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Management of waste from extractive industries: The new European reference document on the Best Available Techniques

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ABSTRACT

The impacts from an inappropriate management of extractive waste may endanger the environment or human health and even result in disasters. The Best Available Techniques (BAT) Reference Document for the Management of Waste from Extractive Industries provides up-to-date information and data on the management of extractive waste and a list of BAT to prevent or reduce any related adverse effects on the environment and human health. The elaboration of BAT constituted a major challenge due to the vast diversity in extractive waste activities, sectors, geography, climatic and site specific conditions in Europe. These all influence the resulting emissions to soil, water and air. The application of a risk-specific approach has enabled reflecting this diversity and adapting the deployment of techniques according to an evaluation of the environmental risks and possible impacts. Based on this evaluation, generic and/or risk-specific BAT are identified as cornerstones for setting performance objectives and managing risk.

A key priority for this reference document was safety. On the one hand, this was addressed by risk-specific BAT on structural stability, including approaches for design for closure and integrated design. On the other hand, BAT were identified to help ensuring the physical and chemical stability of extractive waste and the reduction of dangerous substances. The re-use and recycle of excess water and waste hierarchy principles were also analysed as central elements towards a circular economy. The monitoring of this reference document implementation will support the continuous learning and the international developments in extractive waste management and related BAT.

1. Introduction

The extractive industry as a whole plays a crucial role in the economic and societal development of Europe (EC, 2008, 2013). Mineral resources are commonly grouped into fossil fuels, metalliferous ores, industrial minerals and construction minerals and all play an important role in Europe's economy. The sector as whole counts more than 17500 companies, employs more than half a million people and generates more than EUR 200 billion turnover (Eurostat, 2015a).

Nevertheless, the extraction of mineral resources also generates important amounts of extractive waste. This can vary from a few kilograms of extractive waste per tonne of product in the case of peat or clay, for example, to several millions tonnes of extractive waste per tonne of product in the case of gold (BRGM, 2001; EC-JRC, 2009; IAI, 2015; Spitz and Trudinger, 2008). In total, about 550–750 Mt of extractive waste are generated in the EU every year (Eurostat, 2015b). In any case, the waste generated will require appropriate management. This is usually done by accumulation or deposition of extractive waste in dedicated areas, including installations known as Extractive Waste Facilities (EWFs) (e.g. ponds or heaps). The EU-28 has about 9700 EWFs that are in operation, in the process of being closed, or abandoned (EC, 2016; Garbarino et al., 2018). About 200 EWFs out of these 9700 have been reported to be classified as Category A, i.e. those facilities whose failure or incorrect operation could give rise to major accidents or those that contain hazardous waste or substances classified as dangerous above certain thresholds, according to the criteria listed in the Extractive Waste Directive (EWD; Directive, 2006/21/EC) (EC, 2006) and related Commission Decision 2009/337/EC (EC, 2009). The costs related to the design, construction, maintenance, closure and rehabilitation of these areas may be significant. Lessons learned from the past show that, while extractive projects are synonymous with economic growth and jobs, possible negative impacts on the environment and human health might

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be generated by extractive waste management activities. In some extreme cases, failures and accidents have caused environmental devastation and human health deterioration, including casualties (Bowker and Chambers, 2017; Chambers and Bowker, 2019; Rico et al., 2008b; Roche et al., 2017; WISE, 2019).

To avoid these issues, many efforts have been made in the last few decades by several players in the extractive industry to prevent, reduce and minimise the negative impacts from the management of extractive waste, by deploying new management strategies and technologies. Furthermore, minimising the environmental impacts contributes to improving the social perception and acceptance of mineral resource extraction. In that context, the Best Available Techniques (BAT) Reference Document for the Management of Waste from Extractive Industries (MWEI BREF) (Garbarino et al., 2018) plays an important role. BAT are defined as *the most effective and advanced stage in the development of activities and their methods of operation which indicates the practical suitability of particular techniques for providing the basis for emission limit values and other permit conditions designed to prevent and, where that is not practicable, to reduce emissions and the impact on the environment as a whole* (EC, 2012). The MWEI BREF is a technical document representing the results of the exchange of information, organised by the European Commission, on BAT for the management of extractive waste and associated monitoring.

The MWEI BREF has been drawn up within the framework of the EWD, which is different from the Industrial Emission Directive (EC, 2010) framework under which most BREFs by the European Commission are developed or reviewed. In addition and in line with the general requirements of the EWD, the MWEI BREF is to be seen as a reference aiming at providing extractive industries, competent authorities and other relevant stakeholders with up-to-date information and data on the management of extractive waste. It supports decision makers by providing a list of identified BAT to prevent or reduce as far as possible any adverse effects on the environment and human health from the management of extractive waste, duly taking into account the technical characteristics of the waste facility, its geographical location and the local environmental conditions. Nevertheless, the techniques listed in the MWEI BREF are neither prescriptive nor exhaustive and other techniques that ensure at least an equivalent level of environmental protection may be used.

The MWEI BREF is the result of an in-depth review of the BREF for the management of tailings and waste-rock (MTWR BREF) (EC-JRC, 2009), published in 2009. One of the main reasons to review this MTWR BREF was to extend the scope from a limited number of extractive activities, concentrated on classic mines, to all extractive activities, in line with the scope to the EWD. The EWD scope includes the management of extractive waste from mines, quarries and on-shore oil and gas operations. In addition, one of the goals was to collect more information on water management and enhancing the focus on safety. This follows from the observation that - although guidance for the design, construction and closure of safe EWFs was available in many relevant guidance documents (AU DITR, 2016b; UNECE, 2014), including the MTWR BREF itself (EC-JRC, 2009) - major accidents have continued to occur in Europe and worldwide in the last decade. In Europe, events with main impacts were, e.g. the dam failure in Kolontár, Hungary in 2010 or the leakage of mine water at the Talvivaara mine, Finland in 2012 (WISE, 2019). Not only an inappropriate EWF design, but also the inappropriate management of extractive waste during operation can be catastrophic. Prevention measures and correct management tools are usually less costly than remediation (Garbarino et al., 2018; Orman et al., 2011).

2. Materials and methods

The review process of the MTWR BREF centred on the exchange of information between a Technical Working Group (TWG) consisting of stakeholders from the extractive industries, civil society and EU Member State representatives. It was carried out following the provisions of what is known as the "Sevilla process" (EC, 2012). This process aims at reaching consensus based decisions on what can be considered BAT, known as the BAT conclusions, through an iterative process. This involved the identification of key environmental issues encountered in the management of extractive waste and the examination of the most relevant techniques to address pollution. The examination included an assessment of the final levels of pollution achieved following application of different techniques, known as environmental performance levels, and the conditions under which these levels were achieved. Furthermore, the BAT conclusions contain information on techniques to monitor pollution.

The review process started at the end of 2013 and the MWEI BREF was published in December 2018. The following main sources of information were consulted for the review: (i) general data and information provided by the TWG, together with scientific and technical literature (consultation of more than 2000 books, reports, publications and standards, all published and shared until September 2017); (ii) site-specific data and information reported by operators via dedicated questionnaires; (iii) expert input by the TWG members (including about 2500 comments on draft documents); and (iv) information and data gathered from site visits.

Data and information were collected from different extractive waste management sites in Europe using the above mentioned questionnaire developed for that purpose.

On the one hand, the questionnaire aimed at specific information on the extractive waste, the EWF and the adverse effects on the environment and human health. On the other hand, it included questions to collect contextual or site-specific information.

Specific questions on the extractive waste included questions on the characteristics and management of the extractive waste, e.g. the treatment of extractive waste prior to or after deposition if any, the composition of the extractive waste, and the leaching properties and other characteristics of the extractive waste before and after treatment, e.g. mixing of acid generating extractive waste with limestone or alkaline materials, destruction of cyanides from the slurried tailings, removal of caustic soda from red-muds using filter presses or thermal treatment of drilling muds to remove oil. In addition, the specific questions on the adverse effects on the environment and human health encompassed questions on (i) safety and structural integrity of the extractive waste facility; (ii) emissions to soil and groundwater, emissions to surface water and emissions to air along with information on pollution prevention and control techniques possibly applied to reduce emission levels; (iii) consumption of energy, usage of water and consumption of reagents, auxiliary materials and feedstock; and (iv) noise and odour disturbance.

Site-specific information including the geographical location, technical characteristics and local environment of the EWF was also requested. Detailed questions on the type of EWF, its confining structure, the waste transport and delivery, the water management, the prevention of erosion, the planned closure and after-closure, and the land-use, the visual impact and the measures to protect biodiversity were included. It also included additional questions to capture some contextual information such as the vicinity of specific areas and water bodies and climate conditions, i.e. qualitative and quantitative indicators reflecting annual temperatures, precipitations, evaporations and wind conditions. Climate condition data helped defining the BAT applicability rules, particularly in the case of restrictions, such as for dry stacking that may be restricted in the case of wet climatic conditions, or for water spraying restricted in the case of limited water availability and cold climate. In addition, questions on the origin of the extractive waste were also included, e.g. the type of mineral resources extracted, the type of deposit, the type of extractive method, and type of mineral processing when relevant. The questionnaires targeted different types of EWFs, e.g.: land based heaps or ponds, oil and gas specific surface and underground waste facilities.

Finally, operators had the possibility to provide, through the questionnaire, a detailed description of techniques they consider BAT candidates in a so-called 10-headings structure (EC, 2012).

3. Results

3.1. Data overview

In total, 87 questionnaires were collected from different sites located across the EU, Norway and Turkey (35 for the metalliferous ores sector, 28 for the industrial and construction minerals sector and 24 for the energy sector). The questionnaires were distributed to sites selected by the Technical Working Group (TWG) and considered as representative of the sector and well performing. In Europe, the 17500 companies operate some 30000 extraction sites (mines, quarries or on-shore oil and gas exploration and production sites) and about 10000 EWFs, therefore the 87 questionnaires cover only a minor number of these 10000 sites (~1%). However, these sites were selected by the TWG as representative. When it comes to the mineral resources, on the one hand, the 87 selected sites cover most of the major mineral resources extracted in Europe (~80%); on the other hand, not all sites provided detailed data on consumption and emission levels, which in return limits the representativeness of the data presented.

Most of the operators (62 out of 87) reported heap- and/or pond-type EWFs. Almost half of the ponds were classified as Category A, whereas for heaps this ratio was 3% only.

A majority of operators reported consumption data, but less than a half of them reported data on emission levels to air, soil and groundwater or surface water. As for emission to air, no stack emissions were identified. Only diffuse emissions were reported, mainly dusting, and the distinction on the origin, i.e. the extractive waste management or the extraction itself, was not possible. Emissions to soil and groundwater resulting from the management of extractive waste are usually also diffuse emissions such as seepage from extractive waste. Finally, data on emissions to surface water includes batch and continuous direct discharge of excess water in one reference year. Operators had the possibility to report the total volume discharged, as well as the concentration of different pollutants in the influents (before treatment) and effluents (after treatment). The questionnaire aimed at collecting minimum, maximum, average and median levels.

Finally, it should be noted that the site specific data, collected with these questionnaires, report exemplary achieved performances using specific techniques from a wide range of extractive waste management operations. These data cannot be generalised for all installations, but serve as indicative performance levels, while reflecting the extractive

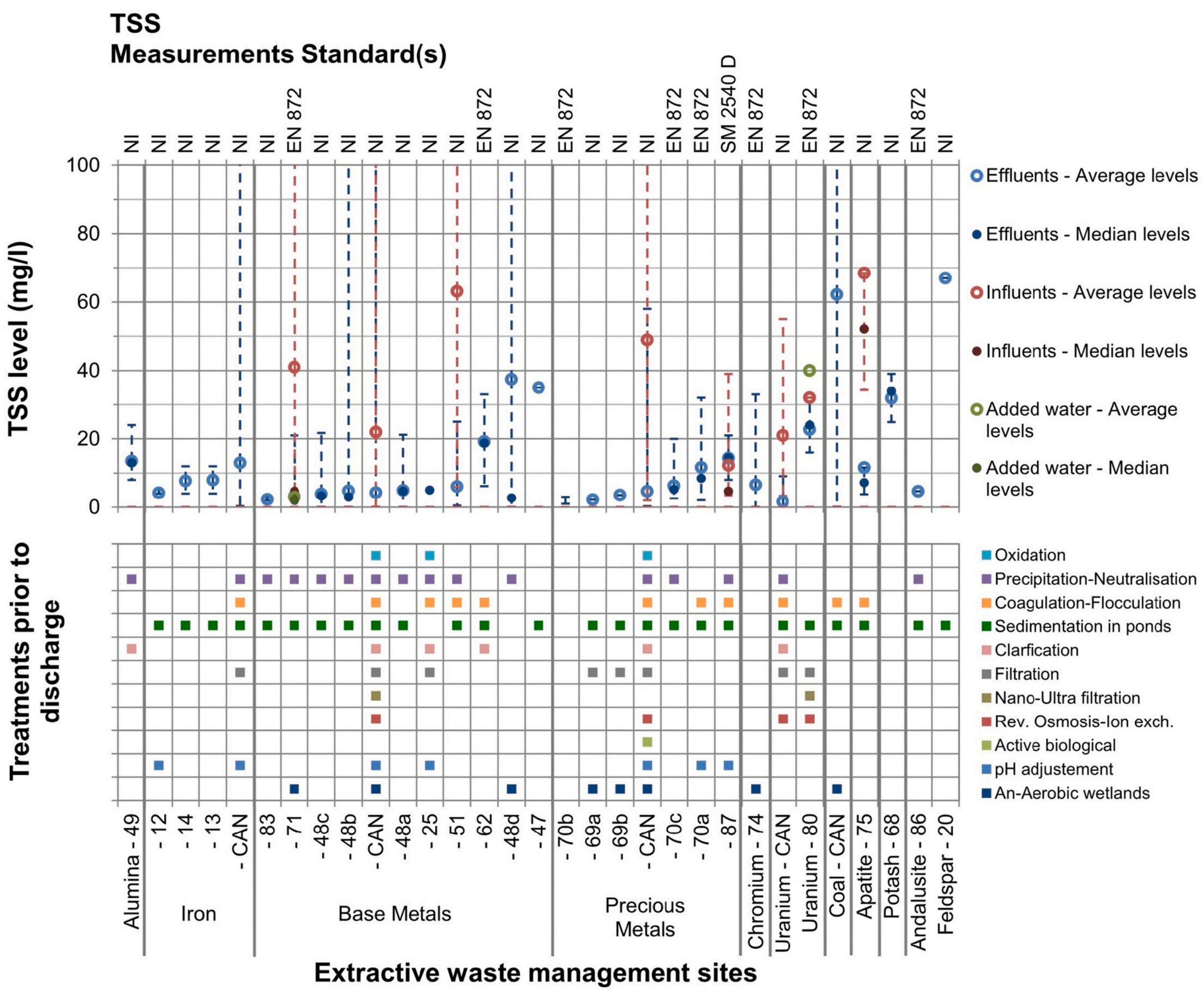

Fig. 1. Annual TSS levels and contextual information reported by operators (site numbers indicated) and supplemented with literature data related to sites in Canada.

waste characteristics, the technical characteristics of the EWF, its geographical location and the local environmental conditions.

Data on Total Suspended Solids (TSS) are some of the most provided data by operators and as such represent a good example of what the questionnaire aimed for. The data collected and provided by operators are presented in Fig. 1. The figure shows that 21 operators (24%) reported data on emission levels of Total Suspended Solids (TSS). Data were supplemented with literature data extracted from a Canadian study (MEND, 2014). Yearly averages, minima and maxima for certain pollutants in influents and effluents sent to tailing ponds have been extracted from this document for a number of mineral resource categories: base metals, precious metals, iron ore, uranium and coal. When possible, these data were presented along with the data collected with the questionnaires. However, it is important to note that the Canadian study included as far as possible data from all the sites and did not focus necessarily on well or best performing ones. This may help explain why the min-max ranges reported from this study are broader than the ones from the EU questionnaire. Five operators provided data on levels of TSS in both influents and effluents. Two operators provided data on TSS levels in added water. Therefore, it was not always possible to estimate the removal efficiency. In addition, the measurement standard used was reported by 7 operators. Some operators reported several discharge points indicated with a letter a, b, c, and d. When reported by operators, maximum, average, median, and minimum levels are plotted on Fig. 1 for the influents (EWF input stream), effluents (EWF output stream) and added water (EWF additional input stream such as mine water). Maximum levels above 100 mg/l levels are not visible on the plot.

In addition to emission levels, Fig. 1 presents the different treatment techniques of Extractive Waste Influenced Water (EWIW) prior to discharge, including BAT candidates. Some operators did not report any treatment of water prior to discharge, whereas others usually reported a combination of techniques. Data from literature refer to average levels calculated from different sites in Canada and therefore all the treatment techniques applied at different sites are reported.

3.2. From data to BAT

3.2.1. Challenges in translating data into BAT

Differently from Directive (2010)/75/EU on industrial emissions, which applies to activities reaching certain capacity thresholds, the EWD does not define any thresholds. Accordingly, the MWEI BREF should apply to the management of extractive waste from any extractive activity, ranging from small quarries to large metal mines and including on-shore oil and gas exploration and production.

EWFs and extractive waste management may vary significantly from one sector to another, or from one region to another. The management of extractive waste from oil and gas exploration and production, alumina production or dimension stones extraction represent three very different examples of mineral resources extraction where the operator will have to face different issues and challenges. Additionally, the management of extractive waste in Nordic countries also has different constraints compared to Mediterranean countries because of the different climates. Nevertheless, all these operators share the same objective: to ensure the short-term and long-term safe and environmentally responsible deposition of extractive waste, including chemical, physical and mechanical stability over time, in order to prevent any accident and to minimise emissions that could have a negative effect on the environment and/or human health.

Another relevant issue is related to the site-specific conditions, which influence both the extraction and treatment of mineral resources and the management of extractive waste. More specifically, the geological characteristics of the deposit constitute the determining factor in the choice of extraction and mineral processing methods. These influence the method selected for the management of extractive waste, together with the extractive waste characteristics, the technical characteristics of the EWF, its geographical location and the local environmental conditions. Climate changes including extreme weather events may greatly influence and increase complexity in the extractive waste management.

Emissions to soil, water and air are also complexly related to the site-specific conditions, including the geological background, the techniques applied to prevent or minimise them and the other activities carried out on site. Furthermore, differently from emissions to surface water where point sources are identifiable, emissions to soil, groundwater and air resulting from the management of extractive waste are usually diffuse emissions, encompassing also fugitive emissions (e.g. seepage, leakage or fugitive emissions of gas or volatile organic compounds).

Moreover, at most sites, extractive waste management is usually part of the overall ore extraction or oil and gas drilling operation and the possible treatment of minerals. Often, emissions are associated to all the above mentioned activities and they cannot be linked directly to the management of extractive waste only. This is for instance the case for dusting from blasting and mineral processing as well as from the management of the related extractive waste.

Some of the potential impacts on the environment and human health can also be reduced substantially by considering the whole life cycle of the EWFs from the very beginning. This comprises the planning and design phase, the operational phase, and the closure and the after-closure phases. It has therefore to be specified in which life cycle phase the BAT apply. An overview of the main challenges is shown in Fig. 2.

3.2.2. Towards a risk-specific approach

Due to the wide variety of sectors and related potential environmental issues to be considered in the BAT conclusions, a sector-specific approach, previously applied in the MTWR BREF, was abandoned in favour of a risk-specific approach. This was particularly based on the TWG experts' feedback, who greatly supported applying this change within the MWEI BREF. The risk-specific approach is based on rigorous risk assessment and management principles to evaluate the potential impacts of an EWF along the whole life cycle. Apart from the extractive waste management (AU DITR, 2016b; Golder and Associates, 2016; ICMM, 2016; IRMA, 2018), these principles have also been applied to mining and post-mining activities (AU DITR, 2011, 2016a; IRMA, 2018; MAPAMA, 2016). This approach aimed at adapting to the diversity of extractive waste types, sites and operators, at focusing on key environmental issues and at covering a broad range of potential risks to be considered by operators responsible for the management of extractive waste. Apart from changing the sector-based approach previously applied in the MTWR BREF, the novelty introduced in the MWEI BREF consisted not only of focusing on the risk assessment overarching principle, but of deploying the BAT as the basis for setting performance objectives and managing risk.

Risk assessment provides an improved understanding of the risks that could affect the achievement of the objectives, and of the adequacy and effectiveness of the controls/monitoring already in place. This in turn provides a basis for decisions about the most appropriate approach to be used to treat the risk. The Environmental Risk and Impact Evaluation is therefore a key part of the management of all the life cycle phases of the extractive waste management (EC-DG ENV, 2011; EC, 2016; ICMM, 2016; ICOLD, 2011a; MAPAMA, 2016; Rico et al., 2008b; Roche et al., 2017).

An appropriate and comprehensive Environmental Risk and Impact Evaluation considers the full spectrum of hazards and risk elements, including source-pathway-receptor linkages, for a given extractive waste management site. It is based, among others, on information related to the initial characterisation of extractive waste, the extractive waste site options and the extractive waste management options, which includes handling/transport, treatment and deposition alternatives. It is adapted to the site-specific conditions. The relevant principles of the ISO standards on risk management are taken into consideration (ISO, 2009a, b, c), prioritising environment, human health and safety. Furthermore, it

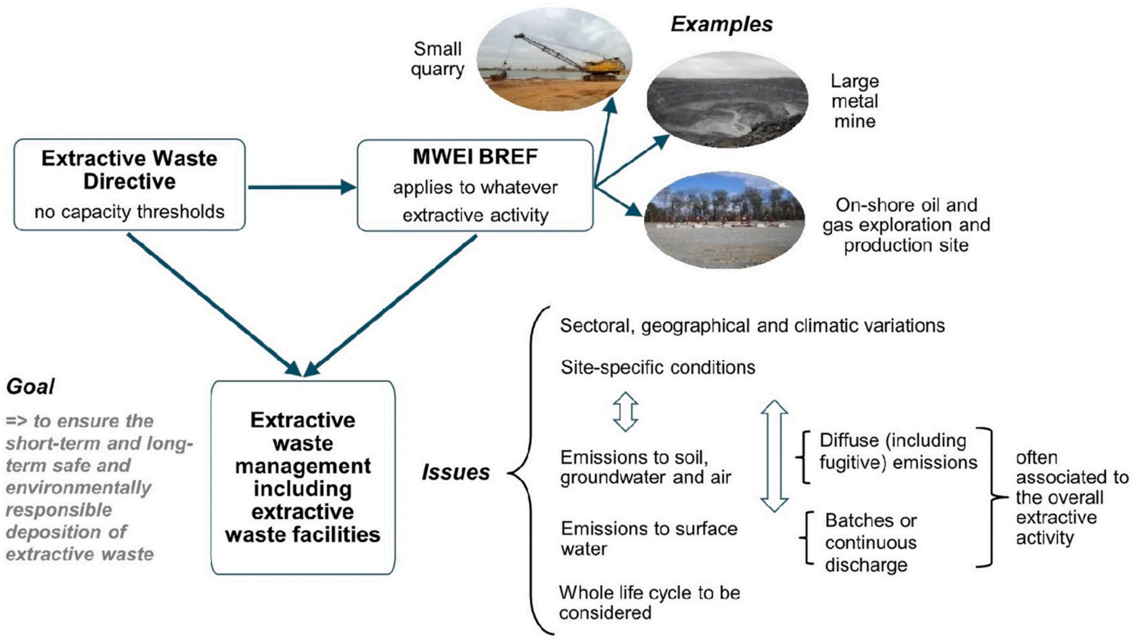

Fig. 2. Overview of the main challenges in translating data into BAT.

may be integrated into existing procedures on Environmental Impact Assessment in place for certain extractive activities (EC, 2014; Jantunen et al., 2015). An example of risk-specific objectives and potential hazards and risk/impact elements from the management of extractive waste is given in Supporting Table 1.

In summary, an Environmental Risk and Impact Evaluation consists of a structured, dynamic and often iterative process, which is part of the risk management, where all the environmental risks and impacts from the management of extractive waste are identified, analysed and evaluated over the whole life cycle.

Depending on the outcome of this evaluation, one or more generic and/or risk-specific BAT are identified and applied to minimise each overall risk, and to prevent or reduce, as far as possible, any adverse effects on the environment and human health. The overview of the generic and risk-specific BAT identified in the MWEI BREF is shown in Fig. 3. Generic BAT are generally applicable in every site where extractive waste is managed, while risk-specific BAT are applicable to sites where specific environmental risks and possible impacts are identified. The Environmental Risk and Impact Evaluation is the core BAT in the new approach. It serves to identify risks of major accidents, pollutant leaching/release, water status deterioration and soil and air pollution and the related measures to prevent or minimise the impacts. It is also updated over time to reflect changes in the operation or closure and after-closure and background conditions, by applying the related BAT on the management of change, based on the monitoring findings.

3.2.3. *The main outcomes*

Following this approach, the MWEI BREF document contains 57 BAT conclusions, of which 10 generic BAT conclusions and 47 risk-specific BAT conclusions (see Figs. 3 and 4), addressing 25 generic and risk-specific objectives, and providing information about almost 200 techniques. The following processes and activities are considered: (i) the management of extractive waste from onshore extractive activities; (ii) the handling/transport of extractive waste (e.g. loading, unloading and on-site transport); (iii) the treatment of extractive waste: a) physical and mechanical treatment (e.g. sorting, blending, dewatering, thickening); b) chemical treatment (e.g. desulphurisation, cyanide detoxification); c) biological treatment (e.g. biological sulphide reduction); (iv) the deposition of extractive waste: a) temporary deposition; b) permanent deposition in extractive waste deposition areas (including EWFs); (v) the activities directly associated with the management of extractive waste: a) treatment of EWIW; b) preparing extractive waste to be placed back into excavation voids.

Generic BAT on corporate management, extractive waste characterisation, identification of extractive waste site and management options, Environmental Risk and Impact Evaluation and waste hierarchy aim at improving the overall environmental performance of the extractive waste management operation (see Fig. 4 and Supporting Fig. 1 in the Supplementary data). The waste hierarchy principles - i.e. the decreasing order of preference given to extractive waste prevention, generation reduction, possible re-use, recycling and recovery before considering disposal - form a key element in the context of sustainable development and the transition to a circular economy. Prevention of the generation of solid extractive waste, reduction of the generation of non-inert and hazardous extractive waste, and recovery of solid extractive waste, together with reduction of extractive waste from oil and gas exploration and production to be deposited, are identified as generic BAT (see Figs. 3 and 4 and Supporting Fig. 1 in the Supplementary data).

Risk-specific BAT on safety aim at helping to ensure the short-term and long-term structural stability of the extractive waste deposition areas (see Fig. 4 and Supporting Fig. 2 in the Supplementary data) and the physical and chemical stability of extractive waste (see Fig. 4 and Supporting Fig. 3 in the Supplementary data). Other risk-specific BAT aim at preventing or minimising water status deterioration, air and soil pollution (see Figs. 4 and 5, Supporting Figs. 4 and 5 in the Supplementary data) or other risks to human health, flora and fauna, related to noise emissions, odour nuisance, visual and footprint impacts and extractive waste containing Naturally Occurring Radioactive Materials (NORMs) (see Fig. 4 and Supporting Fig. 6 in the Supplementary data).

BAT conclusions have been derived based on the exchanged data and information and by pondering relevant principles, recommendations and developments on extractive waste management proposed in well-conceived international initiatives or peer-reviewed publications over the past 15 years, particularly on extractive waste characterisation (CEN, 2012; INAP, 2014; Lottermoser, 2010), best practices and techniques to reduce the impacts to human health and the environment (Hawley and Cunning, 2017; IFC, 2007a; ITRC, 2010; Kerr and Ulrich, 2011; Martin et al., 2002; Orman et al., 2011; Pinasseau et al., 2018;

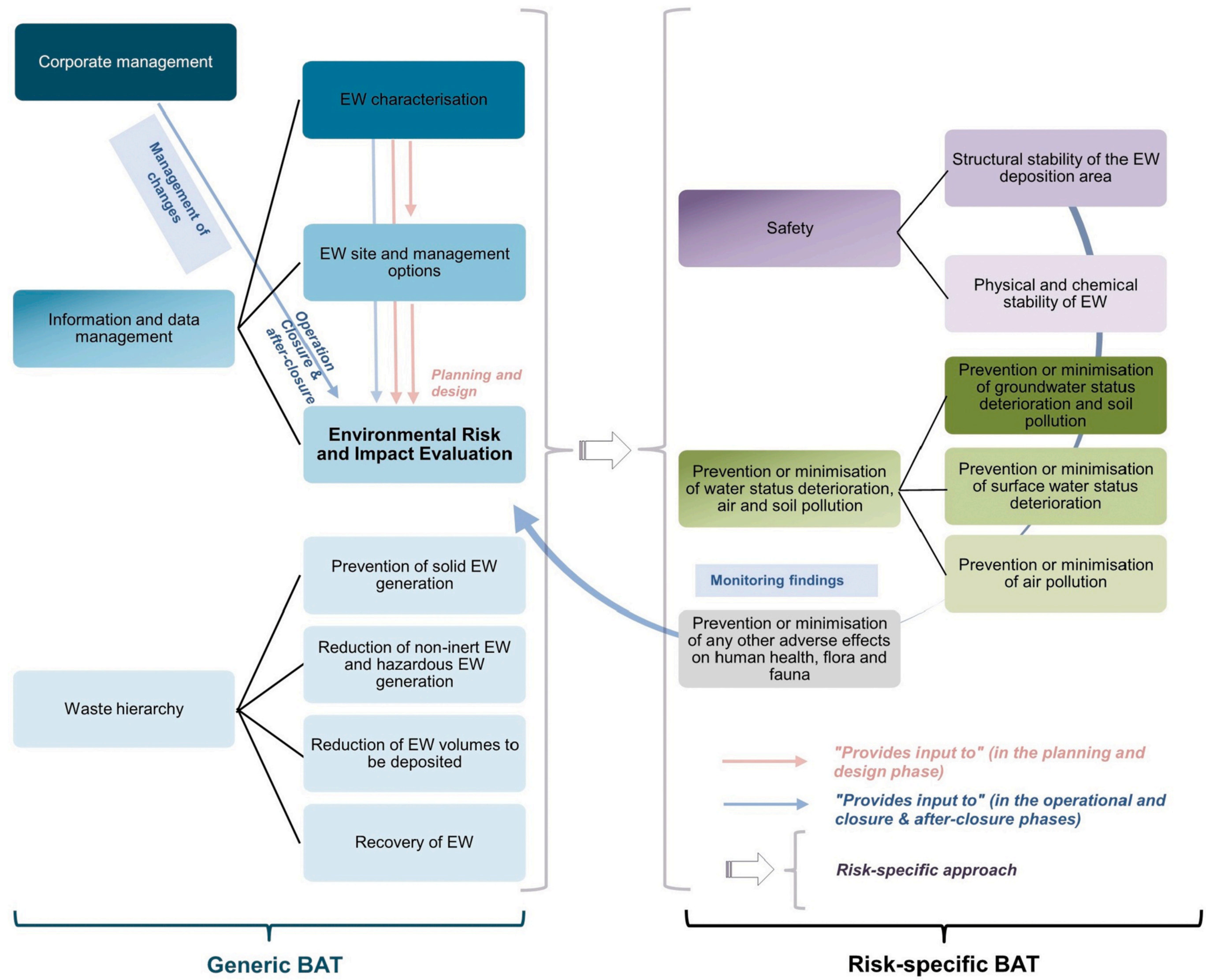

Fig. 3. Overview of the generic and risk-specific BAT identified in the MWEI BREF by applying a risk-based approach.(For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)(For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

SME, 2011; UNECE, 2014), responsible mining activities (IRMA, 2018) and extractive waste alternative approaches (Edraki et al., 2014; Franks et al., 2011).

A number of BAT conclusions are important and may be interlinked. The applicability of some depends on the result of others and an integrated approach is required for the implementation of BAT. The following paragraphs illustrate a number of key examples of BAT.

In addition, different best practices and techniques applied in the management of waste from **specific extractive sectors**, such as those published by international organisations and/or public authorities (IAI, 2015; IFC, 2007b; IOGP, 2009, 2016; Kauppila et al., 2013; UK EA, 2016), have also been considered to evaluate the **applicability** and the **relevance** of each BAT. Together with the application of a **risk-specific approach**, this allowed deriving the BAT for a wide variety of sectors and related potential environmental issues (see the relevance identified for the different BAT in the schemes reported in the Supporting Information).

As an example, the risk-specific BAT on the prevention or minimisation of groundwater status deterioration and soil pollution (see Fig. 5) encompass BAT on basal structures, covering, groundwater and soil pollution remediation, monitoring supported by detection and control systems (apart from leakage detection systems for the temporary storage). These are relevant for extractive waste types of different nature (such as non-inert, non-hazardous, Potentially Acid Generating PAG extractive waste), except for those produced by the oil and gas sector. Furthermore, they are also relevant for different kinds of extractive waste deposition areas, such as ponds, dams, heaps and extractive voids where extractive waste is placed back.

Finally, because a BAT can be used for achieving different objectives, a system of **cross-references** has been introduced in order to highlight the different links. Diversion of water run-off systems and landscaping and geomorphic reclamation are, for example, mainly applied to prevent or minimise emissions to surface water (see Supporting Fig. 4 in the Supplementary data), while drainage systems primarily help to ensure the structural stability of extractive waste deposition areas (see Supporting Fig. 2 in the Supplementary data). However, because they are also aimed at preventing or minimising emissions to soil and groundwater, a cross-reference is included in water streams management (see Fig. 5).

Based on the TWG experts' feedback and in line with the UNEP assessment (Roche et al., 2017), risk-specific BAT on **safety** are presented as key measures. They encompass about one third of the total

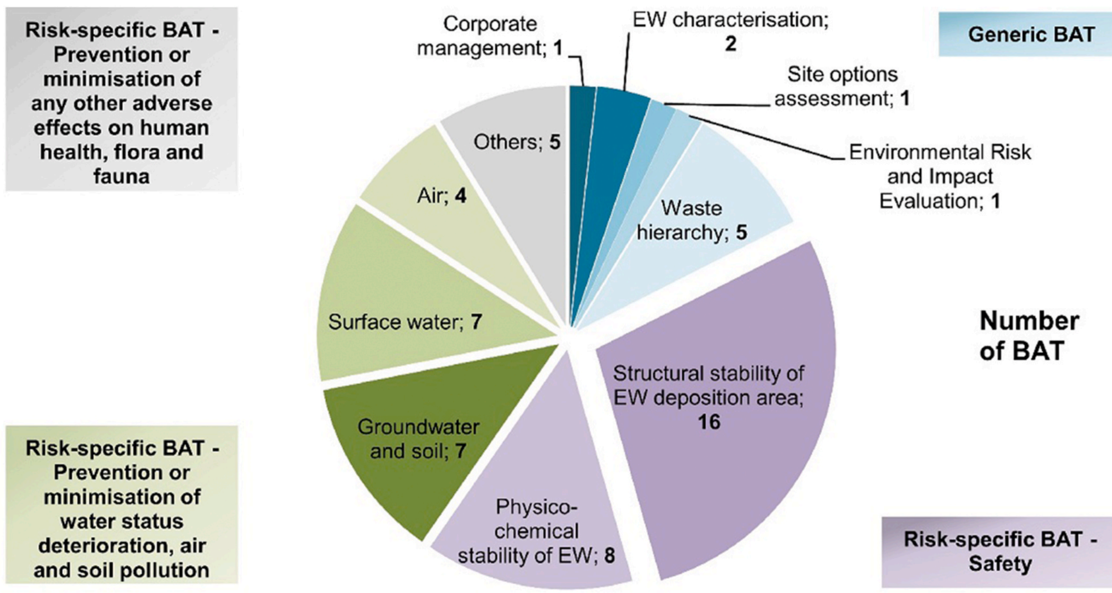

Fig. 4. Number of Generic and Risk-Specific BAT conclusions. *[EW: Extractive Waste.]*

number of BAT proposed.

The short-term and long-term structural stability of the extractive waste deposition areas is addressed by a number of BAT such as design for closure, ground investigation, dam construction materials selection, construction methods for dams and heaps, design flood, free water management, drainage systems, geotechnical analysis, monitoring of the physical stability supported by conformance checks and audits, together with specific organisational and corporate management tools (such as quality assurance/quality control, management of changes and mitigation of accidents) (see Supporting Fig. 2 in the Supplementary data).

They reflect relevant principles on planning, design, construction, operation, closure and after-closure as identified in the exchanged information, international initiatives (ANCOLD, 2012; Davies et al., 2002; ICOLD, 2001, 2011a, b; Kossoff et al., 2014) and recommendations and standards on geotechnical design (CEN, 2004a, 2007; 2012; EC-JRC, 2013; Fleurisson and Cojean, 2014; Ozcan et al., 2013), seismic design (CEN, 2004b; ICOLD, 2016; Wieland, 2012) and design flood, including extreme climatic conditions (Franks et al., 2011; ICOLD, 2011a; Rico et al., 2008a).

In line with the principle of perpetual waste management defined in the UNEP assessment (Roche et al., 2017), and based on the TWG members' feedback and the exchanged information, a **design for closure approach** has been introduced, gathering the recommendations of updated guidelines and projects (ICOLD, 2011b; IFC, 2007a; Kauppila et al., 2015; Williams, 2014). To achieve environmentally responsible management of extractive waste, it is important that its deposition is planned and designed for closure from the very beginning and that appropriate attention is given to quantification of the long-term environmental behaviour and structural stability of the deposition area. For example, the planned closure design life of the dam retaining extractive waste is usually as long as 1000 years or more in the case of large storage ponds (ICOLD, 2011b; UNECE, 2014). The management of extractive waste deposition areas is continuously adapted and improved, based on the outcomes of appropriate operational and corporate management systems and the monitoring results during the whole life cycle phases.

An **integrated design approach,** defined in the MWEI BREF as a design that takes into account all the relevant parameters in order to optimise the overall environmental, human health and safety aspects of a project in the short and long term, has also been applied.

The integrated design applied to dams intended for total solids and partial water retention is outlined in Fig. 6. The selection of a dam construction method is based on the results of a proper Environmental Risk and Impact Evaluation. BAT is to rigorously design the dam using modern engineering principles to ensure that the embankments are adequately drained, that an appropriate beach length is guaranteed at all times, including a minimum beach length during extreme flood events, and that the phreatic surface is controlled. The dam is monitored and maintained during the operational phase and the closure and after-closure phase, while applying corporate management systems and a design for closure approach. BAT is also to include a basal structure, whose structure and permeability are related to the nature of the extractive waste to be contained.

The integrated design approach consists of selecting the dam construction method by considering all the relevant parameters from the design for closure, ground investigation, dam construction materials selection, design flood evaluation, free water management, drainage systems and geotechnical analyses. Furthermore, a composite basal structure (an impermeable basal structure in combination with a proper drainage system) is designed based, among others, on the hydraulic conductivity of the basal structure, the extractive waste characteristics, the water balance and on the design criteria resulting from the dam construction material selection and the geotechnical analysis.

Similar principles and approaches apply for the BAT on construction methods for heaps.

Safety is also prioritised by helping to ensure the **physical stability** of extractive waste by applying BAT on solid/liquid control of extractive waste, stabilisation of extractive waste for placing it back into excavation voids and subsequent compaction, consolidation and deposition techniques. The latter include thickened/paste extractive waste subaerial deposition, wet or dry filter cake deposition and co-disposal (see Supporting Fig. 3 in the Supplementary data). Furthermore, safety is prioritised by helping to ensure the **chemical stability** of extractive waste, by applying BAT on prevention or minimisation of pollutant leaching, Acid Rock Drainage (ARD) and self-ignition of extractive waste, and **the reduction of dangerous substances** in extractive waste, including reducing the cyanide concentration in ponds and hydrocarbon concentration in drilling extractive wastes (see Supporting Fig. 3 in the Supplementary data).

These BAT have been derived based on the outcomes of the information exchange process, the TWG members' feedback and by considering relevant technical guidance documents (AU DITR, 2016b; INAP, 2014) and papers (Davies, 2011; Davies et al., 2010; Edraki et al., 2014;

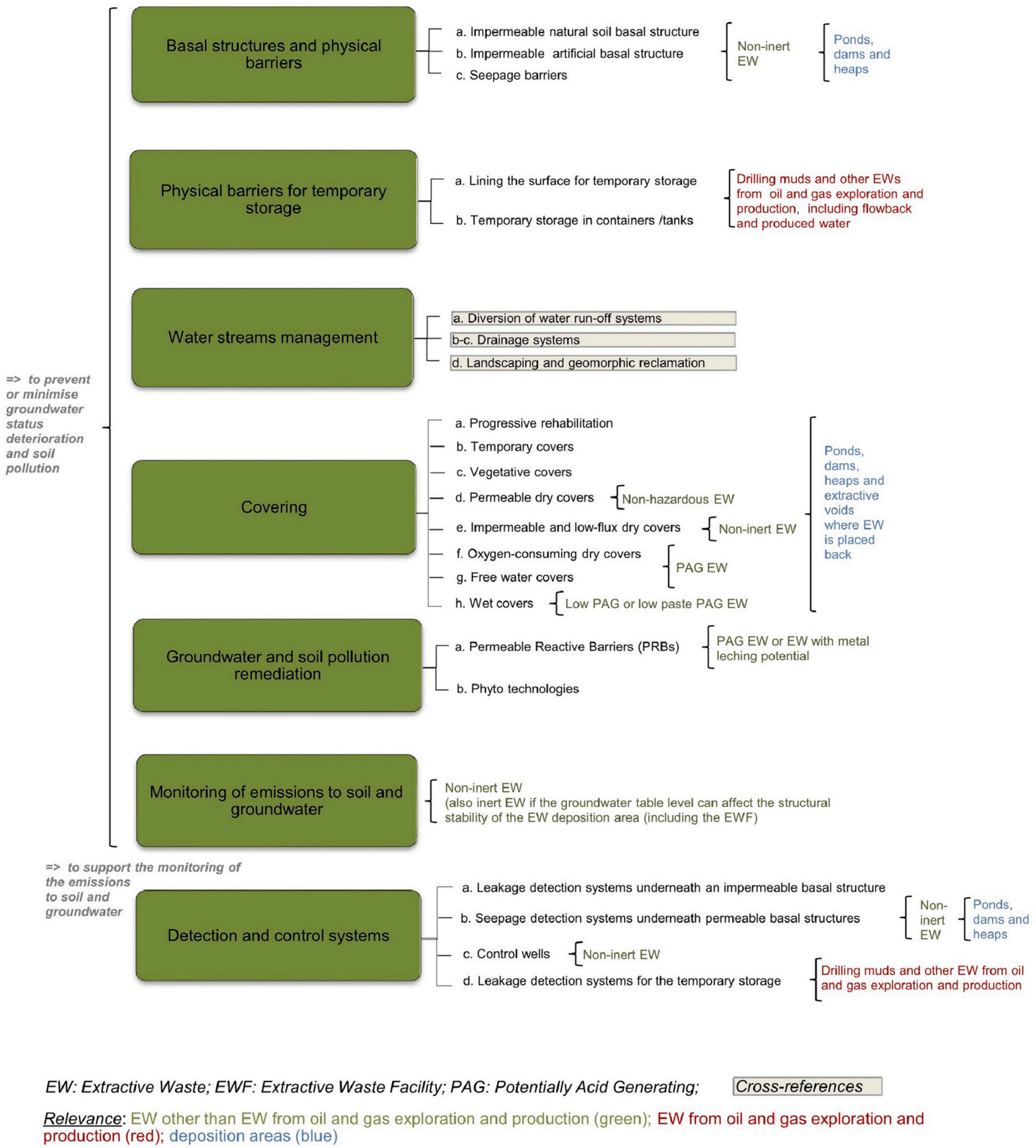

Fig. 5. Scheme of the risk-specific BAT to prevent or minimise groundwater status deterioration and soil pollution, including BAT objectives and relevance.

Junqueira et al., 2009; Kossoff et al., 2014; Williams, 2015).

For example, solid/liquid control BAT, such as thickening and clarifying or dewatering by means of a pressure gradient or a centrifugal force, followed by wet or dry filter cake deposition (or dry stacking) or mud farming, are particularly relevant for extractive waste from alumina refining (red muds) (see Fig. 7). They are applicable based on the results of a proper Environmental Risk and Impact Evaluation. As for the integrated design, the level of dewatering and so the selection of the appropriate solid/liquid control technique will depend on the design criteria of the EWF, including the selection of dam construction materials, the geotechnical analyses and the characterisation of the extractive waste.

Finally a specific focus to the **management of EWIW, including treatment techniques,** is given in the MWEI BREF, which considers relevant recommendations and guidelines published in the last decade (Brinkmann et al., 2016; CSM, 2009; ITRC, 2010; Lee et al., 2014;

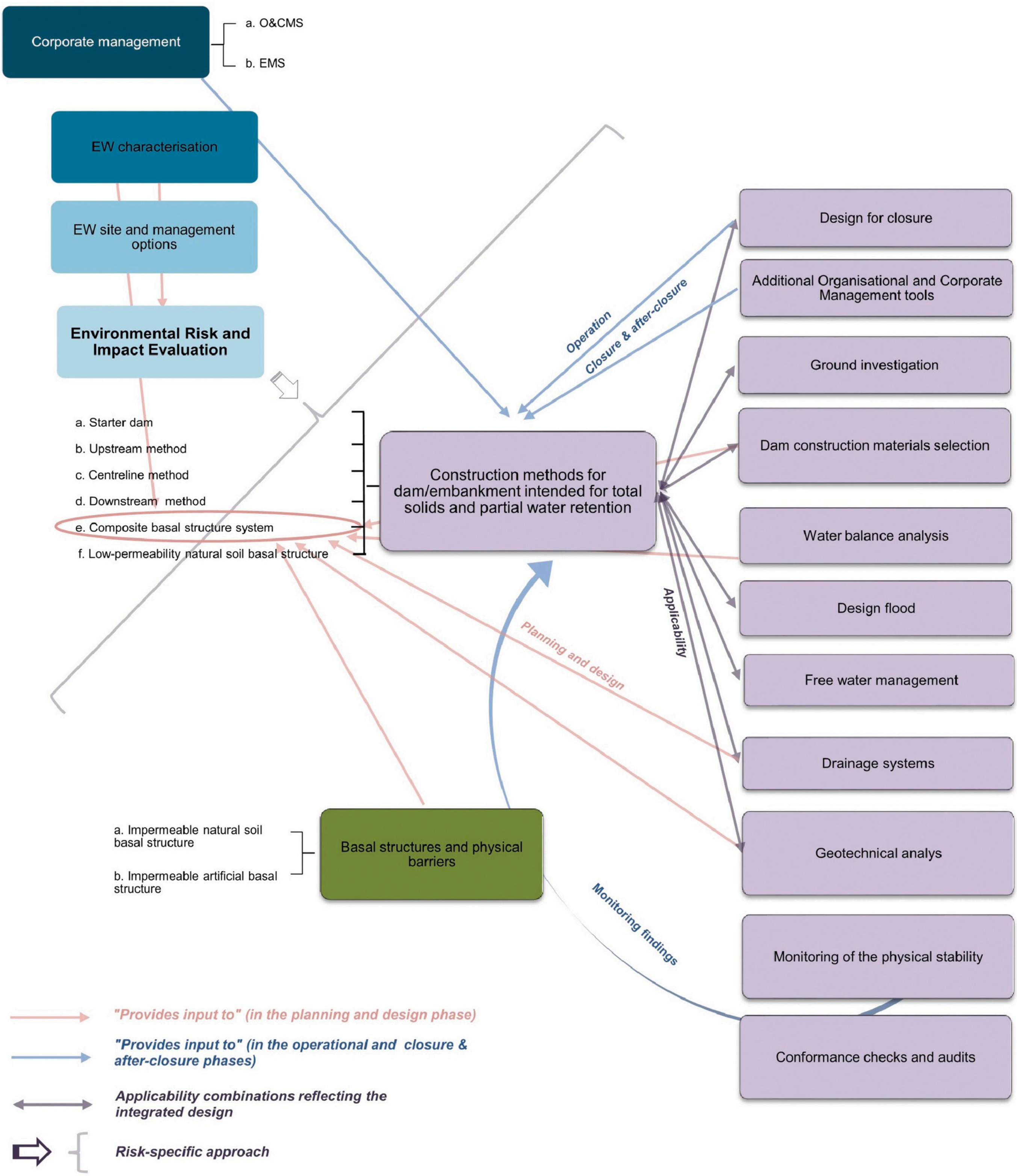

Fig. 6. Integrated design for dam/embankment intended for total solids and partial water retention. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)
O&CMS: Organisational and Corporate Management System; EMS: Environmental Management System; EW: Extractive Waste

MEND, 2008, 2014; Papirio et al., 2013; Punkkinen et al., 2016; US EPA, 2014). BAT such as re-use or recycling of excess water, diversion of water run-off during operation and landscaping and geomorphic reclamation aim at preventing or minimising the EWIW generation. Moreover, measures such as re-use and recycling of excess water in the extraction, mineral processing and extractive waste management help fostering the circular economy growth. Emissions to surface water are minimised by applying BAT such as the removal of suspended solids or suspended liquid particles, removal of dissolved substances, neutralisation of EWIW prior to discharge by active or passive treatments, and

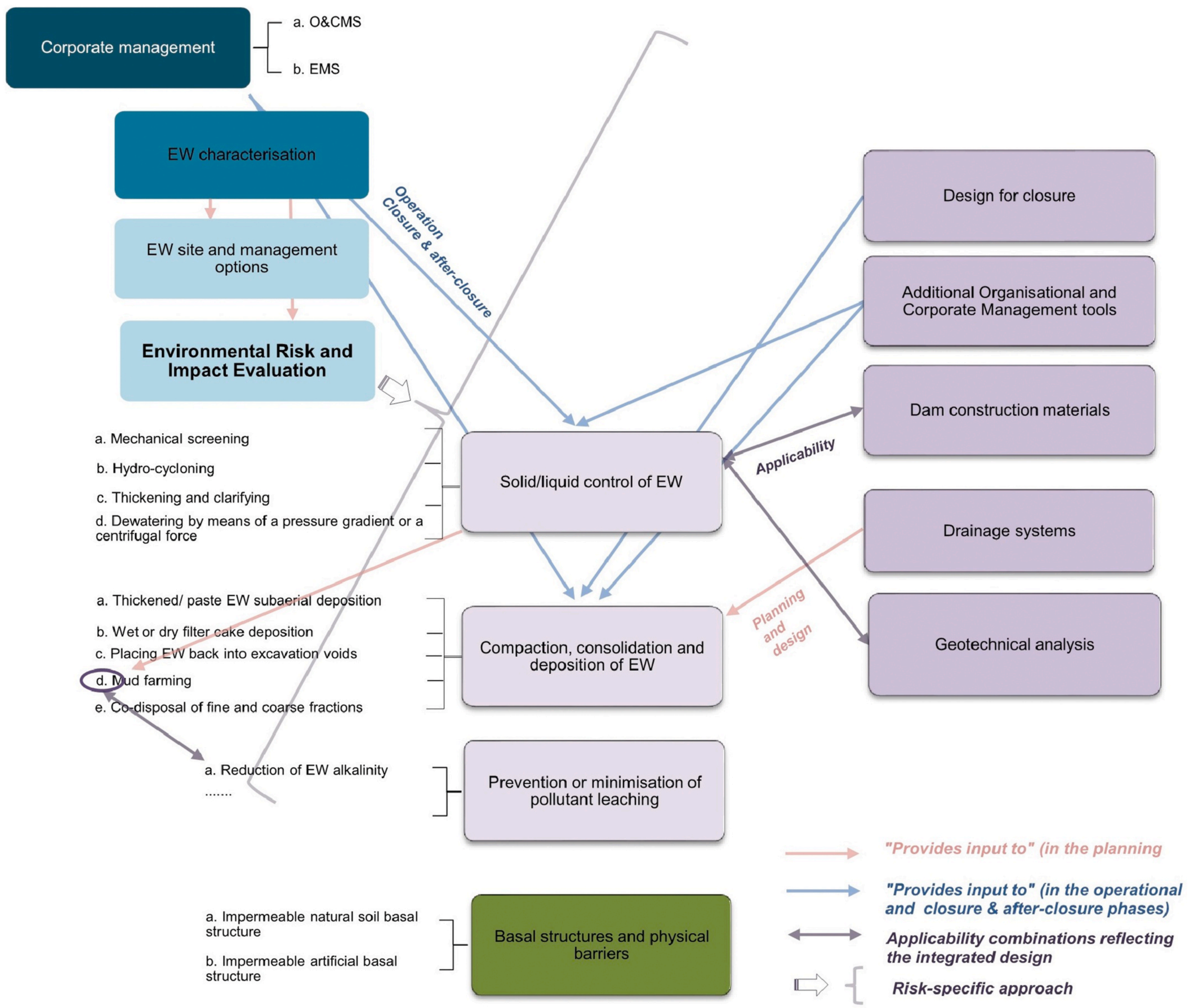

Fig. 7. Scheme of the BAT for management of red muds according to the MWEI BREF. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)
O&CMS: Organisational and Corporate Management System; EMS: Environmental Management System; EW: Extractive Waste

monitoring (see Supporting Fig. 4 in the Supplementary data).

4. Discussion

The application of the **risk-specific approach** allows to encompass the diversity of extractive waste types, operators and sites, as well as related possible risks. The new approach introduces BAT as a basis for setting performance objectives and managing risk. This implies that the deployment of techniques is adapted according to an evaluation of the environmental risks and possible impacts, which is updated over time to reflect changes in the operation or closure and after-closure and background conditions, based on the monitoring findings. Apart from the MWEI BREF, other recent guidance documents considered this approach (IRMA, 2018; MAC, 2017).

Considering **safety** as a priority for human health and the environment, different design approaches, structural stability analyses and monitoring techniques, organisational and corporate management systems, and tools are identified as BAT. This fosters the zero failure goal, which needs to be the common objective inspiring activities among regulators, designers, industry, inspectors and communities (Bowker and Chambers, 2017; IEEIRP, 2015; Roche et al., 2017). While economic factors cannot be neglected, other aspects, such as the costs of externalities or the extractive waste life cycle management for perpetuity (Roche et al., 2017), need to be thoroughly assessed. Particularly for new EWFs, the Mount Polley Independent Expert Engineering Investigation and Review Panel recommended to evaluate safety attributes separately from economic considerations and to not consider cost as the determining factor (IEEIRP, 2015).

The MWEI BREF considers that the impacts from an **inappropriate management** of extractive waste, particularly from an improper EWF design and operation, could be catastrophic. Dam collapses can cause severe environmental damage and lead to human casualties. Major accidents continue to occur at an average of about two to three per year (worldwide) (Roche et al., 2017; WISE, 2019). It is particularly noticed that dams retaining extractive waste have a failure rate that is significantly higher than that of water supply reservoir dams (on average 0.01%, one chance in 10000 dams) (Martin et al., 2002). According to some authors (Chambers and Higman, 2011; Kossoff et al., 2014; Martin et al., 2002), the yearly failure rate of major dams retaining extractive waste varies from 0.06% to 0.14% over the total number of active ponds considered by these studies (about 3500 worldwide). This failure rate may increase to about 1% if considering minor accidents (Martin et al., 2002). Additionally, in the last 6 years at least 11 failures with severe environmental damages and, in some cases, human victims occurred (Roche et al., 2017; WISE, 2019). Moreover, the overall trend of frequency of major failures and their severity, measured in released volumes and run-out distances, appears to be increasing (Bowker and Chambers, 2015, 2017).

Furthermore, in the MWEI BREF, it is concluded that **dam raising techniques**, such as upstream or centreline methods, whose cost might be lower in the short term, can be more susceptible to instability from seismic loading compared to downstream methods (Chambers and Higman, 2011; ICOLD, 2001, 2011a; 2016; Kossoff et al., 2014). They are thus not applicable when the slightest risk of liquefaction has been identified after seismic evaluation of dams.

The investments needed to protect the environment and human health will pay off by avoiding the possible **costs for remediating** the consequences of accidents, which could be many times higher. Proper planning, design and operation are imperative to avoid clean-up and remediation costs due to EWF failures (Orman et al., 2011), which can reach several hundred million euro (e.g. Los Frailes, Aznalcóllar, Spain about EUR 270 million (Kossoff et al., 2014), Baia Mare, Romania EUR 190 million (Kossoff et al., 2014), Mount Polley mine, Canada about at least EUR 150 million (Lee, 2014), of which only one third was spent so far in 2015 (Schoenberger, 2016).

Companies generally face other financial costs, related to the environmental liability, fines, civil claims and compensations, together with reputational losses.

In 2016 the mining company Samarco, owned by BHP Billiton and Vale, reached a deal with the Brazilian government to pay about EUR 5 billion in damages over 15 years from the deadly failure of the dam at Bento Rodrigues in 2015 (Boadle and Eisenhammer, 2016).

A big burst of an upstream dam occurred in January 2019 at Brumadinho, Brazil, and left more than 250 dead (WISE, 2019). In the following months the Brazilian Government ordered the elimination of all upstream dams until 2021 and the Brazilian judicial authorities froze EUR 2.7 billion of Vale's assets (BBC, 2019). Vale could face damages as high as EUR 6.4 billion for the current disaster (Millan Lombrana, 2019).

A **proper management of water in** and **on** the **extractive waste**, i.e. the pore water contained in the interparticle voids and the water on the surface (e.g. the supernatant water) is crucial to help ensuring the structural stability of the EWF and the physical stability of extractive waste. To this aim, BAT on water balance analysis, free water management, drainage systems, geotechnical analysis, monitoring, solid/liquid control and compaction, consolidation and deposition of extractive waste, including thickened/paste extractive waste deposition or dry stacking, apply. The elimination of the water from the pond and the deposition of thickened/paste extractive waste or wet or dry filter cakes is recommended by some experts (Adiansyah et al., 2015; Edraki et al., 2014; IEEIRP, 2015). However, getting rid of all free water depends on the deposition method and the closure strategy chosen. Free water covers are, for example, BAT to prevent ARD from PAG extractive waste, i.e. to help ensuring the chemical stability of extractive waste. In this case, extractive waste is covered with a water layer in order to isolate contaminants, reduce erosion, dusting and oxygen infiltration. Anyhow, any measure for achieving chemical stability first needs to ensure the structural stability in the short and long term (IEEIRP, 2015). Hence, a free water cover is a long-term closure option applicable on the base of the results of a proper of Environmental Risk and Impact Evaluation. This closure strategy is identified since the very beginning, in the initial closure and after closure plan, together with an assessment of costs related to the proposed and alternative closure strategies, including a cost benefit analysis, details on the final landform and surface rehabilitation, long-term stability analyses and control and monitoring procedures.

The safe depositing of extractive waste could be further challenged by an increased climate variability, **climate change** and the occurrence of **extreme weather events** (Roche et al., 2017). Unusual rain is, for example, the first identified cause of dam failure in Europe and worldwide (Rico et al., 2008b). The EWF planning and design need to consider this uncertainty and the associated risks. Risk management should include measures to ensure EWFs are resilient enough that risks continue to be appropriately managed, also in the closure and after-closure phase (MAC, 2017). By utilizing existing climate projections, coupled with good planning and a zero-risk approach, it may be possible to mitigate against climate-related changes (Roche et al., 2017). In the MWEI BREF, it is suggested to include reliable data on climate change in the baseline studies to help an appropriate identification of the extractive site options and environmental risk and impact evaluation. Moreover, the BAT for design flood evaluation indicates that EWFs, and related decant systems and emergency spillways, need to accommodate extreme hydrologic events, considering also climate change scenarios and consequent anomalies, such as sudden snowmelt, extreme rainfall or ice clogging. Furthermore, BAT is to guarantee an appropriate beach length and freeboard at all times, including a minimum beach length during extreme flood events. Finally, the management of changes system address the procedures to follow when any changes occur, including extreme events.

Another key aspect analysed is the integration of the **extractive waste management into the mine planning** (Edraki et al., 2014; IEEIRP, 2015; Schoenberger, 2016). In the BAT conclusions it is recommended to integrate the EWF closure and after-closure planning into the periodic extraction plans as for the design for closure and to consider together the EWIW and Acid Mine Drainage (AMD) issues in an integrated water management plan.

The application of proper **management, monitoring** and **auditing systems** is BAT to enhance the overall environmental performance of the extractive waste management along the whole life cycle. Independent external auditing is also proposed, in line with the technical review by a panel of third party experienced engineers identified as key measure in several guidance documents (Golder and Associates, 2016; IEEIRP, 2015; MAC, 2017).

A key contribution to a more **circular economy** may come from extractive waste, because this often contains residual valuable minerals (Mathieux et al., 2017). The recovery of extractive waste is not a widely applied practice in the EU. Nevertheless, there are some notable examples that not only demonstrate the potential, but also the availability and economic viability of technologies, and the existence of a highly innovative sector (Blengini et al., 2019). These examples have already shown that the occurrence of critical raw materials may not per se justify a re-mining activity. Both critical and other valuable raw materials need to be included in the evaluation of the cut-off grades. Furthermore, the recovery of these raw materials may be neither economic nor sustainable without the proper management of the residual extractive waste.

Regarding the **data analysis**, in general, derivation of sector-specific BAT associated environmental performance levels (BAT-AEPL) or associated emission levels (BAT-AEL) was not possible at this stage (e.g. for metal mining, coal mining, oil and gas drilling, construction minerals quarrying). This was mainly due to the limited number of data provided on emission levels. Besides, derivation of BAT-AEL for the entire extractive waste management sector was complicated by the nature of the extractive waste management process itself. The management of extractive waste is in general carried out in EWFs that are in interaction with their environment and not in closed reactors. Moreover, the composition of extractive waste is influenced by the composition of the mineral resource and the material in which this is embedded. Therefore, to derive BAT-AEL, one should not only consider the prevention and control measures implemented by operators, but also other site-specific information such as climate and geological conditions or the variety of different types of extractive wastes and EWFs. In that sense, the difficulty lies in the large variety of different combinations of extractive waste origins (e.g. excavation, mineral processing, drilling), extractive waste properties and compositions, waste facility types (e.g. heaps, ponds with downstream, upstream, centreline dams), waste transport options (e.g. covered or uncovered conveyors, trucks or pipelines) and treatments of extractive waste (e.g. dewatering, compaction, detoxification, blending).

In addition, with EWFs generally being located close to the extractive sites, it was not possible to quantify the contribution of the extractive waste management activity to the total emission level that includes also the extractive activity itself (e.g. the mining or quarrying). This was the case for example for dust emissions or dust deposition emissions. After all, a part of the dust originates from the extraction site itself, e.g. the mine or the quarry, and a part from the extractive waste management.

Nevertheless, it was possible to identify BAT for pollution prevention and control. In particular for emissions to surface water, it was possible not only to identify BAT but also exemplary performance levels achieved and reported by operators.

5. Conclusion

The MWEI BREF, and more specifically the BAT conclusions section, provides competent authorities in the EU with the technical basis to be considered when setting permit conditions. These BAT result from the information exchange and consensus decisions taken by of a TWG composed of European extractive sector experts during a 5-years intensive collaboration. The expanded scope now covers all the on-shore extractive waste management activities in Europe.

The monitoring of the MWEI BREF implementation in Europe will support the **continuous improvement** process on the management of extractive waste, together with other recent guidance documents (Cambridge et al., 2018; Roche et al., 2017). It will also support new international framework initiatives, such as i) the UNEP proposal of establishing a UN Environment stakeholder forum (Roche et al., 2017); ii) the Global Tailings Review, aimed at establishing an international standard (ICMM et al., 2019) and iii) the Investor Mining and Tailings Safety Initiative (Church of England and Swedish Public Pension Funds Council on Ethics, 2019).

The **future review** of the MWEI BREF will also beneficiate from the outcomes of these initiatives. It should also consider that not all the challenges in translating data into BAT have been solved in the current BREF. In particular, a recommendation for future work includes improving the data collection, allowing for a more in depth analysis and understanding of the links between the site specific conditions (e.g. geological background) and the different techniques applied, leading to a certain final level of pollution reduction or prevention.

Finally, the BAT implementation is already supported by ongoing actions of the European Commission, such as the ones aimed at further striving towards a more **circular approach** (Blengini et al., 2019) where extractive waste is re-mined instead of opening up new deposits.

Disclaimer

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Declaration of competing interest

The authors declare no conflict of interest.

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Appendix A. Supplementary data

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References

Adiansyah, J.S., Rosano, M., Vink, S., Keir, G., 2015. A framework for a sustainable approach to mine tailings management: disposal strategies. J. Clean. Prod. 108, 1050–1062. https://doi.org/10.1016/j.jclepro.2015.07.139.

ANCOLD, 2012. Guidelines on Tailings Dams - Planning, Design, Construction, Operation and Closure. Australian National Committee on Large Dams.

AU Ditr, 2011. A guide to leading practice sustainable development in mining. In: Leading Practice Sustainable Development Program for the Mining Industry. Australian Government - Department of Industry Tourism and Resources.

AU Ditr, 2016. Risk management. In: Leading Practice Sustainable Development Program for the Mining Industry. Australian Government - Department of Industry Tourism and Resources.

AU Ditr, 2016. Tailings management. In: Leading Practice Sustainable Development Program for the Mining Industry. Australian Government - Department of Industry Tourism and Resources.

BBC, 2019. Brazil's Vale ordered to pay compensation for dam disaster. https://www.bbc.com/news/world-latin-america-48935651. Accessed 06 November 2019.

Blengini, G.A., Mathieux, F., Mancini, L., Nyberg, M., Viegas, H.M., Salminen, J., Garbarino, E., Orveillon, G., Saveyn, H., Mateos Aquilino, V., Llorens, G.T., García Polonio, F., Horckmans, L.D.H.P., Balomenos, E., Dino, G., de la Feld, M., Mádai, F., Földessy, J.G.M., Gombkötő, I., Calleja, I., 2019. Recovery of Critical and Other Raw Materials from Mining Waste and Landfills: State of Play on Existing Practices. Publications Office of the European Union, Luxembourg, p. 130. https://doi.org/10.2760/494020.

Boadle, A., Eisenhammer, S., 2016. Vale/BHP's Samarco to pay $5.1 billion in damages for dam disaster. http://www.reuters.com/article/us-brazil-damburst-deal-idUSKCN0W42WP. Accessed 07 December 2019.

Bowker, L.N., Chambers, D.M., 2015. The Risk, Public Liability, and Economics of Tailings Storage Facility Failures, p. 56.

Bowker, L.N., Chambers, D.M., 2017. In the dark shadow of the supercycle tailings failure risk & public liability reach all time highs. Environments 4 (4), 75. https://doi.org/10.3390/environments4040075.

BRGM, 2001. Management of Mining, Quarrying and Ore-Processing Waste in the European Union. European Commission, p. 79.

Brinkmann, T., Giner Santonja, G., Yükseler, H., Roudier, S., Delgado Sancho, L., 2016. Best Available Techniques (BAT) Reference Document for Common Waste Water and Waste Gas Treatment/Management Systems in the Chemical Sector. Publications Office of the European Union, Luxembourg, p. 664. https://doi.org/10.2791/37535.

Cambridge, M.C.N., Czajewski, K., Diaz, M., Ferguson, G., Molloy, C., Monroy, R., Roberts, J., Saint, J., 2018. The Hydraulic Transport and Storage of Extractive Waste: Guidelines to European Practice. Springer, Cham.

CEN, 2004. CEN/TC 250 - Structural Eurocodes - Eurocode 7 - Geotechnical Design - Part 1: General Rules, EN 1997-1:2004. European Committee for Standardization.

CEN, 2004. CEN/TC 250 - Structural Eurocodes - Eurocode 8 - Design of Structures for Earthquake Resistance - Part 5: Foundations, Retaining Structures and Geotechnical Aspects, EN 1998-5:2004. European Committee for Standardization.

CEN, 2007. CEN/TC 250 - Structural Eurocodes - Eurocode 7 - Geotechnical Design - Part 2: Ground Investigation and Testing, EN 1997-2:2007. European Committee for Standardization.

CEN, 2012. CEN/TC 292 - Characterisation of Waste - Overall Guidance Document for Characterization of Waste from the Extractive Industries. European Committee for Standardization. CEN/TR 16376:2012.

Chambers, D., Higman, B., 2011. Long-term Risks of Tailings Dam Failure. Center for Science in Public Participation, p. 34.

Chambers, D.M., Bowker, L.N., 2019. World Mine Tailings Failures - from 1915 accessed. https://worldminetailingsfailures.org/. (Accessed 7 November 2019).

Church of England and Swedish Public Pension Funds Council on Ethics, 2019. Investor Mining and Tailings Safety Initiative. https://www.churchofengland.org/investor-mining-tailings-safety-initiative. Accessed 07 November 2019.

CSM, 2009. An Integrated Framework for Treatment and Management of Produced Water. Technical Assessment of Produced Water Treatment Technologies. Colorado Schools of Mines, p. 158.

Davies, M., 2011. Filtered Dry Stacked Tailings – the Fundamentals, Tailings and Mine Waste 2011, p. 9. Vancouver, Canada.

Davies, M., Lighthall, P., Martin, T., 2002. Design of Tailings Dams and Impoundments. AGM SME, Phoenix, p. 18, 2002.

Davies, M., Lupo, J., Martin, T., McRoberts, E., Musse, M., Ritchie, D., 2010. A dewatered tailings practice - trend and observations. In: The Organizing Committee of the 14th International Conference on Tailings and Mine Waste, first ed. Taylor & Francis, London, p. 10. Tailings and Mine Waste 2010.

EC-DG ENV, 2011. Guidance Document for a Risk-Based Pre-selection Protocol for the Inventory of Closed Waste Facilities as Required by Article 20 of Directive 2006/21/EC (European Commission).

EC-JRC, 2009. Reference Document on Best Available Techniques for Management of Tailings and Waste-Rock in Mining Activities. European Commission Joint Research Centre, Luxembourg.

EC-JRC, 2013. Eurocode 7: Geotechnical Design. Worked Examples Presented at the Workshop "Eurocode 7: Geotechnical Design" Dublin, 13-14 June, 2013. Support to the Implementation. harmonization and further development of the Eurocodes, Luxembourg, p. 172. https://doi.org/10.2788/3398.

EC, 2006. Directive 2006/21/EC of the European Parliament and of the Council of 15 March 2006 on the Management of Waste from Extractive Industries and Amending Directive 2004/35/EC. OJ L102.

EC, 2008. Communication from the Commission to the European Parliament and the Council, the Raw Materials Initiative - Meeting Our Critical Needs for Growth and Jobs in Europe.

EC, 2009. Commission Decision 2009/337/EC of 20 April 2009 on the Definition of the Criteria for the Classification of Waste Facilities in Accordance with Annex III of Directive 2006/21/EC of the European Parliament and of the Council Concerning the Management of Waste from Extractive Industries. OJ L102.

EC, 2010. Directive 2010/752/EU of the European Parliament and of the Council of 24 November 2010 on Industrial Emissions (Integrated Pollution Prevention and Control). OJ L334.

EC, 2012. Commission Implementing Decision 2012/119/EU of 10 February 2012 Laying Down Rules Concerning Guidance on the Collection of Data and on the Drawing up of BAT Reference Documents and on Their Quality Assurance Referred to in Directive 2010/75/EU of the European Parliament and of the Council on Industrial Emissions. OJ L63.

EC, 2013. In: European Commission (Ed.), Strategic Implementation Plan for the European Innovation Partnership on Raw Materials. Part I.

EC, 2014. Directive 2014/52/EU of the European Parliament and of the Council of 16 April 2014 Amending Directive 2011/92/EU on the Assessment of the Effects of Certain Public and Private Projects on the Environment. OJ L124.

EC, 2016. Report from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions on the Implementation of Directive 2006/21/EC on the Management of Waste from Extractive Industries and Amending Directive 2004/35/EC, COM(2016), p. 553 (final).

Edraki, M., Baumgartl, T., Manlapig, E., Bradshaw, D., Franks, D.M., Moran, C.J., 2014. Designing mine tailings for better environmental, social and economic outcomes: a review of alternative approaches. J. Clean. Prod. 84, 411–420. https://doi.org/10.1016/j.jclepro.2014.04.079.

Eurostat, 2015. Waste Generation and Treatment. Publications Office of the European Union. http://ec.europa.eu/eurostat/data/database. Accessed 18 Mar 2015.

Eurostat, 2015a. Annual enterprise statistics for special aggregates of activities. http://ec.europa.eu/eurostat/web/structural-business-statistics/data/database. Accessed 10 March 2015.

Fleurisson, J.-A., Cojean, R., 2014. Error reduction in slope stability assessment. In: Bhattacharya, Jayanta, Lieberwirth, H., Klein, B. (Eds.), Surface Mining Methods, Technology and Systems. Wide Publishing, p. 41.

Franks, D.M., Boger, D.V., Côte, C.M., Mulligan, D.R., 2011. Sustainable development principles for the disposal of mining and mineral processing wastes. Resour. Pol. 36, 114–122. https://doi.org/10.1016/j.resourpol.2010.12.001.

Garbarino, E., Orveillon, G., Saveyn, H., Barthe, P., Eder, P., 2018. Best available techniques (BAT) reference document for the management of waste from extractive industries. In: Accordance with Directive 2006/21/EC. Publications Office of the European Union, Luxembourg, p. 692. https://doi.org/10.2760/35297.

Golder and Associates, 2016. Review of Tailings Management Guidelines and Recommendations for Improvement. International Council on Mining and Metals, p. 14.

Hawley, M., Cunning, J., 2017. Guidelines for Mine Waste Dump and Stockpile Design. CRC Press, Washington, D.C.

IAI, 2015. Bauxite Residue: Management Best Practice. International Aluminium Institute & European Aluminium Association, p. 31.

ICMM, 2016. Position Statement on Preventing Catastrophic Failure of Tailings Storage Facilities. International Council on Mining and Metals (ICMM).

ICMM, UNEP, PRI, 2019. Global Tailings Review. https://globaltailingsreview.org/. accessed 07 November 2019.

ICOLD, 2001. Tailings Dams Risk of Dangerous Occurrences. Lessons Learnt from Practical Experiences. CIGB ICOLD International Commission on Large Dams, Paris.

ICOLD, 2011. Improving Tailings Dam Safety. Critical Aspects of Management, Design, Operation and Closure. CIGB ICOLD International Commission on Large Dams, Paris.

ICOLD, 2011. Sustainable Design and Post-closure Performance of Tailings Dams. CIGB ICOLD International Commission on Large Dams, Paris.

ICOLD, 2016. Selecting Seismic Parameters for Large Dams. Guidelines. CIGB ICOLD International Commission on Large Dams, Paris.

IEEIRP, 2015. The Report on the Mount Polley Tailings Storage Facilities Breach. Province of British Columbia, Vancouver, p. 156. Province of British Columbia.

IFC, 2007. Environmental, health and safety guidelines for mining. In: Environmental, Health, and Safety Guidelines. International Finance Corporation World Bank Group.

IFC, 2007. Environmental, health, and safety guidelines for onshore oil and gas development. In: Environmental, Health, and Safety Guidelines. International Finance Corporation World Bank Group.

INAP, 2014. GARD Global Acid Rock Drainage Guide. INAP International Network for Acid Prevention, p. 473.

IOGP, 2009. Guidelines for waste management with special focus on areas with limited infrastructure. In: OGP Publications. International Association of Oil & Gas Producers.

IOGP, 2016. Drilling waste management technology review - report 557. International Association of Oil & Gas Producers.

IRMA, 2018. IRMA Standard for Responsible Mining IRMA-STD-001. Initiative for Responsible Mining Assurance, p. 202.

ISO, 2009. Risk Management - Principles and Guidelines. International Organization for Standardization. ISO 31000:2009.

ISO, 2009. Risk Management - Risk Assessment Techniques. International Organization for Standardization. ISO 31010:2009.

ISO, 2009. Risk Management - Vocabulary. International Organization for Standardization. ISO Guide 73:2009.

ITRC, 2010. Mining Waste Guidance. Mining Waste Treatment Technology Selection. Interstate Technology and Regulatory Council, Washington, DC.

Jantunen, J., Kauppila, T., Räisänen, M.L., Komulainen, H., Kauppila, P., Kauppinen, T., Törmä, H., Leppänen, M., Tornivaara, A., Pasanen, A., Kemppainen, E., Raunio, A., Marttunen, M., Mustajoki, J., Kauppi, S., Ekholm, P., Huttula, T., Makkonen, H., Loukola-Ruskeeniemi, K., 2015. Guide: environmental impact assessment procedure for mining projects in Finland. In: Ministry of Employment and the Economy Guidelines and Other Publications. Ministry of Employment and the Economy Finland, 102. 978-952-227-964-4.

Junqueira, F., Wilson, G., Oliveira, M., 2009. Surface paste disposal of high-sulphide tailings at neves corvo mine in Portugal Part 1: estimation of tailings desaturation and implications on ARG generation. In: Curran Associates Inc (Ed.), 8th International Conference on Acid Rock Drainage (ICARD) and Security the Future: Mining, Metals & the Environment in a Sustainable Society 2009 (Sweden).

Kauppila, P., Räisänen, M.L., Myllyoja, S., 2013. Best environmental practices in metal ore mining. In: Finnish Environment. Finnish Environment Institute, Helsinki, p. 222.

Kauppila, P.M., Kauppila, T., Pasanen, A., Backnäs, S., Räisänen, M.L., Turunen, K., Karlsson, T.A., Tornivaara, S.L., Larkins, C., Hentinen, K., Hämäläinen, E., Lerssi, J., Eskelinen, A., GTK Geological Survey of Finland, Wahlström, M., Laine-Ylijoki, J., Mroueh, U.-M., Kaartinen, T., Punkkinen, H., Merta, E., Niemeläinen, E., Mäkinen, J., Bomberg, M., Juvankoski, M., VTT Technical Research Centre of Finland, 2015. Mine closure technologies resource – closedure. https://mineclosure.gtk.fi/closedure-project/. Accessed 15 December 2019.

Kerr, T., Ulrich, B., 2011. Tailings impoundments and dams. In: Darling, P. (Ed.), SME Mining Engineering Handbook, third ed. Society for Mining, Metallurgy, and Exploration, Inc, pp. 645–665.

Kossoff, D., Dubbin, W.E., Alfredsson, M., Edwards, S.J., Maclin, M.G., Hudson-Edwards, K.A., 2014. Mine tailings dams: characteristics, failure, environmental impacts, and remediation. Appl. Geochem. 51, 229–245. https://doi.org/10.1016/j.apgeochem.2014.09.010.

Lee, A., 2014. Cleaning up after Canada's largest tailings pond leak. http://www.macleans.ca/news/canada/cleaning-up-after-canadas-largest-tailings-pond-leak/. Accessed 16 November 2019.

Lee, C.S., Robinson, J., Chong, M.F., 2014. A review on application of flocculants in wastewater treatment. Process Saf. Environ. Protect. 92, 489–508. https://doi.org/10.1016/j.psep.2014.04.010.

Lottermoser, B.G., 2010. Mine Wastes – Characterization, Treatment, Environmental Impacts, third ed. Springer-Verlag Berlin Heidelberg.

MAC, 2017. A Guide to the Management of Tailings Facilities. The Mining Association of Canada, p. 86.

MAPAMA, 2016. Guidance Document for a Risk-Based Pre-selection Protocol for the Inventory of Closed Waste Facilities as Required by Article 20 of Directive 2006/21/EC. Government of Spain, Ministerio de Agricultura y Pesca, Alimentación y Medio Ambinte, Ministerio de Economía, Industria y Competitividad.

Martin, T.E., Davies, M.P., Rice, S., Higgs, T., Lighthall, P.C., 2002. Stewardship of tailings facilities. In: MMSD - Mining, Minerals and Sustainable Development Project. International Institute for Environment and Development and World Business Council for Sustainable Development, p. 37.

Mathieux, F., Ardente, F., Bobba, S., Nuss, P., Blengini, G., Alves Dias, P., Blagoeva, D., Torres De Matos, C., Wittmer, D., Pavel, C., Hamor, T., Saveyn, H., Gawlik, B., Orveillon, G., Huygens, D., Garbarino, E., Tzimas, E., Bouraoui, F., Solar, S., 2017. Critical Raw Materials and the Circular Economy – Background Report. https://doi.org/10.2760/378123.

MEND, 2008. Application of membrane separation technology to mitigation of mine effluent and acidic drainage. In: MEND Report 3.15.1. The Mine Environment Neutral Drainage (MEND) program.

MEND, 2014. Study to identify BATEA for the management and control of effluent quality from mines. In: MEND Report 3.50.1. The Mine Environment Neutral Drainage (MEND) program.

Millan Lombrana, L., 2019. Brazil's burst dam disasters blamed on cheap storage of mining waste. https://www.insurancejournal.com/news/international/2019/02/01/516518.htm. Accessed 06 November 2019.

Orman, M., Peevers, R., Sample, K., 2011. Waste piles and dumps. In: Darling, P. (Ed.), SME Mining Engineering Handbook, third ed. Society for Mining Metallurgy and Exploration Inc, pp. 667–680.

Ozcan, N.T., Ulusay, R., Isik, N.S., 2013. A study on geotechnical characterization and stability of downstream slope of a tailings dam to improve its storage capacity (Turkey). Environ Earth Sci 69, 1871–1890. https://doi.org/10.1007/s12665-012-2016-1.

Papirio, S., Villa-Gomez, D.K., Esposito, G., Pirozzi, F., Lens, P.N.L., 2013. Acid mine drainage treatment in fluidized-bed bioreactors by sulfate-reducing bacteria: a critical review. Crit. Rev. Environ. Sci. Technol. 43, 2545–2580. https://doi.org/10.1080/10643389.2012.694328.

Pinasseau, A., Zerger, B., Roth, J., Canova, M., Roudier, S., 2018. Best Available Techniques (BAT) Reference Document for Waste Treatment. Publications Office of the European Union, Luxembourg. https://doi.org/10.2760/407967.

Punkkinen, H., Räsänen, L., Mroueh, U.-M., Korkealaakso, J., Luoma, S., Kaipainen, T., Backnäs, S., Turunen, K., Hentinen, K., Pasanen, A., Kauppi, S., Vehviläinen, B., Krogerus, K., 2016. Guidelines for mine water management. In: VTT Technology. VTT Technical Research Centre of Finland Ltd.

Rico, M., Benito, G., Díez-Herrero, A., 2008. Floods from tailings dam facilities. J. Hazard Mater. 79–87. https://doi.org/10.1016/j.jhazmat.2007.09.110.

Rico, M., Benito, G., R, S.A., Díez-Herrero, A., Pereira, H.G., 2008. Reported tailings dam failures. A review of the European incidents in the worldwide context. J. Hazard Mater. 846–852. https://doi.org/10.1016/j.jhazmat.2007.07.050.

Roche, C., Thygesen, K., Baker, E., 2017. Mine Tailings Storage: Safety Is No Accident. A UNEP Rapid Response Assessment.

Schoenberger, E., 2016. Environmentally sustainable mining: the case of tailings storage facilities. Resour. Pol. 49, 119–128. https://doi.org/10.1016/j.resourpol.2016.04.009.

SME, 2011. SME Mining Engineering Handbook, third ed. Society for Mining, Metallurgy, and Exploration, Inc. third ed.

Spitz, K., Trudinger, J., 2008. Mining and the Environment: from Ore to Metal. CRC Press, Taylor & Francis.

UK EA, 2016. Onshore Oil & Gas Sector Guidance. Environment Agency, Bristol.

UNECE, 2014. Safety Guidelines and Good Practices for Tailings Management Facilities. United Nations Economic Commission for Europe (UNECE), p. 42.

US EPA, 2014. Reference Guide to Treatment Technologies for Mining-Influenced Water. US-EPA United States Environmental Protection Agency.

Wieland, M., 2012. Seismic Design and Performance Criteria for Large Storage Dams. 15th World Conference on Earthquake Engineering, Lisboa, pp. 3677–3686, 2012.

Williams, D., 2014. Mine Planning for the Final Landform, 5th International Mining and Industrial Waste Management Conference. John Wates, Proceedings Book, Rustenburg, South Africa, pp. 1–52.

Williams, D., 2015. Towards the Elimination of Conventional Surface Slurried Tailings Storage Facilities, Tailings and Mine Waste Management for the 21st Century 2015. The Australian Institute of Mining and Metallurgy, Sydney, pp. 11–26.

WISE, 2019. Chronology of Major Tailings Dam Failures. http://www.wise-uranium.org/mdaf.html. Accessed 06 November 2019.