth-dependent source in the water column. Other less mature systems have been proposed, but they are still untested at commercial scale. For instance, vertical transport via autonomous underwater vehicles has been proposed by Impossible Metals. The noise footprint of such a system is unknown, although it is expected that the peak intensity will be lower than a riser system.

Noise radiated by the riser is expected to be caused inter alia by the nodules impacting the riser walls and each other, the noise of the pumps or the injection and decompression of the lifting air. The resulting noise level will depend on the riser characteristics (walls material and dimensions – diameter, thickness and length), and the sediment flow (stream speed; density and dimensions of hard mineral elements). It is also likely that the riser-generated noise characteristics will vary along its length. Unlike other noise sources which can be considered in the far field as radiating point sources, the riser is expected to radiate noise as an extended source along its total length.

Modelling of such systems is complex. Each system requires to be considered within the context of the complete collection of technologies deployed. While no full-scale operational tests have been undertaken to obtain experimental data against which models could be tested, it is understood that NORI (2022) undertook acoustic measurements of its riser during its mining test, but this information was not available at the time of writing this report. In the absence of comprehensive field data, it is suggested that the relevance of existing related systems, such as shallow water dredging be considered as starting points of extrapolations towards future DSM systems.

5.2.4 Seabed collectors

Sound produced during dredging and collecting operations on the seafloor will be strongly influenced by sediment properties as well as the collector's operational mode (e.g. full collecting mode, system paused but with pumps on, collector vehicle moving but without collection system active). Recent tests of prototype collectors developed by GSR and NORI provided some initial measurements. In both collectors, the pumps/compressors used to lift the nodules to the mining vessel are not contained within the collector.

The ocean bottom seismometer measurements conducted by MiningImpact showed higher noise levels closer to the GSR's pre-prototype collector Patania II (100-110 dB re 1 µPa in 100 m distance). Noise levels dropped linearly with distance. 80 dB re 1 µPa was the background noise level in 400 m distance. The recorded linear drop of the noise levels with distance suggests that the OBS recorded vibrations of the seafloor. This is in line with the frequency below 10 Hz of this noise. Noise recorded at higher frequencies (up to 2 kHz) resulted from the surface vessel.

Patania II is 1/3 scale of its expected commercial size and is equipped with four suction heads that use a jet water pump system to raise the nodules slightly off the seabed before sucking them into the collector tank. The commercial scale collector vehicle will have three suction heads of the same size, and the combined noise level is calculated as 84.8 dB re 1 µPa (pers comm, GSR).

NORI recorded higher noise values during test mining, with noise levels below 110 dB re 1 µPa at 400 m from the source (Clarke, pers. comm.). NORI's trial collector is 1/5 scale and uses a similar overall design.

While initial consideration of substrate vibration has focused on impulsive sound sources (pile driving) (Martin et al., 2021), significant propagation distances are also likely to be found from substrate vibrations produced by DSM collectors. Seabed vibration, with particles oscillating sideways to the direction of travel, known as shear waves, can carry particle motion that ranges from just over 100 m to well over 1km from the source, depending on frequency (Hazelwood, 2012; Hazelwood and Macey, 2016).

5.2.5 Surveying systems

During the exploration and exploitation phases of DSM activity, acoustic surveys will be required to characterise and manage the resource as well as to monitor the environmental conditions of the mine site. The following are the main acoustic survey technologies that are expected to be used. Source spectra and levels of these systems have been summarised by Erbe et al. (2025).

5.2.5.1 Echosounders and side-scan sonars

Echosounders and sidescan sonars are related acoustic seabed surveying techniques. Both operate by transmitting short acoustic pulses in narrow beams steered either downwards or laterally in order to scan the seafloor along the carrier vehicle track. Echosounders can be either single-beam (one single transmit sector steered vertically) or multibeam (transmitting inside a fan-shaped transverse sector) and can be mounted on either ship's hulls or subsea vehicles with vessel-mounted systems being generally more powerful. The current models of echosounders range between 10 kHz and 1 MHz; the choice of frequency is dictated by the expectation in terms of coverage range and measurement accuracy. Side-scan sonars are most-often deep-towed systems transmitting high frequencies (typical models range between 100 kHz and 1 MHz) in two lateral fan-shaped sectors. All these various seafloor-mapping systems transmit narrow-band signals with slow recurrence periods (10 to 100 times the pulse duration).

5.2.5.2 Sub-bottom profilers

A sub-bottom profiler (SBP) is an echosounder recording the penetration of a low-frequency signal inside surficial sediment layers for geophysical imaging purposes; they offer a good resolution capability but a modest penetration depth. SBPs operate at frequencies between 2 and 10 kHz, often with a modulated signal covering a significant frequency range to enhance their resolution. With a few exceptions, SBPs are single-beam systems transmitting downwards, and their radiating sector is not steered for ship's motion compensation. Their beamwidths are strongly frequency-dependent; typical values are found between 10° and 30°.

5.2.5.3 Acoustic Doppler Current Profilers (ADCP)

ADCPs are designed to measure ocean currents and suspended sediments below the vessel. Current ADCPs exist at various frequencies typically between 30 kHz and 1 MHz, depending on their operational needs in range and accuracy. They always transmit inside 3 or 4 very narrow beams tilted downwards around vertical. Their power levels are usually modest compared to echosounders

5.2.5.4 Remotely Operated and Autonomous Underwater Vehicles

During the exploration and exploitation phases, tethered remotely operated vehicles (ROVs) and autonomous underwater vehicles (AUVs) will be deployed in the water column and near the seabed to take measurements and samples as well as optical or acoustical imagery. These vehicles radiate noise through their propulsion system and their active acoustic sensors. Their relative contribution to the global noise field caused by DSM activities is expected to be low.

5.2.5.5 Positioning and communications systems

During all underwater operations, accurate positions of the subsea components have to be measured, mainly using dedicated acoustic transmitters of various technologies. Specific acoustic systems are also used for underwater communication and data transmission. Acoustic positioning or communication systems usually transmit almost continuous streams of relatively low-energy modulated signals possibly occupying significant bandwidths.

5.3 Biological responses to noise

Anthropogenic noise can cause a range of biological responses from multiple acoustic characteristics, including sound pressure level, frequency content, duration, temporal pattern, and the associated particle motion and substrate vibrations generated by sound propagation. Elevated sound pressure levels can induce behavioural responses and physiological impacts. Different taxa exhibit distinct hearing sensitivities and use different ranges of frequencies. Particle motion (the oscillatory movement of water particles associated with sound waves) may represent the primary acoustic cue detected by many fishes and invertebrates. Sound-induced substrate vibrations may also affect benthic organisms that rely on mechanoreceptors to detect environmental cues, prey, predators, or conspecifics.

Responses related to sound pressure levels and frequencies are known from controlled laboratory experiments, field studies and modelling, the vast majority of which from marine mammals, although some data are also available from fish, turtles and invertebrates. Such studies have provided the data required to establish noise exposure thresholds for species or hearing groups, i.e. categories of species understood to have similar hearing abilities.

For marine mammals, at the longest ranges over which a noise is audible, the effects of noise may be subtle. At somewhat higher levels, animals might experience acoustic masking. Some animals have compensation mechanisms, such as spatial release from masking and comodulation release, which reduce the amount of masking to some extent. Animals might also change their signals to improve communication in noise. Common acoustic responses include alterations in frequency of calls, duration of calls and call amplitudes. Such changes in acoustic behaviour may come with changes in physical and functional behaviour. Noise might interrupt feeding, mating, nursing and other behaviours. Common behavioural changes include alterations in diving structure, swimming direction and changes in group structure. There often is no direct correlation between the level of the noise and the level of behavioural impact. Rather, behaviour also depends on context, prior experience and other non-acoustic pressures.

Noise exposure at higher levels may induce hearing loss, which can be temporary or permanent, with the latter being considered injury. Noise at any level may induce stress. Stress becomes a health concern if exposures are chronic. Ongoing exposures might ultimately lead to abandonment of important habitat. All these impacts could result in changes to individual vital rates such as decreased foraging success, higher energetic demands, or decreased reproduction. While research studies may demonstrate impacts on individual cetaceans from noise (e.g., those reviewed in Guan and Brookens 2023), population-level effects have remained particularly hard to estimate and detect.

There are no specific data on hearing by deep-sea fishes, but Popper and Thomsen (2026) described the structure and ultrastructure of the ears in diverse species leading to the suggestion that all deep-sea fishes can hear sounds ranging from a few hertz up to 500 to 1000Hz, while some deep-sea species with specialized hearing adaptations may hear higher frequencies. Given the likely overlap of noise levels from DSM activities and the sounds detected by fish, Popper and Thomsen (2026) considered reasonable to assume that DSM sounds have the potential to interfere with the normal use of sounds for communication and learning about their environment by these animals. Williams et al (2025) reviewed noise sensitivity of across taxonomic classes in the CCZ and highlighted that Soniferous fish, which rely on acoustic communication, are particularly vulnerable to noise.

Behavioural changes in fish may include long-term changes in distribution, such as moving from preferred sites for feeding and reproduction, or alteration of migration patterns. In close proximity to a noise source, energy levels may be sufficient to physically affect the hearing of an individual fish, either through impact to the inner ear or the swim bladder.

There is considerable uncertainty surrounding how different acoustic stimuli influence marine invertebrate individuals, populations and species (Sole et al. 2023, Popper & Thomsen 2026).

Aquatic invertebrates lack the gas-filled cavities needed for vertebrate hearing systems, and it is suggested they mostly (but not solely) perceive particle motion of the sound (Hawkins and Popper 2017). For example, sensory hair cells common in cnidarians, tunicates, bivalves, molluscs, crustaceans, and annelids are stimulated by mechanisms that respond to particle motion and convert these motions to electrical signals that stimulate the nervous system. Systems able to sense vibration are known in cephalopods and crustaceans (Solé et al. 2023).

Anthropogenic noise is known to have detrimental impacts on aquatic invertebrate behaviour and physiology, with defence responses having been investigated in detail (Davies et al., 2024). Prominent physiological responses were related to biochemistry, genetics, larval development and morphology (Davies et al., 2024). Arthropods and molluscs show the most pronounced physiological responses to anthropogenic noise (Davies et al., 2024).

Finally, in addition to water-borne sound, benthic species are likely sensitive to substrate vibration that would be produced by DSM collectors, though little is known about the impact of such signals on animals [e.g., Hawkins et al. (2021)]. The spatial footprint of substrate-borne vibration therefore remains a critical unknown in evaluating DSM impacts on fishes and invertebrates (Guan et al., 2025).

5.4 Existing thresholds and examples from other industries

Anthropogenic underwater noise has been recognised for decades as a stressor on the marine environment, and a number of industries and regions have developed regulatory responses for protection of marine mammals and fish, initially focused on high-intensity activities such as seismic airgun surveys or pile driving. Underwater radiated noise from commercial shipping has been addressed by the International Maritime Organization, which issued guidelines for its reduction (MEPC.1/Circ.906/Rev.1) as well as proposed mitigation measures in response to the ubiquity of its global impact.

Noise management can be approached either by regulating noise source levels or by controlling noise impacts on biological receptors. The two approaches are related. Source level thresholds are readily related to engineering considerations. A small subset of underwater noise regulations use explicit, source-based thresholds (limits on what the activity or equipment may emit). Where they exist, they are usually framed as emission caps, event limits, or per-activity limits. Sound propagation modelling tools have to be used to estimate noise levels at various distances from the sound source. Most management strategies use these "isopleths" in combination with known acoustic responses for different species / group of species to develop a set of distances from a particular source where injury or behaviour thresholds are expected to occur. Noise restrictions are applied when animals are at risk of crossing these thresholds.

The management approach that is taken will depend on a complex interaction of factors and is likely to include consideration of both sources and receptors. This is in line with Environmental Impact Assessment, where there is an embedded expectation that any operation will function in accordance with national and international pollution legislation, and where impacts to receptors are usually the basis for project-level and regional-level impact assessment. An overview of existing underwater noise regulatory frameworks, guidelines and thresholds across different industries and jurisdictions is provided in supplementary information.

5.4.1 Regulation at source

The most prominent global industry that manages its noise footprint through interventions at the source is the shipping industry through the International Maritime Organisation (IMO). Although the individual impact of ships may be small compared to that of other sources of underwater noise, it has been recognised that the cumulative noise level of shipping does impact the marine environment and requires a global response. This is led through the IMO which developed non-mandatory guidelines to reduce the impact of underwater radiated noise from shipping on marine life (IMO 2014, 2023).

Another example of regulation at source is for offshore seismic surveying, although this is mostly undertaken at a national level with some degree of regional coordination. These activities use airgun arrays that generate impulsive noise with very high energy output. Operation planning for each seismic survey requires a specific environmental impact assessment. Additionally, shutdown zones and regulations for starting the power source are generally established by regional or national authorities.

The regulation of offshore pile driving, commonly used for wind-farms installations, varies between different countries. Guidelines for mitigation measures at the source have been developed in some cases, suggesting source mitigation techniques such as modified impact hammers and vibratory installation, reduces noise by altering pulse duration or shifting soil vibration modes.

5.4.2 Regulation at receptor level

Existing regulations and policies at receptor level have prioritised the impacts on marine mammals. The IEG considered that these receptor-based regulatory approaches may also be applicable to fish and invertebrates.

5.4.2.1 Marine mammals

Two metrics are used when assessing the impacts of impulsive sound. One of these metrics is also used for continuous sound. The peak sound pressure level ($L_{p,0\text{-}pk}$), used when assessing impulsive sound, is the level of the greater of the magnitudes of the zero to positive peak and zero to negative peak pressure of a sound, measured in decibels (dB) referenced (re) to a pressure of 1 micropascal (μPa) and is denoted as dB re 1 μPa. The sound exposure level (L_E), used for both impulsive and continuous sound, considers both received pressure as well as the duration of exposure, and is computed as the level of the squared pressure integrated over time, denoted as dB re 1 $\mu Pa^2 s$. Under US guidelines, this metric is weighted to account for the distinctive hearing response of the various marine mammal groups.

Current US guidelines define:

- **Temporary threshold shift** (TTS): Temporary decrease in hearing sensitivity at a specific frequency, or in a portion of an individual's hearing range, above a previously established reference level. Hearing sensitivity returns to baseline levels after a period following the noise exposure.

- **Auditory injury** (AUD INJ): Damage to the inner ear that can result in destruction of tissue, such as the loss of cochlear neuron synapses or auditory neuropathy. This may result in a **permanent threshold shift** (PTS), which is an irreversible increase in the hearing threshold at a specified frequency or portion of an individual's hearing range above a previously established reference level.

While noting that there will be both interspecific and intraspecific differences in responses to noise, Southall et al. (2019) divided marine mammals into eight hearing groups (Table 10), of which three are the most relevant to polymetallic nodule areas: Low Frequency (LF - all baleen whales), High Frequency (HF - most dolphins, beaked whales, sperm whales and orcas), and Very High Frequency (VHF - true porpoises, pygmy / dwarf sperm whales and some oceanic dolphin species).

Table 10 Summary of hearing characteristics of hearing groups as per Southall et al. (2019), with Generalised Hearing Range taken from National Marine Fisheries Service (2023).

Marine Mammal Hearing Group	**Auditory Weighting Function**	**Genera (Species) Included**	**Generalised Hearing Range***
Low-frequency cetaceans	LF	Balaenidae (Balaena, Eubalaenidae spp.); Balaenopteridae (*Balaenoptera physalus*, *B. musculus*)	7 Hz - 36 kHz
		Balaenopteridae (*Balaenoptera acutorostrata, B. bonaerensis, B. borealis, B. edeni, B. omurai; Megaptera novaeangliae*); Neobalenidae (*Caperea*); Eschrichtiidae (*Eschrichtius*)	
High-frequency cetaceans	HF	Physeteridae (*Physeter*); Ziphiidae (*Berardius spp., Hyperoodon spp., Indopacetus, Mesoplodon spp., Tasmacetus, Ziphius*); Delphinidae (*Orcinus*)	150 Hz - 160 kHz
		Delphinidae (*Delphinus, Feresa, Globicephala spp., Grampus, Lagenodelphis, Lagenorhynchus acutus, L. albirostris, L. obliquidens, L. obscurus, Lissodelphis spp., Orcaella spp., Peponocephala, Pseudorca, Sotalia spp., Sousa spp., Stenella spp., Steno, Tursiops spp.*); Montodontidae (*Delphinapterus, Monodon*); Plantanistidae (*Plantanista*)	
Very-high-frequency cetaceans	VHF	Delphinidae (*Cephalorhynchus spp.; Lagenorhynchus cruciger, L. austrailis*); Phocoenidae (*Neophocaena spp., Phocoena spp., Phocoenoides*); Iniidae (*Inia*); Kogiidae (*Kogia*); Lipotidae (*Lipotes*); Pontoporiidae (*Pontoporia*)	200 Hz - 165 kHz
Sirenians	SI	Trichechidae (*Trichechus spp.*); Dugongidae (*Dugong*)	n/a
Phocid carnivores in water	PCW	Phocidae (*Cystophora, Erignathus, Halichoerus, Histriophoca, Hydrurga, Leptonychotes, Lobodon, Mirounga spp., Monachus, Neomonachus, Ommatophoca, Pagophilus, Phoca spp., Pusa spp.*)	40 Hz - 90 kHz
Other marine carnivores in water	OCW	Odobenidae (*Odobenus*); Otariidae (*Arctocephalus spp., Callorhinus, Eumetopias, Neophoca, Otaria, Phocarctos, Zalophus spp.*); Ursidae (*Ursus maritimus*); Mustelidae (*Enhydra, Lontra feline*)	60 Hz - 68 kHz

*Represents the generalized hearing range for the entire group as a composite (i.e., all species within the group), where individual species' hearing ranges are typically not as broad. Generalized hearing range chosen based on ~65 dB threshold from normalized composite audiogram, with the exception for lower limits for LF cetaceans (Southall et al. 2007) and PW pinniped (approximation).

These groups are used in regulation of impact on receptors, including the United States' National Marine Fisheries Service expert group recommendation currently published as National Marine Fisheries Service (2024), Southall et al.'s (2007, 2019) Marine Mammal Noise Exposure Criteria and the European Marine Strategy Framework Directive Technical Group on Underwater Noise reports on impulsive noise (Sigray et al., 2023) and continuous noise (Borsani et al., 2023).

Auditory injury and TTS energy levels for each mammal frequency group within their sensitivity range are listed below (Table 11)

Table 11 Summary of Auditory Injury and TTS criteria for LF, HF and VHF marine mammals (National Marine Fisheries Service, 2024). Lp,0-pk: zero-to-peak sound pressure level, sometimes noted SPLpk); LE,p: sound exposure level, SEL.

Marine Mammal Hearing Group	Auditory Weighting Function	TTS Onset in Impulsive/ Intermittent Noise, Crit. 1: SPL 0-pk [dB re 1 µPa], unweighted	TTS Onset in Impulsive/ Intermittent Noise, Crit. 2: SEL [dB re 1 µPa2s], 24h cum, weighted	TTS Onset in Non-Impulsive Noise: SEL [dB re 1 µPa2s], 24h cum, weighted	AUD INJ in Impulsive/ Intermittent Noise, Crit 1: SPL 0-pk [dB re 1 µPa], unweighted	AUD INJ in Impulsive/ Intermittent Noise, Crit 2: SEL [dB re 1 µPa2s], 24h cum, weighted	AUD INJ in Non-Impulsive Noise: SEL [dB re 1 µPa2s], 24h cum, weighted
Low-frequency cetaceans	LF	216	168	177	222	183	197
High-frequency cetaceans	HF	224	178	181	230	193	201
Very-high-frequency cetaceans	VHF	196	144	161	202	159	181
Sirenians	SI	219	171	180	225	186	200

While behaviour thresholds for impulsive and non-impulsive noise exist in the literature, Southall et al. (2021) and others have suggested that these can lead to significant errors when predicting behavioural impacts, instead advocating dose response frameworks that objectively assess available science to identify probabilistic response functions.

5.4.2.2 Fish

Three levels of physical impact have been identified for fish:

- A **temporary threshold shift (TTS)**: is a temporary reduction in hearing sensitivity caused by exposure to intense sound. It can consist of short- or long-term changes in hearing sensitivity that may or may not reduce fitness. .
- **Recoverable injury**: injuries, including hair cell damage, minor internal or external hematoma, etc. None of these injuries are likely to result in mortality.
- **Mortality and mortal injury**: energy levels are sufficient to cause immediate or delayed death.

Next to direct physical injuries, auditory masking occurs when noise interferes with the detection of biologically relevant signals. Masking can decrease fitness for example due to disrupted communication, ability to detect predators or prey or mating partners.

While noting that there will be both interspecific and intraspecific differences in responses to noise, Popper et al. (2014) divided fish into five hearing groups, of which all are relevant to polymetallic nodule areas (see Table 12). These groups have been realised in the UK regulatory context as:

- Group 1 – Fishes lacking swim bladders and other gas-filled cavities that are sensitive only to sound particle motion and show sensitivity to only a narrow band of frequencies (e.g., flatfishes, Pleuronectiformes; sharks skates and rays, Chondrichthyes). Some barotrauma may occur from the exposure to sound pressure;
- Group 2 – Fishes with a swim bladder or other gas-filled chambers where that organ does not appear to play a role in hearing. These fish are sensitive only to particle motion and show sensitivity to only a narrow band of frequencies. Some barotrauma may occur from the exposure to sound pressure. This group includes salmonids (Salmonidae) and some tunas and mackerels (Scombridae), but many other species are likely to fit into this category as well;
- Group 3 – Fishes with swim bladders that are close, but not intimately connected, to the ear. These fishes are sensitive to both particle motion and sound pressure and show a more extended frequency range than groups 1 or 2, extending up to about 500 Hz. These species are susceptible to barotrauma. This group includes cod fishes (Gadidae), eels (Anguillidae), some drums and croakers (Sciaenidae), and perhaps other fish;
- Group 4 – Fishes that have special structures mechanically linking the swim bladder to the ear. These fishes are primarily sensitive to sound pressure, although they also detect particle motion. They have a wider frequency range, extending to several kHz and generally show higher sensitivity to sound pressure than fishes in groups 1, 2, or 3. These species are susceptible to barotrauma. The group includes some of the squirrel fishes (Holocentridae), drums and croakers (Sciaenidae), herrings (Clupeidae) and the large group of otophysan fishes; and
- Group 5 – Fish eggs and larvae - These are also considered to be receptors of concern by Popper *et al*. (2014), due to their vulnerability, small size and reduced mobility.

Popper et al (2014) provide guidelines for impact to fish related to explosions, pile driving, seismic airguns, low and mid frequency naval sonar and shipping and other continuous noises. Among these categories, impact levels identified for shipping and other continuous noises (see table 12) could be considered as a starting point for investigating impact from future DSM systems, recognizing that deep-sea species may be more vulnerable and face cumulative noise impacts from DSM operations.

Table 12 Summary of noise impacts related to Shipping and Other Continuous Noises (Popper et al 2014) N: near, I: intermediate, F: far

	Mortality / potential mortal injury	Recoverable injury	TTS	Masking	Behaviour
Fish: no swim bladder	Low	Low	N – Moderate I/F - Low	N / I – High F - Moderate	N / I –Moderate F - Low
Fish: swim bladder not used in hearing	Low	Low	N – Moderate I/F – Low	N / I – High F – Moderate	N / I –Moderate F - Low
Fish: swim bladder involved in hearing	Low	170 dB rms for 48 hrs	158 dB rms for 12 hrs	N / I / F– High	N – High I – Moderate F - Low
Sea turtles	Low	Low	N – Moderate I/F - Low	N / I – High F – Moderate	N – High I – Moderate F - Low
Eggs and larvae	Low	Low	N – Moderate I/F - Low	N – High I – Moderate F - Low	N / I – Moderate F - Low

5.4.2.3 Invertebrates

Hawkins and Popper (2017) note that there is insufficient information to guide the setting of criteria for any invertebrate species, with criteria often just assumed or derived from poorly designed and controlled studies. Metrics often are not based on particle motion, including vibration. Existing evidence suggests that those species studied are primarily sensitive to particle motion at frequencies well below 1 kHz (Budelmann, 1992; Mooney et al., 2010, 2012), and more recently Solé et al (2023) noted that invertebrates for which there are hearing data also detect sounds below a few hundred hertz.

5.5 Development of threshold values, including early warning and uncertainty levels

The IEG considered that where international guidelines are available that contain quantitative or semi-quantitative understanding of thresholds of injury for marine mammals, other megafauna, and fish, such guidelines should be followed. In particular, it is recommended that values contained within National Marine Fisheries Service (2024) are used in determining distances and management measures for operations to prevent and/or minimize impacts for marine mammals, and recommendations in Popper et al (2014) for fish, and potentially invertebrates.

Currently, these guidelines would be applicable to the operations taking place at surface (mining and support vessels). Considerable uncertainty exists for developing such guidelines for the seafloor and midwater environments (see below section 5.6).

5.5.1 Application of Ecological Reference Points and Zones of Impact

The application of existing noise guidelines to the zone of impact model and associated ecological reference points is exemplified in the sections below.

Defining Ecological Reference Points and Zones of Impact related to noise emissions from seabed collectors, other supporting equipment on or near the seabed and vertical transport, requires further consideration, including:

- Estimating spatial (three-dimensional) and temporal patterns of noise propagation on the seafloor and water column using attenuation models,
- Characterising ambient noise levels, and
- Understanding the noise effects on fish and invertebrates and the extent to which shallow water species may serve as surrogates for deep-sea species.

5.5.1.1 Marine mammals

Auditory injury and TTS thresholds exist for marine mammals and are used to develop impact mitigation and management options in consenting processes. Use of thresholds for behavioural change, however, carry considerable levels of uncertainty (e.g. Southall et al., 2019), though are still used for some consenting processes.

Boundaries between Zones of Impact could be assigned based on type of impact, such as auditory injury and TTS. For example, the boundary between ZoHI and ZoMI could correspond to the lowest noise level that would cause auditory injury, and the boundary between ZoMI and ZOI could correspond to TTS levels. ZoI could relate to ambient sound levels and their levels of natural variability.

5.5.1.2 Fish

A few auditory injury and TTS thresholds exist for fish that have their swim bladder involved in hearing. For the most part, however, there are no data on exposure or received levels that enable guideline numbers to be provided. Only relative risk of an effect is considered as being “high,” “moderate,” and “low” with respect to source distance and animal type. Popper et al (2014) indeed note that the rating for effects in the guidelines is highly subjective and represents general consensus within the expert working group that undertook the analyses.

Boundaries between ZOI can be assigned based on type of impact. As such, the boundary between ZoHI and ZoMI could correspond to the lowest value of TTS, and the boundary between ZoMI and ZOI could correspond to behavioural change. The noise at source can be louder than the defined ERPs if sufficient attenuation occurs to reduce noise to levels below the ERPs before reaching the receptor.

5.5.1.3 Invertebrates

Recent UK guidance (ABPmer, 2025) notes that currently marine invertebrates can only be considered on a qualitative basis, as there are no criteria available by which to make an assessment, despite the increase in publications discussing impacts of underwater noise on marine invertebrates (Hawkins and Popper, 2017, Carter et al., 2020, Wale et al., 2021, Solé et al., 2023). Aligning to conclusions in Popper and Thomsen (2026) the IEG considered that no zone of impact framework can yet be established for invertebrates, and further studies are required for understanding the impacts of noise on deep-sea invertebrates (see also Guan et al. 2025).

5.5.2 Identification of appropriate indicators

Existing noise regulatory practices have already identified a series of indicators and metrics that allow establishing pressure-receptor relationships, especially for marine mammals and fish. Responses of deep-sea invertebrate species, populations and communities to noise impacts are less understood and require further research (see below section 5.6).

Spatial scale is critical in appropriate use of indicators and metrics for noise impact analysis. For results to be useful in a management context, analyses and resulting thresholds need to be tailored to fit the environmental constraints and spatial scale of that area. An example of such an approach is the framework of risk-based noise exposure indicators for use in quantitative management targets developed by Merchant et al. (2018). These indicators quantified the proportion of a population or habitat exposed, and the associated exposure duration, within a defined management area. This follows the principles developed by the Marine Strategy Framework Directive's Level of Onset of Biological Adverse Effect (LOBE). For short-term exposure (i.e., daily exposure), the maximum fraction of the habitat of an indicator species that is allowed to be exposed to impulsive noise levels higher than LOBE over 1 day is 20% or lower. For long-term exposure (i.e. yearly exposure), the maximum fraction of the habitat of an indicator species that is accepted to be exposed to impulsive noise levels higher than LOBE, averaged over 1 year, is a 10% or lower. The MSFD Technical Group on Underwater Noise (TG Noise) advised setting continuous noise threshold values such that no more than 10% of the target habitat has noise levels above LOBE in any month of the assessment year, aligned with underlying conservation objective of maintaining 80% of carrying capacities/habitat sizes.

To assess the area of a site that may be affected by noise disturbance, the guidance recommended the use of Effective Deterrence Ranges (EDRs), equivalent to the mean loss of habitat per animal (Tougaard et al. 2013) related to an impulsive noise event from which harbour porpoises are disturbed/deterred.

5.6 Identification of knowledge gaps and research priorities

Several significant knowledge limitations and research needs were identified by the IEG.

5.6.1 Noise sources from DSM equipment components

Noise level measurements of DSM equipment components are rare, and no data are yet available for noise emissions from commercial-scale DSM equipment. Noise measurements are necessary both in controlled conditions and in the field, with a particular emphasis on riser pipes and seafloor mining collectors. Data must include not only sound pressure, but also particle motion and substrate vibrations.

Source characteristics of coastal operations have been considered as a starting point for estimating the potential effects of DSM noise. However, such extrapolations may not be adequate to fully capture the source levels and operational scale of a DSM operation (Popper and Thomsen, 2026).

Technological development and engineering solutions to minimize noise levels should be encouraged. It is also noted that accurately modelling propagation characteristics of acoustic waves radiated from multiple sources throughout the water column can be very challenging, considering several sound speed layers, the surface mixed layer, seasonal thermocline and main thermocline, the sound fixing and ranging (SOFAR) channel, and the deep isothermal layer that incorporates seabed geoacoustical influence (Jensen et al., 2011).

5.6.2 Characterisation of ambient noise in contract areas

- Spatial-temporal acoustic characteristics in contract areas are very poorly studied. Characterization of soundscapes, including deep-sea ambient noise in exploration areas, in area-based management zones and in wider regional characterisation should be documented (see case study described in

Annex 3 – Case study: Project for Monitoring the Underwater Acoustic Landscape of the Santos Basin (PMPAS-BS)). Account should be taken of seasonal and depth variations. In addition, potential effects in sound propagation affecting the DSM-caused noise fields, such as water temperature and salinity changes in the vicinity of the mining ship or around the riser requires further research, as well as a better understanding of seabed sound absorption changes and propagation effects of the sediment plumes in the extraction area. Monitoring over long time periods across exploration contracts is suggested.

5.6.3 Receptors

The impacts of noise on benthic and midwater invertebrate species and populations and deep-sea fish represent a major knowledge limitation. Assessing these impacts is challenging due the practical difficulties of studying animals adapted to extreme depths. Many deep-sea species cannot be easily brought to the surface for laboratory experiments without risking physiological stress or altered sensory function, and their hearing systems may be uniquely adapted to high-pressure environments [e.g., Deng et al. (2011, 2013, 2023)]. As a result, there is limited understanding of how these organisms detect sound, particularly particle motion and substrate vibrations, which are likely important components of DSM-generated noise. The scarcity of data on hearing sensitivity, sound production, and behavioural responses further constrains robust assessment of potential impacts.

Research priorities should focus on improving understanding of the auditory systems of representative deep-sea species through detailed morphological and physiological studies (e.g., Popper et al. (2022), Deng et al. (2023), Popper et al. (2023), and Guan et al. (2025)). Where direct experimentation is not feasible, carefully selected shallow-water surrogate species may help inform assessments, although differences between deep- and shallow-water taxa must be recognised. Future studies should investigate hearing sensitivity, sound discrimination, sound source localisation, and responses to particle motion and substrate vibration. In addition, behavioural observations conducted at depth using autonomous platforms, hydrophones, and camera systems are needed to evaluate how animals respond to mining-related noise in their natural environment. These efforts are essential for reducing uncertainty and supporting more reliable environmental risk assessments of DSM activities.

6 Light pollution

In this report, "light pollution" is considered any light introduced into the environment by human activities at intensities that are higher than the natural levels at that time for the given environment (see. e.g. Mayer-Pinto et al 2022). Another common term for light pollution that applies to DSM context is Artificial Light at Night (ALAN), which refers to any human-made illumination during nighttime, disrupting natural dark cycles with light from sources like vehicles and electronic devices, significantly impacting the overall ecosystems. The variability of ALAN wavelengths generated by multiple light sources disrupts natural rhythms, affecting marine organisms from the tiniest zooplankton to the largest whales (Chortos, 2024).

Most underwater organisms have some type of photosensitive organs or systems to detect light and light variation in their environment; therefore, disruptions caused by artificial light that interferes with signals at important periods or locations, can have serious consequences (Sale, 1991; Warrant, 2004; Warrant & Locket, 2004).

In organisms that have eyes, pigments are stored in photoreceptors located in the rear of the receptive organ (retina or rhabdom). Cones and rods are photoreceptive sensory cells found in single-lens eyes that contain these pigments. Rods are crucial for scotopic (low light) vision, whereas cones are crucial for photopic (bright) circumstances, particularly for colour detection (Dusenbery, 1992). Fish that live in deeper water and at night, like squirrelfish and soldierfish (Holocentridae), have rod-dominated visual systems with pigments that are suited to low light levels (Marshall & Vorobyev, 2003; Iglesias et al., 2018; Luehrmann et al., 2019; de Busserolles et al., 2021).

Aside from eyes, various non-visual tissues and organs, such as the pineal gland or bioluminescent organs (which have extraocular photoreceptors), can sense light and influence organisms' physiology and behaviour (Tong et al., 2009). The light wavelength is an important factor for its intensity and composition changes. Therefore, in addition to the changes in the intensity, changes to light composition can affect how organisms' sense and interpret cues (Cheney et al., 2013).

While the impact of anthropogenic light at the surface has been recognised for several decades and has caused the progressive development of regulation and policies designed to mitigate these impacts, the impact of anthropogenic light on the marine environment remains a relatively novel field.

6.1 Variability of naturally occurring ambient light

Few studies have focused on changes in light wavelengths. It appears from those studies that shorter wavelengths (less than 495 nm) predominate in deeper seas. As a result, deep-sea species have evolved to thrive in bluer light environments and with shorter light wavelengths. For example, the vision of deep-sea shrimp is modified to detect the bioluminescence light (shorter wavelengths) released by conspecifics (Chamberlain, 2000). In addition, species below the photic zone have also evolved mechanisms to see in short wavelength lights, such blue or even ultraviolet light, which mimic the filtered or bioluminescent sources they emit or are exposed to (Frank & Case, 1988; Cronin & Frank, 1996; Schweikert et al., 2020). Due to their delicate and specialized visual systems, these creatures may be most vulnerable to impacts from artificial point sources of light, even though they may rely on vision far less than animals in brighter environments.

Light intensity declines by about 1.5 orders of magnitude with every 100 m depth. Because of the combination of the general light and the amount of various light wavelengths and types, the shallowest waters are typically the brightest. In the water column, long wavelength light travels the shortest distance while short wavelength light travels the furthest (Denny, 1993; Tamir et al., 2017). The most prevalent source of light in marine trenches, deep-sea and the aphotic zone is bioluminescent light, which may also be found at all depths, from close to the surface to the ocean's depths (Caves, Sutton & Johnsen, 2017).

Artificial light can disrupt the perception of all natural sources of light by introducing light that is potentially different in spectral makeup and occurs in high intensity or from unnatural source locations at odd times. Differences in intensity and wavelengths result from the significantly more efficient alteration, attenuation, or blocking of light's pathway in water as opposed to air.

Therefore, many marine species have visual systems that are tailored to the way light bends and moves in their environment because of light structuring (Collin & Mashall, 2003).

6.2 Characteristics of light sources

Although significant uncertainty exists in the final design of DSM systems, it is possible to make broad assumptions on the configuration of equipment that will be required to undertake mining operations and the lighting characteristics of this equipment. All existing proposals for DSM have included the following sources of light.

6.2.1 Mining ships

Mining ships are expected to have similar or identical lighting characteristics to dynamically positioned, ultra deep-water drill ships from which initial proposals are derived. Mining vessels are expected to use artificial light to fulfil navigation and signalling requirements, for safety purposes, within technical equipment operation and for emergency operations.

International, national and maritime regulations and resolutions provide requirements for types and configurations of lighting to be used for navigation and safety purposes (in particular the Convention on the International Regulations for Preventing Collisions at Sea (COLREGS)). Chromaticity of navigation lights is specific covered by the International Commission on Illumination. Minimum luminous intensity may be specified in national guidelines. Energy efficiency within lighting is regulated by IMO with the Energy Efficiency Existing Ship Index (EEXI).

For example, COLREGs Rule 22/23/25, requires specific visibility ranges and arc angles for navigation safety. Masthead lights (white) must be visible for 6 NM (>) or 5 NM, while side (112.5°, red/green) and stern lights (135°, white) must reach 2–3 NM. Emergency lighting must maintain high, functional output.

6.2.2 Ancillary Ships

The mining ships are expected to require the support of several kinds of ancillary ships. Tender vessels, survey vessels, including ROV support vessels and bulk transport vessels for transporting the ore from the mining vessel to land. Light will be needed at all times during any passage from the mine site to port facilities. All of these are existing vessel types with equal requirements for light as the mining ship. According to Ludvigsen et al (2018), ALAN from both a large research vessel and headlamps on a small open vessel introduce light pollution that induce an avoidance response in the pelagic community down to more than 80-m depth.

The same study showed that diffuse sky light irradiance increased by 15 times (Ludvigsen et al 2018). This effect could be seen up to ~190 m away from the ship. Irradiance increased from <0.01 m Wm^{-2} (~5×10^{-9} mmol photons m^{-2} s^{-1}) away from the RV Helmer Hanssen to over 0.15 m Wm^{-2} (~7×10^{-7} mmol photons $m^{-2}s^{-1}$) in its vicinity. Additionally, it is showed that diffuse sky light irradiance increased by 15 times when the Jetyak departed or returned to the research vessel (RV) (that is, at the beginning and end of all deployments) (Ludvigsen et al 2018). Each time the ASV Jetyak approached the RV Helmer Hanssen, the acoustic signal showed that zooplankton reacted by avoiding the artificial light field of the vessel (that is, the acoustic backscatter decreased) rather than slowly descending as when ambient irradiance was changing gradually.

6.2.3 Seabed collector

Several seabed nodule collector technologies have been tested. Both GSR and NORI tested collectors in 2021 and 2022 respectively. While lights are not strictly needed for mining operations (e.g., sonar could be used instead to navigate), it is useful for monitoring and, in the future, for subsea equipment connections and maintenance.

6.2.4 Remotely Operated and Autonomous Underwater Vehicles

During DSM operations remotely operated and autonomous underwater vehicles will be deployed in the water column and near the seabed to obtain imagery and aid in collector maintenance and the use of these induces variant or different sources of ALAN. This use of various ALAN sources will generate different light emissions with wavelengths equally different that will propagate in the deep-sea environment in the mining site. Even considering the attenuation principle of the light wave with the distance, the cumulative effects from those remote and autonomous vehicles cannot be neglected.

6.3 Biological responses to light

Surface artificial light (particularly at night) is known to cause behavioural changes in marine organisms, often related to timing and rhythm of activities, such as predation patterns, spawning synchronization, inhibition of vertical migration patterns (Bregazi and Naylor, 1972; Marangoni et al, 2022; Navarro-Barranco & Hughes, 2015; Torres et al., 2020), as well as changes in life history traits and masking of navigational cues (e.g. for seabirds and sea turtles). Effects are related to spectral nature and sensitivities. ALAN has also been shown to affect the reproduction, activity and predation of fish (Fobert et al 2019, Bolton et al 2017, Yeung et al 2025).

Increase of artificial light levels has been identified as a threat for seabirds and, particularly, petrels (Dias et al., 2019; Rodríguez et al., 2019). Many seabirds forage by diving in the water column, where the light spectrum changes rapidly with depth (Regular et al., 2011). Seabirds must adapt to rapid changes in intensity and spectra of light. Increase of underwater light levels could enhance the foraging of pursuit-diving visual predator seabirds, such as murres and penguins (Cannell & Cullen, 1998; Elliott & Gaston, 2015; Regular et al., 2011). Artificial lights can also concentrate seabird prey resources.

Knowledge on light-induced mortality at sea is quite limited (Gjerdrum et al., 2021; Glass & Ryan, 2013; Merkel & Johansen, 2011; Ronconi et al., 2015; Ryan et al., 2021). Recent research has shown, however, that light pollution can increase mortality of fish through increased predation. It has also been shown that ALAN functions as an ecological trap for coral reef fish by increasing the settlement of wild fish while decreasing survival (Schligler et al 2026).

Underwater light influences pelagic organisms in relation to behaviour such as prey availability, predation success, daily vertical migration as well as influencing initiation and magnitude of phytoplankton blooms. How artificial light affects different organisms vary across species, for example some pelagic species are known to be attracted to light and others are known to avoid it (references in Marangoni et al 2022).

Many marine species respond, negatively or positively, to light across their life-stages. Small fishes, invertebrates and/or plankton can move towards light sources, through positive phototaxis, disorientation or curiosity, while larger fishes and invertebrates from higher trophic levels can be attracted to the light itself, or by the abundance of prey around the light source. Effects are, often, however, taxon-specific and can vary with the intensity, duration and type of light (i.e. wavelength).

In the marine environment, ALAN can act as ecological traps. For example, through the attraction and the increasing of the abundance of amphipods - the dominant taxa within emergent zooplankton (Navarro-Barranco & Hughes 2015), which is an important food source for nocturnal planktivorous predators (e.g. corals, fishes) (Aldregde & King 1985, Fobert et al 2023). Furthermore, the larval stages of many sessile animals (e.g. barnacles, oysters) are sensitive to light, meaning ALAN is likely to disrupt settlement cues, ultimately modifying the distribution of key taxa (Manriquez et al 2021, Kim et al 2021). ALAN can also alter the settlement and photosynthetic activity (Maggi & Bendetti-Cecchi 2018,) as well as herbivory rates (Yeung et al 2025, Trethewy et al 2023), with probable consequences for local primary productivity and other ecosystem functions (see e.g. Fobert et al 2023).

Our knowledge on the effects of different types of light (i.e. wavelengths or spectra) on marine organisms is still very limited. But relatively recent research has shown that different lights can have different effects. For example, exposure to green light has increased gaping activity of the blue mussel *Mytilus edulis*, but white and red-light spectra caused reduced activity (Christoforou et al., 2023). Green and red-light spectra can promote phytoplankton growth by favouring bloom-forming diatom species (Diamantopoulou et al., 2021), while blue wavelengths, such as those emitted by broad-spectrum white Light-Emitting Diodes (LED), causes the highest suppression of nocturnal melatonin in taxa like birds (e.g., *Parus major*), insects (e.g., *Teleogryllus commodus*), fish (e.g., *Perca fluviatilis*), and mammals (e.g., *Macropus eugenii*).

A recent study comparing the effects of High-Pressure Sodium (HPS) lamps and warm and cool white Light- Emitting Diodes (LEDs) on the activity, feeding behavior and growth of the isopod *Tylos spinulosus* found that all three types of light had impacts on the animals' locomotor activity and feeding behavior, with cool-white LEDs showing the most severe effects on both biological traits (Quintanilla-Ahumanda et al 2024). Growth of isopods was not, however, affected by the light spectra, potentially due to the short-term length of the experiment.

6.4 Existing thresholds and examples from other industries

Current regulatory framework is complex, diverse, and lacks coherence and often focus on energy efficiency, often neglecting environmental impacts (Yakushina 2025). In Australia, for example, light pollution is not regulated under the Protection of the Environment Operations Act 1997, the main pollution law in New South Wales. Although guidelines exist, such as the National Light Pollution Guidelines for Wildlife (DCCEEW 2023), these are limited, largely focused on vertebrates and are not legally enforceable.

Within the European Union, light is a recognised pollutant under Descriptor 11 of the Marine Strategy Directive (Directive 2008/56/EC 2008). The lack of sufficient scientific evidence to define criteria of Good Environmental Status for underwater ALAN have however prohibited translation of ALAN targets and management into the national legislatures of member States. It leaves ALAN unrecognised by environmental agencies and international governance structures including the OSPAR Commission, Helsinki Commission (HELCOM) and The Barcelona Convention, where action plans and monitoring programmes for underwater noise pollution are now common (OSPAR 2025; HELCOM 2021).

A renewed focus on the management of light pollution across both terrestrial and aquatic ecosystems has emerged in recent years, evidenced by the development of key policy briefs, guidance documents, and management frameworks produced by the European Commission (European Commission 2023), the International Union for the Conservation of Nature (Welch et al. 2024), the Convention on Migratory Species (Convention on Migratory Species 2024), Fisheries and Oceans Canada (Bundy et al. 2025), the Australian Government (DCCEEW 2023), the New Zealand Government (Lohrer et al. 2024), and the Great Barrier Reef Marine Park Authority (Great Barrier Reef Marine Park Authority 2024). Several additional countries (Germany, Croatia, France, Mexico and Japan) have now introduced significant legislative improvements to address light pollution although not always in marine contexts (Yakushina 2025).

Attention to light pollution has taken three main directions: (1) promoting recognition of light pollution as a form of environmental pollution; (2) setting targets for its reduction; and (3) supporting the immediate action for reduction of ALAN levels and mitigation of its impacts. The Bonn Convention in its Resolution 13.5 recognised ALAN as an emerging stressor for biodiversity and encouraged countries to implement solutions to reduce its impacts to meet human comfort and ensure environmental protection (UNEP/CMS/Resolution 13.5, 2020).

Light impacts from deep-sea mining can be divided into two categories:

- Those with science-based regulation/policies, namely surface light related to navigation and signalling.
- Those that are novel, and without current regulation, namely underwater light sources and additional light from surface technical operations.

Light impacts are likely to relate to a function of the attenuation factor at the surface as well as in the water column and the seabed where the nodules are lying. This impact will also depend on the cumulative effects of different mining ships from contractors mining operations sites.

6.5 Development of threshold values, including early warning and uncertainty levels

There are no receptor specific guidelines or regulation regarding light emissions nor is there a globally recognized standard method, or agreed unit of measurement, for monitoring biologically active light (Barentine, 2019). An indicative value of 0.1µW m-2 s-1 white light has been adopted for biologically significant marine light pollution in several scientific studies (Davies et al. 2020; Smyth et al. 2021). This indicative scientific value is derived from the light sensitivity of *Calanus* copepods (Batnes et al., 2013), one of the lightest sensitive marine animals so far quantified. The number of marine taxa for which those indicative values have been quantified is too small so this indicative value still far from representative (Davies and Smyth, 2025).

To apply the *Calanus* value of light sensitivity is therefore applying the precautionary principle. Additional caution should however be considered when taking a light sensitivity value response from a photic zone species responding to moonlight and sunlight in an aphotic zone context and applying it in an aphotic zone context where the primary light source is bioluminescence. Given the extraordinarily low light levels in the aphotic zone, it seems likely that at least some species will have a greater sensitivity to light from mining operations suggesting that irradiances below $0.1\mu W\ m^{-2}\ s^{-1}$ could have greater than anticipated impacts.

So far, formal thresholds of impact in marine ecosystems have not been defined and adopted by any policy framework. The 0.1 μW m-2 s-1 indicative value has proved to be a useful metric for quantifying the depth that ALAN can penetrate and still have biological impacts (Zc) (Smyth et al. 2021). This depth or distance-based metric is useful from a management perspective because it removes the need to quantify ALAN irradiance at multiple distances from a light source. The metric has recently been proposed as tool for quantifying Good Environmental Status of ALAN in pelagic ecosystems (Table 13, Davies et al. 2026).

Table 13 Proposed distance-based metric criteria for defining GES of ALAN in pelagic ecosystems based on the depth of biologically important light pollution, Zc. From Davies et al. (2026).

Distance-based metric (m)	Exposure risk category	Exposure risk score
$Zc = 0$	Nil	1
$0 < Zc \leq 1$	Low	2
$1 < Zc \leq 10$	Moderate	3
$10 < Zc$	High	4

While designed to measure the risk posed by ALAN based on its depth of penetration, this concept easily translates to distance horizontally from a seabed mining operation using ALAN, allowing Zc to be measured *in situ* or modelled such that halos of risk around a particular light source can be mapped in line with the zone of impact model. Alternatively, risk exposure scores could be calculated at different depth across the seabed area of a mining operation such that exposure risk can mapped and aggregate risk exposure scores calculated.

This framework has been used to quantify aggregate exposure risk in pelagic ecosystems across the regional seas of the European Union (Davies et al. 2026) and presents a potentially useful, intuitive and low-cost management tool that translates naturally into the DSM context

6.6 Identification of knowledge gaps and research priorities

Current knowledge of underwater light impacts are only available from a small number of habitats, none of which are in the deep sea. Few studies are available from contractors concerning light use in equipment tests. Further, threshold light sensitivities of deep-sea taxa remain unquantified, making an accurate determination of how much light is acceptable challenging. While thresholds of impact can be borrowed from species in the surface ocean to provide frameworks for measuring and managing impacts, for greater accuracy research should focus on:

- Measurements of the intensity and spectra of lights expected to be used in collector vehicles
- Quantifying threshold light intensities that elicit biological responses in deep sea taxa.
- Understanding of long-term (chronic) impacts as well as short-term impacts

7 General remarks for the development of environmental threshold values

The report reflects the state of scientific knowledge and current regulatory practices that can inform the establishment of Standards and guidelines on the development of environmental threshold values for seabed mining activities of polymetallic nodules.

Existing regulatory frameworks for other offshore industries often provide detailed guidance on approaches and concepts about how to derive and implement site-specific values and assess risks and effects, recognizing that the development of threshold values is an ongoing process. In order to establish thresholds as management tools, metrics of changes in environmental conditions must be set in an appropriate framework, consider environmental objectives as well as economic, social and political values, and meet legal requirements.

The IEG emphasizes that the development of quantitative environmental thresholds in the context of DSM must be derived within an integrated framework and adapted as operational and ecological data accumulate.

7.1 The Zone-of Impact model and ecological reference points

A two-component approach is proposed as a first step towards developing project-specific threshold values. The first element is the Zone of Impact model which accounts for the spatial distribution of impact at different levels of pressure along the gradient. The boundaries between zones are defined by the second element, Ecological Reference Points (ERPs), which correspond to measurable changes from impact on the ecosystem. This risk-based approach will inform the development of threshold metrics and indicators for the mitigation and monitoring of environmental impacts.

The report illustrates how the zone of impact models can be applied for the four individual pressures discussed by the IEG subgroups, using the available scientific knowledge and existing industry practices. Several approaches and metrics are currently available that can be used to determine pressure-specific ERPs, including hazardous concentration levels (HC) for metal toxicity and turbidity/sedimentation, auditory injury shifts and exposure risk scores for light pollution. However, there is some discrepancy between levels of these metrics (e.g. percentage of protection/ percentage affected) across different applications for specific pressures, associated with specific indicators and biological receptors. Translating ERPs into thresholds for the DSM context will need to consider the specific dynamics of deep-sea ecosystems, including the vulnerability and potential recovery of biological communities across the impact/risk gradient, taking into account environmental objectives and socio-economic values.

It is clear that the extent of the zones of impact, both horizontally and vertically, may differ for each pressure, and for other potential pressures that may be examined in future. Therefore, the IEG stresses that cumulative and potentially synergistic interactions among pressures and impacts need to be considered under specific conditions of the mining operations and local environments, as well as over time. The proposed Zones of Impact model provides a structured way to translate impacts along a gradient of pressures into operational management zones.

This allows the more sensitive ecological receptors or spatially extensive pressure to drive the application of ERPs as regulatory boundaries. In this framework, ERPs are derived for each pressure separately, but can then either be treated separately to derive threshold values, or the suite of ERPs across various pressures can be considered in an integrated way to derive a smaller number of management zones based on precaution or taking the most conservative zones of impact. The framework can be adapted to a variety of management approaches.

7.1.1 Cumulative impacts

Environmental impacts occur along a gradient of pressure values, which depend upon the nature and spatial-temporal extent of the pressures, as well as on the local environmental conditions. These factors affect all pressures considered here, as illustrated with the following examples.

Interaction between toxicity and turbidity/sedimentation in sediment plumes

Toxic metals can be carried in sediment particles which act as the physical vector for their dispersal. It is currently unknown how the physical sediment and associated chemical plume compare in terms of spatial and temporal extent. If an assessment of these factors indicates that sedimentation effects extend farther from the mine site than metal-related toxicity, it may be appropriate to delineate Zones of Impact based primarily on sedimentation or turbidity thresholds rather than on metal concentrations alone. Conversely, the addition of chemicals in the sediment plume may increase the impact of the sediment at lower particle concentrations.

Understanding the cumulative and potentially synergistic effects of these pressures highlights the importance of bulk toxicity tests (see chapter 3). Such tests can help determine how many dilutions are required to reach a defined water quality level for metals *vs* a defined water quality level for sediment – the one requiring the most dilutions and the greatest distance to reach background levels should be the one that defines the impact zones to ensure a conservative approach is taken.

Interaction between acoustic and light fields and sediment plumes

Similarly, it is important to understand the spatial and temporal extent of noise and light effects, especially from mining collectors and monitoring systems, and how these interact with the sediment/chemical plumes.

Empirical data is necessary to better understand and be able to predict the combined effects of light pollution and other stressors because individual stressors may have species-specific impacts, can impact different sensory systems (e.g. visual (light pollution), auditory (noise pollution) and olfactory (chemical pollution)) within individuals, and can have interactive, additive or antagonistic effects.

In addition to experimental work, modelling tools will be critical for estimating vertical and horizontal distances for defining the zones of impact and identifying adequate indicators for mitigating and monitoring the pressures and ecological responses.

7.1.2 Indicators

Indicators that are relevant to the individual pressures were discussed in chapters 3, respectively. However, it can often be difficult to directly attribute a change in higher-level community or ecosystem structure and function to a single pressure, especially when there may be multiple pressures causing cumulative effects. Hence, it can also be useful to consider indicators that can detect overall system-level changes.

Hiddink et al. (2023) proposed a method for categorizing five indicators into eight impact states for human activities in general, rather than for specific industries.

- **Indicators**: species richness, community abundance and biomass, abundance and biomass for long-lived biota, time to recover to the range of natural variation, and ecosystem process.
- **Impact states**: undisturbed, indistinguishable from undisturbed, process continues, maximum yield, loss of sensitive species or ecosystem processes, key species or ecosystem processes lost, unable to recover, and ecosystem lost.

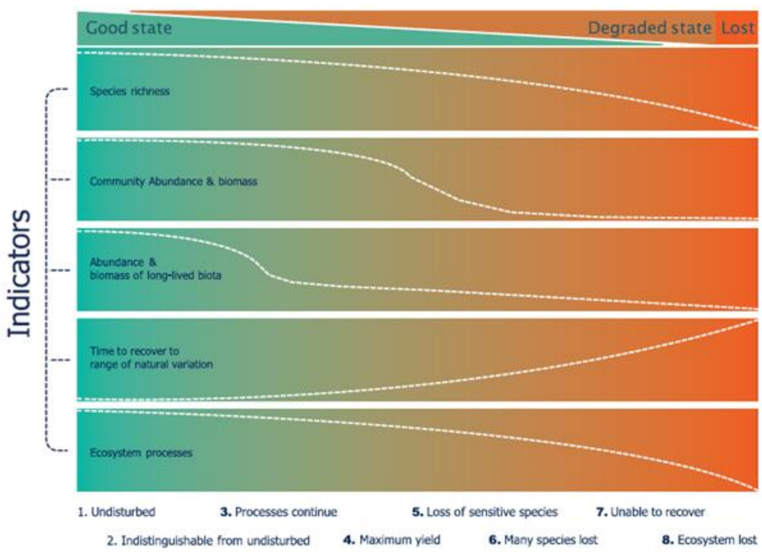

Figure 12 Graph of the expected conceptual changes in indictor levels as an ecosystem shifts from undisturbed through increasing pressure levels (Hiddink et al 2023)

When using communities as indicators, they should ideally cover a wide range of taxa, functional groups, size categories, and ecological characteristics, while also expressing their abundance and sensitivity/vulnerability. Even if all these aspects cannot be covered, a certain degree of representativeness is required, and an adequate number of data sets is needed to ensure statistical power. The selection will be habitat- and site-specific (Simon-Lledó et al., 2023) and must be justified in Environmental Impact Assessments (EIAs) and Statements (EISs). Candidate groups for benthic indicators include:

- **Biomass dominants** within local communities (e.g. sponges, holothurians, brittle stars, anemones, Nematoda)
- **Key functional taxa** that maintain ecosystem services (e.g. holothurians)
- **Taxa suitable for caging and monitoring** during operations (e.g. amphipods)
- **Sensitive taxa** such as filter feeders (e.g. corals, sponges, anemones)

Molecular approaches like transcriptomics and other 'omic' techniques are also effective for evaluating various multiple taxonomic groups and ensuring sufficient sample sizes. However, it is currently difficult to ensure a consistent level of accuracy for these analyses across different laboratories and there remain issues of data interpretation that must be resolved. Other potential ecological indicators can measure aspects of ecosystem function, such as sediment community oxygen consumption (SCOC) rates and oxygen microprofiles, which are linked to bacterial consumption and production.

7.2 Key limitations and future directions

This report focused on abyssal plain environment where polymetallic nodules occur, which is potentially more homogeneous than habitats associated with sulphides in mid-ocean ridges or crust resources in seamounts. Specific considerations will be required to assess impacts from sulphide and crust mining operations, including differences in the nature and extent of mining operations and impacts, and hence spatial scales of zones of impact. While less is currently known about the actual mining technology to be applied with these resources, the approach and methodology here developed can be applied to the other resources and habitats in due course.

The toxicity and turbidity groups focussed on benthic pressures resulting from the direct mining disturbance on the seabed. While acknowledging that turbidity and toxicity impacts will also apply to any discharge of processing waters (i.e. discharge plumes), there is very little information about the nature of such plumes, and their impacts on the pelagic ecosystem. In the case of noise, major limitations include understanding the impacts in midwater and benthic communities, especially invertebrates, caused by vertical transport system and mining collectors for which the noise data is very limited. Understanding the impacts of artificial light in the marine environment remains a novel field, more so at depths below natural light penetration in the oceans.

Knowledge gained from equipment tests by contractors will be essential for understanding the levels of pressure from various types of mining operations. Similarly, experimental work by their scientific teams and other research institutes will be important for developing species sensitivity distributions for a wider range of taxa and pressure levels that will better reflect the type of exposure faunal communities will face. This needs to be complemented with physical models that can help predict the spatial and temporal extent of sediment plumes and attenuation curves of sound and light.

Collaborative research priorities for the coming years should include:

- Conducting bulk toxicity tests with site-specific sediments, elutriates, and return waters.
- Expanding experimental studies for generating species sensitivity curves that can directly inform specifications of ERPs.
- Developing monitoring programmes during and post impact aiming to determine chronic and sub-lethal effects and assess cumulative impacts of multiple stressors
- Include studies addressing impacts on microbial, macro-and meio-faunal communities in addition to megafauna.
- Standardizing methodologies for sampling, analysis, and reporting across contractors.

- Ensuring that all data collected is made accessible through ISA databases to facilitate transparency and comparability.

By focusing research and monitoring efforts on these priorities, the Authority in collaboration with contractors, as part of their EIA studies, and coordinated scientific initiatives will build the knowledge base needed to develop and refine thresholds, reduce uncertainty, and strengthen the protection of the marine environment.

8 Tables and Figures

8.1 List of Tables

8.2 List of Figures

9 References

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Annex 1 – Variability of metal concentrations

This annex provides additional information on metal concentrations measured in water samples collected in BGR, GSR and NORI contract areas.

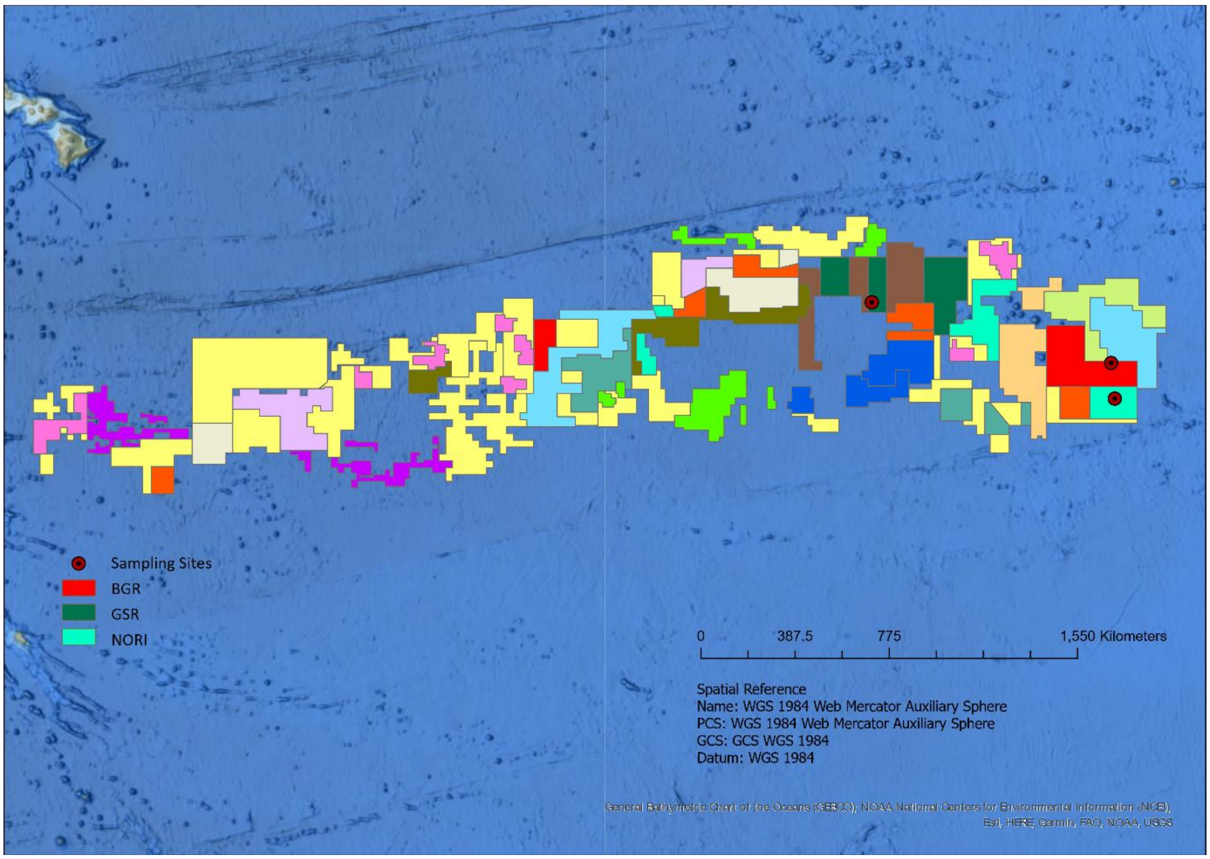

Figure 13 Location of samples obtained from BGR, GSR and NORI contract areas

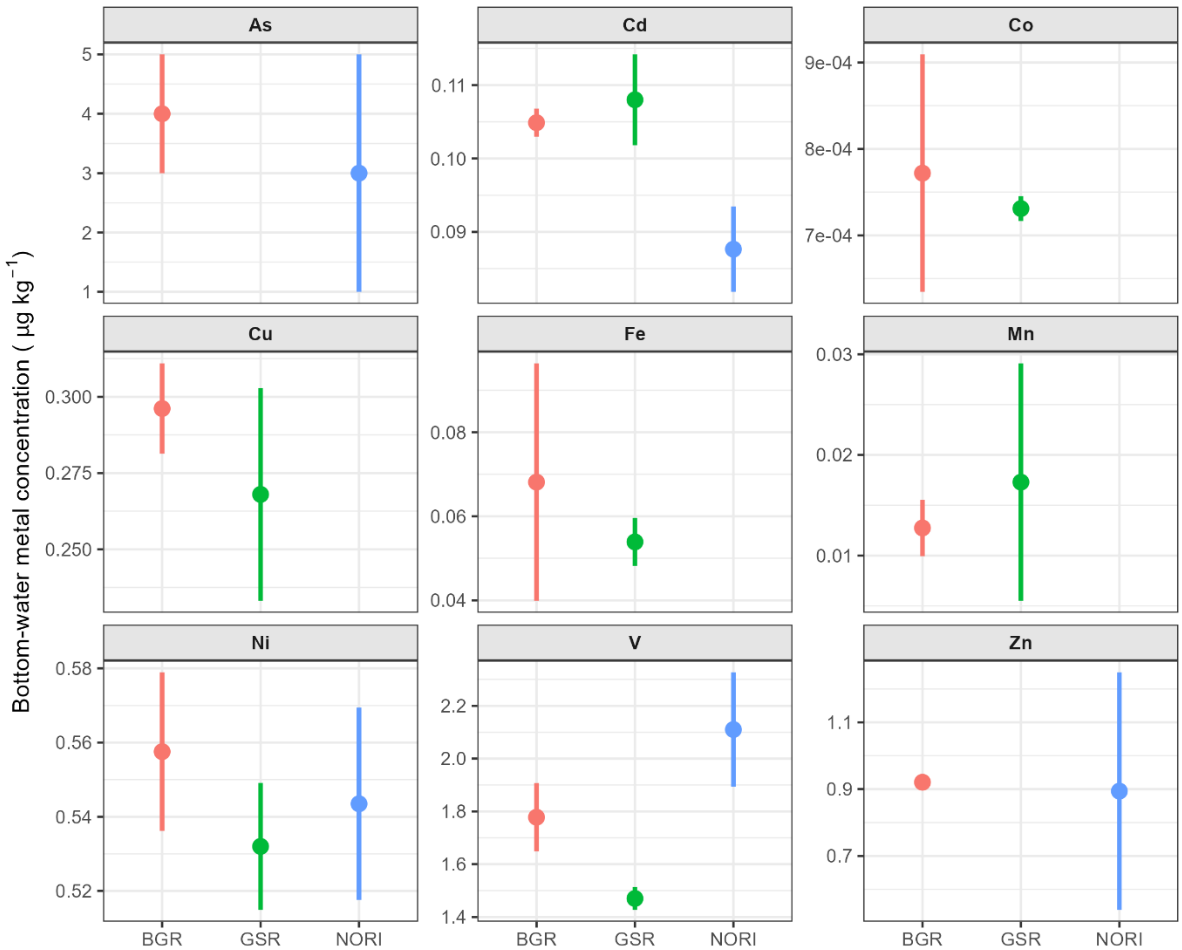

Figure 14 Bottom-water metal concentrations in the BGR (red; 5 m above the seafloor; filtered < 0.2 µm; n = 5), GSR (green; 5 m above the seafloor; filtered < 0.2 µm; n = 2) and NORI (blue; 50-200 m above the seafloor; unfiltered; n = 20) exploration contract areas in the CCZ. Dots denote average values and vertical lines indicate standard deviations. Only metals measured in at least two contract areas are shown. Mn and Pb concentrations from the NORI area were excluded because they were derived from unfiltered samples and therefore include particulate-bound metals. Given the strong particle reactivity of Mn and Pb in deep-sea environments, such data are not directly comparable to the filtered (<0.2 µm) pore-water concentrations. Data from the BGR and GSR contract areas are from Schmidt et al., (unpublished) and data from the NORI contract area were compiled from the DeepData database.

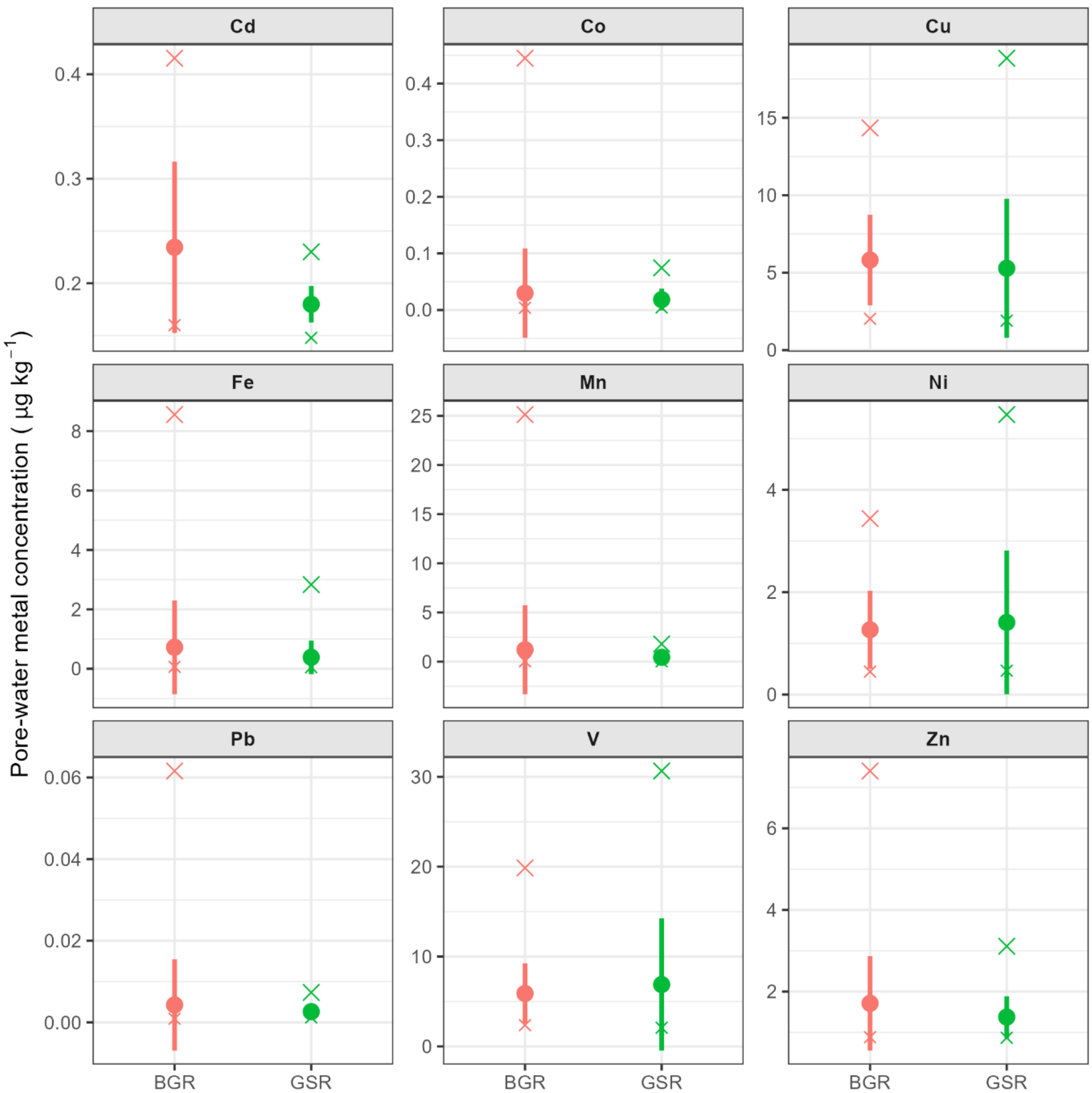

Figure 15 Sediment pore-water metal concentrations in the BGR (red) and GSR (green) exploration contract areas in the CCZ. Data are derived from multicorer samples (0-5 cm sediment depth, sampled at 1-cm intervals; n = 29 per metal for the BGR area and n = 24-25 per metal for the GSR area) collected in 2021 and 2022 (Schmidt et al., unpublished). Dots, vertical lines, and crosses denote average values, standard deviations, and minimum–maximum ranges, respectively.

Annex 2 – Case study: Solwara 1 Project

This annex provides a practical example on the use of elutriate tests proposed under the environmental impact statement (EIS) of the Solwara 1 project for mining polymetallic sulphides. Further details can be found in the full EIS (Coffey, 2008).

1 Summary

The EIS for the Solwara 1 project aimed to ensure that discharge water from the dewatering plant would be diluted sufficiently to meet environmental standards. Specifically, the EIS calculated dilution factors necessary to comply with the Australian and New Zealand Environment and Conservation Council (ANZECC) guidelines.

In the case of the Solwara 1 EIS, a Mixing Zone Boundary (MZB) approach was used to define the boundary of impact expected from the return water plume (due to discharge from the ship-based dewatering plant). The MZB approach is similar to the Zone of Impact approach, except that there is just one boundary, which in the case of Solwara 1 was defined as the point at which 95% protection levels were met in terms of water quality.

It was determined that a 600-fold dilution was required to meet ANZECC/ARMCANZ (2000) water quality guidelines for dissolved metals (95% protection). Through hydrodynamic modeling, it was determined that this target would be achieved within 85 metres from the point of return water discharge (discharge from the dewatering plant).

2 Mineral Reactivity and Elutriate Tests

Elutriate tests were conducted, which entailed using samples of representative run-of-mine materials obtained from the seafloor of Solwara 1, crushed to 25-mm diameter chips. Note that prior to this test the effect of particle size was investigated, with the following size ranges tested: 4-30 mm, 1-4 mm, 0.25-1.0 mm, 0.063-0.25 mm and <0.063 mm. It was found that metal release rates from one size fraction were not consistently greater than others. Effect of total suspended solids concentration, the effect of pH, time and temperature were also examined. It was found total suspended solids (TSS) and the resuspension time had the greatest effect on metal concentrations in the elutriate waters.

The first round of repeat elutriate tests was carried out at 6°C to investigate the effect that the holding time onboard the surface vessel may have on the material. Under these conditions, the metal requiring the most dilutions to meet ANZECC/ARMCANZ (2000) guidelines was zinc, which would require a 300-fold dilution to achieve 95% protection levels.

A second round of repeat elutriate tests was carried out to investigate the possible effects that temperature change has on contaminant release from the material. Separate tests were carried out at 12 and 24°C over a period of 180 minutes. Results showed that the metal controlling the number of dilutions required to meet ANZECC/ARMCANZ (2000) guidelines was, again, zinc. At these higher temperatures, to meet 95% protection levels, a 600-fold dilution would be required.

The reactivity and elutriate tests were undertaken in part to understand the risks of reactive changes taking place in the ore material when at the surface, and in part to assess the potential impacts if discharges from the dewatering plant were to occur at depths in the water column where these materials do not occur naturally.

However, the Solwara 1 project proposed to discharge the return water close to the seafloor in the region of its source, with an aim to reduce impacts to mid-water quality, given there is already an elevation of metal concentrations from natural sources closer to the seafloor.

Hydrodynamic modelling of the return water discharge showed that a 600-fold dilution – required to meet ANZECC/ARMCANZ (2000) 95% protection limits – would be achieved within 85 m of the point of discharge.

It is important to be mindful that the approach used to set a MZB limit to a zone of impact is highly dependent on assumptions used.

3 Suspended Sediment and Plume Formation

The ANZECC/ARMCANZ (2000) target for total suspended solids (TSS) is 1.2 mg/l (note that baseline water column measurements at Solwara 1 location show a background range of 0.1 to 6.6 mg/l and maximum TSS concentrations of 14 mg/l.

Based on a return water discharge rate of 1,000 m^3/h and an estimated 5,000 mg/l maximum fine sediment residual in this discharge, the dilutions required to meet the ANZECC/ARMCANZ (2000) target are approximately 4,200.

For the purposes of the impact assessment, a conservative dilution of 5,000 was adopted for return water discharge as being necessary to meet the ANZECC/ARMCANZ (2000) guidelines for all contaminants discharged to the environment in the return water stream.

Stochastic hydrodynamic modelling was undertaken to estimate the behaviour and fate of the return water and associated material <8 µm post-discharge (<8 µm refers to the final filtration of the return water before it is released to the deep-sea). Based on engineering data, two discharge temperature scenarios were modelled, namely a discharge temperature of 5.8°C and 11.4°C.

Modelling results showed that:

- For both discharge temperatures, a subsurface plume would be formed which will initially exceed the ANZECC/ARMCANZ (2000) TSS target of 1.2 mg/L.
- Plumes will rapidly dissipate and achieve 5,000 dilutions, at which time TSS concentrations will meet the ANZECC/ARMCANZ (2000) TSS target.
- During the time it takes for 5,000 dilutions to occur, plumes will stay between 1,300 and 1,475 m water depth (i.e., below the plume created by a nearby active subsea volcano)

Table 14 and Figure 16 show the probability of the return water plume exceeding the ANZECC/ARMCANZ (2000) TSS target a certain distance (and associated area) from the point of discharge over a 12-month period.

Table 14 Plume concentrations probability

Probability of Exceedance (%)	Area (km^2) from Point of Discharge	Distance from Point of Discharge (km)	Area (km^2) from Point of Discharge	Distance from Point of Discharge (km)
	Discharge Temperature = 5.8°C		**Discharge Temperature = 11.4°C**	
0-10	11.6	4.2	9.71	5.0
10-20	3.78	2.5	2.49	1.9
20-30	2.33	1.7	1.50	1.2
30-40	1.61	1.2	1.05	0.95
40-50	1.11	1.0	0.76	0.81
50-60	0.81	0.9	0.58	0.67
60-70	0.60	0.7	0.43	0.58
70-80	0.42	0.6	0.29	0.44
80-100	0.27	0.41	0.19	0.36

On average (i.e., for 183 days per year), at a discharge temperature of 5.8°C, it was modeled that sediment plumes would not extend more than 900 m beyond the point of discharge (and cover an area of 0.81 km^2) before meeting the target TSS concentration.

The maximum distance plumes will travel before meeting the TSS target was modelled to be 4.2 km, at which point it will cover an area of 11.6 km^2; and this is expected to occur less than 37 days per year.

Figure 16 shows that plumes will not affect North Su (active subsea volcano) or South Su (proposed set-aside and reference area for the Solwara 1 project).

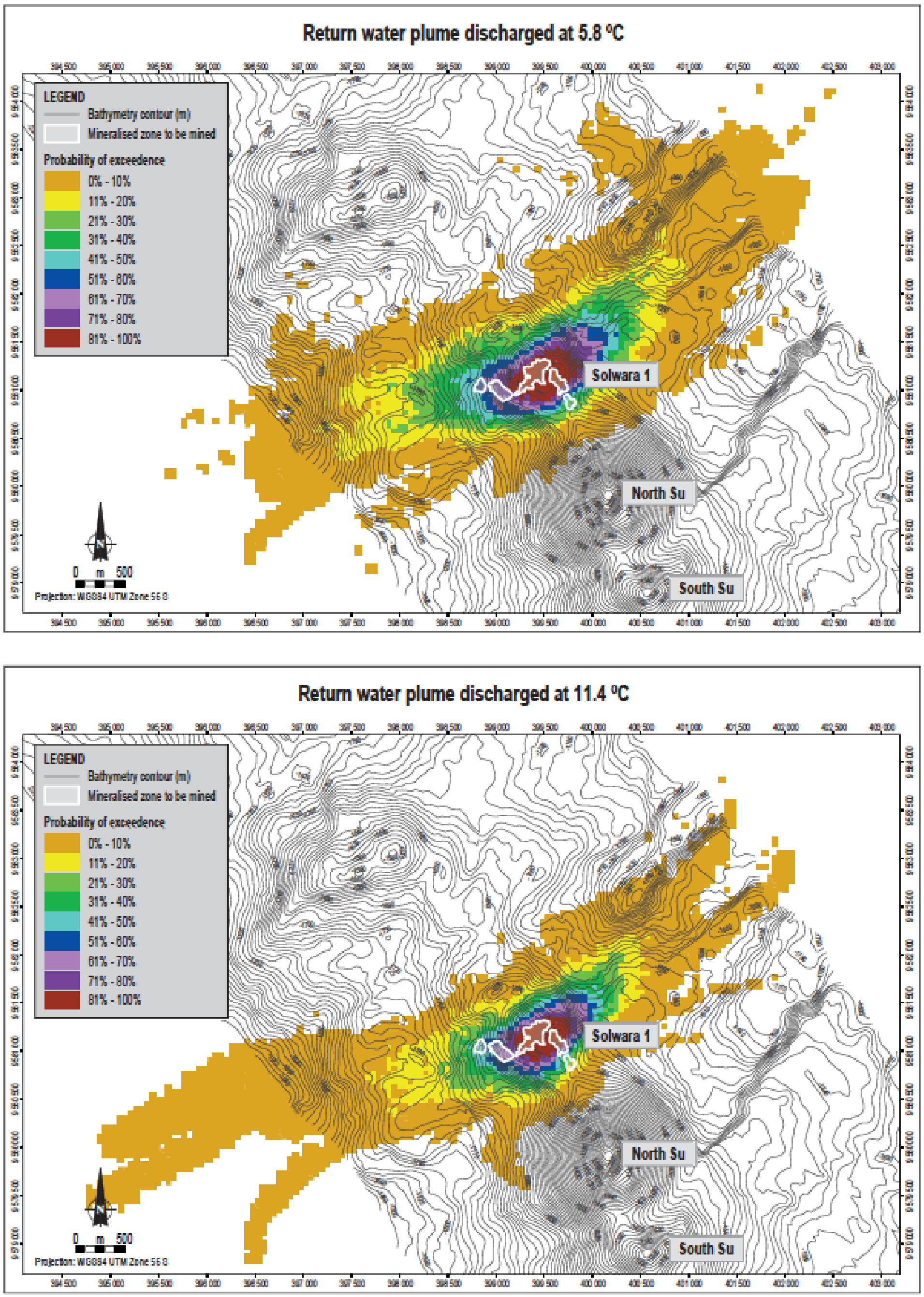

Figure 16 Probability of return water sediment plume exceeding ARZECC/ARMCANZ (2000) suspended solids target at Solwara 1, with a return water discharge at 5.8°C (top) and 11.4°C (bottom).

4 Solwara 1 Toxicity Tests (Elutriates)

Toxicity of initial elutriate test waters exposed to ore was assessed to understand the characteristics of the material and the potential impacts if return water discharges were to occur at shallower depths in the water column where organisms are not naturally exposed to (or tolerant of) elevated metals.

The toxicity of the elutriate waters was investigated using tests that determine inhibition of growth rate of the alga *Nitzschia closterium* and inhibition of mobility of the marine copepod *Acartia sinjiensis*. The elutriate test water was prepared with a high solid:water ratio to provide high solids load and sufficient test water. Metal concentrations measured in the elutriate waters prepared for the toxicity tests were higher than those measured in the elutriate tests for the same sediment material.

Based on the metal concentrations measured in the elutriate waters prepared for the toxicity tests, copper requires the most dilutions at 4,000 to meet 95% protection levels of the ANZECC/ARMCANZ (2000) water quality guidelines.

The toxicity assessment used surrogate species, as no tests using local species from Solwara 1 were available or practicable, i.e., animals living at Solwara 1 do not survive for very long under conditions found at the surface. The philosophy of using surrogate species is that it is expected that species with similar exposure pathways and similar sensitivity will exist at the local sites. It was recognised that that may not be the case, however, as species that exist at Solwara 1 have both differing exposure pathways and sensitivity to metals.

In the metal-enriched sediments and waters surrounding the active chimneys, it is likely that these vent-dependent species have specialised behaviour (e.g., chemotrophic feeding) adapted for the local conditions. Nevertheless, the tests were undertaken to provide some context of the likely toxicity that would be expected for typically used shallow water test organisms exposed to such water quality.

The undiluted elutriate waters prepared from the cold sediment and crushed active and weathered chimney mineral samples were found to be toxic to both the algae and copepods. Dilutions of up to 700 times would be required to result in no toxicity from the elutriate waters to these two species. These results are expected to be quite conservative for a number of reasons. They are indicative of responses of shallow water species, which will not come into contact or be exposed to such elutriate waters during normal operating conditions and are not considered to be relevant to the vent-dependent species, which are naturally exposed (and potentially more tolerant) to higher metal concentrations.

Annex 3 – Case study: Project for Monitoring the Underwater Acoustic Landscape of the Santos Basin (PMPAS-BS)

1 Introduction

PMPAS-BS has been implemented in four-year cycles, with the first cycle taking that started November 2015 and lasted until December 2021. During this period, monitoring involved data collection through various tools such as gliders, free-drifting acoustic profilers, and fixed underwater observatories, in addition to acoustic propagation modeling. The second cycle, which began in 2022, enhanced the sampling effort and continued with acoustic modeling.

The study area covers approximately 251,000 km², including both the coastal and oceanic regions of the Santos Basin. The project's main concern is to identify and monitor anthropogenic noise sources, such as oil exploration activities and vessel traffic, which can negatively impact marine life.

2 Measurement Conditions

Acoustic measurements in the PMPAS-BS are conducted using equipment installed at strategic points and mobile devices like gliders. Measurement conditions involve the continuous and pulsed collection of acoustic data, focusing on the 63 Hz and 125 Hz frequency bands, which are particularly sensitive to anthropogenic noise, such as that generated by vessels and exploration activities. These measurements are carried out at different depths and regions of the basin, including areas with high exploration activity, navigation routes, and more remote and older regions.

The gliders and acoustic profilers capture data along their planned paths, while instrumented mooring lines (FA) and underwater observatories (OS) conduct measurements at fixed points (Figure 1). The continuous recordings made by the gliders cover long periods, allowing for detailed analysis of the acoustic conditions over time.

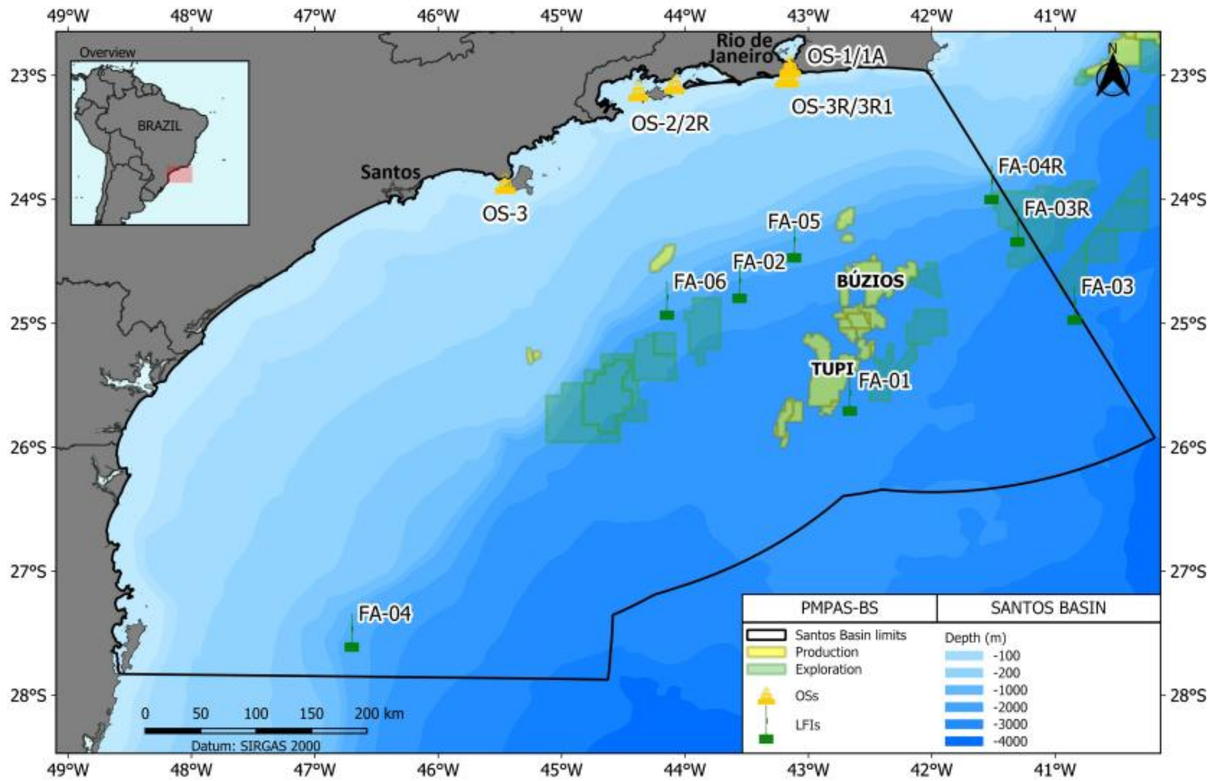

Figure 17 Map of Santos Basin with the positions of PETROBRAS O&G production and exploratory blocks (colored regions), the position of 6 instrumented oceanic mooring lines FAs (green marks) and the 3 coastal underwater observatories OSs (yellow triangles). Some measurement stations were repositioned during the 1st cycle (FA-03 to FA-03R; FA-04 to FA-04R; OS1 to OS1A; OS2 to OS2R; OS-3R then to OS-3R to OS-3R1). The black line delimits the geographical limits of the Santos Basin. Tupi and Buzios are major oil production fields. From Lima et.al 2024.

3 Monitoring Methods

The project adopts a robust approach to monitoring the submarine soundscape, divided into three main components:

1. Mobile Monitoring: This includes the use of gliders and acoustic profilers to collect data while moving across the Santos Basin. These measurements provide information about the spatial and temporal variations in underwater noise levels. The data are used to create acoustic maps that indicate noise levels in different regions and frequency bands. Key monitoring areas, such as R1 (intense exploration activity), R2 (shipping route), and R3 and R4 (regions without exploration activity), have been identified. In the second monitoring cycle, the use of acoustic profilers was replaced by an increased number of gliders (Figure 18).

2. Fixed Coastal Monitoring: This involves installing underwater observatories in strategic locations, such as Guanabara Bay, Cagarras Islands, Ilha Grande, and the São Sebastião Channel. These observatories continuously record underwater noise data, allowing for the analysis of temporal and spatial variability in important coastal areas.

3. Fixed Oceanic Monitoring: Instrumented mooring lines are placed at fixed locations in the oceanic region of the basin. These lines continuously monitor noise levels in areas near oil exploration activities, shipping routes, as well as less impacted regions.

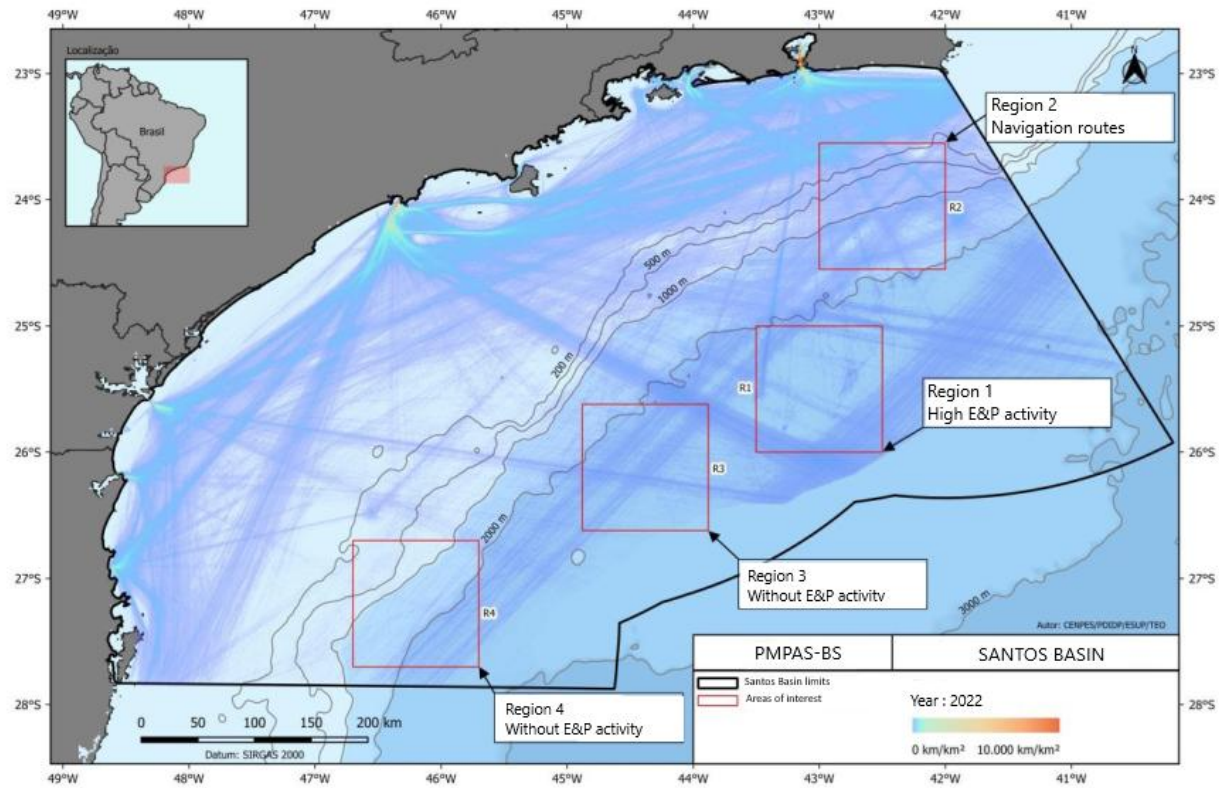

Figure 18 Regions of Interest and Navigation Density of Vessels Serving Petrobras. From: Project for Monitoring the Underwater Acoustic Landscape of the Santos Basin (PMPAS-BS) - 7th Technical Report: November 2015 to December 2022. Revision 00, August 2023. Single Volume. Rio de Janeiro: Petrobras, 2023.

4 Results and Conclusions

The PMPAS-BS project results indicate that the main sources of underwater noise are concentrated in areas of intense oil and gas exploration (R1 region) and along shipping routes (R2 region). Monitoring showed significant variation in noise levels across the Santos Basin, with some regions displaying higher noise levels due to human activities.

- Mobile Monitoring: Acoustic maps generated from glider data revealed that the R1 region, associated with intense oil exploration and production activities, exhibits the highest noise levels. The analyses also showed relative stability in noise levels over the years, although there was a slight increase in noise in R1 between 2021 and 2022, possibly due to specific seismic monitoring campaigns (airgun).

- Fixed Oceanic Monitoring: The instrumented mooring lines confirmed that areas near the R1 region are the noisiest. There was a trend of increasing noise overtime at one of the lines (FA02), located near a high-activity region, with an increase of 5 to 8 dB between 2017 and 2022. Depth analyses showed no significant differences in noise levels at different depths, although the 950-meter depth exhibited slightly higher levels, possibly due to its proximity to the SOFAR channel, which facilitates low-frequency noise propagation.

- Fixed Coastal Monitoring: The underwater observatories showed that Guanabara Bay is the noisiest region, while Ilha Grande and the São Sebastião Channel are the quietest. Measurements indicate that the soundscape in coastal areas is strongly influenced by various sound sources, including vessels, biological activities, and environmental conditions (e.g., waves, rain). These distinct acoustic signatures play a crucial role in the local ecology.

- Underwater Acoustic Modeling: The Submarine Acoustic Modeling System (SIMAS) was developed as part of PMPAS-BS to predict the soundscape using navigational, oceanographic, and geophysical data. The model showed good accuracy in reproducing the spatial variation patterns of noise in the Santos Basin, with a general trend of slightly underestimating measured noise levels. SIMAS is continually being refined and validated with field data to improve its precision.

5 Final Conclusions

The PMPAS-BS project has been crucial in understanding and mitigating the impacts of underwater noise generated by oil and gas exploration activities in the Santos Basin. The data collected and analyses conducted have provided a solid foundation for assessing environmental impacts and informing decision-making regarding environmental licensing and management in the region. Additionally, the project has contributed to the improvement of acoustic prediction models and to understanding the distribution and behavior of marine fauna in response to underwater noise.

Through the Terms of Reference CGPEG/DILI/IBAMA 002/13, IBAMA determined the scope, procedures, and criteria for the preparation of the Environmental Impact Study (EIA) and the respective Environmental Impact Report (RIMA), instruments that will support environmental licensing for Oil and Natural Gas Production and Flow Projects in the Santos Basin Pre-salt Pole (Figure 19).

Within this document, the Noise Level Characterization and Monitoring Project stand out, with the following text:

“A project should be implemented with the general objective of characterizing and monitoring the level of underwater noise (underwater soundscape) in the region of the Pre-salt in the Santos Basin. This project aims to establish a characterization of the current scenario of noise occurrence at different frequencies, which can serve as a comparative basis for evaluating the probable increase in noise levels associated with the development of the oil production chain in the Santos Basin, already expected, considering the project in question, the Integrated Projects for the Production and flow of oil and natural gas from the Pre-Salt e 1 and the prospects for E&P in the Santos Basin.

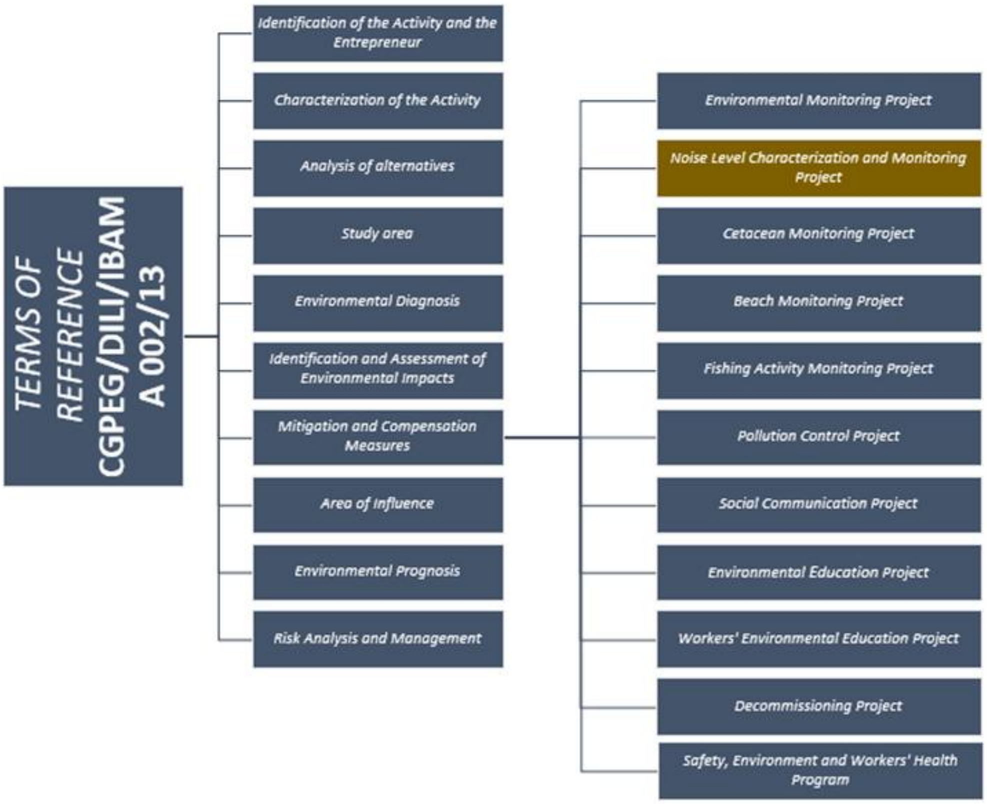

Figure 19 Framework for environmental assessment of the project under terms of reference CGPEG/DILI/IBAMA No. 002/13, including scope, procedures, and criteria for the preparation of the Environmental Impact Study (EIA) and the corresponding Environmental Impact Report (RIMA).

The characterization of the submarine soundscape will seek to understand the noise levels perceived by marine fauna and their seasonal variation, considering the routine and extraordinary activities that will take place in the region.

A methodology should be proposed for measuring noise levels at different frequencies, especially those that noticeably interfere with marine biota. The sampling grid should consider both the installation and operation of the UEPs the transit of vessels engaged in the project and other possible sources of emissions. The duration of the monitoring should be equivalent to the duration of the operation. However, different sampling efforts may be used for the characterization and monitoring stages.

Considering that there is no consensus in the technical literature on the best way to represent the acoustic pressure level for environmental impact assessment purposes, it is requested that at least the values in decibels (i) peak-to-peak, (ii) RMS and (iii) energy flow be considered."

Supplementary information

Supplementary information relevant to the production of the IEG report, which is not for stakeholder consultation, is available at: https://isa.org.jm/protection-of-the-marine-environment/environment-thresholds/

This includes the following documents:

A. *Report on the assessment of biological responses to suspended sediments in the deep ocean in support of environmental threshold development*

B. *Overview of underwater noise regulatory frameworks, guidelines and thresholds across different industries and jurisdictions*