The environmental impacts of a major mine tailings spill on coastal and marine environments

Lessons and recommendations for *ex post* impact assessment

L.E. Sánchez, F.A.R. Barbosa, M.C.W. Brito, P. May, C. Maroun, J. Renshaw, Y. Kakabadse

RIO DOCE PANEL THEMATIC REPORT NO. 5

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The economic, environmental and social context of the Rio Doce watershed is dynamic and rapidly changing. The Rio Doce Panel has prepared this report with the best publicly available information at the time of its writing, and acknowledges that new studies and information are emerging that will shed further light on the restoration effort.

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Acronyms

IA	Impact Assessment
CIF	Comitê Interfederativo (Inter-Federative Committee)
CT	Câmaras Técnicas (Technical Chambers)
CT–Bio	Câmara Técnica de Conservação e Biodiversidade (Technical Chamber for Biodiversity Conservation)
ECLAC	UN Economic Commission for Latin America and the Caribbean
EIA	Environmental impact assessment
ES	Espírito Santo
FBDS	Fundação Brasileira para o Desenvolvimento Sustentável (Brazilian Foundation for Sustainable Development)
FEST	Espírito Santo Technology Foundation
IBAMA	Instituto Brasileiro do Meio Ambiente (Brazilian Institute of the Environment and Renewable Natural Resources)
ICMM	International Council on Mining and Metals
IEMA	Instituto de Meio Ambiente e Recursos Hídricos (Institute of Environment and Water Resources)
ISO	International Organization for Standardization
IUCN	International Union for Conservation of Nature
MG	Minas Gerais
NOAA	National Oceanic and Atmospheric Administration
NRDA	Natural Resource Damage Assessment
PAH	polycyclic aromatic hydrocarbons
PMBA	Programa de Monitoramento da Biodiversidade Aquática (Program for Monitoring Aquatic Biodiversity).
RRDM	Rede Rio Doce Mar (Rio Doce Sea Network)
TTAC	Termo de Transação e Ajustamento de Conduta (Terms of Transaction and Conduct Adjustment)

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- Renova Foundation technical team, especially in Biodiversity, Tailings Management and Impact Curatorship areas, who participated intensively in the workshops and provided information and feedback.
- Representatives of the Technical Committee and Advisory Board of Renova Foundation.
- Specialists from Fundação Brasileira para o Desenvolvimento Sustentável (FBDS).
- Representatives of the Technical Chamber for Biodiversity Conservation of the Interfederative Committee.

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Foreword

Sixteen days after the Fundão Dam failed in Minas Gerais, the tailings sludge reached the mouth of the Rio Doce – dumping 16 million m^3 of mining tailings into the ocean. The mud, which had travelled almost 670 km, changed the colour of the sea and spread along the southeast coast of Brazil, reaching beaches north and south of the state of Espírito Santo. Despite the shocking images seen by the world and the large amounts of information and data produced over seven years, the environmental impacts on the estuary, ocean, and coastal zone, as well as on its biodiversity, still represent one of the main knowledge gaps for restoration work.

The Thematic Report that follows aims to close this gap. This report proposes a methodology to evaluate the impacts on the marine-coastal environment of the Rio Doce Basin. The Rio Doce Panel also describes how the produced knowledge complements the complex governance system of the watershed. This adds to the scientific studies and continuous monitoring of the affected environments, which continues to generate information about the state of the landscape's environmental health. It is important that an information and data management system be incorporated into this governance system so as to produce the necessary data for decision-making.

However, in addition to complex governance, other factors impede the progress of the socio-environmental programmes carried out by the Renova Foundation. These include lawsuits, as well as a divergence of methodologies and scientific approaches. The Panel demonstrates how these factors pose a risk to the advancement of restoration since they can generate different and conflicting conclusions. To avoid the risks described above, this report was prepared collaboratively with Renova technical teams and partners, and the methodology presented and discussed with different parties involved in restoration.

This final Thematic Report also reinforces recommendations by the Rio Doce Panel since 2018 that point out pathways to improve the understanding of the impacts caused by the Fundão failure, to integrate knowledge into the ongoing restoration process and – crucially – move towards substantial results.

These five years of the Panel's existence have continuously reinforced one message: Science and joint solutions are needed to generate knowledge and guide actions for a more prosperous, resilient, and sustainable future. Large corporations and governments need to adopt good practices based on this knowledge to recover from any similar future disasters – and more importantly, to prevent disasters like this from happening again.

Dr Bruno Oberle
Director General
IUCN, International Union of Conservation of Nature

Preface

Since its work began in 2017, the Rio Doce Panel has consistently spoken about the need for a more integrated understanding of the Fundão Dam disaster and its environmental impacts. When we are able to identify, describe, and classify these impacts, then we can also pinpoint the right measures to restore the region's ecosystems, including the river mouth.

Local communities used to depend heavily on these ecosystems for their water supply and food security. Although the tailings disaster polluted mangroves, lakes, wetlands, and ocean areas, local communities are still waiting for vital decisions to restore their ecosystems and to rebuild their livelihoods.

Not enough is known about the environmental impacts of this disaster. The complexity of information, size of territory, and lack of integrated data analysis has made it difficult to identify the extent and levels of damage. Enormous amounts of data has been collected, but we still know too little about how the tailings mud affected the aquatic environments and biodiversity within the estuarine and marine areas contiguous to the Rio Doce.

With this fifth and final Thematic Report, the Rio Doce Panel deepens its collaboration with the Renova Foundation, adding new value by developing this important methodology. Renova's technical teams had requested that the Panel build an approach for impact assessments of marine and coastal environments, and this methodology is the fruit of our combined new working modality.

This methodology was a joint effort between technical teams from Renova and external consultants, who collaborated in eight workshops, led by the Panel, from late 2021 through to mid-2022. The extent of participation and levels of engagement reflect the strong desire for guidance on impact assessments.

This report begins with a discussion of impact assessments used so far in the coastal area, pointing out the gaps and possible disagreements between the different methodologies. The paper also takes lessons learned from other disasters on the application of IA principles. It highlights the facts, first, that such uncertainties are not unusual and, second, that mitigation measures are therefore necessary.

This methodology envisages the use of data from monitoring and impact assessments, as well as from experiments or known correlations. It enables us to draw conclusions about causal relationships based on existing information.

Facts and sound analysis are vital to restoration of the Rio Doce basin. This report, together with its proposed methodology, helps the region to rebuild its health as well as its sustainable livelihoods.

Rio Doce Panel

Executive summary

Planning actions for *ex post* mitigation or remediation of environmental impacts in post-disaster situations requires adequate assessment and understanding of the disaster's environmental impacts. Good practice requires that such an assessment should: (i) follow systematic procedures; (ii) be grounded on scientific knowledge; and (iii) recognise the possibility of different interpretations regarding the significance of every impact.

Based on the volume of tailings releases and the distance they travelled, the Fundão Dam failure in southeast Brazil (Mariana, Minas Gerais state) was the largest ever environmental disaster in Brazil's mining industry, and one of the world's most serious. As they dispersed downriver, the tailings accumulated along the riverbanks and reached the Rio Doce estuary in the Eastern Brazilian Marine Ecoregion. The Rio Doce estuary has central importance for water and food provision to local communities who have been under major threat after this disaster. Six years later and despite massive effort to understand the impacts, there is still much that we do not know about the impacts of this disaster on the marine and coastal environments.

When the dam failed, the mining company and government agencies conducted rapid assessments. But while the government set up a five-year monitoring programme, it took almost a year after the disaster to issue official guidelines and another two years of negotiations and approvals before the data collection began. In this Thematic Report, the Rio Doce Panel looks at government mandated monitoring reports as well as peer-reviewed papers, most of which were authored by independent researchers, to assess our knowledge about the disaster's impacts on marine and coastal areas.

The Rio Doce Panel recommends:

(1) That the methodological approach described in this thematic report be used to consolidate the multiple existing assessments of the Fundão Dam failure's environmental impacts. This consolidation should use all applicable data and information, including scientific publications, results from the Aquatic Biodiversity Monitoring Programme, and other relevant technical reports. To facilitate communication, reports should be written in plain language and a non-technical summary should be prepared.

(2) That the Renova Foundation, preferably in agreement with CIF and relevant stakeholders, establish a database linked to an information management system that tracks any impacts identified. This database should be continuously updated, registering time-series data and any measurable outcomes from an impact mitigation plan. Follow-up would include periodic revisions of the list of impacts, as well as communication of actions and outcomes to all interested parties.

Mineral tailings sludge from the Fundão Dam, located in Bento Rodrigues, in the city of Mariana, Mina Gerais, which burst on 5 November 2015. The sludge reached the ocean in the Regencia district, in Linhares, Espírito Santo, after traveling along the Rio Doce bed for 16 days.

1. Introduction

In November 2015, the Fundão Dam collapsed near the town of Mariana, in Brazil's Minas Gerais state, releasing an estimated 39.2 million cubic meters[1] of mining waste, known as tailings. Over the next 17 days, sludge from the dam surged some 670 km down the Rio Doce, across the estuary and river mouth, and into the Atlantic (Figure 1), causing extensive environmental and human harm.

Immediately after the disaster and keen to put in place a thorough process of compensation and restoration, multiple federal and state government agencies signed an agreement in March 2016 with the mining company Samarco and its shareholders, Vale SA and BHP Billiton. The agreement, known as the Terms of Transaction and Conduct Adjustment (TTAC), set up 42 restoration and compensation programmes and created an independent organisation, funded by the companies, the Renova Foundation, to implement and manage these programmes[2]. A committee formed by representatives of the federal and state governments, as well as representatives of municipalities and affected people, the Inter-Federative Committee (CIF) was formed to oversee implementation of these programmes, with support from technical boards, the Technical Chambers (CTs), of which there were eventually 11.

The Rio Doce Panel, which was set up by IUCN in 2017, aims to provide the Renova Foundation and other stakeholders with independent technical and scientific advice pertaining to the restoration of ecosystems and livelihoods affected by the Fundão Dam failure. In this study, the Rio Doce Panel presents a methodological approach for assessing the impacts on the coastal and marine areas, a necessary step to guide decisions about restoration.

Extensive environmental monitoring programmes are currently underway in all affected environments of the Rio Doce estuary and adjacent coastal and marine areas. However, specific ecosystem restoration actions have not yet been determined by the CIF. In the meantime, a fishing ban remains in force at the river's mouth, affecting local livelihoods and food security, largely due to uncertainties regarding the cumulative and persistent impacts of the tailing's deposition in the coastal zone.

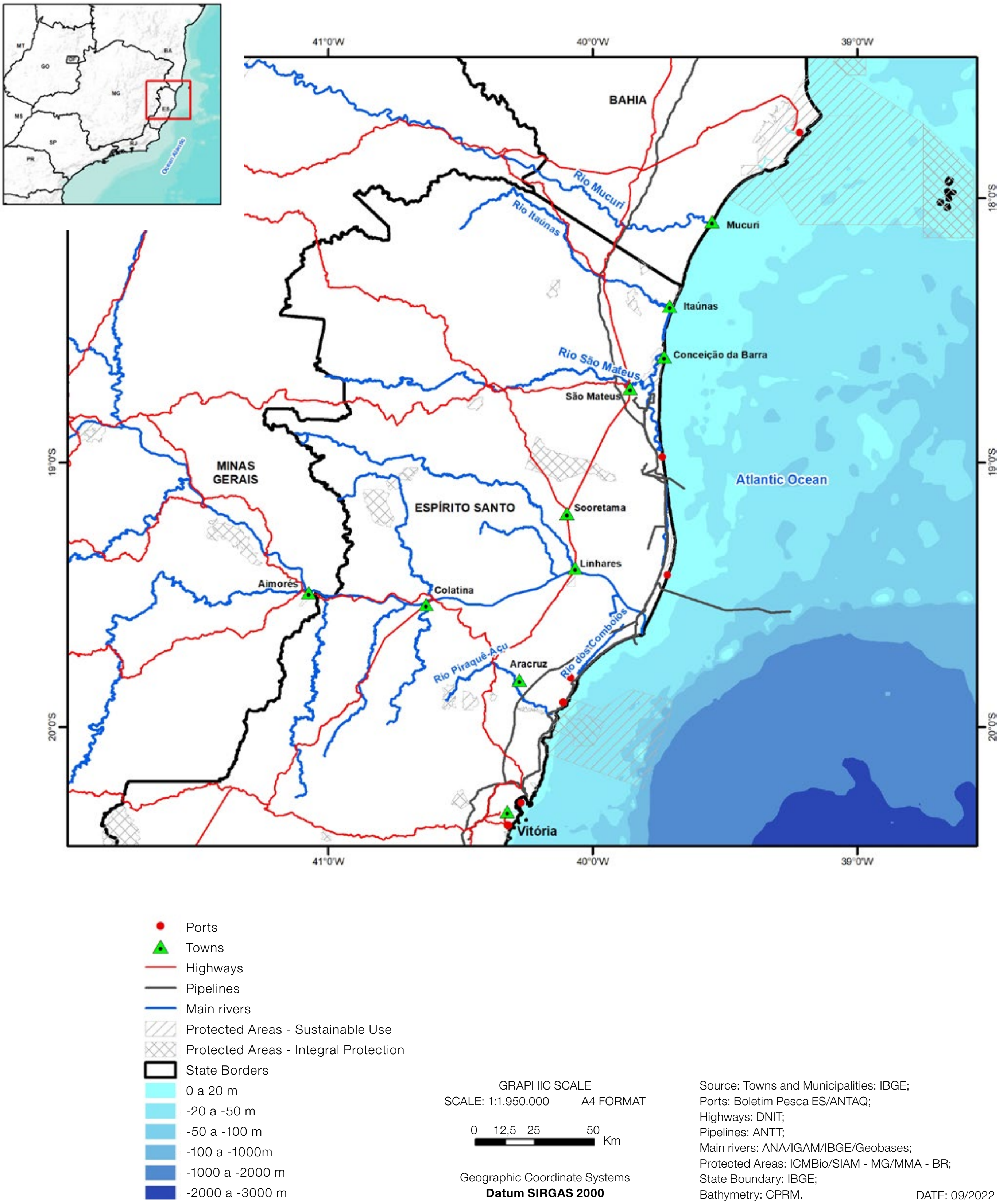
The Panel understands that restoration decisions should be guided by a comprehensive and evidence-based impact assessment. The field of *ex post* environmental impact assessments associated with disaster events such as the Fundão Dam break is less developed than *ex ante* assessments. Hence, this study builds on the Panel's prior recommendations for *ex post* impact assessments of the Fundão Dam failure (Sánchez et al., 2018).

After Sections 1 and 2, which introduce the report and its goals, Section 3 then describes the various institutions connected with the ongoing efforts to monitor, compensate, and restore the affected ecosystems and livelihoods. It highlights several difficulties, related to the complexities of the governance structure. Section 4 provides a brief background on monitoring and impact assessment initiatives in coastal and marine environments and highlights some of its methodological issues, including the prioritisation of environmental monitoring over impact assessments.

Section 5 briefly describes the different types of studies that have been done in the coastal and marine areas, underscoring the complexity of bringing the different strands of information together. Section 6 takes examples from other countries to see what lessons might be learnt from the environmental impact assessment of disasters there. Section 7 proposes an impact assessment methodology that considers the large volumes of data and information produced by the ongoing environmental monitoring programme. In Section 8, the Rio Doce Panel presents conclusions and makes recommendations.

1 https://www.fundacaorenova.org/manejo-de-rejeito/
2 https://www.fundacaorenova.org

Figure 1 – Lower Rio Doce region and adjacent coastal area



2. Objective and purpose

The objective of this study is to propose a method for an *ex post* assessment of the environmental impacts caused by the dispersal of the Fundão Dam tailings across coastal and marine environments.

Its main purpose is to contribute to informed decision-making relating to mitigation and compensation for the adverse environmental impacts on those ecosystems. It therefore aims to contribute to the so-called "Integrated Action Plan for Recovery and Conservation of Aquatic Biodiversity of the Rio Doce Watershed and the Coastal and Marine Environments", which, at the time this study was initiated, had not yet been developed by the responsible entities.[3] This study also supports: (i) the Renova Foundation's Impact and Reparation Management System[4]; (ii) the ongoing process of reviewing Terms of Reference 4[5]; and (iii) improvements to environmental impact assessments within the ongoing Aquatic Biodiversity Monitoring Programme.

7 September 2017 Renova Foundation - Aerial view of people surfing in Regencia district, near the mouth of the Rio Doce.

3 As required by the Interfederative Committee charged with overseeing the reparation. This committee is presented in Section 4.

4 The Renova Foundation is presented in Section 3. The impact management and reparation system is an internal tool used by the Renova Foundation.

5 These Terms of Reference were prepared by government authorities as a guide for monitoring the impacts in coastal and marine areas. This document is explained in Section 4.

3. Study context

By 2 March 2016, nearly four months after the Fundão Dam collapse, an out of court agreement had been reached between Brazilian government institutions on the one hand and owners of the mine on the other. Government parties included the federal government and federal agencies, together with the state governments of Minas Gerais (MG) and Espírito Santo (ES), and their respective agencies responsible for the environment, water resources, forestry, and agriculture. The mine owners were Samarco SA and shareholders, Vale SA and BHP Billiton Brasil Limited, (Maroun et al., 2021).

This agreement, the TTAC, provided a framework for the restoration of the areas affected by the Fundão Dam break, allowing the agreed measures to begin immediately. It thus removed any doubts raised about the start date since federal and state prosecutors had brought a civil lawsuit against the owners of the mine, demanding indemnification. Finally, the TTAC also established the Renova Foundation as an independent organisation, to manage 42 restoration programmes,[6] the funding for which would come from the corporate shareholders of the mine.

Right from the start, however, implementation faced multiple difficulties. The agreement generated multiple layers of institutional complexity. The sheer numbers of TTAC stakeholders complicated efforts to understand the disaster's impacts, as well as to mitigate, compensate, and restore. The 42 programmes are overseen by CIF, which in turn is chaired by the federal environmental agency IBAMA, and includes representatives from federal and state governments, as well as the 40 affected municipalities and Rio Doce Basin Committee. Technical expertise to the CIF is provided by 11 technical boards, while the Renova Foundation was structured in line with the 42 programmes within two broad groupings (Socioeconomic and Socioenvironmental).

But the sheer number of institutions led to a compartmentalised approach focused on separate albeit related issues and a fragmentation of supportive knowledge. Rather than examining and explaining relationships between the different issues, the compartmentalised approach led to the preparation of complex and often single focus technical studies on water quality or sediments, hardly integrated into a coherent synthesis. Nor do they offer a unified and comprehensive understanding of the disaster's impacts, particularly on coastal and marine ecosystems. In particular, the complexity of information, and the difficulties of understanding different impact pathways, has inevitably delayed this programme for the marine and coastal ecosystems.

Clause 06 of the TTAC states that restoration should return conditions to their pre-disaster state, "as determined by science-based impact assessments to be carried out by experts". The same clause proceeds to set out a phased approach, including a preliminary assessment, determination of the situation prior to the disaster, the definition of restoration projects, and subsequently followed by monitoring, and reporting to the CIF for approval, including public consultations.

By the end of 2021, however, no comprehensive impact assessment had been conducted. Specific requirements had been established for each of the 42 programmes, covering surveys, sampling, analysis and other actions. But carrying out such a task in comprehensive fashion in the entire river basin is severely hampered by the sheer variety of ecosystems, communities, heritage, livelihoods, infrastructure and other aspects affected by the dam failure.

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6 The governance of Renova Foundation was later modified. The Rio Doce Panel has analysed the various governance issues related to the restoration in a previous Thematic Report (Maroun et al., 2021).

2 October 2018
Renova Foundation | Expedition Caminho da Reparação. In the image, waves at the mouth of the Rio Doce

Aerial image of the stretch affected by the rupture of the Samarco mining tailings dam, in Mariana, Minas Gerais, taken during the inspection carried out by the Brazilian Institute of Environment and Renewable Natural Resources (Ibama) in July 2016

Sludge from the Rio Doce after the collapse of the Samarco tailings dam, in the district of Bento de Freitas, in Mariana, Mina Gerais, arrives at the city of Linhares, in Espírito Santo.

Fisheries at Lagoa Juparanã, in Linhares, 2019.

Nor was this the only obstacle to a clear and understandable assessment. Clause 165 required the Renova Foundation to propose a methodology for the monitoring of fauna in the Rio Doce estuary and affected marine and coastal areas. It required a detailed plan to assess the disaster's impact on water quality in freshwater, estuarine and marine environments by June 2016, as well as the impact on food chains and on the seabed by May 2017.

However, the Technical Chamber for Biodiversity Conservation (CT-Bio) didn't approve Renova's initial proposal. Instead, Renova was tasked with a monitoring programme in line with Terms of Reference 4 to be implemented over five years. Progress towards proposing reparation measures for coastal and marine areas has therefore been slow. It has been difficult to reach agreement on the critical steps, including the definition of the terms of reference and the selection of team members to carry out the monitoring. In Section 4, this report provides more detail on this process.

Besides the instructions from CIF and technical boards, the Renova Foundation has also faced delays connected to numerous court decisions. Since 2019, various suits were brought before the 12th Federal Court in Belo Horizonte. These suits challenged the execution of most programmes that Renova was responsible for, establishing new commitments. They also determined that compensation payments should be raised and that participation of people and communities affected by the disaster should be increased. Many of Renova's restoration programmes therefore became subject to judicial review, as was the case with the monitoring of marine and coastal areas.

4. A short chronology of actions pertaining to environmental monitoring and impact assessment in the coastal and marine areas

Developed by one of the 11 technical boards and CT-Bio a set of monitoring guidelines illustrate some of the difficulties with gathering information.

The CT-Bio finalised the guidelines in October 2016 and then on 27 June 2017[7] the CIF approved them for use within one of the 42 programmes, the Programme for Monitoring Aquatic Biodiversity (PMBA). Known as Terms of Reference 4, the guidelines set out an extensive list of topics for research including the conservation status of different species, water quality, seafloor habitat, and more. They also listed the disaster's possible impacts.

It then took another year to negotiate and sign an agreement with the FEST Foundation (Fundação Espírito-santense de Tecnologia) and the Federal University of Espírito Santo, who were set to conduct the monitoring programme. In the meantime, the Rede Rio Doce Mar (RRDM), a pool of researchers from 27 universities, began work in September 2018. As they worked and delivered data, they found – and suggested to the CT-Bio – that these guidelines could be improved.

One key issue was that the guidelines focused on environmental monitoring and not on impact assessment, which is mentioned only once. Indeed, the programme's original goal was:

> water quality monitoring and ecotoxicological studies to check for contamination in aquatic biodiversity (...), to inform (1) decisions about catch levels and consumption, (2) the process of assessing the state of conservation of aquatic biodiversity and, (3) measures for the recovery and conservation of fauna and the aquatic environment.

This appeared to contradict the requirements of the programme, which went well beyond water quality and ecotoxicology. They included:

- I Ecotoxicology monitoring and study
- II Fresh water environment monitoring and study
- III Estuarine and marine environment monitoring and study
- IV Beach monitoring and study
- V Mangroves monitoring and study
- VI Marine megafauna (chelonians, birds, and mammals)
- VII Estuarine and marine ichthyofauna monitoring and study
- VIII Abrolhos Marine National Park and associated areas monitoring and study

In December 2018, RRDM reviewed early studies as required by the guidelines. They collected 17 consultant reports and two reports by government organisations containing data on the coastal and marine environments.[8] RRDM have prepared subsequent reports each year since then, so that by March 2022, three annual reports had been submitted.

7 The CIF ruled on the monitoring plan on three occasions: On 27 June 2017 (Deliberação CIF 77) a deadline was established for the Renova Foundation to adjust its working plan to implement the monitoring programme. Monitoring could only start after approval of the required adjustments. On 28 September 2018 (Deliberação CIF 218), CIF determined that Renova Foundation budget for the execution of the monitoring programme. Finally, on 24 April 2019 (Deliberação CIF 279), the monitoring programme was approved for immediate execution.

8 The RRDM is also in charge of monitoring river ecosystems in Espírito Santo.

7 September 2020
Renova Foundation. In the image, parts of the Rio Doce estuary in Linhares.

In 2021, the PBMA held a workshop (*Jornada de revisão*) to review the guidelines. By that time, some 247 potentially useful documents had been gathered, containing about 26,000 pages.[9] The *Jornada* was attended by researchers from the RRDM, government officers, Renova Foundation staff and others, totalling more than 50 participants. *Fundação Dom Cabral*, a management school and consultancy, facilitated the process.

In a draft of the revised guidelines, PMBA goals included the following:

1. Comply with the provisions of TTAC Clause 165, particularly as concerns identifying, evidencing, and monitoring the impacts caused by the Fundão Dam failure on the Rio Doce's biodiversity (the Capixaba1 portion) and on the estuarine, coastal, and marine environments affected by the dam failure, as well as indicating measures to recover and conserve this biodiversity, monitoring and evaluating the effectiveness of recovery and conservation measures.

2. Generate technical knowledge to provide strategic guidance for mitigation and reparation of damages resulting from the dam failure and for the good management of the basin's aquatic and riparian ecosystems with a view to improving their environmental quality to at least their pre-dam failure conditions, but ideally beyond it.

3. Ensure the continuity of ongoing monitoring with data and analyses of the aquatic environment and biodiversity and using time series.[10]

The draft revised guidelines also listed the parameters to be monitored, the number of sampling stations, and periodicity. It contained a new section "Impact assessment and data integration", stating that:

> "In addition to the environmental approach, the PMBA will incorporate all the results obtained, or to be obtained henceforth, thereby forming an integrated analysis and environmental impact assessment report in the form of a Results Matrix, as presented in the PMBA-Fest-RRDM Annual Report 2020 (Annex 5).
>
> This aquatic biodiversity impact analysis will follow the impacts evidence method already adopted in the PMBA, which starts by defining the concepts and criteria that will be used to identify the impacts associated with the Fundão Dam failure, as described below.
>
> Based on the concept of 'impact', as well as on the impact assessment criteria presented above, an effort was made to present the results obtained in the first two years of monitoring and research in a complementary and integrated manner. To this end, a spatial-temporal analysis of direct and/or indirect impacts associated with the dam breach was conducted considering the various criteria mentioned above, individually or together, to produce a Results Matrix. Annex 3 presents the information and procedures used to prepare the Results Matrix as well as the results obtained after its completion. This approach will be maintained in the next years while the PMBA is implemented."[11]

The draft revised guidelines also established various other requirements for impact assessments. A "Results Matrix", which refers to a way of describing impacts, was introduced into the RRDM's second annual report (2020)[12] and is described in Section 5.

In yet another section[13], the draft revised guidelines set out the required qualifications of the implementation teams. It lists the profiles of 13 lead researchers and 17 other researchers. It also sets out the qualifications required for laboratories. However, it does not require the participation of professionals with any prior experience of impact assessments.

Table 1 shows the key official documents relating to the monitoring of coastal and marine environments in this programme, as well as the main directives.

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9 Fundação Dom Cabral (no date), Report of the Event to Review the Terms of Reference 4 TR4 2020/2021.

10 Terms of Reference – PMBA / CTBIO-CIF. Aquatic Biodiversity Monitoring Program, First Revision, no date, pg. 6.

11 Idem, pg. 40.

12 FEST, Aquatic Biodiversity Monitoring Program of the Environmental Area I – Capixaba Portion of the Rio Doce and Adjacent Marine and Coastal Areas. PMBA Annual Report 2020 /Fest-RRDM. Results Matrix, Freshwater, Coastal and Marine Environments. RT-36F RRDM/TEN 20. Vitória, December 2020.

13 Terms of Reference – PMBA / CTBIO-CIF. Aquatic Biodiversity Monitoring Program, First Revision, no date, pg. 47 and following pages.

Table 1 – Key documents on the monitoring of estuarine, coastal, and marine environments.

DATA	EVENT OR DOCUMENT
March 2016	TTAC signed
October 2016	CT-Bio approves TR4/2016, guiding and referencing the implementation and execution of the Aquatic Biodiversity Monitoring Program - PMBA
27 June 2017	CIF approves TR4 (Deliberation nº 79)
September 2018	Rede Rio Doce Mar starts implementing the PMBA
December 2018	FEST report on analysis of prior data on acute and chronic impacts
23 April 2019	CIF Resolution No. 279 on the PMBA continuity strategy
May 2019	1st RRDM semester report
November 2019	1st RRDM annual report
9 March 2020	Start of planning for the TR4 review event
29 July 2020	Start of TR4 review
August 2020	2nd RRDM semester report
December 2020	2nd RRDM annual report
January 2021	TR4 review event
16 February 2021	Ruling on PMBA continuity
October 2021	3rd RRDM semester report
4 November 2021	3rd semester report presentation event
February 2022	3rd RRDM annual report and presentation seminar

Sources: Richards et al. (2020) and “Terms of Reference 4 - PMBA / CTBIO-CIF Aquatic Biodiversity Monitoring Program, First Review” (no date)

5. Brief description of studies in the coastal and marine area

It took 16 days for the wave of tailings to reach the Rio Doce mouth. Five days after the dam failed, Espírito Santo's state-level environmental agency (IEMA) began to rescue aquatic and terrestrial animals, while the state government ordered the Rio Doce mouth to be widened, accelerating the outflow of sediments and tailings. Before the tailings reached the area, samples were taken in the river, estuary, coastal, and adjacent marine zones. These samples included water, sediments, fish, and other organisms. They were taken by a mix of government bodies, including state and federal environmental agencies, independent researchers, and the mining companies too.

In the first three years following the dam failure, Samarco also hired consulting firms to conduct numerous studies, and the Renova Foundation followed suit. Since the Aquatic Biodiversity Monitoring Programme began in November 2018, other systematic studies have also been done, while researchers have also been looking at the impacts of tailings in the region. The following subsections provide an overview of these studies as context. Together, this section shows the complexity and number of different studies being done.

5.1 Impact assessment in monitoring studies

At the onset of its work, the RRDM evaluated the studies done between November 2015 and July 2018. Their report,[14] which aims to "provide a first diagnostic assessment of the impact on biodiversity" assesses the studies on: ecotoxicology; marine hydrogeochemistry; marine benthic, phytoplanktonic, zooplanktonic and ichthyoplanktonic communities; marine ichthyofauna; reef bottoms and rhodolites; numerical modelling; sedimentology; beach ecosystem; mangrove ecosystem.[15]

According to their analysis, "the reports issued over almost three years after the event do not contain an effective or diagnostic analysis of the impact caused by the ore tailings (page 18), since many ecosystems were sampled only once and many reports show results without interpreting them". The document also points out that "the production of individual reports did not really help the impact assessment due to the lack of an integrated analysis" (page 19).

The six-month and annual reports provide a detailed description of studies conducted, as well as RRDM's methods, sampling points and results. In December 2020, they synthesised the analyses and results from two years of monitoring, then presented them in a single document, "Results Matrix for Freshwater, Coastal and Marine Environments". Its purpose was:

> "Assessing—based on a list of impacts defined by researchers who conducted the specific PMBA/Fest-RRDM studies—impacts occurring in different compartments (abiotic and biotic) and trophic levels, using criteria based both on the impact frameworks used in environmental impact statements, and on the experience of implementing the PMBA." (page 7)

14 FEST, Avaliação e Consolidação de Dados Pretéritos (Sistemas Pelágico, Sedimentos, Comunidade Biótica e Ecotoxicologia). RT-01RRDM/OUT18. Vitória, October 2018.

15 This report also addresses freshwater environmental studies not included herein.

In February 2022, a new “Results Matrix” was presented.[16] It outlined 64 impacts on the coastal environment and 137 impacts on the marine environment. The RRDM studies indicate changes in several abiotic components, biotic components of the coastal environment, and marine environment too.[17] Some of the results have been published in peer-reviewed articles.

5.2 Academic literature

Several researchers looked at the dam failure’s impact on coastal and marine environments. This subsection summarises some of these papers and discusses selected results. No systematic literature review has been done.[18] Key points are presented in Tables 2 and 3 covering the estuary, and coastal and marine environments respectively.

Table 2 – Selected published studies on the impacts of tailings in the Rio Doce estuary

AUTHORS	COMPARTMENT OR ECOSYSTEMS	STUDY AREA	STUDY PERIOD AND SAMPLING	METHODS
Queiroz et al. (2018)	Estuarine wetland soils	Rio Doce estuary	December 2015	Lab determination of particle size, mineralogical composition, organic matter, metals concentration
Bernardino et al. (2019)	Benthic fauna (0-5 cm)	Rio Doce estuary	August 2017 20 stations	Determination of environmental DNA, metals, total organic matter, and grain size in sediments
Gabriel et al. (2020a)	Surface sediments (0-10 cm)	Rio Doce estuary	August 2017, January 2018, August 2018 - 17 stations	Determination of metal concentration Evaluation against 4 sediment quality indices
Gabriel et al. (2020b)	Bottom sediments and estuarine demersal fishes	Rio Doce estuary	August 2017	Determination of metal concentration in sediments and protein in liver and muscle of five fish species
Gabriel et al. (2021)	Bottom sediments (0-5 cm)	Rio Doce estuary	5 campaigns from August 2017 to January 2020	Lab determination of particle size, organic matter, metals concentration Comparison with a pre-disaster data set
Ferreira et al. (2022)	Estuarine wetland soils	Two islands in the estuary	Sampling in August 2019	Sampling of soils and plants, lab measurement of iron in soils and plant tissues

16 FEST, Aquatic Biodiversity Monitoring Program of the Environmental Area I – Espírito Santo Portion of the Rio Doce and Adjacent Marine and Coastal Areas. PMBA/Fest-RRDM Annual Report 2020. Results Matrix: Fresh Water, Coastal and Marine Environments. RT-39F RRDM/FEV 22. Vitória, February 2022.

17 Abiotic components here include water, restinga sediments, mangroves, beach, and sea. Biotic components of the coastal environment include benthos, mangrove crabs, birds, beach invertebrates, mangrove vegetation and restinga vegetation. The marine environment includes microbiota, phytoplankton, zooplankton, ichthyoplankton, crustaceans, benthos, corals, fish, turtles, cetaceans, birds, and algae.

18 A Scopus (www.scopus.com) search conducted on June 13 2022 found 46 papers (Search terms = TITLE-ABS-KEY ((fundao OR samarco) AND impact* AND (coast* OR ocean* OR marine)) in the period 2016-2022.

Table 3 – Selected studies on the impact of tailings in the coastal and marine environment

AUTHORS	COMPARTMENT OR ECOSYSTEMS	STUDY AREA	STUDY PERIOD AND SAMPLING	METHODS
Hatje et al. (2017)	Water and sediment	Rio Doce and coastal area	75 days after dam failure – 5 stations in the sea near the river mouth	Water, sediment and suspended particulate material sampling
Ruddorf et al. (2018)	Water and sediment	Continental shelf off the Espírito Santo coast	May 2013 to August 2017 for Landsat-8 images and water sampling from November 2015 onwards	Analysis of Landsat TM5 and Landsat-8 OLI images and in situ turbidity sampling (samples collected by the National Water Agency) for the near mouth area. Analysis of MODIS-Acqua satellite images for the larger area
Richard et al. (2020)	Water and sediment	Coastal area up to ~20 km from the coast	Between November 2015 and August 2017 – 28 stations	Daily water quality and weekly sediment sampling at 10 stations within 5 km from the river mouth, 12 stations more than 5 km away and 6 stations at a marine protected area further away
Schettini and Hatje (2020)	Water	Rio Doce mouth	From 22 November to 5 December 2015	Measurements of water flow at the river mouth at different tidal stages and water sampling at 0.5 m and 2 m depth twice a day to determine suspended sediment concentrations and estimate the amount of sediments and metals discharged
Quaresma et al. (2021)	Sea bottom sediments	Espírito Santo Continental Shelf	October 2015 and April 2017	Collection of 71 surface sediments samples at depths between 15 and 40 m and determination of metals contents
Longhini et al. (2022)	Surface and bottom seawater and surface sediments	Espírito Santo Continental Shelf	October 2018 to March 2020 (28 to 52 months post-disaster)	Monthly collection of samples and determination of nutrients, metal(loid)s and Polycyclic Aromatic Hydrocarbons (PAHs) and calculation of quality indexes

Some of these studies provide useful context for the following sections and are therefore presented below.

Ferreira et al. (2022) explain how the tailings changed sedimentary and fluvial dynamics in the estuary, building on work by Hatje et al. (2017) and Duarte et al. (2021). The temporary and bare sandy islands normally form in the estuary, built by the flow of predominantly coarse (sandy) sediments ("other non-vegetated areas"). But the arrival of tailings meant that they were covered with fine particles rich in Fe oxyhydroxides. This modified environment supported the establishment and growth of macrophytes, which in turn decreased the turbulence, enhanced the accumulation of tailings, and led to plant colonisation.

Queiroz et al. (2018) note that the iron tailings deposited in these islands and river margins are associated with trace metals which are potentially bioavailable given the redox conditions of estuarine soils. One important impact is that the increase of bioavailable iron in poorly aerated (anoxic) conditions may induce iron toxicity. Ferreira et al. (2022) demonstrate that this could have a severe and negative impact on the biota. It also presents a risk to human health. Given this, a ban on inshore fishing was introduced along a large area of the Espírito Santo coast. Bernardino et al. (2019) say that potential chronic pollution in the estuary will likely demand long term monitoring.

Because mining, industry and towns had already been developed, the Rio Doce basin had already been polluted. So the trace metals, which built up rapidly when the tailings reached the estuary, were likely attached to iron oxides as they travelled downstream. According to Gomes et al. (2017), the concentration of metals in the sediments was observed to grow quickly by a factor of between 2 and 20, including for iron, manganese, chromium, nickel, copper, zinc, and arsenic. Cadmium was also found to be associated with the tailings, while arsenic was released by the mudflow (Duarte et al., 2021).

In August 2017, almost two years after the dam failure, sediment concentrations of iron, lead and selected trace metals in the Rio Doce continued to be 2 to 20 times higher than in smaller estuaries on the Espírito Santo coast, including those with well-preserved ecosystems such as the Piraquê-Açu-Mirim estuary and polluted estuaries such as Vitoria Bay. This latter is located in a major metropolitan and industrial area about 100 km to the south (Gomes et al., 2017).

Queiroz et al. (2018) documented that the tailings had enriched the estuarine soils with trace metals, noting that the soil's physical-chemical characteristics favour reduction of ferric ion (Fe^{3}+). This would enhance the bioavailability of trace metals and thus potentially contaminate the food chain.

Gabriel et al. (2020b) found a high risk of metals contamination and corresponding biological risks. Based on the precautionary principle, they recommend both a fishing ban and the monitoring of people's health in the areas with chronic metal contamination.

Gabriel et al. (2021) collected and analysed sediments from the estuary, comparing their results with values obtained by Gomes et al. (2017). By collecting samples some two, nine, and 11 days before the arrival of the tailings, they established baseline (or background) concentrations. They thus calculated the ratio of a metal(loid) concentration in the samples and its baseline concentration, as well as the ecological risk factors and indexes. They found "that 4.2 years after the impact, arsenic, chromium, copper, and nickel concentrations were still above the threshold effect levels of toxicity, while cadmium and lead exceeded probable effect levels".

Gabriel et al. (in press) also found that "sedimentary metal(loid) contents after the impact were continuously above the background values for the Rio Doce estuary". Concentrations peaked in 2017 and they then identified "a period of stability until 2020". This reduction of most metal concentrations is assumed to result from "the continued transport of tailings and bound metals from the estuary to the Atlantic Ocean". Gabriel et al. (2021) have findings consistent with the conceptual model put forward by Queiroz et al. (2018). They said that plant activity in the estuary would increase the soil's organic matter content and might stimulate the reduction of iron oxides and consequent release of trace metals into the water body.

Gabriel et al. (2021) also did an ecological risk analysis, which "suggested that sediment metal(loid) concentrations are high enough to cause adverse biological effects, supporting the hypothesis that there is chronic long-term contamination of the estuarine ecosystem". This fits with previous studies of metals in fish by Gabriel et al. (2020b), which found a "high biogeochemical mobility of toxic elements between sediments and the bottom-dwelling biota in estuarine ecosystems." There is "so far limited evidence for the accumulation and ecological effects of tailings over the seafloor at distances of over 10 km from the Rio Doce mouth (Richard et al., 2020), even though tailings may be transported along with the river plume at greater distances," the authors said.

Bernardino et al. (2019) found that "the Rio Doce eDNA composition was similar to other estuarine and marine sediments assessed by metabarcoding methods".

Richard et al. (2020) collected water and sediment samples a few days before the tailings arrived at the river mouth and in the following 21 months. They selected "relevant water quality parameters", that is, those "which persistently or repeatedly changed in response to the dam failure", including total suspended solids, turbidity, total and dissolved iron, aluminium, and manganese. For these parameters, "pulses of concentration increases were observed right after the arrival of the plume in the coastal zone and during the subsequent rainy seasons. Exceedances of prebreach conditions were more frequent closer to the Rio Doce mouth. During the dry season, concentrations tended to decrease, reaching prebreach levels for several parameters, with small short-term pulses associated with metocean factors."

The sediment quality parameters of most relevance are particle size for iron, aluminium, and manganese. The authors found that "iron was the only one which clearly resulted from the dam breach, which was mediated by river influence and oceanographic factors affecting particle size distribution". They concluded that "the Fundão Dam failure did affect water and sediment quality in the Atlantic Ocean, with greater impacts closer to the river mouth and immediately after the arrival of the tailings plume, with concentrations gradually returning to pre-event levels over time".

Ferreira et al. (2022) showed that the increase of iron bioavailability within redox environments constitutes an environmental risk. These authors demonstrated the role of plants in the iron biogeochemistry within the estuary and their potential for phytoremediation. They described the portioning of iron in distinct plant compartments, namely root surfaces, roots, and leaves. According to their studies, ferric ion (Fe^3+) formed in aerated soils, while iron bioavailability was below the nutritional threshold for plants. In poorly aerated soils (anoxic conditions) the solubility increases sharply due to the dissolution of ferrous ions (Fe^2+). This increases iron bioavailability and may induce iron toxicity with severe effects for plants and biota. In response, wetland plants may have distinct physiological strategies to cope with high ferrous ion (Fe^2+) levels, for example by forming iron plaque.

On the sea floor, Quaresma et al. (2021) compared the metal content of sediments before and after the disaster. They found "a continental shelf already contaminated before the dam failure by trace metals and iron". This was a question of the local geology, "but also anthropogenic sources, including mining in the Iron Quadrangle region". In addition, concentrations of copper, lead, chromium, and nickel before the tailings arrived "all surpassed threshold or probable effect levels suggesting that pre-accident values posed risk to biota." After the disaster, metal concentrations increased in the study area to become "drastically worse than before the rupture of the dam". The tailings contained iron and trace metals, but "finer material certainly acted as a carrier for trace metals present along the mud path toward the coast, through the capture of dissolved fraction, and remobilisation of the riverbed."

After the dam collapse, Quaresma et al. (2020) observed an increase in clay and silt particles in the seabed sediment on the continental shelf. The authors discuss how this can increase the presence of trace metals in the environment, since these elements are frequently transported with finer grain sizes.

Longhini et al. (2022) studied metals, nutrients and concentrations of polycyclic aromatic hydrocarbons (PAH) in the ocean. They found that the offshore and alongshore dispersal of contaminants is linked to flood events and consequent intense river discharge. These high shelf hydrodynamics and high Hs (2019/2020 – wet scenario) led to a recovery of environmental quality in their sampling domain. They explain that "resuspension of fine sediment and suspended Fe (III) oxy-hydroxide nanoparticles by waves seem to be the main processes for releasing metal(loid)s into the water column". Intense river discharge on the continental shelf is associated with the dilution of aqueous metal(loid)s.

5.3 Other sources

Other studies were conducted. Commissioned by Renova or its parent companies, they aimed to understand the impacts on coastal and marine zones. Here we briefly present select information from these additional sources.[19]

One study investigated the possible geographical reach of the tailings plume by modelling the hydrosedimentological conditions in an area around the Rio Doce mouth (Coppetec, 2019). This study considered the particles load in the river, the intensity and the direction of ocean currents, and other variables. The study period was from 1 November 2015 to 30 June 2019, when the currents were mostly running to the south-southwest (SSW) along the coast, consistent with previously established patterns. River sediment and tailings thus travelled mostly to the south of the river mouth. But when cold fronts arrive from the south, an inversion occurs and the currents flow towards the north-northeast (NNE). The report also notes that at a short distance from the coast, these currents flow towards the northeast most of the time.

The Coppetec study estimated that between November 2015 and April 2016, some 740,000 tons of tailings flowed through the river mouth. After that period, the mass of total sediment was considered to be irrelevant (page 28). The report does not give an estimate of the total sediment mass over that the period, but for

19 In preparing their reports and providing advice, it is policy of the Rio Doce Panel to consider only publicly available documents. Notwithstanding, in preparing this report, the Panel found it would be necessary to review other studies, in order to provide a comprehensive and inclusive view of the studies on the environmental impacts on the coastal and marine environments.

November 2015 to June 2019 it estimates the total mass of sediment transported (tailings plus river sediments) to be about 7 million tons.

The study estimates the amount of sediment deposition on the ocean floor. Because of the predominant currents, most particles are found in a zone that stretches from the Rio Doce mouth about 40 km to the south-southwest with a maximum width of about 15 km. The authors remark that 15 percent of the total sediment load was transported somewhere else. On the other hand, the authors expected to find suspended sediments as much as 43 km to the north-northeast, albeit at low concentrations (10 to 100 mg/L for 1 percent of the time). To the south-southwest, they expected to find sediments at this concentration range for 16 percent of the time. The study found that the tailings significantly contributed to the sediment load for the first 90 days following the disaster. After 180 days, they observed resuspension, following cold weather fronts and increased flow during the rainy period, as other, smaller rivers flowed into the sea north and south of Rio Doce.

Between April 2018 and late 2019, consulting firms studied the concentration of metals and metalloids in the tissue of fish and crustaceans, together with fish biomass, sediment quality, benthos, phytoplankton and environmental DNA (Hydrobiology and Econservation, 2020a, 2020b). The firms had been contracted by BHP Brasil, one of the two mining companies that own Samarco, and their purpose was to “analyse the post-impact recovery of the coastal and marine ecosystem” (Hydrobiology and Econservation, 2020b, page 44).

Their samples were taken from two areas, the mouth of Rio Doce (11 stations) and the mouth of Rio Jequitinhonha (8 stations), a river located some 430 km to the north. The study found no evidence that the tailings had changed metal concentrations in tissues (Hydrobiology and Econservation, 2020b, page 46) and said “multiple lines of evidence” had failed to “indicate any impact on the marine and coastal ecosystems following the Fundão Dam failure” (Hydrobiology and Econservation, 2020a, page 82).

Possible impacts on sea turtles were another important concern in the months immediately after the dam failure. The Espírito Santo coast is a spawning ground for *Caretta caretta* (loggerhead sea turtle) and *Dermochelys coriacea* (leatherback sea turtle), an endangered species classified as vulnerable by the IUCN Red List of Threatened Species™.[20] Critically endangered in Brazil, the leatherback’s spawning period runs from September to February, peaking in November and December, the exact period when the tailings were discharged. The area around the Rio Doce mouth is the second biggest reproduction site of loggerhead and the only area on the Brazilian coast, which is known for regular spawning of leatherback (Fundação Projeto Tamar, 2020).

Projeto Tamar, a not-for-profit Brazilian organisation, has been monitoring sea turtles along the coast for more than 40 years and working with local communities to protect them. It has a base on Comboios beach, Regência, some four kilometres from the Rio Doce mouth.

In March 2018 – hired by the Renova Foundation and with the consent of CIF – Foundation Pró-Tamar, which supports the research work of Projeto Tamar, began monitoring the sea turtles’ reproduction. Their work lasted three years from August 2017 to July 2020, and they used four stations along 159 km of coastline, both north and south of the Rio Doce mouth (Colman et al., 2019). Using eleven years of data, Tamar (2020) found that the arrival of females was within the fluctuation range and both spatial and temporal distribution were unchanged. The report did however recommend caution with the conclusions, since the impact of the tailings might be long-term and late effects cannot be discarded. Continued studies are necessary, they said (page 48).

5.4 Discussion

The three types of sources reviewed above help to advance understanding of the coastal and marine ecosystems and how they were affected by the dispersal of tailings and sediments.

The research summarised above covers a wide variety of approaches. They were conducted at different moments following the Fundão Dam failure, they encompass different study areas, and they focus on a wide array of ecosystem components, including water, sediment, benthic communities, phytoplankton, fish and more. Researchers used different techniques for sampling, laboratory determinations and data analysis. Because they have different goals, these academic papers and technical reports may differ in the ways they discuss their results or compare them with other literature. It is appropriate here to note that the published papers were

20 The IUCN Red List of Threatened Species™ is the world’s most comprehensive inventory of the global conservation status of plant and animal species, https://www.iucnredlist.org/

Aerial view of Foz do Rio Doce, located in Regencia, Espírito Santo, path of the flood of mining tailings from the Fundão Dam, which descended through the Rio Doce reaching the Atlantic Ocean.

blind peer-reviewed, but this was not the case for the technical reports.

These studies are just one part of a larger set of papers and reports on the consequences of the Fundão Dam failure, and several items have not been mentioned here. This growing set of documents add to the body of knowledge and provides an excellent foundation for science-based decision-making.

Although the ongoing monitoring and research carried out in affected areas has strengthened the knowledge base about coastal and marine ecosystems, as well as about the role played by the tailings in disturbing these ecosystems, much remains to be studied. For example, the potential harm caused by the increase of bioavailable iron in poorly aerated (anoxic conditions) conditions may induce Fe toxicity with potentially severe effects for the biota and could also represent a risk to human health. Another issue, still not adequately investigated in the Rio Doce basin is the generation of harmful synergistic compounds which can result in “reactive chemical cocktails” capable of causing further effects on the biota composition and the local environment.

However, the parts involved in the monitoring and in decisions about reparation still face a very significant challenge, because the integration of all this information and knowledge from multiple sources is no easy task. When asking different research questions, studies can reach conclusions that are different, if not conflicting. However, integrating information and knowledge from multiple sources is essential if science is to inform decision-making about restoration and compensation. Given the complexity of the coastal and marine environments and the fragmentation of research, it is a real puzzle to figure out the “whole picture”. Uncertainty is inevitable, and it can be daunting to attribute a detected change in the environment to one particular cause.

In the next sections, the Panel presents approaches that will help to frame scientific information and knowledge and to inform post-disaster impact assessments.

6. The assessment of environmental impacts of disasters

Not much literature exists on *ex post* impact assessments or post-disaster impact assessments, especially in respect to the environment. Guidance is available, however, for the rapid assessment of social and economic impacts. Examples include the Handbook for Estimating the Socio-Economic and Environmental Effects of Disasters (ECLAC, 2003) and the World Bank's Guidance Notes on Damage, Loss and Needs Assessment (Jovel & Mudahar, 2010). Both look at issues such as the value of destroyed assets or temporary production loss. The latter aims to guide assessments for short-term government interventions, the costs of post-disaster recovery and reconstruction, and the management or reduction of disaster risk. The World Bank has published other practical guides (2015a, 2015b), which also focus on social impact assessments to be done as soon as possible following a disaster. Guidance has been applied to several cases of so-called "natural" disasters, such as an assessment of needs following floods and landslides in India (United Nations Development Program et al., 2018). Such guidance helps to estimate the losses to people and business resulting from disasters, but positive economic impact also comes from the restoration and clean-up efforts following technological disasters, such as major oil spills (Cohen, 1995).

Environmental impacts are the focus of the guidelines "Rapid Environmental Assessment in Disasters" (Kelly, 2018). These include the environmental consequences of relief operations. They provide guidance for rapid assessments immediately after a disaster, using the findings to guide recovery and restoration.

These documents guide short-term assessments and therefore inform emergency responses, but to design mitigation it is necessary to obtain an accurate understanding of a disaster's long-lasting impacts: what environmental components and processes have been affected? What damage has been done? What is the extent, duration, and intensity of these impacts?

The literature on the risks relating to tailings dams does not usually answer these questions. Instead, it is mostly focused on understanding the causes of incidents and failures and seeking to prevent future events. The new international standard on tailings management (ICMM et al., 2020) contains the following requirement: "In the event of a catastrophic tailings facility failure, assess social, environmental and local economic impacts as soon as possible after people are safe and short-term survival needs have been met" (Requirement 14.2). However, it does not provide guidance on how to undertake the assessment, nor does its companion "compendium".

In the United States, the practice of assessing the long-term environmental impacts of disasters is structured and regulated in line with a procedure known as the Natural Resource Damage Assessment (NRDA). The procedure is triggered by situations such as oil spills and follows standard steps (Mauseth & Parker, 2011). A pre-assessment identifies the natural resources damaged or at risk, then field surveys and other data collection methods are used to complete this preliminary assessment, later completed in a second step to inform the restoration plan. The final step is to implement the plan and to monitor implementation. Public consultation is required throughout. An environmental impact statement must be prepared to assess the restoration alternatives and their likely impacts.

One major example of NRDA is the Deepwater Horizon disaster, when an offshore oil rig released some 500,000 cubic metres of oil into the Gulf of Mexico. Beginning on 20 April 2010 and lasting 87 days, the Deepwater disaster was "the largest offshore oil spill in U.S. history" (NOAA, 2016, page 4-69). The assessment, which found that the oil slick affected about 112 thousand square kilometres of sea surface, 1000 square kilometres of sea floor, and at least 2,100 km of coastline (NOAA, 2016), provides a useful approach to assess the impact of the Fundão tailings dispersal in the coastal and marine environments. Selected aspects are presented below.

First, to determine injury[21], "the Trustees[22] determined the degree (severity), geographic extent, and temporal extent (amount of time) of the injuries and service losses that occurred. To do this, the Trustees compared the injured resources and services with baseline conditions—that is, the condition that would have existed if the Deepwater Horizon incident had not occurred. The Trustees could not quantify every injury that occurred. Instead, they focused on where injury quantification could be most helpful for restoration planning" (Section 1.5.1.2).

The size of the oil spill and area affected meant that "Evaluation of all potentially injured natural resources in all potentially oiled locations was cost-prohibitive and scientifically impractical. For these reasons, the Trustees determined that it was not feasible to study every species or habitat potentially affected by the incident in all locations exposed to oil or response activities. Instead, they employed an ecosystem approach to the assessment by evaluating injuries to a suite of representative habitats, communities, and species, as well as select human services, ecological processes, and ecological linkages. The Trustees used the information collected to develop scientifically informed conclusions not only about injury to the resources, processes, and locations studied, but also, by scientific inference (Section 4.1.5.3), about injury to resources, ecological processes, and locations that they could not directly assess." (page 4-9)

The study was consequently directed at selected components:

- To assess the impacts on water column resources, representative fish species were selected to evaluate injuries to the large variety of fish species in the Gulf.
- In the nearshore marine ecosystem, selected species such as brown shrimp, red drum, and oysters were chosen "to represent the many different fauna that rely on the edges of coastal salt marshes".
- To assess injury to the coastal marshes, which support several important ecosystem processes, "the Trustees considered one of these processes (the role of healthy marsh habitat in stabilizing the marsh and slowing coastal erosion rates) as representative of other ecological processes that marshes support." (page 4-10)

Aerial image of the stretch affected by the rupture of the Samarco mining tailings dam, in Mariana, Minas Gerais, taken from Brazilian Institute of Environment and Renewable Natural Resources (Ibama) inspection carried out in July 2016.

21 In a NRDA, injury is the term used to designate harmful impacts to natural resources. According to the US National Ocean and Atmosphere Administration, "During this phase, we conduct scientific studies to identify and quantify the negative impacts of the pollution or physical injury, including those resulting from cleanup or other actions taken as part of a response". https://darrp.noaa.gov/getting-restoration/assessment

22 Trustees are the equivalent of the Inter-federative Committee. The group includes several federal government agencies and representatives of the governments of the five affected states.

At ecosystem-level, "the Trustees' injury assessment evaluated injuries across a range of components and functions of Gulf of Mexico ecosystems". The injury assessment "was conducted at multiple scales of organisation, including the cellular, individual, species, community, and habitat levels" and "considered organism life history requirements and reproductive biology by evaluating injuries to embryonic and juvenile organisms and adult organisms". (pages 4-10).

Finally, where necessary, they used not only direct evidence of impact, but also applied "scientific inference (…) to make informed conclusions about resources and locations that could not practically be assessed". The impact assessment clarifies that "Scientific inference is the process of using data, observations, and knowledge to make reasonable conclusions about things that may not have been directly observed" (pages 4-13).

A different practical approach to *ex post* environmental assessment of disasters is employed in Canada. When the Mt. Polley copper and gold mine tailings dam failed on 4 August 2014, it spilled about 25 million cubic meters of tailings, construction materials and water into riverine and lacustrine environments. A Post-Event Environmental Impact Assessment Report, was prepared in line with provincial government legislation on responses to environmental emergencies (Golder Associates, 2016). Human health and ecological risk assessments were subsequently prepared in May and December 2017 respectively. And a phased approach was used to prepare a Remediation Plan, which was finally completed in March 2019 (Golder, 2019).

Following a short-term impact assessment and preparation of a conceptual site model to identify the impact pathways, an environmental impact report was prepared. This contained a detailed site investigation of the soils, groundwater and surface water, as well as sediment quality, risk assessment, and a description of remediation options. In the first six to eight months following the dam failure, studies were done to identify the physical, chemical, and biological impacts. Ten months later, the final report was publicly released. Remediation measures were subsequently implemented.

Common to both cases is a pre-existing regulatory framework, which guided both the impact assessments and the preparation of remediation plans. The two examples differ in the sense that one was a large oil spill affecting vast areas of coastal and marine environments with major socioeconomic impacts, while the other was a mine tailings spill whose impacts were essentially restricted to the nearby riverine and lacustrine environments. The regulatory approaches to both examples were also different.

For several years in the US, the NRDA has been applied to oil spills, both small and large, informing joint state and federal action. The assessment of injuries (impacts) is mandatory for the establishment of restoration alternatives. These require further assessment using statutory environmental impact assessment (EIA) procedures under the National Environmental Policy Act of 1969, the internationally pioneering EIA legislation. In British Columbia, provisions to manage contaminated sites, under the Environmental Management Act, apply also to areas affected by mine tailings. A site assessment was prepared, impacts identified, risks to human health and to the ecosystems evaluated, and an EIA report summarising the findings was then filed. A widely used tool for contaminated sites management, risk assessment, was done to inform decisions about remediation.

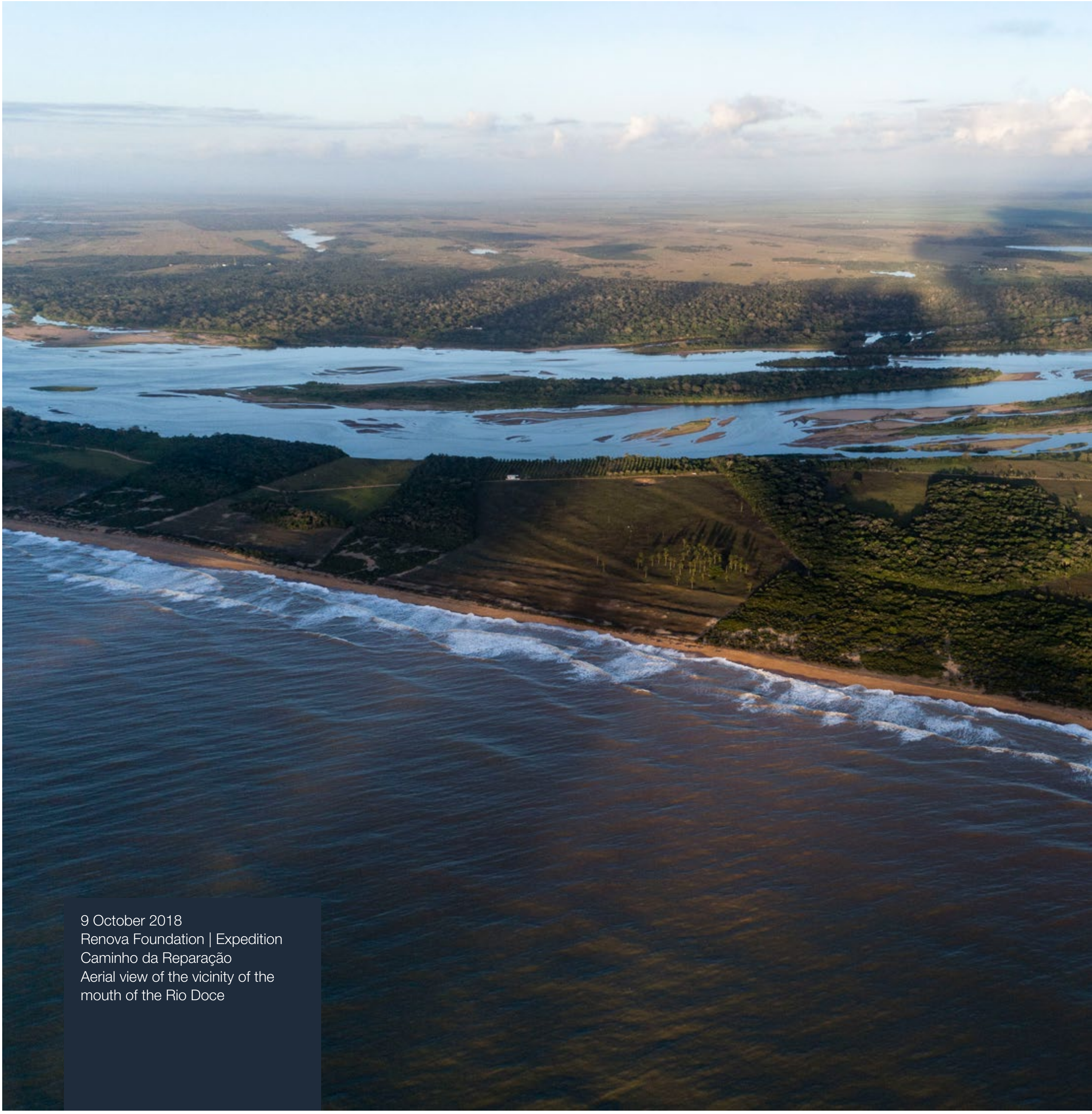
Uncertainties are explicitly acknowledged in the assessment documents of both cases and key findings are summarised to facilitate stakeholder involvement. The cases provide useful lessons for assessing the impacts of other disasters. They are relevant to the Rio Doce, since the Deepwater Horizon affected coastal and marine environments and the Mt. Polley is a well-documented and recent case of environmental impacts resulting from a tailings dam failure. We could not find other well documented and publicly available information regarding impact assessment of other important tailings releases despite the high number of failures.[23]

Major disasters cause an array of interconnected environmental and social impacts. Their consequences can be studied under different, but complementary approaches, including environmental justice (Malin et al., 2019) and *ex post* social impact assessment (Gill & Ritchie, 2020). The Rio Doce Panel has addressed social impacts in other publications (Alonso et al., 2019; Brito et al., 2019; May et al., 2019, Maroun et al., 2020). At the time of writing, it was considered that important gaps remained about the ecological impacts on the coastal and marine ecosystems, which is the main focus of this report.

In the following section the Panel presents its proposed approach, which builds upon well-established *ex ante* EIA literature, the Rio Doce Panel's previous recommendations for comprehensive post-disaster impact assessment (Sánchez et al., 2019), and lessons from the above mentioned cases.

23 https://worldminetailingsfailures.org/

7. A tailored approach for assessing the impacts of tailings on the coastal and marine environment



9 October 2018
Renova Foundation | Expedition
Caminho da Reparação
Aerial view of the vicinity of the mouth of the Rio Doce

Seven years have passed since the Fundão Dam failure and a large volume of data has been collected. The challenge now is ***to transform this data and information into knowledge that will usefully inform decisions on impact mitigation***.[24] It is beyond the scope of this study to make recommendations on the application of this knowledge for reparation or compensation. However, the Panel notes that a more appropriate and functional governance structure would make it easier to apply the knowledge that we have for mitigation, compensation and restoration. The Rio Doce Panel addresses this subject in another publication (Maroun et al., 2021).

An analysis of the environmental impacts on the coastal and marine areas of the Rio Doce mouth[25] would help to inform decisions about mitigation, but such an analysis has yet to be completed. In this section a conceptual impact assessment framework that may be of interest following other disasters for environmental impact assessments is presented.

7.1 Fundamentals

Ideally, environmental monitoring that follows a large-scale disaster would be structured around impact hypothesis. The literature on *ex ante* environmental impact assessments establishes this methodology classically (Beanlands & Duinker, 1983). In the case of the Fundão Dam collapse, however, there is the ongoing long-term Aquatic Biodiversity Monitoring Programme led by Rede Rio Doce Mar (Section 5.1), the studies performed soon after the dam failure (Section 5.1), and a range of scientific publications (Section 5.2), some of which were authored by RRDM researchers and some of which were done independently, as well as other technical reports (Section 5.3). From these documents there is a need to extract information and knowledge to assess impacts and plan restoration.

24 The term impact mitigation is used here as it is used in other Panel publications, encompassing actions to remediate, restore and compensate for adverse impacts.

25 Recommendation 1 of the Panel's 1st Thematic Report.

This report uses the terms "data", "information" and "knowledge" as per Table 4. The monitoring programmes collect data. When duly interpreted, this becomes information, which might determine for instance whether a change in an environmental parameter is associated with the presence or dispersion of tailings or the sediments mobilised by the movement of tailings along the Rio Doce channel.

Table 4 – Data, information, and knowledge within the scope of impact assessment and environmental management

TERM	CONCEPT	EXAMPLES
Data	· captured (recorded and stored) symbols and signal readings · objective facts (numbers, symbols, figures) without context and interpretation	· raw results from monitoring · water consumption at an industrial plant
Information	· a message that contains relevant meaning for decision or action · data in context	· water quality at a certain location and moment · percentage of time emissions are below or above a threshold
Knowledge	· cognition (know-what) · acting capacity (know-how) and · understanding (know-why, know-where)	· effectiveness of mitigation · how to avoid or to reduce impacts · a project's area of influence

Source: Sánchez (2012)

At this point therefore, two key challenges have to be faced when trying to transform data and information into knowledge about the impacts of the Fundão Dam failure on marine and coastal environments:

- systematising monitoring data for the specific purpose of assessing impacts
- inferring causality from non-experimental data.

Unlike experimental data collected in a laboratory field data presents the challenge of "disentangling causal relationships in the absence of experiments" (Larsen et al., 2019). Monitoring can detect the presence or dispersion of tailings, but the causal link with tailings from the Fundão Dam still needs to be established.

Data collection should also follow an appropriate sampling design. A hypothesis should be established, based on theoretical grounds, and then an experiment should test it. In the case of the Fundão Dam collapse, assumptions are made that any environmental changes can be linked to the Fundão Dam failure. The process has therefore become a matter of **using the monitoring data to extract evidence of impacts**.

This can be done in two ways:

- Comparison with a reference situation in the past (diachronic comparison)
- Comparison with a reference situation in the present (synchronic comparison)

Both should be accompanied by the appropriate statistical analyses, which should support the conclusions. Comparison with a reference situation or environmental standards, such as sediment quality guidelines, may help to extract evidence of impact, but generally speaking this approach is incapable of substantiating the impacts identified.

One frequently-used approach to test hypotheses with experimental data is BACI – Before-After/Control-Impact. This technique measures the variables of interest at two types of places: those which are subject to specific alterations or impacts and those which are not (Runde et al., 2021).

The three questions below can help to identify the impacts:

1. Was the monitoring designed to test the hypothetical impacts?
2. Does the monitoring data show evidence of environmental change?
3. Is evidence of change also evidence of impact?

Environmental changes are always relative to a state or condition supposed unaffected by the phenomenon under investigation. The unaffected condition might be the prior state (pre-dam failure) or the state of a similar area undisturbed by the given phenomenon. Environmental changes entail modifications either to the state of a component such as benthonic communities or estuarine bottom sediments, or modifications to a natural process. One example of the latter is described by Queiroz et al. (2018) who observed that the bioavailability of trace metals was initially lower in the Rio Doce estuary soils, but when a sediment layer rich in iron oxides is deposited then the subsequent plant growth increases organic matter and this stimulates the reduction of iron oxides and consequent release of trace metals into the water body (aqueous phase), making them bioavailable. In this case, tailings have therefore modified the estuarine biogeochemical processes.

Environmental impacts are the consequences of human actions that modify natural or social processes (Sánchez, 2020). A causal relationship must always be established between an action and its consequences (or impacts) for specific environmental receptors or components (Perdicoúlis & Glasson, 2009, 2012). In an *ex ante* impact assessment, it is necessary to associate possible impacts to the activities that will be developed in a project. In *ex post* assessments, a detected environmental change needs to be associated to the phenomenon under investigation for changes to qualify as environmental impacts.

Thus, evidence of environmental change should be obtained and then tested to check whether it corresponds to evidence of an environmental impact. To transform evidence of change into evidence of impact, it must be associated with the phenomenon under investigation. In the case of the Fundão Dam failure, any changes detected empirically should be associated either to the ***presence or dispersion of tailings***, or to the ***remobilisation of pre-existing sediments carried with tailings from the river channel, banks and floodplain***.

Causal relationships are built on the basis of logical associations. They can be represented graphically, through interaction networks, or with descriptive causal diagrams (Perdicoúlis, 2016; Sánchez, 2020; Voegeli et al., 2019), using illustrative diagrams (for example, Queiroz et al., 2018) or described in narrative form (Eccleston, 2000). They must always be based on a theory or concept.

Regardless of how it is described, a logical association produces a ***hypothetical*** impact. Monitoring may detect changes, but in the absence of theory it becomes more difficult to confirm that these changes should be interpreted as impacts.

To facilitate the task of demonstrating evidence of impact from the monitoring data, the process should be well documented to render it transparent and traceable. A two-phased approach is recommended. First, establish the causal relationships and describe or characterise the impacts. Then, determine the significance of each impact to prioritise the mitigation measures. The following sections present recommendations on both steps.

7.2 Identifying and characterising impacts

Building on the ideas above and the collection and analysis of data so far, the following approach is suggested to structure the identification and characterisation of impacts. The Panel proposes that a synoptic table is used to register the impacts, their characteristics, and the sources of evidence (Table 5). The next section outlines recommendations for assessing the significance of these impacts.

Interpreting the field data to complete the synoptic table will require experts from different disciplines to collaborate. In addition to experts from the different natural and social sciences, the Panel strongly recommends the inclusion of professionals with training or experience in impact assessments. The table should represent the best available knowledge. Successive versions can be updated as new data is collected and interpreted.

To make it easier to visualise the information, a synoptic table can be prepared for each affected environment: estuarine, coastal, and marine. The table has fifteen columns, as described below. In several ways, it is similar to the Rio Doce Panel's previous proposal (Sánchez et al., 2018). One of the main differences is that this version emphasises the need to document how the impacts were identified, being explicit about the types and sources of evidence used, as well as the degree of confidence in confirming that the environmental changes are associated with the dispersion of tailings or the remobilisation of sediments.

I. Affected component. The choice of components follows criteria similar to those for *ex ante* assessments. High levels of aggregation, such as "impacts on fauna", should not be used. Instead, the question should be ***what was – or may have been – affected by the presence or dispersion of tailings or the remobilisation of sediments?*** It may be convenient in the first place to divide this into the type of environment affected – estuarine, coastal, or marine – and this requires determining the boundaries of these environments.

Components can be further divided into subcomponents. In fact, dividing them into subcomponents may make it easier to interpret the table contents. An excessive level of aggregation makes it harder to characterise the impacts and to select the indicators.

II. Impact. It is important that impacts are described in concise and precise expressions. The impact title must give a synthetic description of the change and its meaning (such as "degradation of ...", "increase in ..."). An impact title might be "increased concentration of metals in fish muscles", for example. This concise statement must be entered in the table. However, it must be detailed or explained in order to be fully understood. For instance, further detail should be provided about which metals were detected in which fish species.

Aerial image from October 2017 of the area affected by the Fundão Dam failure, in Mariana, Minas Gerais.

It is also important to know the size of the increase (magnitude of the impact), where it was detected (area affected) and how long it lasted (impact duration). These three characteristics are attributes used to describe the impact and must be entered in other columns of the table. It might also be useful to have a narrative, which explains the impact.

Care should be taken that the title describes *what* (is believed to have) *happened with the component*, and not what was measured in relation to this component. As such, a title such as "alteration in a given index" is not the most appropriate to describe an impact. Although there is no standard way to name an impact, Ibama (2020) and Minambiente (2021) suggest a consistent terminology that can be useful as a first approach.

III. Type of evidence. In an *ex post* review, evidence of impact can be obtained in two ways:

- **Empirical evidence**: impact detected through monitoring and/or experimentation.
- **Logical association**: potential impact not verified empirically, but logically associated with the dispersion of tailings and/or perceived by professionals or local communities. A logical association may be backed by field observation or comparison with a pre-disturbance condition, including comparison based on local knowledge.

Empirical evidence is stronger than logical associations, but this latter should by no means be neglected in retrospective impact assessments. There may be several reasons that make it impossible to obtain empirical evidence. For example, errors might have been made in the sampling design, collection, or analysis (Lindenmeyer et al., 2022). Or the impact might no longer have been detectable when the monitoring started, either because the impact was short-term or because there was in fact no impact.

In the *Deepwater Horizon* case, the category used for impacts that were not studied was "scientific inference". This was understood to mean "the process of using data, observations, and knowledge to reach reasonable conclusions about things that may not have been directly observed." (NOAA, 2016). Scientific inference is equivalent to logical association.

IV. Source of evidence. This column can be filled in with information about how the impact was evidenced. Empirical evidence can come from one or both of the following:

- **Diachronic comparison**
- **Synchronic comparison**

If the source is logical association, this expression could be inserted in the column, and preferably complemented in the text with succinct explanations of the association.

V. Impact pathway. A brief description of the causal relationship between the impact identified and the tailings should be provided to describe *how* the presence or dispersion of the tailings or remobilisation of sediments from river stretches through which the tailings were carried affected or may have affected the environmental component in question. A causal diagram can be used to illustrate the pathway.

VI. Other past or present actions that affect the component. Impact assessments which focus on environmental components are cumulative impact assessments. They must, therefore, consider other anthropic actions and natural processes that influence the selected component. For this study, it should be possible to indicate briefly the main past and present actions that may contribute or have contributed to environmental changes, characterised as impact for the purposes of this assessment.

VII. Degree of confidence in the association. This column describes the degree of confidence in the association, or linkage, between the detected environmental change and the disturbance, in this case, the presence or the dispersion of tailings or sediments in the coastal and marine areas. The purpose of assigning a degree of confidence is to assess the quality of evidence for its subsequent use in decisions about mitigation.

The degree of confidence can be classified by type of evidence (empirical or logical association) using a qualitative scale. For empirical evidence, the degree of confidence should be assigned based on (i) interpretation of the monitoring results; (ii) agreement between different sources of evidence; and (iii) judgement about the adequacy of the monitoring. The following scale is suggested:

- **Demonstrated**: the monitoring data, which have been duly interpreted using appropriate statistical support, demonstrate causality between the dispersion of tailings or remobilisation of river sediments and the detected environmental change; the causality is documented in different literature sources, especially in peer-reviewed sources; the monitoring methods and procedures are adequate and have been accurately described.

- **Likely**: the monitoring data, which has been duly interpreted using the appropriate statistical support, indicates that the dispersion of tailings or remobilisation of river sediments may have caused the detected environmental change; causality is not documented in all the sources consulted, particularly in peer-reviewed sources and different sources feature discrepant results; the monitoring methods and procedures are adequate and have been accurately described.

- **Unlikely**: the monitoring data, which has been duly interpreted using the appropriate statistical support, indicates that the dispersion of tailings or remobilisation of river sediments may have caused the detected environmental change; although causality may have been suggested or documented in some sources, particularly peer-reviewed sources, there are discrepant results between sources; additionally, the monitoring methods and procedures are questionable or not fully and adequately described.

The analysis can conclude that an **impact** was **not found**, provided that monitoring data have been duly interpreted, and possible causality was investigated using an appropriate sampling design. Additionally, the analysis can be **inconclusive**, as will be discussed below.

Impacts identified through logical association should also be assigned a degree of confidence. It should be expected that in any *ex post* impact assessment, statistically significant data will not be obtained for most impacts, thus requiring confidence to be evaluated based on other criteria. Logical associations are built upon knowledge of ecological processes and can mobilise both scientific and local knowledge, and a combination of theoretical reasoning and field observation. For example, fishers can make comparisons between the pre- and post-disturbance condition of fisheries or another valued resource. A perceived change can be jointly evaluated by experts and knowledgeable local people and causal diagrams can be used to formalise an association. The robustness of logical associations can be evaluated by a group of experts using a consensus seeking technique or expert elicitation method (Hemming et al., 2018), even if those techniques were conceived for prospective studies (Filyushkina et al., 2018). A two- or three-level qualitative scale can be used to rate the degree of confidence in the logical association between the disturbance and an impact, such as high, moderate, and low confidence.

As such, the degree of confidence in the association depends on how much the sources are trusted, making professional judgement inevitable, including about the soundness of the statistical treatment applied to the monitoring data. If the sources diverge, then the greatest degree of confidence should be attributed to evidence obtained through monitoring and documented in peer-reviewed sources, particularly articles published in journals with selective publishing policies. This is not to say that unpublished reports are not to be trusted. Professionals involved in report preparation may not be interested or do not have time to submit manuscripts to academic journals, or a submitted manuscript is still under review when impacts are being assessed.

Figure 2 shows a sequence of questions that can help to establish the degree of confidence in an association between a change detected and its cause, meaning in this case the presence or dispersion of tailings or the remobilisation of sediments in the stretches of river through which the tailings were carried. Both sources of evidence – monitoring and logical association – are classified.

Using the scheme proposed in Figure 2, one can reach the conclusion that there is no evidence of impact. Furthermore, the analysis can also prove to be inconclusive either because of inadequate sample design or because of practical problems in sampling or analyses. These latter problems might include a loss of samples or the inability to access sampling sites.

In other areas where evidence-based actions are recommended, such as decisions on human health (Ministério da Saúde, 2015) and business administration (Baba & HakemZadeh, 2012), assessments about the quality of evidence are also required. Used in healthcare, the GRADE system classifies evidence into four levels – high, moderate, low, very low. The classification is based on the levels of confidence in the different information sources and other factors that may increase or decrease the evidence quality (Guyatt et al., 2008).

This approach proposed here assesses the quality of evidence based on the levels of confidence in the sources and the extent to which the data has received the appropriate statistical treatment (Figure 2). This column of the synoptic table should include a short explanatory text about the team's reasoning, using the questions in Figure 2 as support.

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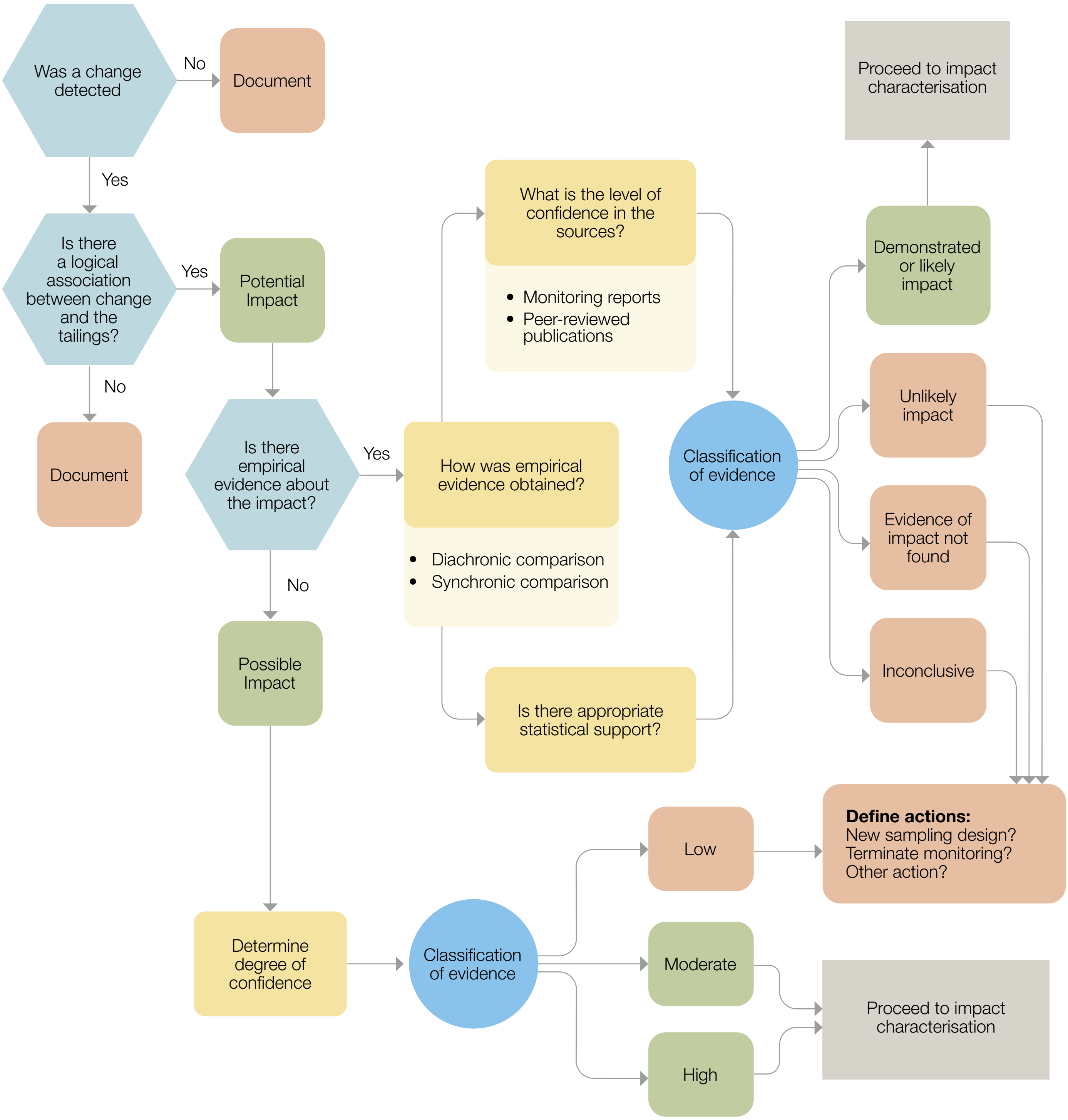
Encounter of the Piranga River with the Carmo River, originating the Doce River, affected by the rupture of the Samarco mining company's tailings dam, in Minas Gerais. Image from July 2016.

Figure 2 – Flowchart to classify the degree of confidence in the association between an environmental impact and the source of disturbance



The flowchart features three possible outputs from empirical evidence: (i) an impact has been demonstrated or showed to be likely, (ii) no evidence of impact was found, or (iii) it is not possible to reach a conclusion. In the first case, if an impact has been documented, the analysis should proceed to characterise and assess the impact. If evidence was not found, in principle no further action would be necessary, but it should be noted that "no evidence found" is different from "absence of impact". A finding of no evidence can result from poor sampling design or because the impact was of short duration and can no longer be detected, or because no effect was measurable. Finally, even after a long monitoring period, it is still possible to be inconclusive. It is conceivable that certain situations will always be inconclusive no matter how many studies are done, and a decision on possible termination of monitoring should be made.

VIII to XII. Impact characterisation. Once an impact has been identified, it needs to be described, according to pre-established characteristics. Three fundamental attributes (or characteristics) are used to describe environmental impacts: magnitude (intensity of the impact), spatial extent (the size of area in which the impact can be detected) and duration. Magnitude, extent, and duration are not independent variables. An impact is often more intense closer to its source and may tend to grow weaker with time and distance from the disturbance.

VIII, IX and X. Impact magnitude. Magnitude is a description of intensity or of "how much" an environmental component has been affected. The magnitude of an impact describes deviation from a reference condition. That is, it represents the difference between the current or actual condition and the anticipated future condition without disturbance. For simplification purposes, in *ex post* impact assessment, it is possible to assume that the anticipated future condition (also known as counterfactual) is similar or equivalent to the pre-disturbance condition.

The nature of impacts differs between distinct environmental components. Since an impact on, say, water quality is different from an impact on habitat, a specific magnitude scale should be used for each impact. Thus, if there is a need to list (and possibly compare) all impacts in order to determine their significance, then classes of magnitude should be used. When appropriate, this description should, to the extent possible, be quantitative or semiquantitative.

Nevertheless, information about the environmental component prior to the impact may be insufficient to support such quantification. In such cases, it may be enough to use a qualitative determination of magnitude, based on expert judgement. And even when it is possible to quantify an impact, it will still be necessary to assign the given values to a qualitative category. In this way, the magnitude can later be used to determine the impact significance. Note that quantification here refers to a set of three attributes – impact magnitude, spatial extent, and duration. Its significance is, by definition, a qualitative characteristic (as shown in Section 7.3).

For practical reasons, the Panel recommends a small number of magnitude classes: small, moderate, and large, for example. To transform the quantitative value of impacts into classes, thresholds between them must be established. This should be done for each impact and based as much as possible on the available literature.

Establishing defendable thresholds may be cumbersome, however. It is important to keep in mind how this operation may be used for impact assessment and, subsequently, for mitigation decisions. There may be a certain degree of uncertainty regarding the impact magnitude, extent, and duration. Any effort to establish a magnitude scale should be proportional to the knowledge available about the impact. Ultimately, whenever decisions are made on action plans where there is a high level of uncertainty about the impacts, the precautionary approach should prevail: a lack of certainty does not justify lack of action.

XI. Affected area. This refers to the spatial boundaries of the area where changes were detected. Ideally this area should be represented on a map, but adequate spatial information will not always be available. It may depend, for example, on the location of sampling stations. If preparing a map is not practically feasible, then locational descriptors could be used to fill the table. In this case, location descriptions should use well-known local names, such as "South Beach" or "Fishers Shoal".

Nevertheless, reaching defendable conclusions about the extent of an impact area can be hampered in those cases where there is no reliable control area for synchronic comparison and/or where there is a poor pre-event database to enable diachronic comparison. In such cases, details about uncertainty on the affected area and its boundaries can usefully be added to the "Other information" column.

XII. Duration. Environmental impacts can be either permanent (an example is loss of habitat due to infrastructure works) or temporary (when the affected environmental component returns to its pre-disturbance condition, either spontaneously (natural regeneration) or with assistance (through restoration measures)). Impacts can also be intermittent, occurring after periodic or occasional disturbance, including those which are linked to seasonal or pulse phenomena. However, temporary is a very broad and inaccurate description of impact duration. Would the affected component return to a previous condition after months, years, or even decades? For that reason, classes such as short term, medium term, and long term are used to characterise the duration of a temporary impact, but the boundaries between classes, in months or years, should be established.

In an *ex post* assessment, continued monitoring might show whether a certain environmental component in a given area is on the road to recovery. However, any conclusion about a return to the pre-disturbance situation requires either a deep familiarity with the situation or a baseline reference area.

In the coastal and marine areas affected by the Fundão tailings, given that the Aquatic Biodiversity Monitoring Programme started late, some of the necessary information about the impacts will likely be found in studies which precede the official monitoring or in other sources. Thus, it is possible that impacts detected in the early post-failure period are no longer detected. On that basis, it is suggested that, in the context of the assessment of the impacts in the coastal and marine areas, short-term impacts are those that have been detected before the start of the PMBA, but are no longer detected. Appropriate scales are yet to be detected for medium- and long-term impacts.

Hence, **temporary** impacts can be classified as short-, medium-, or long-term, reflecting their detected or estimated duration. **Permanent** impacts are those expected to last over a very long time period. **Intermittent** impacts are detected after a periodic or occasional event such as a flood. Although intermittence is not a description of impact duration, it is important to know if an impact has this characteristic. In such a case, its intermittent character could be noted in column XII and briefly described in column XV *Other Information*, informing about seasonality or the recurrence of impacts linked to natural processes such as ocean currents.

XIII. Level of confidence in impact characterisation. Uncertainty is always a given when determining the magnitude, area, or duration of an impact, both in *ex ante* assessments (Tennøy et al., 2006) and in *ex post* assessments. Analyses to establish some level of statistical confidence are rarely available. The qualitative scale recommended in the Panel's previous publication can therefore be used (Sánchez et al., 2019), as follows:

- **High**. The baseline is well known and provides a reference for cross-temporal and cross-spatial comparisons, where applicable. A set of data exists, which can be used as a reference to determine the magnitude, area, and duration of the impact. Deviance from the reference was estimated based on field observations or measurements, remote sensing, statistical analysis, or another well-established technique.
- **Medium**. The baseline is not well known. Impact magnitude is based on a professional opinion or other qualitative approach, including local knowledge.
- **Low**. The baseline is not well known and conflicting information exists about the magnitude of impacts.

Professional judgement is essential to qualify the level of confidence. The fundamental, and possibly unique, role of attributing the level of confidence falls on the teams involved in *ex post* monitoring. A distinction must be made between the degree of confidence in identifying an impact (that is, in attributing an environmental change to a phenomenon under investigation, column VII), and the level of confidence in characterising an impact. It might be well-established that an environmental change is associated with the tailings (impact identification), while uncertainty exists about the magnitude, area or duration of an impact (impact characterisation). When filling out the synoptic table, we advise recording the justification given by the team for the attributed level of confidence.

XIV. Sources. It is very important to record all sources used for each row of the table. Discrepancies between sources (reports, articles) should be expected due to the use of different sampling and analysis methodologies, study areas and periods, and more. To ensure traceability the records must be precise, giving details of the author and title, date, revision, page, and other information that makes it possible to consult the source. Other sources, such as documented interviews and focal groups, can also be used. But to minimise the data overload, the column should mention only the most important documents used for the analysis.

XV. Additional information. This column contains any information that helps with understanding the contents of the table. However, to make it easier to read, the Panel recommends that only the most essential information is included. The reader can be referred to other documents.

Limitations. As with all impact assessments, inherent limitations should be made explicit in the analysis. Different experts can have different confidence levels regarding association between the tailings and changes detected by the monitoring. The document should present how the conclusions in the synoptic table were reached. It should also disclose any uncertainties. The functions of the synoptic table are to synthesise information and to present the selected information categories in standard form. This is all done to facilitate the impact analysis.

Table 5 – Impact synoptic table (with examples)

I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	XIII	XIV	XV
Affected component	Impact	Evidence		Impact pathway	Other past or present actions that affect the component	Degree of confidence in the association	Impact characterisation					Level of confidence in impact characteri-sation	Sources	Other information
							Magnitude			Affected area	Duration			
		Type of evidence	Source of evidence				Indicator	Value	Class					
Estuary soils	Trace metal enrichment	Empirical	Diachronic comparison	Microbial iron reduction in estuarine soils and sediments	Several activities historically conducted in the Rio Doce basin, including mining, steelworks, and agricultural activities	Demonstrated	Concentration of Fe, Mn, Cr, Zn, Ni, Cu, Pb, Co	Short-term increase in concentration from 24 times higher (Mn) to > 200 times higher (Fe)	Large	Rio Doce estuary	Long-term [concentration will vary along time]	High	1	Highest contents generally recorded in the upper 0–3 cm layer, indicating influence of tailings
Estuary water quality	Water quality degradation	Empirical	Diachronic comparison	Microbial iron reduction in estuarine soils and sediments and consequent release of trace metals in the water column	Several activities historically conducted in the Rio Doce basin, including mining, steelworks, and agricultural activities	Demonstrated				Rio Doce estuary	Long-term	High	1	
Estuary sediments	Contamination of estuary sediments	Empirical	Diachronic comparison	Tailings carried along the Rio Doce (ref. 2, pg. 70		Demonstrated	Concentration of As, Cd, Co, Cr, Cu, Mn, Ni, Pb, Zn	Varies over time		Rio Doce estuary	Long-term, with a downward trend detected over time	High	2	
Macroalgae	Biodiversity loss and structural changes in macroalgae assemblages with increased dominance of algae more tolerant to tailings	Empirical	Diachronic comparison	Increased turbidity and its seasonal variation, increased concentration of trace metals		Demonstrated	1) Simpson's Diversity Index (J) 2) species richness of the assemblages	1) J dropped from ~18 to ~10 2) statistically significant reduction in species richness	Large	Costa das Algas Environmental Protection Area and Santa Cruz Wildlife Reserve	Long-term and intermitent	High	3	Loss of cellular integrity in macroalgae contributes to strengthening the association

Note: Examples presented for the sole purpose of illustrating the application of the proposed procedure. The authors did not conduct a detailed examination of the cited documents.

Sources: (1) Queiroz et al. (2018) (2) Gabriel et al. (2021), see Table 2 for concentration results (3) PMBA/Fest-RRDM Annual Report 2021.

7.3 Assessing the significance of impacts

7.3.1 Fundamentals

Once the impacts have been identified and characterised, the next step is to assess their significance. The mitigation actions can then be prioritised depending on their significance. Having said that, we note that for this case, the uncertainty levels of various impacts are expected to be 'average' or 'high' (see Table 5 column XIII). This is because of the difficulty in defining the magnitude, which in turn makes it harder to determine the significance of the impacts.

In *ex ante* assessments the significance of an impact is determined by combining a parameter that describes the pressure exerted by the activities of a project on a given environmental component and the importance (ecological and/or social) of that component (Gronow, 2021; Sánchez, 2020; and Sippe, 1999, among others). Intensity, duration, reversibility, probability of occurrence, social distribution and even affected area are attributes that can be combined to describe pressure. The result of this combination is sometimes called the severity of the impact, although the term "magnitude" is also used. There is no standardised terminology or methodology for assessing the significance of impacts. It must always be adapted to the context (Gibson et al., 2005, page 167), for instance when assessing the significance of environmental aspects and impacts on the activities, products, or services of an organisation, pursuant to the rules of environmental management systems (ISO, 2016, §6.1.2.5).

Certain characteristics describe impacts, such as origin (direct or indirect impacts), but are not useful in assessing significance. Some attributes, such as intensity and affected area, are not independent from each other. For example, intensity varies spatially for many impacts. Duration and reversibility are also connected.

On the other hand, the importance of an affected component or environmental resource should be determined on a case-by-case basis, that is, for each component. The importance of a component can be described using an appropriate qualitative scale of its relevance both for affected communities and for the maintenance of ecological processes or ecosystem integrity (Gronow, 2021; Sánchez, 2020), that is, the so-called social and ecological importance (Beanlands & Duinker, 1983). Legal determinations of importance, such as lists of threatened species, should necessarily be taken into account.

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Aerial view of the vicinity of the mouth of the Rio Doce

To determine impact significance, therefore, qualitative scales must be developed to reflect the severity or magnitude of the impact as well as the importance of the affected component.

It should be noted that determining significance is, by its own nature, always a **qualitative** endeavour (Lawrence, 2007b, 2013; Erlich & Ross, 2015). What can be quantified (despite not always being possible or appropriate) is the magnitude of the impact: its intensity, duration, and area of occurrence. Using weighted scales in which certain attributes have a greater weight than others to determine significance (Lawrence, 2007a) does not represent quantification, but rather a process to classify and prioritise.

7.3.2 A procedure

To develop a coherent impact assessment, one must use context-appropriate criteria. We present here an assessment procedure that can be applied to the given case, noting that there is no single way to determine the significance of impacts.

Begin by *selecting the attributes* that will be used to describe the severity of an impact. In the given example, the attributes which characterise the impacts (Section 7.2) – magnitude, duration, and affected area – combine with reversibility to form the impact *severity* (Table 6).

Every impact must be placed in a category for each of the four attributes and the following range can be applied:

- The **magnitude scale** must be established for each impact, since it depends on the context and requires the use of appropriate indicators; the magnitude should preferably be described using indicators (quantitative or qualitative) of the impact's intensity.
- The **geographic extent** must be adequately established, for instance by determining whether the impact is local or regional and defining the boundaries of such zones.
- For **duration**, a three-level scale can be used (Section 7.2 and column XII of Table 5): short term, medium term or long-term. For the purpose of determining severity, permanent impacts can be equalled to long-term impacts.
- **Reversibility** comprises two classes: reversible impact (the affected environmental component returns to its original condition or close enough either upon cessation of the causative action or through corrective measures) or irreversible impact (the component does not return to the original condition or to a condition close to it). It should be noted, however, that classifying an impact as reversible or not can be extremely challenging. If such is the case, this characteristic can be dropped from the determination of severity.

Table 6 – Key to determine the severity of an impact

<table>
<tr><th>MAGNITUDE</th><th>GEOGRAPHIC EXTENT</th><th>DURATION</th><th>REVERSIBILITY</th><th>SEVERITY</th></tr>
<tr><td rowspan="12">Small</td><td rowspan="6">Local</td><td rowspan="2">Short term</td><td>Reversible</td><td rowspan="9">LOW</td></tr>
<tr><td>Irreversible</td></tr>
<tr><td rowspan="2">Medium term</td><td>Reversible</td></tr>
<tr><td>Irreversible</td></tr>
<tr><td rowspan="2">Long-term or permanent</td><td>Reversible</td></tr>
<tr><td>Irreversible</td></tr>
<tr><td rowspan="6">Regional</td><td rowspan="2">Short term</td><td>Reversible</td></tr>
<tr><td>Irreversible</td></tr>
<tr><td rowspan="2">Medium term</td><td>Reversible</td></tr>
<tr><td>Irreversible</td><td>MEDIUM</td></tr>
<tr><td rowspan="2">Long-term or permanent</td><td>Reversible</td><td>LOW</td></tr>
<tr><td>Irreversible</td><td>MEDIUM</td></tr>
<tr><td rowspan="12">Moderate</td><td rowspan="6">Local</td><td rowspan="2">Short term</td><td>Reversible</td><td>LOW</td></tr>
<tr><td>Irreversible</td><td rowspan="4">MEDIUM</td></tr>
<tr><td rowspan="2">Medium term</td><td>Reversible</td></tr>
<tr><td>Irreversible</td></tr>
<tr><td rowspan="2">Long-term or permanent</td><td>Reversible</td></tr>
<tr><td>Irreversible</td><td>HIGH</td></tr>
<tr><td rowspan="6">Regional</td><td rowspan="2">Short term</td><td>Reversible</td><td>MEDIUM</td></tr>
<tr><td>Irreversible</td><td>HIGH</td></tr>
<tr><td rowspan="2">Medium term</td><td>Reversible</td><td>MEDIUM</td></tr>
<tr><td>Irreversible</td><td>HIGH</td></tr>
<tr><td rowspan="2">Long-term or permanent</td><td>Reversible</td><td>MEDIUM</td></tr>
<tr><td>Irreversible</td><td>HIGH</td></tr>
<tr><td rowspan="12">Large</td><td rowspan="6">Local</td><td rowspan="2">Short term</td><td>Reversible</td><td>MEDIUM</td></tr>
<tr><td>Irreversible</td><td>HIGH</td></tr>
<tr><td rowspan="2">Medium term</td><td>Reversible</td><td>MEDIUM</td></tr>
<tr><td>Irreversible</td><td rowspan="3">HIGH</td></tr>
<tr><td rowspan="2">Long-term or permanent</td><td>Reversible</td></tr>
<tr><td>Irreversible</td></tr>
<tr><td rowspan="6">Regional</td><td rowspan="2">Short term</td><td>Reversible</td><td>MEDIUM</td></tr>
<tr><td>Irreversible</td><td>HIGH</td></tr>
<tr><td rowspan="2">Medium term</td><td>Reversible</td><td>MEDIUM</td></tr>
<tr><td>Irreversible</td><td rowspan="3">HIGH</td></tr>
<tr><td rowspan="2">Long-term or permanent</td><td>Reversible</td></tr>
<tr><td>Irreversible</td></tr>
</table>

Source: Rio Doce Panel

The severity of each impact is then combined with the degree of importance and vulnerability of each environmental component as shown in Table 7, thus classifying the relevance of the impact.

Relevance is classified according to a three-level scale: impact of low significance, moderate significance and significant. Insignificant can also be used as a category, but exclusively for low-severity impact. To determine relevance, severity is combined with the vulnerability of the affected environmental component and with its importance, both of which are qualitatively assessed according to the key in Table 7

Table 7 – Key to determine the significance of an impact

IMPACT SEVERITY	VULNERABILITY OF THE COMPONENT	IMPORTANCE OF THE COMPONENT		
		LOW	MEDIUM	HIGH
Low	Low	Insignificant	Insignificant	low significance
	High	Insignificant	low significance	moderate significance
Medium	Low	low significance	low significance	moderate significance
	High	moderate significance	moderate significance	moderate significance
High	Low	moderate significance	significant	significant
	High	significant	significant	significant

Source: Rio Doce Panel

The vulnerability of the affected environmental component represents the degree to which an environmental component is susceptible or sensitive to the disturbances under investigation. Thus applied, vulnerability is an intrinsic characteristic, and each component should be assessed by professional judgement based on scientific knowledge. Vulnerability can be classified in a simplified manner with a two-level scale: high or low. An intermediate class can, of course, also be used. This classification can be performed by a group of experts on each subject, using well-established criteria such as the Delphi technique.

The following scale can be used to qualify the level of importance of the environmental component affected:

- **High**: component is covered by a legal requirement, or is otherwise important for maintaining the integrity of the ecosystem, or for the community well-being.
- **Medium**: component valued by the community or considered technically important for maintaining the integrity of the ecosystem or community well-being.
- **Low**: in the local context, this component is less important.

The importance of a component can be determined based on scientific criteria or social criteria, or a combination of both. Its scientific importance should be determined by a multidisciplinary team applying professional judgement and a well-founded justification. For the purpose of its application to the *ex post* assessment of impacts, social importance can mainly be determined indirectly, through the duly contextualised professional interpretation of information from sources such as the diagnostic assessment, news published in the press, and public manifestations by citizens or associations.

8. Towards a plan of action for the affected coastal and marine areas

9 October 2018
Renova Foundation | Expedition Caminho da Reparação
Aerial view of a sunrise near the mouth of the Rio Doce

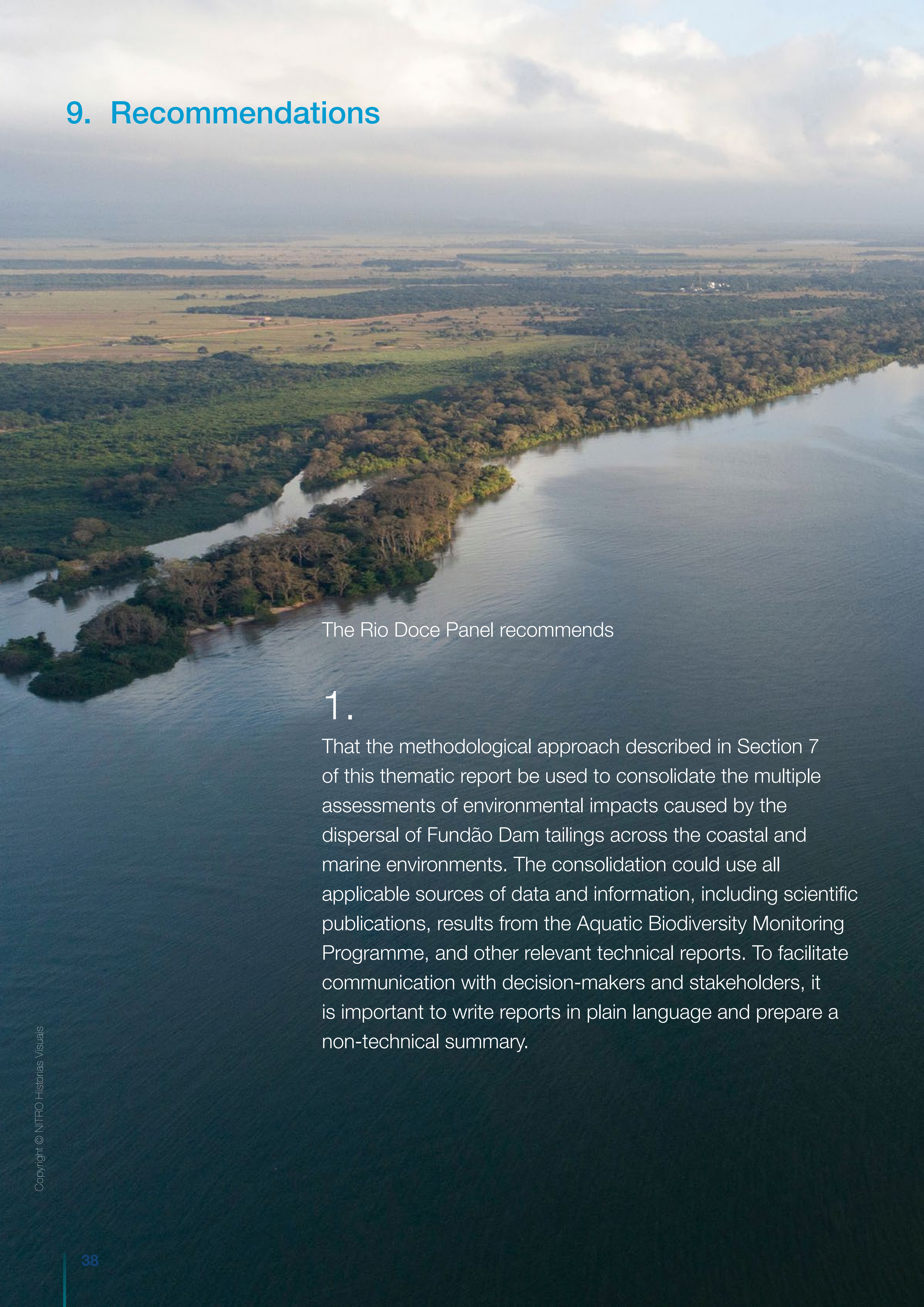
Once the assessment studies are complete, it cannot be forgotten that the marine and coastal areas will continue to be affected by the remaining tailings present in the upper and middle basin. Although there are different interpretations of the effects the tailings have had on the ecosystems, the coastal and marine areas cannot be analysed in isolation.

In this context, it is important to emphasise that the Rio Doce Panel has consistently stressed the need to adopt the combined view of the source-to-sea framework (Granit et al., 2016) and the landscape approach to integrate water quality and biodiversity conservation as affected by social, economic, cultural, and environmental aspects (Brito et al., 2021).

It is often difficult to assign specific responsibilities for the cumulative impacts caused by multiple historical and contemporary factors – for example the historical impacts of mining, steel making, dam building and deforestation in the Rio Doce basin or the recent impacts associated with the construction of ports and industrial enterprises along the Espírito Santo coastline.

In practice, this means that the programmes to mitigate the impacts of the disaster will have to respond to the broader underlying causes, rather than trying to manage specific impacts on the biota through palliative efforts and/ or compensatory programmes.

However, published studies – some of which are referred to in Section 5 – describe impacts from the tailings spill in coastal and marine areas. In addition, there is concern about possible recurrent impacts during periods of flooding, when the tailings that were deposited in the bed of the river, on the floodplain and in the reservoir of Candonga are washed downstream as part of the sediment load that is carried to the Rio Doce estuary, the coastal area and the sea, and which can eventually be deposited on the coast and coastal platform.



9. Recommendations

The Rio Doce Panel recommends

1.

That the methodological approach described in Section 7 of this thematic report be used to consolidate the multiple assessments of environmental impacts caused by the dispersal of Fundão Dam tailings across the coastal and marine environments. The consolidation could use all applicable sources of data and information, including scientific publications, results from the Aquatic Biodiversity Monitoring Programme, and other relevant technical reports. To facilitate communication with decision-makers and stakeholders, it is important to write reports in plain language and prepare a non-technical summary.

2.

That Renova Foundation, preferably in agreement with CIF and relevant stakeholders, establish a database associated with an information management system to follow-up the impacts identified. Such a database should be continuously fed back and updated to register time-series data and any possible measurable outcomes of an impact mitigation plan, once it is established by the authorities. Follow-up would support periodic revisions of the list of impacts and communication of actions and outcomes to all interested parties.

7 September 2020
Renova Foundation | In the image, parts of the Rio Doce estuary in Linhares.

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