Global Tailings Storage Facilities: Categorization by Resource Type & Forecasting Copper Tailings Production until 2040

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Final version: July 4th, 2023
Defense: July 11th, 2023

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Abstract

Tailings are a waste product of primary metal production. Although these metals contribute to the development of modern technology and renewable energy systems, tailings pose significant environmental, economic, and human health risks. Stored behind a dam in tailings storage facilities (TSFs) these waste materials are meant to be isolated from the surrounding environment. However, in the last 120 years at least 350 tailings dam have collapsed, resulting in over 2500 casualties, tens of billions of dollars in financial losses, and severe damage to waterways and the environment. There is a worrying trend of failures becoming more severe and increasing in intensity, and because metal demand is increasing and ore grades are declining, this could potentially become more problematic in the near future.

This study concisely describes the production and disposal of tailings and gives background information on tailings dam failures. Furthermore, it provides a basis for understanding the variations between TSFs across resources categories. Finally, it contributes to the quantification of future copper tailings generation in light of the renewable energy transition. It does so by giving an overview of scientific literature on TSFs, by providing global inventory of TSFs categorized by resource type, and by forecasting the copper tailings production until 2040. Two research question have been answered:

RQ1: To which resources are tailings storage facilities linked?

RQ2: How will the renewable energy transition affect copper tailings production until 2040?

RQ1 presents a comprehensive overview of the resources associated with tailings storage facilities by identifying the primary resources linked to each TSFs. This was done by combining a database on existing TSFs worldwide (GRIDA) with a database that contains mining and mineral processing hubs (USGS MRDS). TSFs have been linked with USGS MRDS hubs by using location data using the geographic information system QGIS and by matching TSFs and mine based on their names. Resource data of TSFs that could not be linked with USGS MRDS data has been manually added by systematically analysis of company websites that own the TSFs, supplemented with scientific literature regarding mining locations, thereby forming the GRIDA+ database.

RQ2 forecasts how the ongoing renewable energy transition will impact copper tailings production up to 2040. Because renewable energy systems use more copper than their fossil equivalents, the energy transition will cause an increase in copper demand. Three IEA energy scenarios (STEPS, SDS, and NZE) have been used as basis for this copper demand. By taking into account the copper recycling rates, ore grades, and smelting efficiency based on scientific literature, this study quantifies the anticipated increase in annual copper tailings production in the period 2020-2040.

This study has identified 27 resource categories linked to TSFs in GRIDA+. The 10 most notable categories are gold, copper, aluminium, lead-zinc, coal, iron, PGE-nickel-chromium, silver, diamond, and manganese. Combined they account for over 90% of TSFs worldwide and 93% of the global tailings volume. Among these categories, the top 3 commodities (copper, gold, and iron) contribute to approximately 74% of the overall tailings volume. Copper accounts for approximately 41% of the total volume reported in the GRIDA+ database, and copper TSFs are among the largest in the world in terms of pond capacity and dam height. The presence of upstream dams in copper TSFs is a cause for concern, as historical data indicates that such dams have a higher likelihood of failure. Additionally, nearly one-third of copper TSFs are inactive, rendering them more susceptible to failure compared to officially closed dams. However, copper TSFs demonstrate relatively favourable performance in terms of stability concerns, the availability of engineering records, and resilience against extreme weather events compared to other resource categories.

The forecasts of the 2040 annual global production indicates that of copper tailings production will grow significantly compared to 2020. The tailings-to-metal ratio of copper will increase from 193:1 to 237:1 and the annual copper demand will increase with 31% to 67%. This will increase the annual copper tailings production with 41% in the STEPS scenario, 47% in the SDS scenario, and 79% in the NZE scenario compared to 2020. In this last scenario the annual tailings production is estimated at 3,740,000,000 m^3, which in volume is equivalent to 66% of the annual global crude oil production. Copper tailings is primarily driven by the growing demand for copper and to a lesser extent by the diminishing copper ore quality. Advancements in recycling rates and the possible deterioration of copper smelting efficiency could respectively have a substantial dampening or additional effect on future copper tailings growth.

Because of the expected surge in copper tailings production enhancing tailings storage facility management and improving copper recycling are two important challenges for the future. Converging factors such as increasing mineral demands, diminishing ore grades, advancements in extractive and processing technologies may cause the mining industry to start new mining operations and rapidly upscale existing projects. This puts additional pressure on existing and planned TSFs, leading to additional risks of tailings dam failures. These developments make urgent action necessary in order to prevent future TSF catastrophes and to assure a save, sustainable, and stable supply of copper and other minerals in the future.

Policymakers should adopt measures to limit copper demand and improve copper recycling rates, aim at including the effects of tailings dam failures in Life Cycle Assessments (LCAs) thereby emphasizing the benefits of recycled copper, and enforce a comprehensive industry standard for tailings management .

Keywords

tailings storage facilities, global tailings inventory, tailings dam failures, tailings-to-metal ratio, copper tailings production, energy scenario

Database

In this study the GRIDA+ database is presented. It can be accessed below. References to this database are found in the in the following format: *GRIDA+ database [#.NAME sheet] [cells, columns, or rows)*

The latest version of this database is *GRIDA+ v20 25-06-2023.xlsx*

Preface

This thesis research was written for the MSc programme 'Industrial Ecology' at Leiden University and TU Delft. Its aim is to explore issues surrounding tailings storage facilities, critical materials, and future copper tailings production. The subject of this thesis was proposed by Dr. E.G.M. Kleijn of the Institute of Environmental Sciences (CML) at Leiden University. The main reason for me to engage on the topic of tailings dam was both my lack of awareness of the existence of the issue, combined with the knowledge that the demand for metals - and thus the production of mine waste and tailings - will further increase in the future because of economic growth and the transition to renewable energy systems. Because of the colossal size of tailings storage facilities and I found this an interesting and important topic to study.

That issues regarding waste from mining operations are not new phenomena is demonstrated by Georgius Agricola, a 16th century German mineralogist, metallurgist, and friend of fellow humanist Erasmus of Rotterdam. He mentioned the negative environmental effects of mining waste and ore processing in his authoritative work *De Re Metallica* (On the Subject of Metals):

> 'The strongest argument of the detractors [of mining] is that the fields are devastated by mining operations. Also they argue that the woods and groves are cut down, and when the woods and groves are felled, then are exterminated the beasts and birds. Further, when the ores are washed, the water which has been used poisons the brooks and streams, and either destroys the fish or drives them away.'
>
> *GEORGIUS AGRICOLA - DE RE METALLICA (1556, BOOK 1, P.8)*

Going back even further, Gaius Plinius Secundus - a 1st century Roman natural philosopher and author - described the effects of washing gold ores in the Iberian provinces of the Roman Empire. Environmental pollution from such mining activities dating back to 2,500 BCE can still be found in Spain *(LEBLANC ET AL., 2000)*.

> 'Another labour is that of bringing rivers from the more elevated mountain heights, a distance in many instances of one hundred miles perhaps, for the purpose of washing debris. [This] earth, carried onwards in the stream, arrives at the sea at last, and thus is the shattered mountain washed away; causes which have greatly tended to extend the shores of Spain by these encroachments upon the deep.'
>
> *GAIUS PLINIUS SECUNDUS - NATURALIS HISTORIA (77 CE, BOOK 33, CHAPTER 21)*

The importance of this issue really hit me when in 2019 the Córrego do Feijão tailings dam in Brumadinho (Brazil). This dam was used to store iron tailings from a nearby mine. An estimated 250 people were killed, dozens of homes, buildings and other infrastructure were destroyed, and ecosystems hundreds of kilometres further downstream were severely polluted. This tailings dam failure - which is among the largest in history - made me further realize that these incidents are not a thing of the past but pose a risk that must be addressed and taken seriously today and in the future. I hope this study will contribute to insights and more awareness on this topic.

Figure 1 - Mural depicting the victims of the 2019 Brumadinho iron tailings disaster in Brazil (OSGEMEOS, n.d.)

Acknowledgements

For all their help, patience and trust these years I would like to thank:

Ratna Timmermans
Iris Otto
René Kleijn
Linda Kamp
Paula van den Berg
Kiki Boomgaard
My parents, sister, family, and friends

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Definitions and abbreviations:

GIS	Geographical information system
GRIDA	Global Resource Information Database Arendal, a UNEP partner from Norway
GRIDA database	Global inventory of TSFs, made by GRIDA
GRIDA+ database	Global inventory of TSFs, complemented with resource types
ICMM	International Council on Mining and Metals
ICOLD	International Commission on Large Dams
IE	Industrial Ecology
IEA	International Energy Agency
MRDS	Mineral Resources Data System of the USGS
NZE	IEA 'Net Zero Emissions Scenario'
QGIS	Free, open source, and cross platform GIS software
SDS	IEA 'Sustainable Development Scenario'
STEPS	IEA 'Stated Policies Scenario'
T/M ratio	Tailings-to-Metal ratio
TSF	Tailings Storage Facility
UNECE	United Nations Economic Commission for Europe
UNEP	United Nations Environmental Programme
USGS	United States Geological Survey
WMTF	World Mine Tailings Failures

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1 Introduction

Since prehistoric times, extraction of materials from the Earths' crust has played a substantial role in human societal development *(HOLMBERG ET AL., 2017, p. 117)*. Up to this day the production of metals, minerals, and fossil fuels is central to the global economic system. Materials such as copper and aluminium are considered 'the building blocks of our way of life' *(KOGEL ET AL., 2006, p. 3)*. Our reliance on these materials makes the mining industry one of the largest global economic sectors, with an estimated $545 billion revenue and $70 billion net profit in 2020 by the 40 largest mining companies *(PWC, 2021, p. 5)*.

However, the extraction and processing of these minerals has significant effects on the environment such as land use, energy consumption, greenhouse gas (GHG) emissions, and water pollution *(DUDKA & ADRIANO, 1997, p. 590)*. Moreover, during the extraction and processing of these minerals into end products enormous amounts of waste are generated *(BRGM, 2001)*. On a global scale, mining waste is larger in volume than 'both domestic and [other] industrial waste' combined *(ICOLD, 2001, p. 10)*.

A substantial portion of mine waste is a processing waste called *tailings*, which remains after the extraction of the desired materials from the ores. Tailings often contain raised concentrations of minerals such as 'antimony, arsenic, cadmium, copper, lead, uranium, and zinc' *(HUDSON-EDWARDS, 2016, p. 288)*. Other examples of hazardous contents are residual cyanide in gold mining *(VICK, 1996)*, radioactive material in uranium mining *(ABDELOUAS, 2006)* and processing salts such as xanthates *(BRGM, 2001, p. 26)*. Tailings can have extreme pH levels and are generally acidic caused by sulphide minerals. They can also be alkaline, e.g. bauxite tailings have pH levels of ~13 *(KOSSOFF ET AL., 2014)*. Since minerals extraction is never exhaustive tailings contain traces of various (heavy) metals *(LOTTERMOSER, 2010, p. 271)*. Because of their toxic, corrosive, and/or radioactive character tailings should be carefully disposed. This is generally done in a tailings storage facility (TSF), which comes in the form of a tailings pond surrounded by a dam *(KOSSOFF ET AL., 2014, p. 232)*. Within the embankment of the dam the tailings are stored separated from the environment.

However, tailings dams break down on a regular basis, despite various legislation on construction from governments and guidelines from organisations such as the International Committee On Large Dams *(ICOLD, 2001, p. 6)*. In 2019 one of the largest tailings dam failures ever occurred near Brumadinho, Brazil. Over 12 million m^3 of iron tailings were released, killing more than 270 people and polluting over 350 kilometres of waterways. A $7 billion settlement was signed by Vale - the company that was responsible for the dam - to compensate for the damage *(AP NEWS, 2021)*. This failure is no isolated incident: since the 1900's there have been over 350 tailings dam failures with a total release of 250 million m^3 of tailings and more than 2500 casualties *(PICIULLO ET AL., 2022, p. 1)*. Although the frequency of tailings dam failures has been declining since the 1980s, the severity of each failure has increased *(BOWKER & CHAMBERS, 2011, p. 4)*.

In the near future the use of products from the mineral mining industry is expected to grow further. The two main drivers for this increase are global economic growth and - more importantly - the transition to clean energy technologies. Renewable energy sources such as wind turbines and solar photovoltaics (PV) are relatively mineral intensive compared to their fossil fuelled predecessors *(International Energy Agency, 2021b; Kleijn et al., 2011)*. The same is the case for electric vehicles (EVs), which typically require six times more minerals than vehicles with internal combustion engines (ICEs) *(International Energy Agency, 2021b, p. 26)*. Based on a scenario that meets the 2015 Paris Agreement goals the mineral demand of the energy sector will quadruple by 2040, making it the leading consumer of minerals such as copper, lithium, nickel, cobalt, and rare earth elements *(International Energy Agency, 2021b)*.

The pattern of a substantial increase in future metal mining activity, and a growing severity of tailings dam failures may have disastrous effects for the future, which could lead to more human casualties, large scale environmental damage, severe economic risks for mining companies, and disruptions of the world's mineral supply.

In this study an existing database with tailings dams (GRIDA) is complemented with resource data to form a new database (GRIDA+). The goal of this is to gain insights on which minerals are linked to currently existing tailings storage facilities, and how future upscaling of mineral production will affect tailings production of copper, an important metal in the renewable energy transition.

1.1 Scientific knowledge gap

In the last century, tailings dam failures have been happening regularly and have caused considerable environmental damage, thousands of human casualties, and tens of billions of dollars in direct damage and financial losses. However, many aspects of this topic are lacking in research and much data is unavailable. In this chapter the knowledge gaps concerning tailings dams will be discussed. Based on these knowledge gaps the research questions for this study will be formulated.

First, there is no standard work on tailings and tailings dam failures. The topic of tailings is complex, and its generation and storage can differ widely depending on the type of ores and materials that are being mined and processed. General information on the topic is difficult to find, making it a tough topic to dive into. Scientific literature on tailings and tailings dams is fragmented and is studies a specific aspect of the topic, making it difficult to get a general overview.

Second, there are limited and widely differing statistics available on the total number of existing tailings ponds worldwide. *Davies et al. (2000)* estimated the total number of active tailings ponds to be around 3,500. However, according to the United Nations Environment Programme (UNEP) this is an underestimation because there are over 30,000 mines globally *(Roche et al., 2017)*. UNEP's scepticism is supported by other research: in China alone 12,655 tailings ponds were counted in 2008, with over half actively in use *(Wei et al., 2013, p. 110)*. *Azam & Li (2010, p. 50)* used a figure of 18,401 tailings ponds in their research on global tailings dam failure rates, although no details or sources are provided on how this number was established. This number has been heavily criticized by *BOWKER (2014)*, particularly because it has been frequently copy-pasted to other scientific research without reservations or context of its origin (i.e. apparently it was an approximation made by the authors). The recently published GRIDA database is an attempt to make a publicly available global overview of tailings storage facilities. However, the minerals (e.g. gold, copper, iron, etc.) that are linked to the TSFs are missing in this database.

Third, there is uncertainty about the level of growth of future tailings production. Economic development and the transition to renewable energy systems is pushing the *modern mining metric*, which is the combination of high mineral demand, declining ore quality, new extractive and processing technologies, and large-scale mining. These developments will cause increasing amounts of tailings production, with related effects. However, it is not known *how far* the modern mining metric will be pushed and what its effect is on tailings production.

1.2 Aim and research questions

The aim of this study is to make a global inventory of existing tailings storage facilities categorized by resource type, and to quantify the future copper tailings production up to 2040. This is done by answering two research questions:

RQ1: To which resources are tailings storage facilities linked?
RQ2: How will the renewable energy transition affect copper tailings production until 2040?

1.3 Research approach

This study is grounded in Industrial Ecology (IE) which is a relatively new academic discipline that focusses on examining material and energy flows from a systems perspective. The size of such a system can vary, ranging between macro- (e.g. a global industrial sector), meso- (e.g. an industrial facility), and microscale (e.g. the process of fuel combustion) *(ALLEN, 1994, p. 51)*. IE is *industrial* because it concentrates on production systems, and *ecological* because of its philosophical foundation and approach to these systems: within IE production systems are circular instead of linear by viewing them ‘in the context of the larger ecosystems’. IE aims to mimic biological systems, because these are ‘especially effective at recycling resources’, which makes waste practically non-existing *(LIFSET & GRAEDEL, 2002, p. 3)*. This comparison between industrial production processes and nature is dubbed the ‘ecological metaphor’ or the ‘biological analogy’ *(EHRENFELD, 2003)*. Another often used metaphor in the context of IE is ‘industrial metabolism’, which pairs industrial processes with living organisms as systems that each use and transform energy and materials *(AYRES, 1989)*.

IE not only examines the technical and environmental aspects of material- and energy flows, but explicitly looks at how solutions can be implemented within a system. Consequently, IE considers the ‘influences of economic, political, regulatory, and social factors on the flow, use, and transformation of [material and energy] resources’ *(WHITE* in *ALLENBY & RICHARDS, 1994, P. V)*.

In this study both elements of IE will be present: an examination of materials flowing through a production system (i.e. from mining and processing of ores to disposal as tailings in a dam), and an evaluation of solutions within this system by exploring future developments and challenges.

1.4 Reading guide

Chapter 2 - Background and literature research:

- Explores current state of scientific literature on tailings dams
- Provides context on tailings dam failures

Chapter 3 - Method:

- Describes the methods and data that has been used to answer the two research questions

Chapter 4 -Results:

- SQ1: Provides the GRIDA+ database made by linking GRIDA with USGS MRDS, company data, and scientific research, which shows the resources that linked to TSFs.
- SQ2: Forecasts the annual copper tailings production until 2040 based on 3 copper demand scenarios, the copper recycling rates, smelting efficiency and ore grades.

Chapter 5 - Discussion and Conclusion:

- Answers the two research questions
- Discusses the limitations of the study
- Places the results in a wider context
- Describes the academic relevance
- Provides recommendations for policymakers and further research

2 Background and literature research

This chapter is a background an overview is given of tailings dams. The chapter is divided into 8 sections. In the 1st section a definition of tailings is given, and its production process is explained. In the 2nd section the disposal and storage of tailings is described, as are the different types of tailings dams and storage facilities. In the 3rd section incidents and failures of tailings storage are discussed. In section 4 an overview is given of historical tailings dam failures. Section 5 and section 6 discuss the causes and effects of tailings dam failures respectively. In the 7th and section prevention of tailings dam failures are discussed, and in the 8th and final section the annual production of the three most produced metals is provided.

This chapter is based on an analysis of scientific literature, and an analysis of databases on tailings dams and databases of tailings dam failures. Two ways of literature research and data gathering have been used, see *Table 1* for more details.

The first is examining the *most cited articles*. The search engine *Scopus* was used to make an overview of the most cited articles on tailings dams failures and to find information on their causes and effects. See *Appendix 1: 33 most cited papers on tailings dam failures* for a list with the 33 most cited papers, and *Appendix 2: Literature search results* for all the search terms used and returned literature.

The second is a *snowballing* approach, which was used in combination with Google Scholar. Literature and data on tailings dam failures have been searched by examining literature that was cited in the *most cited articles*, and by searching the web with the use of the internet search engines DuckDuckGo and Google.

Section	**Title**	***Snowballing***	***Most cited articles***
2.1.1	Tailings	☒	☐
2.1.2	Tailings dams	☒	☐
2.1.3	Tailings dam failures	☒	☒
2.1.4	Historical tailings dam failures	☒	☒
2.1.5	Causes of tailings dam failures	☒	☒
2.1.6	Effects of tailings dam failures	☒	☒
2.1.7	Prevention of tailings dam failures	☒	☒
2.1.8	Tailings production per resource	☒	☐

Table 1 - Data and literature gathering used for the 8 sections of the background chapter. Made by author.

2.1.1 Tailings

> **Tailings** are a type of mining waste, which is '*material resulting from prospecting and extraction treatment, and storage of mineral resources*' that the holder *'discards or intends or is required to discard' (BRGM, 2001, p. 64)*. There are several types of mine waste such as topsoil, overburden, waste rock and tailings. Tailings are a processing waste and defined as '*mixtures of crushed rock and processing fluids from mills, washeries or concentrators that remain after the extraction of economic metals, minerals, mineral fuels or coal from the mine resource' (KOSSOFF ET AL., 2014, p. 230).*

To give a clear picture of what tailings are, we have to begin with how they are produced, i.e. mining activities. The practice of mining concerns the extraction of desired geological commodities such as copper, iron, and other metals and materials from mineral deposits. Mining can be defined as: 'the search, extraction, beneficiation, and processing of solid minerals from the earth's crust through open-pit mining, strip mining, quarrying and underground excavation' *(HOLMBERG ET AL., 2017, p. 117)*. See *Table 2* for the differences between these types of mining.

• Open-pit mines are operated by excavating ores from burrows. They are recognizable by terrace-shaped slopes surrounding a large open hole or pit in the ground *(CHEN ET AL., 2015, p. 77)*. • Strip mining is a method that is being used when the minerals are relatively close to the surface of the earth, for example in coal mining (Stretesky & Lynch, 2011). Unlike the circular method in open-pit mining the ores are excavated strip by strip. Characteristic for strip mining is that most of the mining waste stays in-pit *(DARLING, 2011, p. 989)*. • Quarrying is a variant of open-pit mining for the production of dimension stone *(YARAHMADI ET AL., 2018)* and aggregates *(BESSA ET AL., 2015; DARLING, 2011, p. 407)*. • Underground excavation is an umbrella term for all types of mining that are dependent on 'tunnelling networks to gain access to the zones of valuable minerals' *(DARLING, 2011, p. 364)*. Underground mining is more expensive, but achieves higher ore grades and lower stripping ratios[i] compared to open-pit mining *(BEN-AWUAH ET AL., 2016, p. 1)*. The higher selectivity and lower stripping ratios lead to up to ten times less mining waste compared to open-pit mining *(BRGM, 2001, p. 24)*.

Table 2 – Four types of mining. Made by author.

Generally, there are three steps in mining of ores, independent of the type of mining or ores involved. These are preparation, extraction, and processing *(BRGM, 2001, p. 24)*. During each step different types of mine waste are produced (see *Figure 2*).

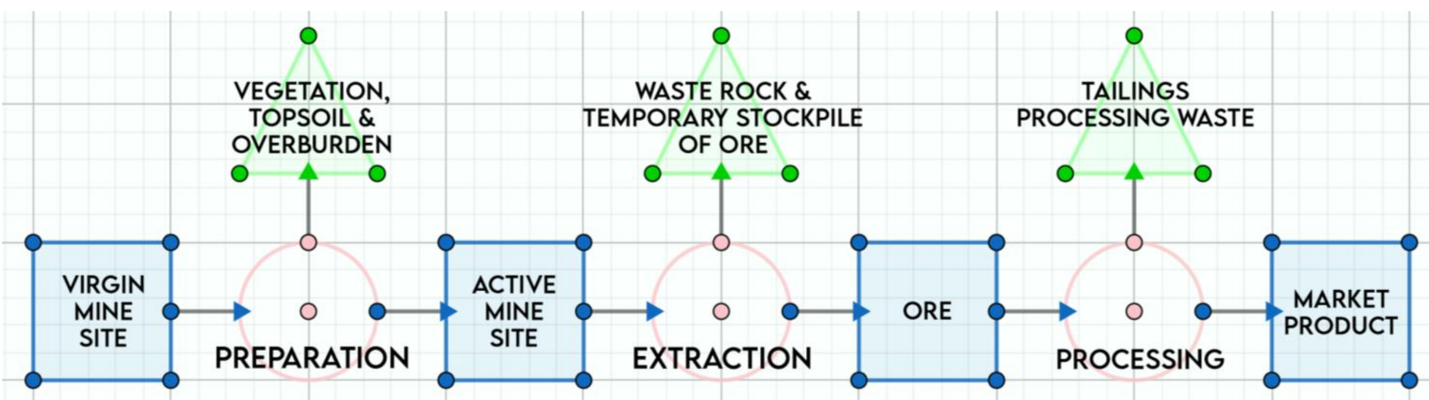

Figure 2 – Schematic overview of ore mining, based on DARLING (2011) and BRGM (2001, P. 7). Blue squares = resources, pink circles = activities, green triangles = waste types. Made by author.

[i] The stripping ratio is 'the unit amount of spoil, overburden, or waste that must be removed to gain access to a unit amount of ore' *(DARLING, 2011)*. A higher ratio means that more units of waste are excavated for each unit of useful ore.

Preparation: In order to reach the desired ores below the surface, the unusable material on top of the ores is removed. First, forests and other vegetation are cleared by logging companies to be sold as timber *(BURNS, 2007)*. After clearing the vegetative cover the *topsoil* is removed. The topsoil is commonly regarded to be waste, e.g. by *BRGM (2001, P. 7)*. However, it is has been argued that topsoil should not be defined as such, since the careful removal and storage of this organic material is essential for successful land reclamation in the end-of-life (EoL) phase of mines *(DARLING, 2011; GHOSE, 2001)*. In the last step of preparation the *overburden* is removed, which are layers of unusable bedrock on top of the ores *(YELLISHETTY ET AL., 2008, p. 1284)*.

Extraction: When overburden is removed the ores become accessible and ready for mining. Extraction of the ores can be done with various methods, e.g. drilling, stripping, excavation, and blasting *(DARLING, 2011)*.

Processing: In the case of metal production there are three stages of processing: ore processing, extractive metallurgy and refining *(BRGM, 2001, p. 19)*

1. The first stage is ore processing in a *concentrator*. During this stage the ores are prepared for transport after they have been mined. This generally starts with preliminary processing such as sorting and washing of the ores *(LOTTERMOSER, 2010, p. 16)*, decreasing the particle size by crushing or grinding *(ZHANG ET AL., 2015, P. 149)*, and removing the *gangue*. Gangue consists of rocks and minerals that are mixed with or found in the proximity of the ores. It is economically worthless materials and is therefore seen as waste *(BRGM, 2001, p. 24)*.
2. The second stage of processing is extractive metallurgy. This entails the physical extraction of the metals from the ore. Depending on the type of ore and material involved extractive metallurgy is done with various methods, e.g. pyrometallurgy, electrometallurgy, hydrometallurgy *(BRGM, 2001, p. 19)* or ionometallurgy (see e.g. *BONOMI, DAVRIS, BALOMENOS, & GIANNOPOULOU, 2017*).
3. The third stage of processing is refining, which concerns the removal of impurities from the metals. By refining the metal its purity grade is increased. Refining is done by various methods depending on the metal, e.g. electrorefining of copper *(WANG ET AL., 2011)*, the Bayer process for aluminium leaching and refining *(ROSENBERG & ARMSTRONG, 2017)*, and pig iron decarbonization in Linz-Donawitz furnaces *(PATI & SATAPATHY, 2015)*.

Estimates of the global annual amount of mining waste put into storage[ii] differ widely. Blight (2011, p. 88) estimated that it would be enough to cover the island of Ireland to a 'depth of more than 2 meters' of equally distributed material. Jones & Boger (2012) give an estimation of around 65 billion tons, while the International Commission On Large Dams (ICOLD) estimated it to be around 5 billion tons (ICOLD, 1996 in Blight, 2011). A more recent estimate is that 'several billion tons' of mining waste are generated each year *(HUDSON-EDWARDS & DOLD, 2015, p. 82)*.

[ii] According to BLIGHT (2011, P. 78) the term *storage* is preferred over *disposal* when referring to the end-of-life (EoL) phase of mining material, because it can be reused for further resource extraction as a result of improved extractive technologies, commodity price fluctuations, and progress in the circular economy (CE). This practice of reuse is called re-mining. However, since only a fraction of tailings is currently remined this study will use the term disposal for the sake of simplicity.

Tailings are a type of mine waste that is rejected at the tail-end of the extractive metallurgy stage, hence the term *tailings (UNECE, 2021)*. It is estimated that on average tailings make up around 25% of all mining waste *(JONES & BOGER, 2012, p. 10058)*. However, depending on the ore type this can be as high as 99% of the mined material *(LOTTERMOSER, 2010, p. 270)*. Tailings consist of 'mixtures of crushed rock and processing fluids that remain after the extraction of economic metals, minerals, mineral fuels or coal from the mine resource' *(KOSSOFF ET AL., 2014, p. 230)*. They originate from different stages of processing such as concentrators, washeries, and mills, and are produced in a wide array of mineral mining. Because of this, they can vary substantially in contents and characteristics, see Table 3 for a list of variables.

Variables of tailings characteristics
- Mineralogical and geochemical compositions
- Specific gravity of particles
- Settling behaviour
- Permeability versus density relationships
- Soil plasticity
- Consolidation behaviour
- Rheology and viscosity characteristics
- Strength characteristics
- Pore water chemistry
- Leaching properties

Table 3 - Variation in tailings characteristics, from Lottermoser (2010, p. 272). Made by author.

Generally are two main components to tailings: tailings liquids and tailings solids, which are commonly discharged together *(LOTTERMOSER, 2010, p. 272)*. In the next section the contents of each will be briefly discussed.

2.1.1.1 Tailings liquids

The liquids in tailings originate from ore processing, which frequently happens in water. This type of processing is called hydrometallurgy and has become a successful type of extractive metallurgy at the expense of pyrometallurgy since the late 19th century *(GUPTA & MUKHERJEE, 1990)*. Hydrometallurgy is currently the most used method for the processing of bauxite *(JAMIESON ET AL., 2017, p. 74)*, copper(II) oxide *(HABASHI, 1997, p. 550)*, cobalt (*P. 930*), and it is used for the separation and extraction of many types of REE *(ZHANG, ZHAO, & SCHREINER, 2016)*. The water that is used for hydrometallurgy eventually ends up in the TSF, at least partially (in many cases processing water is reused, which is an important aspect of efficient ore processing).

Hydrometallurgy concerns two key steps: leaching and extraction *(HAVLIK & SKROBIAN, 2008, p. 7)*.

2.1.1.1.1 Leaching

Leaching of metals from the ore is done by mixing water with process chemicals (i.e. a leaching agent) to form *process water.* This process water is mixed with the crushed ores to form an aqueous slurry. The process chemicals leach the metals from the ore into the slurry. The types of process chemicals that are used are dependent on the specific ore composition and the characteristics of the metals that are being leached.

2.1.1.1.2 Extraction

The selective extraction of metal from the slurry is generally done by *froth flotation*. This is a widely applicable and adaptable method used for the physical extraction of a large variety of particles and materials. Froth flotation is 'one of the most broadly used separation methods in the mineral processing industry' *(Shean & Cilliers, 2011, p. 58)* [iii]. The procedure of froth flotation is based on water-repellent 'characteristics of the surfaces of various rock and mineral species' that are contained in the aqueous slurry *(Kawatra* in *Darling, 2011, p. 1517)*: some minerals are easily wettable (hydrophilic), while others repel water and are difficult to wet (hydrophobic). By blowing air into to the slurry the particles that are hydrophobic will be trapped in air bubbles. These particles are captured in a thin film that forms the bubbles. The bubbles will float to the surface of the slurry and form a mineral froth. This froth is recovered and dried for further processing. During the process of froth flotation hydrophilic particles - consisting of gangue - settle at the bottom and are removed as tailings.

2.1.1.1.3 Process chemicals

To improve leaching and extraction a wide array of process chemicals is used. These process chemicals alter the hydrophobicity and hydrophobicity of the particles in the slurry so specific minerals can be extracted while others remain in the slurry *(Shean & Cilliers, 2011)*. Process chemicals used for leaching and extraction can be grouped into various categories. The most significant are reagents (i.e. collectors and frothers) and modifiers (e.g. pH regulators, activators & depressants). Other process chemicals are hydrometallurgical reagents, oxidants, and flocculants and coagulants *(Darling, 2011, pp. 1517–1525; Lottermoser, 2010, pp. 271–272)*. Each of these will be briefly discussed below to give an overview of the types of chemicals that are used in processing, which ultimately end up in the tailings in their original or modified form.

2.1.1.1.3.1 Hydrometallurgical reagents

This type of reagent is used for leaching the minerals from the ore. In hydrometallurgy *solvent extraction* (SX) is 'one of the most important separation processes', especially the use of SX agents based on phosphorus. Solvent extraction is used in the case of 'Cu, Ni, Co, Zn, U, Mo, W, V, Zr, Hf, Nb, Ta, rare earths, Ga, Ge, the platinum group metals (PGMs), B, reprocessing of nuclear fuels, purification of wet process phosphoric acid, and nitric acid recovery', among other uses *(Flett, 2005, p. 2426)*.

2.1.1.1.3.2 Oxidants

Oxidants play a key role in the leaching of metals. Examples of oxidants are hydrogen peroxide (H_2O_2) and potassium permanganate ($KMnO_4$) *(Lottermoser, 2010; Ma et al., 2016)*:

- Hydrogen peroxide is used as oxidant in cyanidation of gold *(Pearse, 2005, p. 140)* and for leaching of nickel, cobalt and REE from waste batteries.

[iii] The estimated amount of ores annually processed by this method was around 2 billion tonnes in the early 2000's (Pearse, 2005, p. 140).

- Potassium permanganate and hydrogen peroxide are both used in the leaching of e.g. indium sulphides (In_2S_3) *(MA, XI, ZHANG, HUANG, & CHEN, 2016)*.

2.1.1.1.3.3 Flotation reagents: collectors & frothers

The minerals that are suspended in the aqueous slurry can generally not be processed by froth flotation without adjustment of their hydrophobicity first. Flotation reagents are required to sufficiently adjust their hydrophobicity. This is done with the use of *collectors* and *frothers*.

- Collectors are used 'to selectively adsorb onto the surfaces of particles' in order to separate these particles during froth flotation *(DARLING, 2011, p. 1520)*. Collectors are a large group of different organic chemical compounds *(BULATOVIC, 2014)*. The type of collector that is used depends on the specific composition of the minerals that are processed. They can be grouped based on ionic charge (non-ionic, anionic, or cationic) and on the way they bond with particles (chemisorption or physisorption) *(DARLING, 2011)*.
- Frothers are used to optimize the characteristics of the bubbles and the froth. They play an important role in controlling 'the bubble size [and] the stability and mobility of the froth phase' *(KHOSHDAST, 2011, p. 25)*. Frothers are surface-active chemicals that are heteropolar *(BULATOVIC, 2014)*. The non-polar group is hydrophobic, and the polar group is hydrophilic, causing the frothers to adsorb on the interface between air and water, thereby creating a film that forms the froth. The non-polar group consists of a hydrocarbon chain (CH) *(BULATOVIC, 2014, p. 43)*. The polar group of the frother is 'always hydroxyl [OH], usually in the form of alcohol or glycol' *(PEARSE, 2005, p. 140)*. In volume, the most significant reagents used in mineral processing are lime, sulphuric acid, sodium- and calcium cyanide, and caustic soda *(PEARSE, 2005, P. 139)*.

2.1.1.1.3.4 Modifiers/regulators

The level of adsorption of collectors is altered by *modifiers* (also called *regulators*). Modifiers are used to boost or avoid adsorption of certain minerals. This causes the 'collector only [to] adsorb on particles that are targeted for recovery' *(BULATOVIC, 2014, p. 2)*

The most straightforward method for modifying the level of adsorption is by controlling the pH of the slurry. Typically, minerals become positively charged under low pH (acid) conditions, and negatively charged under high pH (alkaline) conditions. By manipulating the pH-level of the slurry using modifiers the targeting of certain minerals can be optimized. If the minerals in the slurry have non-overlapping pH values where the level of adsorption is greatest, gradual manipulation of the pH level provides a relatively simple method to separate specific minerals from the slurry *(DARLING, 2011)*. Commonly, sulfuric acid (H_2SO_4) is used to lower pH levels, and lime (CaO or $Ca(OH)_2$) is used as alkali to increase pH levels *(PEARSE, 2005)*. In circumstances where these types of modifiers have undesirable side-effects other substances are used, e.g. alkalis based on sodium ($NaOH$ or Na_2CO_3) instead of calcium *(DARLING, 2011)*.

Another method of adsorption modification is by using *activators* or *depressants*. In certain cases, collectors cannot adsorb the desired compounds without the help of an activator. By using activators the adsorption ability of the collector is "turned on". Depressants have a reversed purpose, i.e. preventing collectors to adsorb certain compounds. Depressants are generally used to 'increase selectivity by preventing one mineral from floating while allowing another mineral to float unimpeded', thereby improving purity and efficiency of the process *(Darling, 2011, p. 1525)*. Activators and depressants can be either organic or inorganic chemicals *(Bulatovic, 2014, p. 2)*.

2.1.1.1.3.5 Flocculants and coagulants

Flocculants and coagulants accelerate the clotting together of particles. This causes particles to stick together, forming increasingly larger flocs. Flocculants play an substantial role in the processing of sulphides, oxides and silicates *(Bulatovic, 2014)*. They are also used in waste water treatment and the dewatering of mineral concentrates and tailings such as coal waste slurry *(Sabah & Erkan, 2006)* and iron ore tailings *(Dash et al., 2011)*. By increasing the particle size using flocculants, the process efficiency of separating residual gangue from the leach solution is improved *(Gupta & Mukherjee, 1990)*. Flocculants may also be added to tailings before they are deposited in the tailings impoundment. This promotes the separation of the liquid and solid part of tailings and improves tailings settling behaviour. However, technological developments have increased the use of mechanical thickening for this purpose *(Darling, 2011, p. 650)*. More than 90% of flocculants are polyacrylamide-based *(Pearse, 2005)*.

2.1.1.1.3.6 Other process chemicals

Processing chemicals that are used other than the ones described above are 'dust suppressants, biocides, emulsifiers, surfactant dewatering aids, cathode smoothing aids, antifoams, levelling agents, solvent diluents or carriers, extender oils, mist suppressants, wetting agents, [and] heavy metal precipitants' *(Pearse, 2005, p. 148)*.

Depending on the climate and local circumstances the concentration of the reagents in the tailings liquids in the ponds can vary over time: precipitation and inflows of run-off will dilute tailings liquids, while evaporation and drainage will increase the concentration. Moreover, 'evaporative concentration causes secondary mineral precipitation at and below the tailings surface' *(Lottermoser, 2010, p. 272)*. The formation of secondary minerals can have various effects, which will be further discussed in the section on *Tailings solids*.

The composition of the process water - and therefor tailings liquids - also depends on the source and composition of the water that is being used. Using fresh, brackish or saline water for processing will cause the composition of the tailings liquids to be different, which in turn can have effects on the behaviour and composition of the tailings. For example, the use of saline ground water as process water can cause salt encrustations in the tailings ponds, might show poorer consolidation of tailings, and reduce evaporation from the tailings liquids. The salinity of tailings liquids is not limited to the process water that is being used, but can also be a result of the process chemicals *(Lottermoser, 2010, p. 272)*.

The list of process chemicals above demonstrates that a wide variety of process agents can be found in the tailings liquids, with different characteristics such as mobility and toxicity. Froth flotation is complex and has many unresolved issues, e.g. uncertainties related to water chemistry, secondary silicates, particle recovery and mineral separation *(Nagaraj, 2010* in *Edraki et al., 2014, p. 413)*. Because froth flotation remains 'relatively inefficient, despite numerous years of research', process chemicals in the tailings liquids can be highly concentrated *(Shean & Cilliers, 2011, p. 58)*.

2.1.1.2 Tailings solids

The solid particles in the tailings normally range in size from 10μm to 1mm *(UNECE, 2021)*. The composition of tailings solids can roughly be divided into 3 parts: gangue, sulphide-oxides, and secondary minerals *(Kossoff et al., 2014, p. 231)*.

Gangue is the unusable fraction of the ores and mainly consists of silicate minerals *(Lottermoser, 2010, p. 62)*. Of these silicates, quartz (SiO_2) is the most common. Other minerals commonly occurring in tailings gangue are feldspar, sericite, chlorite, calcite and dolomite *(Kossoff et al., 2014, p. 231)*.

Sulphide-oxides in the tailings originate from sulphide mineral ores. Many of the base metals are extracted from mineral ores that contain sulphide, e.g. pyrite (FeS_2) *(Lottermoser, 2010, p. 59)*. This is the case for iron, copper, zinc, lead, nickel, molybdenum, gold, and silver *(Dold, 2014, p. 643)*. Sulphide minerals cause acid mine drainage (AMD), which is another substantial environmental issue in mining. AMD occurs when the sulphides in the ores are exposed to water and oxygen. The oxidation of the sulphur in combination with water flows can cause the release of an acidic drainage seeping under and trough the tailings dam. AMD can contain 'high concentrations of iron, aluminium, and manganese [and] low concentrations of toxic heavy metals' *(Akcil & Koldas, 2006, p. 1140)*.

Secondary minerals form when primary minerals in the tailings react with another (Petrunic & Al, 2005, p. 2470). Oxidized secondary minerals form when the tailings solids weather due to contact with oxygen and moisture. The types of secondary minerals that form are highly dependent on the type of primary minerals and circumstances such as 'pH, climate and redox state' *(Kossoff et al., 2014, p. 232)*.

Secondary minerals contain the bulk of the (heavy) metal and metalloid pollutants in the tailings, for example arsenic (As) and lead (Pb) phases *(Kossoff et al., 2014)*. Sulphides in tailings frequently contain As, which is a highly toxic element for both flora and fauna, even in low concentrations. Surface conditions can induce the release of As from these sulphides in the form of secondary oxides and arsenate minerals, which have negative effects on natural ecosystems, human health, and water quality when leaked into the environment *(Zhu et al., 2015)*. Similarly, oxidation of Pb sulphides - commonly galena (PbS) - causes the release of secondary lead contained minerals (with various levels of solubility, mobility and toxicity depending on the conditions) which can severely pollute the natural environment *(Roussel et al., 2000)*.

2.1.2 Tailings dams

Dams are defined as '*barrier[s] preventing the flow of water or of loose solid materials*' (*Merriam-Webster, n.d.*). Tailings dams are goal oriented and are built with the specific objective of temporarily or permanently storing tailings by preventing tailings solids and liquids to flow into the environment.

Historically, dumping and riverine or marine disposal has been the most common methods to discard tailings. Since the London Convention in 1972[iv] and its 1996 successors there has grown a 'wide consensus among industry and stakeholders that riverine and shore marine disposal should be generally banned due to the high risk of environmental contamination' *(Dold, 2014)*. Nowadays, there are only a dozen mines remaining that put this type of disposal into practice, most of them located in Europe, Indonesia, and Papua New Guinea *(Vogt, 2013, p. 9; Rusdinar et al., 2013* in *Edraki et al., 2014, p. 411)*.

Most other mines that are currently active make use of tailings storage facilities (TSFs). TSFs contain the tailings in order to avoid environmental damage from their polluting contents. Storage can be temporarily pending for future processing, or - in most cases - as permanent disposal (BRGM, 2001, p. 41). In a tiny minority of TSFs containment is done in combination with tailings reuse or recycling, but in most cases the aim of a TSF is to contain the tailings indefinitely *(Fontes et al., 2016)*. There are several categories of TSFs, e.g. *terrestrial impoundments (BRGM, 2001, p. 41)*, *backfilling in underground mines (Wei et al., 2013, p. 111)*, *in-pit storage (Adrien Rimélé et al., 2018)*, and *dry stacking (Gomes et al., 2016)*.

Terrestrial impoundments are the most common TSFs *(BRGM, 2001, p. 41)*. In general, a terrestrial impoundment entails the construction of a tailings dam *(Kossoff et al., 2014, p. 232)*. Within the embankment of this dam the tailings solids and liquids are deposited, thereby forming a tailings pond.[v]

There are several distinct types of impoundments, e.g. *cross-valley impoundments*, *sidehill impoundments*, *above-grade impoundments*, *below-grade impoundments*, *above-grade stacks*, or combinations with *waste rock dumps* (see *Figure 3*).

[iv] The *Convention on the Prevention of Marine Pollution by Dumping of Waste and Other Matter* or 'London Convention' (1972), and its updated and more modern version 'London Protocol' (1996) are 'the principal international instruments for the protection of the oceans from anthropogenic pollution' *(Dold, 2014, p. 649)*.

[v] Not all tailings ponds are constructed this way: a TSF near Udachny, Russia was made in 1974 by blowing a crater in the ground with the use of a 1.7 kt TNT equivalent nuclear explosion *(Artamonova et al., 2022)*.

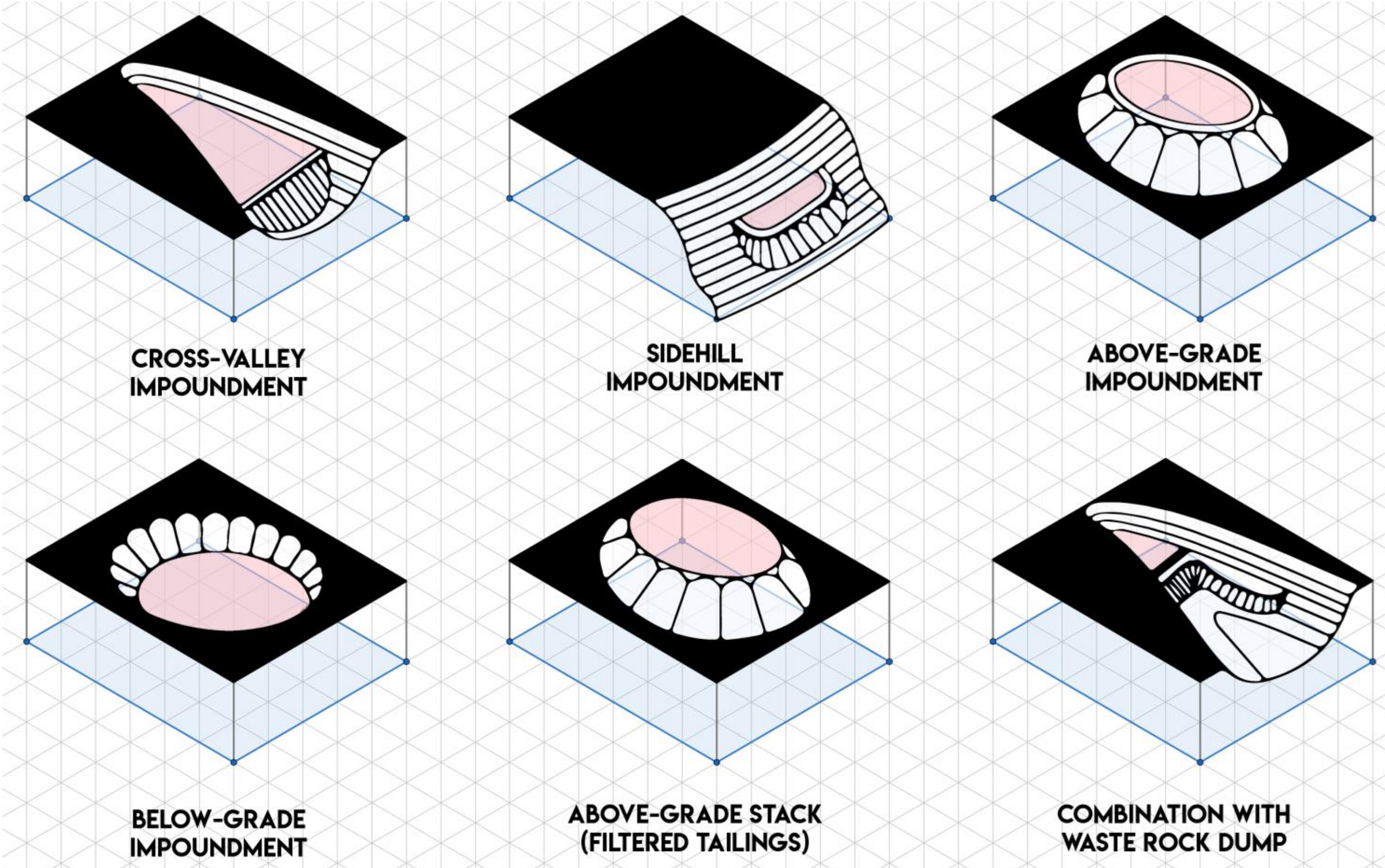

Figure 3 - Types of terrestrial tailings impoundments, with the tailings marked in pink. Based on DARLING*, 2011 (p. 647), adapted from* ZAHL ET AL. *(1992). Made by author.*

Because of the liquid part of tailings maintaining a proper water balance is an important aspect in proper and safe TSF management, see *Figure 4*.

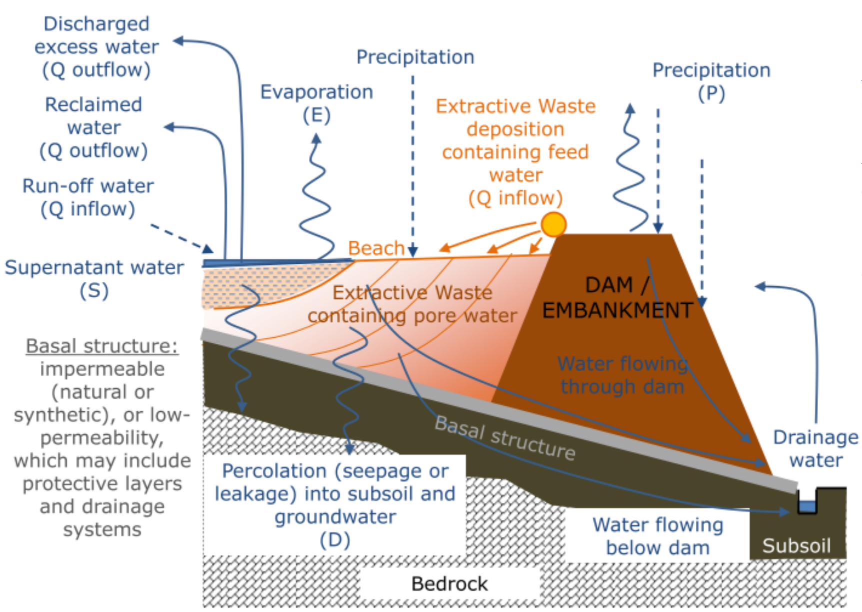

*Figure 4 - Typical water balance in a TSFs (*EUROPEAN COMMISSION*, 2018, p. 251).*

P = precipitation, Q = run-off inflows, E = evapotranspiration (evaporation + transpiration), D = deep percolation.

The general hydrologic equation for the water balance ΔS (change in water storage) = P + Q – E – D

In literature these construction are referred to in diverse ways, for example as *tailings impoundment (YIN ET AL., 2011)*, *mine waste dump (PASTOR ET AL., 2002)*, *tailings storage facility (WEI, YIN, WANG, WAN, & LI, 2013)*, but also as *tailings dam (KOSSOFF ET AL., 2014)*, *tailings dyke (EL-RAMLY, MORGENSTERN, & CRUDEN, 2003)*, or *tailings pond (RICO ET AL., 2008)*. Within this study the term tailings storage facility (TSF) is used when referring to any type of tailings containment.

Single stage dams are built in one step and not further enlarged. These are exclusively used in the case of smaller mining operations where the size of the required tailings ponds is limited, or duration of mineral extraction is relatively short. However, most tailings dams are gradually enlarged as the pond is being filled. The reason for this is not technical, but financial: it is not economically viable to build a dam that is sufficiently large for the entire life cycle of a mine in a single construction phase. This gradual enlargement affects the distance between the surface level of the tailings and the top of the dam (i.e. *freeboard*): the freeboard is relatively small compared to water retention dams *(RICO, BENITO, & DÍEZ-HERRERO, 2008, p. 81)*. Therefore, a tailings ponds is always nearly completely filled.

There are three main construction types of tailings dams: downstream, centreline, and upstream, see *Figure 5*. In some instances combinations of these three main types are used *(RICO, BENITO, & DÍEZ-HERRERO, 2008)*.

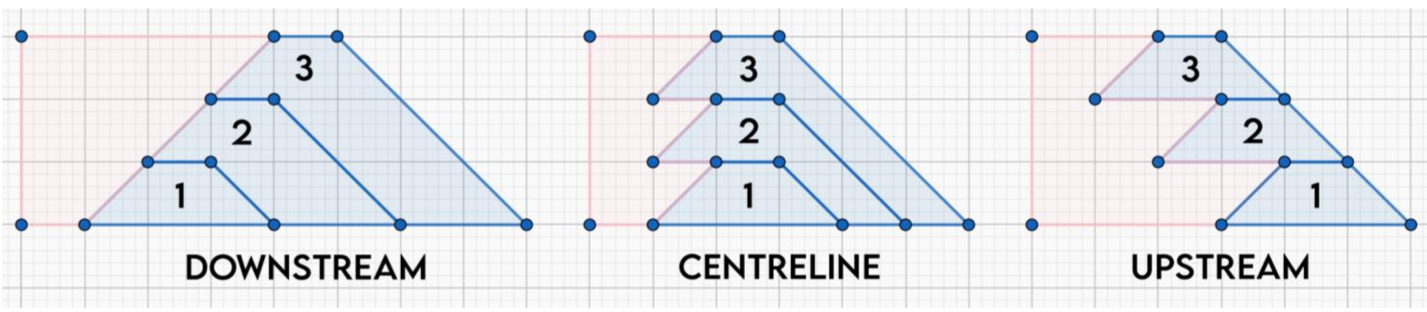

Figure 5 – Schematic cross-section of a downstream, centreline, and upstream tailings dam. Tailings are in pink; the dams are in blue. The numbers indicate the sequence of the construction stages. Adapted from KOSSOFF ET AL. (2014, P. 233). Made by author.

Tailings dams are enlarged in incremental stages. For downstream and centreline dams the ground surface area of the dams grows for each stage of dam construction. Additionally, both downstream and centreline dams require increasing volumes of material for every subsequent stage. This is not the case for upstream dams: the ground surface area of TSFs with an upstream dam remains the same. Because each stage is the same size the same amount of material is used. This makes upstream dams cheaper and easier to expand: for a similar height upstream dams require three times less material than downstream dams *(VICK, 1990, p. 79)*.

Figure 6 - A TSF of a copper mine located in Żelazny Most in Poland that has been in operation since 1977. This is the largest TSF in the European Union, and one of the largest TSFs worldwide. The immense size of this TSF is illustrated by the zoomed in part of the photo that reveals tractors, trucks, and other large size construction equipment on top of the dam.

This dam is up to 75 meters high and of the upstream type; this can be seen from the stacked construction layers on the outside of the dam. It has a circumference of 14.3 km and a ground level area of 13.94 km^2 (STRZELECKI ET AL., 2015, P. 94), which is about twice the size of the Amsterdam Centre borough. It currently stores 634 million m^3 of copper tailings (GRIDA, 2021) and its maximum capacity is 1,100 million m^3 (STRZELECKI ET AL., 2015, p. 94).

Photo by BUDIMEX S.A. (2018)

2.1.3 Tailings dam failures

2.1.3.1 Definition of tailings dam failures and other related incidents

In the broader geological context **failures** are defined as '*an unacceptable difference between expected and observed performance*' *(LEONARDS, 1982* in *DAVIES ET AL., 2000)*. In the case of tailings dams this unacceptable difference occurs when the dam fails its purpose of containing the tailings. By combining the earlier mentioned definitions of **tailings** and **dams** with **failures** the definition for tailings dam failures is formulated as following:

'An unintended flow released from constructions built to - temporarily or permanently - store mixtures of crushed rock and processing fluids from mining- and extractive activities.'

It should be made clear that not all incidents or problems related to tailings are included in this study. For example, the Uranium Mill Tailings Remedial Action project (UMTRA) was the large-scale reclamation of uranium mill tailings in the United States in the second half of the 20th century, and is claimed to be the largest materials management program in the world *(MOGREN, 2001)*. Although it concerned the dangerous consequences of careless disposal of tailings, it is not related to dam failures, and is thus outside the scope of this research. Moreover, not all problems related to tailings dams are considered failures. ICOLD loosely distinguishes two types of incidents related to tailings dams: *failures* and *accidents*. Failures are defined as major incidents that either have led to complete abandonment of the dam or could later be repaired. Tailings dam accidents are less severe than failures and could be 'rectified before failure occurred'. However, ICOLD did not clearly define what the difference is between an incident that could 'be repaired' and an incident that was 'rectified before failure occurred' *(ICOLD, 2001, P. 13)*. *AZAM & LI (2010, p. 53)* define *intermediate* failures as 'manageable' in terms of damage and pollution, and *catastrophic* spills when loss of life has taken place.

Although not mentioned by ICOLD, a third category of incidents can be distinguished. These are incidents that are related to tailings dams, but do not concern the structural integrity of the dams. Instances of such incidents are leaks to surface and ground water or emissions to air *(DAVIES, 2002, p. 32)*. Examples are releases of dust, acid mine drainage (AMD) from mines depending on sulphide ores, and emissions of volatile organic compounds (VOC), reduced sulphur compounds (RSC), and greenhouse gases (GHG) from e.g. oil sands tailings *(SMALL, CHO, HASHISHO, & ULRICH, 2015)*. For an overview of the three types of tailings incidents see Table 4.

Affecting structural integrity?	Type of incident	Examples of incidents	Source
Yes, major	Tailings dam failure	Incidents beyond repair leading to abandonment, partial breakdown of tailings dam, and major failures of dam during operation	*(ICOLD, 2001)*
Yes, minor	Tailings dam accident	Incidents that: - could be resolved or repaired before failure happened - occurred before filling of the pond	*(ICOLD, 2001)*

		- occurred during initial filling of the pond - did not causing damage to the dam itself (e.g. overflow)	
No	Other incidents related to tailings dams	AMD, emissions to air, dust, seepage, leaks to groundwater, greenhouse gases, etc.	*(Davies, 2002; Small et al., 2015)*

Table 4 - Types of tailings dam incidents, based on Davies (2002); ICOLD (2001); Small et al. (2015). Made by author.

Some (environmental) incidents in mining are related to or overlapping with tailings dam failures, such as the earlier mentioned acid mine drainage *(Johnson & Hallberg, 2005, p. 3)*. Other examples of such incidents are overburden dump slope failures *(Chaulya et al., 1999, p. 276)*, liquefaction flowslides *(Dawson et al., 2011, p. 329)*, open-pit mining slope failures *(Herrera et al., 2010, p. 1123)* and coal waste impoundment failures *(McSpirit et al., 2007, p. 83)*. Below a brief description of each of these types of incidents will be given:

- *Acid mine drainage* (AMD) is the discharge of low-pH water, caused by a chemical reaction of sulphide, oxygen and water. Although AMD also occurs in natural conditions it is commonly associated with mining activities, caused by the increased exposure of sulphide-containing materials to water and air. It is one of the most significant environmental problems directly related to the mining industry *(Akcil & Koldas, 2006, p. 1139)*.
- *Overburden dump slope failures* are unintended flows of debris from slopes of overburden dumps. These overburden dumps are used in open-pit mining to store the material that needs to be removed to reach the ores *(Kainthola et al., 2011)*. The combination of an accumulation of overburden material and attempts to minimize ground area use for economic reasons has led to increasing heights and slopes of dumps, and consequently increasing numbers of failures *(Chaulya et al., 1999)*.
- *Liquefaction flowslide* is the 'sudden collapse [and] rapid run-out of granular material or debris [with] a meta-stable, loose or high porosity structure [giving the material] a semi-fluid character' *(Hutchinson, 1988 in Dawson et al., 2011, p. 329)*. Although liquefaction flowslides are not the same as tailings dam failures, they can be the cause of the collapse of tailings dams, see for example *Dawson et al. (2011)* and *Fourie et al. (2001)*.
- *Open-pit mining slope failures* are the collapse of the slopes that surround open-pit mines. The slopes of these mines are 'excavated to the steepest possible angle' to minimize costs *(Zare Naghadehi et al., 2013, p. 1)*. However, steeper slopes increase the likelihood of landslides in ways comparable to overburden dump slope failures.
- *Coal waste impoundment failures* are the collapse of impoundments constructed to contain coal waste. Coal waste is a result of coal mining and coal preparation *(Sabah & Erkan, 2006)*. During various stages of coal processing, different coal wastes are produced such as *coal slurry (McSpirit et al., 2007)* or *blackwater (Rey & Aplan, 1993).* In literature these more specific terms are occasionally used, but the phenomena is also described with the generic term of *coal tailings* (see e.g. *Sabah & Erkan, 2006*).

The first four of the above-mentioned types of incidents will not be further discussed in this study. Although they are accidents related to mining processes and mine waste, they are different from tailings dam failures in their physical aspects and materials involved. Therefore, they should be considered as separate phenomena. However, the last incident type (coal waste impoundment failures) has a significant overlap with tailings dam failures: both are waste products of mining activities, and both are generally stored in structures surrounded with dams. Also, coal waste impoundment failures are commonly included in statistics on tailings dam failures, see for example *Bowker & Chambers (2015, Appendix 1, p.3)*. Lastly, coal is explicitly mentioned in the earlier cited definition of tailings by *Kossoff et al. (2014)*. Coal waste impoundment failures are thus a specific subset of tailings dam failures.

2.1.3.2 Characteristics of tailings dam failures

Tailings consist of solids and liquids. This causes tailings to have Bingham plastic liquid properties, meaning that tailings behave as solids under low stress, but as liquids once a threshold of stress has been met, e.g. when a dam breaks down.

Historically, most dam-break analyses have been focusing on water-storage dams *(Rico, Benito, & Díez-Herrero, 2008, p. 80)*. However, flows of tailings behave differently than water because they contain high concentrations of sediment, which 'provides a wide range of fluid behaviour from debris flow to muddy floodwater' *(Rico, Benito, & Díez-Herrero, 2008, p. 82)*. This can be illustrated with the hydrograph of the Aznalcóllar tailings dam failure, which shows two peaks in the flow: one peak consisting of tailings liquid, and a second peak consisting of the more viscous load of tailings solids, see *Table 5*.

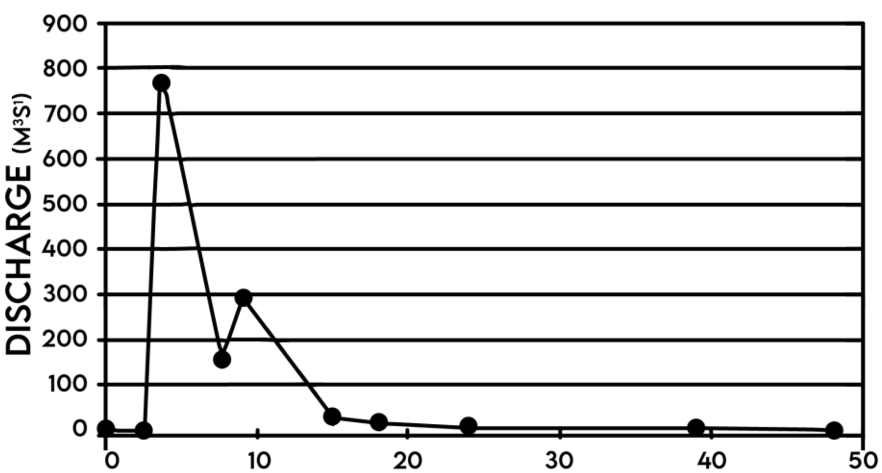

Table 5 - Tailings flood hydrograph taken from a river downstream of the tailings dam failure in Aznalcóllar, Spain. Visible are the two peaks in discharge flow (in m³ per second): the first peak is caused by the tailings liquids, the smaller second peak comes from the slower flowing tailings solids. Adjusted from Ayala-Carcedo, 2004 (p. 728). Made by author.

Dam height	*H*
Reservoir volume	*V*
Outflow volume	V_F
Dam Factor	*H × V*
Tailings Dam Factor	*H ×* V_F

Research by *JEYAPALAN ET AL. (1983b, p. 173)*[vi] shows that during a failure most tailings behave like a viscous liquid with laminar flow. In the case of a water dam failure the magnitude of the effects is mostly influenced by the *outflow volume*, which is correlated to the *reservoir volume* and *dam height*. To estimate the discharge of a failing water dam the *dam factor* (*H×V*) was developed in the 1980s *(HAGEN, 1982; NATIONAL RESEARCH COUNCIL, 1983)*. This *dam factor* is calculated by multiplying the *dam height H* with the *reservoir volume V* and gives a rough estimate of the energy that is released during a dam failure.

RICO, BENITO, & DÍEZ-HERRERO (2008) found similar correlations between TSF *dam height H* and *reservoir volume V* and 'the hydraulic characteristics of floods resulting from released tailings.' (*P. 79*). However, tailings dams are seldom completely emptied during failures: this was only the case in 2 of the 29 tailings dam failures in the database they used. Therefore, the authors proposed the more suitable *tailings dam factor* (*H x* V_F). Instead of *reservoir volume V* this factor uses tailings *outflow volume* V_F. There is a good correlation between *V* and V_F ($r^2 = 0.86$) although V_F is also influenced by the 'liquefaction process, break time, breach size and water content' of the TSF *(RICO, BENITO, & DÍEZ-HERRERO, 2008, p. 80)*. A lot of uncertainty surrounds the V_F in historical failures because of inaccurate and missing data. Available data shows that on average between 20% *(AZAM & LI, 2010, p. 52)* to 33% *(RICO, BENITO, & DÍEZ-HERRERO, 2008, p. 83)* of the *reservoir volume V* is released as *outflow volume* V_F during a tailings dam failure. The *outflow volume* V_F in turn is correlated ($r^2 = 0.57$) with the total *run-out distance* of the tailings flow. This *run-out distance* is measured in kilometres and is the zone directly affected by the flow - or in simpler terms – the distance the tailings will flow from the TSF.

2.1.4 Historical tailings dam failure

In this section the current state of research on historical tailing dam failures will be discussed, based on available scientific research and databases.

For a long time, an official and 'complete worldwide database of all historical [tailings dam] failures' did not exist *(RICO, BENITO, & DÍEZ-HERRERO, 2008, p. 80)*. The reason for this is that most tailings dam failures have never been reported, both in scientific literature and in media. This is predominantly the case in developing countries or countries where legislation is inadequate and the attention for environmental damage is limited. In the minority of cases where failures have been reported basic characteristics concerning the dam and its contents are missing, e.g. the dam height and type, the storage volume of the dam, and the mineralogical composition, thickness, and water content of the tailings. In the reports that do exist the data on these characteristics is 'incomplete and heavily biased' *(RICO, BENITO, & DÍEZ-HERRERO, 2008, p. 80)*. In general, the quality of reporting on tailings dam failures is 'highly

[vi] Please note that there are two papers by *JEYAPALAN ET AL. (1983)* in the top #33 most cited papers that are almost identical in title and content, although page numbers differ.

disparate, being satisfactory only in [the] USA and Europe' *(Rico, Benito, Salgueiro, et al., 2008, p. 847)*. Therefore, *Azam & Li (2010)* state that the databases that are available data should be seen as a subset of the actual number of tailings dam failures.

2.1.4.1 Databases on tailings dam failures

In the last few decades several attempts have been made to fill this gap in the data. A list of notable databases on tailings dam failures can be found in Table 6.

Authors and year published	**Number of reported failures***	**Geographic region**	**Details**
United States Committee on Tailings Dams (1994)	185	United States of America	Database on tailings dam failures in the USA in the period 1917-1989. Contains 'a large amount of information on incidents' *(Rico, Benito, & Díez-Herrero, 2008, p. 80)*.
United States Environmental Protection Agency (1997)	62	United States of America	This database gives a summary of 62 damage cases in the USA. The database should not be considered as 'exhaustive' or 'statistically representative' *(United States Environmental Protection Agency, 1997, p. 7)*
UNEP (1996)	59	Global	Survey of 'recent incidents to identify environmental and safety impacts, the frequency of incidents, and environmental and human consequences' (UNEP, 1996, preface). Focused on the period 1980-1996, with 7 selected cases before 1980.
'Bulletin 121' *(ICOLD, 2001)*	221	Global	Preliminary attempt at a database with global cases of tailings dam failures. In this bulletin lessons learnt from practical experience were formulated.
Rico, Benito, Salgueiro, et al. (2008)	147	Global, but focus on Europe	Search and re-evaluation of European tailings dam failures in a worldwide context.
WISE	163	Global	Database of the World Information Service on Energy, an NGO founded in 1978 that aims at a 'global 100% renewable energy system [...] without nuclear power' *(WISE, n.d.)*. Therefore, WISE separately lists a database with uranium tailings dam failures.
Rico, Benito, & Díez-Herrero (2008)	~250 (28)	Global	Compilation of tailings pond geometric parameters and hydraulic characteristics of floods caused by a tailings dam failure. A total of around 250 failures are identified, of which 28 have sufficient data for analyses.
Azam & Li (2010)	218 (167)	Global	Review of tailings dam failures of the last hundred years. A total of 218 failures are identified, of which 167 had sufficient data for analysis.
Bowker & Chambers (2015)	224	Global	
Carmo et al. (2017)	308	Global	Database of the Instituto Prístino in Brazil. Mainly based on *Bowker & Chambers (2015)* and *ICOLD (2001)*
World Mine Tailings Failures (2020). Also	356	Global	This is the most exhaustive databases currently available and put together by Bowker & Chambers. Based on the ICOLD Bulletin 121 and reformatting of the

published online as the CSP2 (2019) database.			WISE databases. The data is further expanded and complemented with data from other sources, 'principally legal documents and technical reports' *(World Mine Tailings Failures, n.d.)*
* If two numbers are mentioned the first number is the total amount of failures recorded. The second number in round brackets is the number of records with sufficient datapoints for analysis according to the authors			

Table 6 - Available databases of tailings dam failures, sorted by year of publication. Made by author.

When sorting the databases on tailings dam failures in order of publication it indicates that the number of records in each database has been steadily increasing as each database builds upon the other. The most recent and exhaustive database to date is created by Bowker & Chambers and is published at the Center for Science in Public Participation (CSP2). There appear to be two similar versions of this database under different names and published by two different websites (CSP2 and WMTF).

CSP2 operates in the United States of America and Canada and 'provides training and technical advice to grassroots groups on water pollution and natural resource issues, especially those related to mining' *(CSP2, 2020)*. However, the CSP2 website is not available from The Netherlands; only with the use of a VPN-service the website can be visited.

The World Mine Tailings Failures (WMTF) website contains the same database as the CSP2, but also includes trend analyses, e.g. on increasing frequency and severity of failures, and cumulative tailings depositions. However, the availability of the WMTF is under pressure. The website states that their work cannot continue 'without funding and volunteer compilers' *(WMTF, 2020)*. About the use of the database the website states the following:

> 'Unless we can also do the work of our charter which is to provide the analysis and vetting of data elements we will not continue to make just the database available. It is only a data set for the work we do. There is no value in a list of failures and we will not maintain or provide a mere list of failures or allow our data base to be used only to support prescriptive non viable [sic] advocacy or to focus only on proof of increasing severity and frequency. If we cannot continue the work ourselves, we will take what legal measures are necessary to insure [sic] that the name "World Mine Tailings Failures" and the data base [sic] may never be used except in the context of the work and the charter that guides that work.
> If we do not raise the funds needed to continue our work by December 1, 2020 we will reformat the website and provide a permanent open access archive as a model for a future global failures data base [sic]. But even that work requires more than we have in our checking account.'
>
> *(WMTF, 2020)*

No follow-up on this statement was given (July, 2023).

Since the first manifestations of databases on tailings dam failures started in the 1990s, research has been done on failure rates. *Azam & Li (2010)* estimated that the average failure rate of a TSF over its entire lifetime is 1.2%. This is estimated to be over one hundred times higher than the average failure rate of water retention dams, which is estimated at 0.01% *(ICOLD, 2001)*. According to *Bowker (2014, para. 13)* such high failures cannot reasonably be attributed by chance but 'indicate[s] human error at work, i.e. an established pattern of failure to take reasonable precautions'.

2.1.4.2 Developments in tailings dam failures

In *Table 7* an historic overview of tailings dam failures rates over their entire lifetime can be found. Although failure rates remain relatively high, the data shows that improvements have been made over time.

Year	Recorded failure rate
1850 - 1900	13%
1900 - 1910	7%
1910 - 1920	5%
1930 - 1950	1%
1950 - 1960	0.2%

Table 7 - Failure rates of tailings dam over entire lifetime (ICOLD, 2001, p. 14). Made by author.

Between the 1970s and 2000s there have been roughly 2 to 5 major tailings dam failures every year *(DAVIES ET AL., 2000, pp. 1 & 4)*. *Azam & Li (2010)* found that the absolute number of failures has peaked between 1960 and the end of the 1980s to around 50 failures per decade, and then declined to 20 failures per decade because of 'stricter safety regulations', see *Figure 7*.

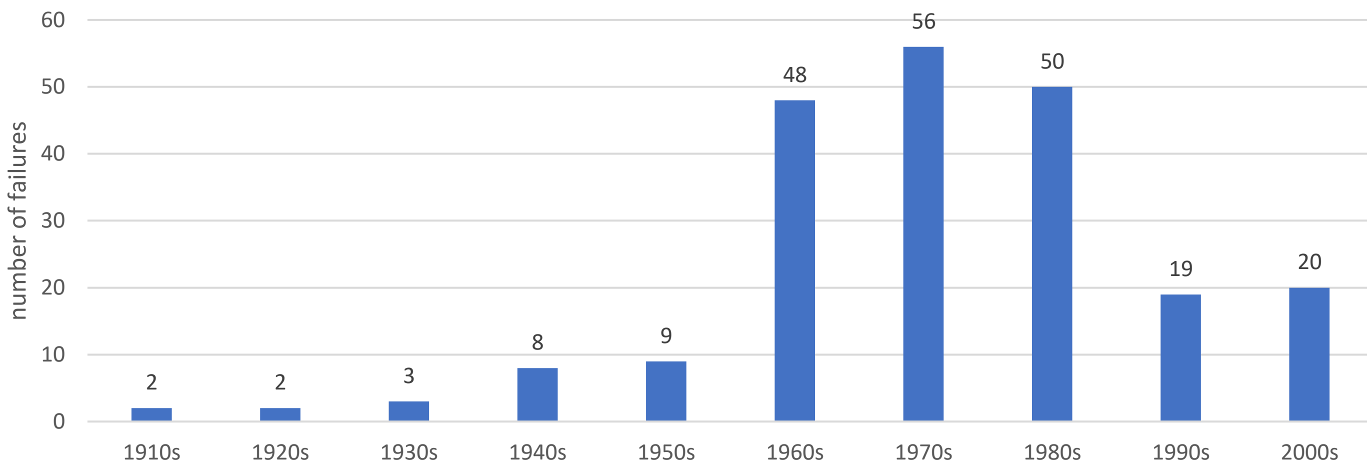

Figure 7 - Number of tailings dam failures per decade, based on data from AZAM & LI (2010, P. 50). Made by author.

However, the trend of decreasing tailings dam failures is contested by WMTF, which states that the '[copper] failure rate per million tonnes of ore produced from 0.00044 (1998-2007) to 0.00045 (2008-2017) appears to be significant and to forecast a continuing upward trend' *(WMTF, n.d.-b)*.

Moreover, the frequency of failures only tells half the story. Even if it is correct that the frequency of tailings dam failures has decreased in the last decades, the severity of failures has been rising. Almost half (33 out of 67) of all tailings dam failures that have been rated as *serious* or *very serious* between 1940 and 2010 occurred since 1990 *(BOWKER & CHAMBERS, 2011)*. This data does not include the several *very serious* tailings dam failures that have happened in the last decade, such as the Fundao tailings dam failure in 2015 and the Brumadinho tailings dam failures in 2019, both in Brazil. Of all tailings that have ever been released during a failure (~250 million m^3), near half (115 million m^3) can be attributed to tailings dam failures occurring between 2000 and 2022 *(PICIULLO ET AL., 2022, p. 1)*.

Another trend is that the occurrence of tailings dam failures has shifted from developed to developing countries: pre-2000 failures mainly occurred in the Americas and Europe, while post-2000 failures mainly occurred in Asia (because of economic development) and Eastern Europe (because of better reporting after collapse of the USSR) *(Azam & Li, 2010)*.

2.1.5 Causes of tailings dam failures

In this section literature on the causes of tailings dam failures is discussed. There are four papers that did meta-analyses on causes of failures. They are used as main sources in this section. For each of these meta-analyses the most important findings are mentioned. When necessary, these findings are put in context with the use of other literature. These four papers are:

- ICOLD. (2001)
  Tailing dams: risk of dangerous occurences - lessons learnt from practical experiences (bulletin 121)
- RICO, M., BENITO, G., & DÍEZ-HERRERO, A. (2008)
  Floods from tailings dam failures
- RICO, M., BENITO, G., SALGUEIRO, A. R., DÍEZ-HERRERO, A., & PEREIRA, H. G. (2008)
  Reported tailings dam failures - a review of the European incidents in the worldwide context
- AZAM, S., & LI, Q. (2010)
  Tailings dam failures: a review of the last one hundred years

2.1.5.1 Dam characteristics

As described in *2.1.4.1* tailings dams appear to be failing much more often compared to their water retention counterparts. Although the accuracy of the 100-fold difference as mentioned by *Azam & Li (2010, p. 50)* is contested - e.g. by *(WMTF, n.d.-a)* - it is an established fact that tailings dams are more prone to failure.

The disparity between failure rates of water dams and tailings dams can be explained based on the fundamental economic difference between the two: water retention dams are built for profit and provide economic value over their lifetime, e.g. as a source of water or by producing hydroelectricity. In contrast, the construction of a dam to store tailings is an inconvenient obligation for companies and generates a net loss over its lifetime. Because there is no immediate return-on-investment, this prompts mining companies to build TSFs with the lowest possible expenses *(ICOLD, 2001, p. 6)*.

Rico, Benito, & Díez-Herrero (2008, p. 79) describe five characteristics of tailings dams that make them more susceptible to failures:

1. Tailings dams are not constructed with building materials specifically sourced for this purpose. In general they are constructed by inferior locally sourced materials such as 'soil, coarse waste [and] overburden' (*p. 79*). In many cases the tailings itself are used for the construction of the dam, especially in upstream dams.

2. Tailings dams are generally not constructed in a single build. The dams are a continuous work-in-progress, meaning that they are build and then further raised when the pond is filled with tailings, 'effluent, and runoff from precipitation' (*P. 79*).
3. There is a lack of regulations and policies on specific design criteria.
4. There is a lack of monitoring and control of dam stability during 'emplacement, construction and operation of the dam' (*P. 79*).
5. Maintenance of the tailings dams is associated with high cost during use and after mine shutdown. This links back directly to the fundamental economic difference between water- and tailings dams.

Other dam characteristics of tailings dam that fail are related to their height. Up to 2009 the majority of failures occurred in relatively small TSFs with dam heights up to '30 meter high, with a maximum tailings volume of 5 million m^3 *(AZAM & LI, 2010, p. 53)*. When looking at dam failures in the European context a similar relation with dam height was found, see *Table 8*.

Dam height	% of failures
<15 meters	45%
15-30 meters	33%
>30 meters	22%

Table 8 – Tailings dam failures in relation to dam height up to 2009 (RICO, BENITO, SALGUEIRO, ET AL., 2008).

In Europe 90% of the tailings dam failures occurred in actively used dams, in contrast to 10% of failures in abandoned dams and zero cases in inactive-but-maintained dams. However, this might be caused by a 'lack of reported incidents' in this category of tailings dams *(RICO, BENITO, SALGUEIRO, ET AL., 2008, p. 849)*. The authors also looked at failures rates depending on the type of dam. They distinguish the same three types of dams as mentioned in this study: upstream, downstream, and centerline dams, plus a fourth category of dams that uses combinations of these three main types. Upstream dams are overrepresented both globally and in Europe, however, downstream dams have a much higher representation in failures in Europe, see *Table 9*. This difference is explained by the fact that downstream dams are more common in Europe.

	Global	Europe
Upstream	76%	47%
Centerline	5%	7%
Downstream	15%	40%

Table 9 - Failure rates by dam type, globally and in Europe (RICO, BENITO, SALGUEIRO, ET AL., 2008)

2.1.5.2 Main reasons for failures

SCHOENBERGER, 2016 (P. 119) argues that the tailings dam failures are 'political rather than technical', and *DAVIES ET AL. (2000, p. 11)* stated that 'tailings dam failures are a result of design, construction, operation, and management flaws not *acts of god'*. However, in many instances of tailings dam failures the exact causes are unknown, because of the severe lack of data. Over one third (39%) of the tailings dam failures analysed have not one cause, but are the result of combination of multiple causes *(Rico, Benito, Salgueiro, et al., 2008)*. In 2001, ICOLD identified 3 main reasons for tailings dam failures: the inability of keeping a proper *water balance*, the lack of general *understanding of safe operations*, and a *lack of control* on dam construction, *(ICOLD, 2001)*.

Unusual precipitation and complications with water balance

Of the causes that have been clearly identified in literature the foremost is *unusual rain*: untill 1999 around 25% of the failures was caused by unusual rainfall, between 2000 and 2009 this increased to 40%. This increase is suspected to be caused by changes in the climatic conditions, especially at 'mine sites close to the seas and/or equatorial regions that have received high precipitations' *(Azam & Li, 2010, p. 51)*. *Rico, Benito, Salgueiro, et al. (2008)* also found that instances of *unusual rain* are the main cause in the failing of tailings dams (25% of cases worldwide, and 35% in Europe). They added that *smelting snow* is also a contributor to problems with the water balance of TSFs.

ICOLD (2001) states that the inability of keeping a proper *water balance* is one of the three main causes of tailings dam failures. Countries such as Indonesia and Papua New Guinea do not use tailings ponds for this reason: the unpredictable and torrential rainfall up to 3 meters per year makes appropriate water management exceptionally demanding and expensive *(Rusdinar et al., 2013)*. Both are among the last few countries that as an alternative rely on the currently controversial riverine and marine tailings disposal *(Vogt, 2013, p. 36)*. Since extreme precipitation and melting of snow and glaciers is expected to further increase in the future due to climate change according to the *IPCC (2022),* particular attention should be paid to incorporate proper water management and other climate adaptive measures in TSF design.

Poor management

Another cause of failures mentioned by *Azam & Li (2010)* is *poor management* (10% of cases between 1919-1999, 30% of cases between 2000-2009, and the second most important cause of failures in Europe). Examples of poor management are problems with 'beach management, faulty maintenance of the dam drainage structures, and inappropriate dam procedures (such as rapid dam growth), and presence of heavy machinery in unstable dams'. It is suggested that compliance with 'basic safety regulations would have prevented the accidents' *(Rico, Benito, Salgueiro, et al., 2008, p. 849)*.

Dam construction and placement

The third most important cause *(Rico, Benito, Salgueiro, et al., 2008)* found is related to dam construction and placement, where 'roughly half of the dam breaks could have been avoided with correct tailings dam construction' and appropriate management during its period of activity. Worth noting is 'the lack of incidents caused by earthquakes (seismic liquefaction) in Europe' compared to failures worldwide because of lower seismic activity (p.849). Upstream dams are especially vulnerable to seismic liquefaction caused by earthquakes. Consequently, they are forbidden by law in Chile and Peru *(Schoenberger, 2016)*.

Generally, tailings are deposited as a slurry with high water content withing the tailings storage facility. The larger and heavier particles settle near the dam, whereas smaller and lighter particles settle further away. In proper tailings management the tailings can dry and drain after each deposit, making the tailings mass denser and more stable. However, 'the degree of densification inevitably varies both with time and position in the tailings impoundment (both in elevation and plan) because of e.g. seasonal and other variations in the weather, varying thickness of layers of deposition, demands by mine management for increased deposition rates at times, and increased production to meet market demands' *(Blight & Fourie, 2005, p. 227)*. Therefore, the density of each successive layer of tailings usually is highly variable, which reduces its strength and stability. Especially upstream and centreline dams are vulnerable for problems related to pond control. For example, lack of water management can cause a reduced freeboard (which may lead to overtopping of the dam), increase pore pressure, and increase seepage of water through and under the dam *Darling (2011).*

Because of these issues in tailings consolidation and water scarcity in mining the separation of tailings liquids and solids is a factor of growing importance during the design, construction, and implementation of tailings impoundments. Removing the tailings liquids from the solids has several advantages, see *Table 10*.

	Advantages of liquid-solid separation of tailings
•	Reduced volume and increased density of the tailings
•	Reduced risk of liquefaction flowslides
•	Increased shear strength and stability
•	Reduced capacity demand for drainage
•	Reuse of process water; especially relevant in dry climates because 'water has become the most critical commodity in any [mineral] processing plant' according to Dash et al. (2011, p. 318)

Table 10 - Advantages of liquid-solid separation of tailings (Darling, 2011, p. 650)

Developments on thickening of tailings (such as improved flocculants, new generation thickeners and changed perception on centrifugal pumps for high density tailings transport) could reduce the negative effects of tailings liquids, although the long term effects of these measures are still uncertain *(Fourie, 2009)*. However, it should be noted that dry mining waste can be as dangerous as wet tailings, see e.g. *Blight & Fourie (2005)* on the 1966 coal waste dump failure in Aberfan, Wales which killed 144 people and *Sun et al. (2013)* for an environmental risk assessment system on storage of dry phosphogypsum tailings.

2.1.6 Effects of tailings dam failures

Tailings dam failures cause several types of short- and long-term damage. In scientific literature usually 3 categories of effects of tailings dams are given: loss of human life, environmental damage, and financial/socio-economic damage.

First, in many cases dam failures have caused large numbers of human casualties. *CARMO ET AL. (2017, APPENDIX A)* mention 308 cases of tailings dam failures since 1937. In 36 (12%) of these cases casualties were reported, with an estimated total death toll of 1940, see *Table 11*. Note that this data does not include the 2019 Brumadinho failure in Brazil, where over 270 deaths have been reported.

Year	Country	Mine	Resource	Deaths
1937	Mexico	Los Cedros, Tlalpujahua, Michoacán	gold, silver	>300
1961	Belgium	Jupille	coal	11
1962	China	Huogudu, Yunnan	tin	171
1965	Chile	El Cobre Old Dam	copper	>200
1966	UK	Aberfan, Wales	coal	144
1966	Bulgaria	Mir mine, Sgorigrad	lead, zinc, copper, silver	488
1970	Zambia	Mufulira	copper	89
1971	Romania	Certej gold mine	gold	89
1972	USA	Buffalo Creek, West Virginia	coal	125
1974	South Africa	Bafokeng	platinum	12
1978	Japan	Mochikoshi No.1	gold	1
1978	Zimbabwe	Arcturus	gold	1
1981	USA	Ages, Harlan County, Kentucky	coal	1
1985	Italy	Prestavel mine, Stava, Trento	fluorite	269
1985	China	Niujiaolong, Shizhuyuan Non-ferrous Metals Co., Human	phosphate	49
1986	Brazil	Itabirito, Minas Gerais	iron	7
1986	China	Huangmeishan	iron	19
1988	China	Jinduicheng, Shaanxi Province	molybdenum	20
1993	Philippines	Marcopper, Marinduque Island, Mogpog Philippines	cooper	2
1993	Peru	Marsa	gold	6
1994	South Africa	Harmony, Merriespruit	gold	17
1994	China	Longjiaoshan, Daye Iron Ore Mine, Hubei	iron	31
1995	Philippines	Placer bay, Surigao del Norte Placer	gold	12
1999	Philippines	Placer, Surigao del Norte	gold	4
2000	China	Nandan county, Guangxi province	tin	28
2001	Brazil	Sebastião das Águas Claras, Nova Lima district, Minas Gerais	iron	5
2003	Brazil	Cataguazes, Minas Gerais	aluminum	5
2006	China	near Miliang, Zhen'an County, Shangluo, Shaanxi Province	gold	17
2008	China	Taoshi, Linfen City, Xiangfen county, Shanxi province	iron	277
2009	Russia	Karamken, Magadan region	gold	1
2009	China	Huayuan County, Xiangxi Autonomous Prefecture, Hunan Province	manganese	3
2010	Chile	Las Palmas, Pencahue, VII Region, Maule (COMINOR)	gold	4
2010	Hungary	Ajka Alumina Plant, Kolontár (MAL Magyar Aluminum)	aluminum	10
2014	Brazil	Herculano mine, Itabirito, Região Central, Minas Gerais	iron	3
2015	Brazil	Germano mine, Bento Rodrigues, distrito de Mariana, Região Central, Minas Gerais	iron	19
Total deaths				1940

Table 11 - list of major tailings dam failures since 1937 and their death rates (CARMO ET AL., 2017)

Secondly, damage to the environment is caused through both physical and toxicological effects. The runout of the tailings can destroy ecosystems, buildings, and infrastructure in a range of hundred meters to several kilometres away. Furthermore, the toxicological effects of the tailings can have negative effects to biodiversity to up to hundreds of kilometres downstream over prolonged periods of time. For example, the Aznalcollar TSF failure released very acidic tailings (pH of ~3) containing toxic metals such as 'zinc, lead, arsenic, copper, antimony, cobalt, thallium, bismuth, cadmium, silver, mercury and selenium'. The tailing ended up in Doñana Park, which is 'the largest reserve of bird species in Europe', where it killed all fish and shellfish present in the waterways *(Grimalt et al., 1999, p. 3)*.

Thirdly, tailings dam failures cause financial damage in the form of direct damage to property and loss of income in the local economy caused. Depending on the severity of the failure the total financial damage can be tens of millions of USD *(Davies et al., 2000, p. 6)* up to 7 billion USD in the case of the 2019 Brumadinho tailings dam failures *(AP News, 2021)*. Furthermore disruptions in the supply of materials can occur: after a failure it takes a long time before production capacity of a mining operation has recoverd, if this ever happens: mines can be abandoned if the damage is too large to repair (ICOLD, 2001). In a market where some minerals are supplied by just a handful of operators and mines this can have long term effects on the supply and price of critical minerals. Lastly, tailings dam failures cause direct expenses and reduced cash flow, asset value, and share prices of the companies involved.

2.1.7 Future risks

A risk can be defined as the probability of an event happening, multiplied by the severity of the consequences of this event happening, see *Equation 1*.

$$risk = probability * consequences$$

Equation 1 – Risk assessment formula

The risk of tailings dam failures is based on the probability of a failure happening multiplied by its overall consequences on human health, the environmental, financial damages, etcetera [vii]. Both the probability and consequences of tailings dams failures have increased due to the 'modern mining metric'. This metric involves the increased milling capacity and waste production of mines since the 1900s. The modern mine metric has been discussed in relation to TSFs by *Robertson (2011)*. Based on historic data he states that each third of a century:

- the volume of mining waste has increased 10 times
- the height of tailings dam has increased 2 times *(p.4)*.

This poses a problem for the future, because according to the thesis of *Robertson (2011)* the probability of a tailings dam failures is 'somewhat proportional' to the height of the dam, while the consequences of a failure are 'somewhat proportional' to the volume of tailings in a TSF *(p.5)*.

[vii] For an example of a risk assessment related to tailings dam failures see *Zheng, Xu, & Xu (2011)*.

This means that the increase in potential risk for the coming 30 years could be 20-fold (a 10x volume increase multiplied with a 2x dam height increase), demanding the rapid construction of bigger and additional TSFs *(ROBERTSON, 2011, P. 7)*. However, it should be noted that the positive relation between dam height and probability of failure has been criticized, and that higher dams are not necessarily more prone to failure. A possible explanation is the discrepancy between the perceived and actual risks of tailings dam failures: larger and higher dams are seen as exceptionally dangerous and are therefore under more scrutiny compared to smaller and lower dams. Moreover, it is important to note that larger TSFs are not necessarily more lethal. *OBONI & OBONI (2020, p. 94)* state that there is no correlation between dam volume and number of casualties in the case of a failure.

The probability of future tailings dam failure can be reduced by 'employing proper engineering standards and by avoiding *upstream construction* as much as possible *(AZAM & LI, 2010, p. 53)*: upstream and centreline dams are less prone to failures.

The consequences of future tailings dam failures can be reduced by the introduction of 'new technologies and innovations, such as thickened tailings, dry stacking and paste backfill'. Such innovations increase 'the waste disposal methods available to meet the future challenges to sustainable development' in the mining industry *(FRANKS ET AL., 2011, p. 114)*.

Initiatives to improve tailings safety

In 2021 the United Nations Economic Commission for Europe (UNECE) launched the Online Toolkit and Training Program for Strengthening Mine Tailings Safety. This online toolkit offers 'training for countries […] to improve their knowledge about the impacts and challenges of mine tailings and to apply existing guidelines, including UNECE's tools, to improve tailings safety' *(UNECE, 2021)*. Furthermore, the ICMM (International Council on Mining and Metals) has set as a goal to 'reduce the risk of catastrophic failure[s of TSFs]' *(ICMM, 2022)*. Similarly, the Global Industry Standard on Tailings Management aims at 'zero harm to people and the environment with zero tolerance for human fatality' *(GLOBAL TAILINGS REVIEW, 2020)*.

2.1.8 Tailings production in iron, aluminium, and copper mining

Tailings generation has increased tremendously in the last decades by following the growing metal production. In the 1960s the mining industry produced '10's of thousands tonnes [of tailings] per day', which increased to a '100's of thousands tonnes per day' by the year 2000 *(JAKUBICK ET AL., 2003, p. 1)*. To determine what commodities are the most significant sources of these tailings today, a closer look will be taken at three metals that are produced in large quantities: iron (Fe), aluminium (Al), and copper (Cu), see *Table 12*. In the next few pages, these three metals will be further examined to determine how much tailings are produced for each of these metals.

Metal	Production in 2020 (in tonnes)	Source
Iron (ore)	3,016,000,000	*(BRITISH GEOLOGICAL SURVEY, 2020, p. 33)*
Aluminium (primary)	65,400,000	*(BRITISH GEOLOGICAL SURVEY, 2020, p. 4)*
Copper	20,600,000	*(BRITISH GEOLOGICAL SURVEY, 2020, p. 18)*

Table 12 - Production of Iron ore, primary aluminium, and copper in 2020. Made by author, based on BRITISH GEOLOGICAL SURVEY (2020)

2.1.8.1 Iron

Iron is the most mined resource after coal and oil *(BROWN, 2020)*. It is therefore the most produced and used metal globally *(PAULIUK ET AL., 2013)*. Iron is mainly used in the form of a steel alloy by adding various levels of carbon, or in combination with other metals such as chromium. Because steel is a strong, versatile, and relatively inexpensive material it is considered 'one of the most important and useful metals' *(WÅRELL, 2014, p. 134)*. Its widespread use dates back thousands of years, which lead to naming an entire era after this metal: the Iron Age. The Iron Age is generally considered to have ended once *prehistory* became *history* around 440 BCE when Herodotus wrote the *Histories (YOUNG, 1988)*. However, it has been argued that we have been living in a new or second Iron Age *(SKINNER, 1979)*. This due to the fact that iron is an abundantly used metal of which the production is still increasing *(MATOS ET AL., 2015)*, and because it has various high-tech applications, e.g. as catalyst *(BOLM, 2009)*.

Iron is found in more than three hundred types of minerals, but is generally extracted from three minerals that are found in large enough quantities and with sufficiently high ore grades: magnetite (Fe_3O_4), hematite (Fe_2O_3), and goethite ($Fe_2O_3H_2O$). Other important, but less significant minerals are siderite ($FeCO_3$) and pyrite (FeS_2) *(YELLISHETTY ET AL., 2010, p. 1085)*. Generally, iron ores are economically viable for mining when the iron content is above 25 wt.% *(YELLISHETTY ET AL., 2010, p. 1085)*. The average metal content of iron ore fluctuates around 50 wt.% according to data from 1990-2011 *(MATOS ET AL., 2015)*.

Global iron tailings production

The global production of iron ore was 3,305 Mt in 2016 *(BRITISH GEOLOGICAL SURVEY, 2018, p. 34)* and 3,016 Mt in 2020 *(BRITISH GEOLOGICAL SURVEY, 2020)*. It is estimated that for every ton of iron ore mined 10-25 wt.% of the ore ends up as tailings, however - although not explicitly mentioned in this paper - it seems that this is the case for iron mining in India specifically *(DAS ET AL., 2000, p. 725)*. *MORAN-PALACIOS ET AL. (2019)* estimated the global iron tailings production to be 500 Mt in 2015. However, there seems to be no consensus on this number: *Zhao, Fan, & Sun (2014, p. 540)* state that 'official statistics in 2008 showed that the annual discharge of iron ore tailings in China alone was 0.6 billion tons [Gt]'.

Sun, Zhang, Han, & Li (2020, p. 571) give a higher estimate of 1 Gt of iron tailings in China alone, a country which is currently responsible for around 40% of the global iron ore production *(British Geological Survey, 2018)*: 'The iron ore resources in China are scarce and include low-grade iron, and the annual output of iron ore is approximately 1.5 billion tons, whereas as much as 1 billion tons of iron ore tailings are produced annually'. *Li, Wang, Liu, & Li (2009)* state that the annual production of iron tailings in China is 100 Mt. This in reference to the total production of iron ore in China the same year of 880 Mt *(Brown et al., 2014)*. *Li, Sun, Bai, & Li (2010, p. 71)* state that 'In addition, with the continuous exhaustion of mineral resources, iron ore resources in China become increasingly scarce. According to statistics, the annual emission of iron ore tailings is 130 million tons, while every 1 ton of iron ore concentrate should discharge 2.5–3 tons iron ore tailings'. For this information they refer to *Yan, Bai, Zhang, & J. Zhang (2008)* which is not translated to English and not available online. *Ma, Cai, Li, & Jian (2016, p. 162)* also mention this ratio of 1:2.5-3.0 and state that the cumulative stockpiling of iron tailings in China was 5 Gt by 2013. For both claims they seem to refer to *Zhang et al. (2006)* as original source. However, neither the ratio nor cumulative stockpiling can be found in this paper[viii]. *Cai et al., (2016, p. 361)* state the following: 'Iron tailing is an industrial solid waste mostly result from the process of iron ore exploiting, which the production ratio is 1:2.5–3.0 to iron ore. Iron tailings almost totally piled up through the history of iron ore mining in China. From 2007 to 2011, the stockpiles of iron ore tailings increased by 2.899 billion metric tons; in 2011 in particular, approximately 806 million metric tons were generated. However, the comprehensive recycling of these tailings totaled only 307 million metric tons [*sic*]'.

Because of inconsistent referencing and unclear language use in the literature and referencing, the data from China is deemed to be less reliable. By combining *(Das et al., 2000)* tailings percentage with the data from *(Brown et al., 2014)* the global annual iron tailings production can be estimated to be between 330 and 826 Mt, which is in line with the 500 Mt estimate by *Moran-Palacios et al. (2019)*, see *Table 13*.

[viii] The data for 2013 is supposedly stated in a 2006 paper

Source	Year	Iron ore production	Iron tailings production	ore grade (% or ratio)	
Globally					
(Das et al., 2000)	2000			10% - 25%	of iron ore becomes tailings
(Moran-Palacios et al., 2019)	2015		500 Mt		
(Brown et al., 2014)	2016	3,305 Mt*	330 - 826 Mt		
China					
(Zhao et al., 2014)	2008	824 Mt*	0.6 Gt	73%	of iron ore becomes tailings
(Li et al., 2009)	2009	880 Mt*	100 Mt	11%	of iron ore becomes tailings
(Li et al., 2010)	2010		130 Mt	2.5 - 3	tailings to iron concentrate ratio
(Cai et al., 2016)	2011		806 Mt	1:2.5 – 1:3.0	metal to tailings ratio
(B. guo Ma et al., 2016)	2013			1:2.5 – 1:3.0	metal to tailings ratio
(Y. Sun et al., 2020)	2020	1.5 Gt	1 Gt	66%	of iron ore becomes tailings

*data from *Brown et al. (2014)*

Table 13 - Iron ore and tailings production, globally and in China. Made by author.

2.1.8.2 Aluminium

Aluminium is another widely used metal in various applications because it is strong, lightweight, resistant to corrosion, and is a good conductor of electricity and heat. Aluminium is produced from bauxite ores, which is the fourth most abundantly mined resource after coal, oil, and iron ore *(British Geological Survey, 2018)*. The three most common Al-minerals in bauxite are gibbsite, boehmite, and diaspore *(Kloprogge et al., 2002)*. The process of producing alumina from bauxite ores is complex and varies depending on the exact mineral composition. It generally involves the following steps *(IAI, 2018)*:

- **Milling**
  Grinding, milling, and washing of ROM (run-of-mine) bauxite to prepare the ore for digestion
- **Desilication**
  Depending on the quality of the bauxite ores, an additional step involves the removal of silica (SiO_2). Silica removal can be done in various ways, e.g. by thermochemical alkaline conditioning (TCAC). TCAC involves roasting (i.e. heating) bauxite ores to temperatures of around 870°C and removing the silica containing materials with an alkaline solution *(Rayzman et al., 2003, p. 47).* Another method for the removal of silica is the Serpeck's process, which is done after Bayer processing. It involves milling of the produced aluminium oxide (Al_2O_3) into powder, mixing it with coke, and heating it to around 1800°C in nitrogen gas *(Sharma, 2007, p. 13).*
- **Digestion**
  After milling the bauxite goes into digestion. Globally, the most used method is the Bayer process *(Evans, 2016, p. 316)*. An alternative method - sintering - is less common and unique only to China and Russia. Although less used due to costs, sintering is a viable method to process low grade bauxites and can also be used in hybrid form with the Bayer process *(Liu, Yang, & Xiao, 2009, p. 222)*.
  The Bayer process consists of two phases *(Habashi, 1995)*, starting with the *Bayer liquor loop (Den Hand et al., 2017)*. During this phase bauxite ore is heated in a pressure vessel at around 3500 kPa and mixed with a sodium hydroxide (NaOH) solution *(Sharma, 2007, p. 13)*. The sodium hydroxide leaches the bauxite and produces a sodium aluminate solution.

- **Clarification/Settling**

  During this stage bauxite residue that has not been digested is separated from the sodium aluminate solution. This is done by adding flocculants to speed up the sedimentation process.

- **Precipitation**

  In the second phase of the Bayer process the sodium aluminate solution is cooled down which causes crystallization into aluminium hydroxide $Al(OH)_3$. Earlier formed aluminium hydroxide crystals are added to stimulate precipitation from the solution *(HABASHI, 1995).*

- **Calcination**

  The last step in alumina production is calcination, where free- and chemically connected water are removed from the alumina hydrate crystals *(KLETT & PERANDER, 2015)*. This is done by adding heat to get the following endothermic reaction: $2Al(OH)_3 \rightarrow Al_2O_3 + 3H_2O$ *(IAI, 2018)*.

The end product of this process is alumina (Al_2O_3), which comes in the form of a white powder. With the use of electrolysis (Hall-Héroult process) purified aluminium is made. During the processing of bauxite into aluminium significant amounts of waste are produced, especially in the Bayer process. Tailings from aluminium production are called *bauxite residue* (BR) or *red mud* (RM), which disposal costs approximately $3 per tonne of alumina produced *(LI, 2001, P. 525).* The red colour of these tailings are caused by iron oxides that originate from minerals that naturally occur in the bauxite ores goethite Fe_2O_3 and hematite FeOOH *(RUAN ET AL., 2002, p. 967)*. The concentration of iron in the form of Fe_2O_3 in bauxite tailings is typically between 20-45% *(IAI, 2015, p. 6)*. Besides iron oxides there are various other materials present in bauxite tailings, see *Table 14*.

Component	Typical range (in %)
Fe_2O_3	20 - 45
Al_2O_3	10 - 22
TiO_2	4 - 20
CaO	0 - 14
SiO_2	5 – 30
Na_2O	2 – 8

Table 14 - Typical chemical composition range in bauxite residue (International Aluminium Institute, 2015, table 1)

The most important variables that determine the ratio between alumina and tailings production are *(INTERNATIONAL ALUMINIUM INSTITUTE, 2015, p. 5)*:

1. The aluminium content of the bauxite
2. The type of aluminium oxide hydroxide (boehmite or diaspore) or aluminium hydroxide (gibbsite)
3. The conditions in the extraction vessel during Bayer processing. These conditions are mainly depended on local energy prices and the concentrations of aluminium oxide/hydroxide in the bauxite as stated in 2. For certain aluminium oxides/hydroxides a higher temperature and more aggressive causticity is needed to extract the aluminium from the bauxite ores *(IAI, 2015, p. 5)*. The pressure in the vessel is not of concern for the process, but is dependent on the required steam temperature, which are *(IAI, 2018)*:

- 140 - 150°C for gibbsite bauxite
- 220 - 270° C for boehmite bauxite
- 250 - 280°C for diasporic bauxite

Bauxite ores are regarded *high quality* when their alumina content is over 50%. However, many ores are of lower quality with alumina contents below 40% *(HIND ET AL., 1999, p. 360)*. Between 1990 and 2012 the average alumina content of bauxite was 37,46% *(MATOS ET AL., 2015)*. Low quality ores cause relatively large amounts of tailings: broadly speaking, tailing production falls withing the range of 0.3 to 2.5 tonnes per tonne of alumina produced, but bauxite processing plants typically operate within the range of 0.7 to 2.0 tonnes of RM per tonne of alumina produced *(INTERNATIONAL ALUMINIUM INSTITUTE, 2015, p. 5)*. In less recent scientific papers this range was estimated to be 1 to 1.5 metric tonnes *(ZHANG, XU, & WANG, 1996 IN ZHANG, ZHENG, MA, & ZHANG, 2011, P. 827)* and 1 to 2 metric tonnes *(HIND ET AL., 1999, p. 367)*.

Global bauxite tailings production

The annual production of alumina in 2016 was 118,900,000 metric tonnes *(BRITISH GEOLOGICAL SURVEY, 2018, p. 2)*. Consequently, when assuming the 0.7-2.0 range to be correct between 83-238 Mt of RM was produced in 2016. Similar estimations are found in other literature, although exact numbers differ, e.g. 150 million tonnes *(EVANS, 2016, p. 316)* and 70 million tonnes *(LIU, LIN, & WU, 2007, P. 255)*[ix].

Despite increasing attention to find others uses for RM - see e.g. *LIU, YANG, & XIAO, (2009) AND RIVERA, ULENAERS, OUNOUGHENE, BINNEMANS, & VAN GERVEN (2018)* - only 4 Mt of 150 Mt is '[re]used in a productive way' *(EVANS, 2016)*.

	Amount	**Source**
global annual production	289 Mt bauxite	*(BRITISH GEOLOGICAL SURVEY, 2018)*
	119 Mt alumina	*(BRITISH GEOLOGICAL SURVEY, 2018)*
tailings-to-metal ratio	0.7 to 2.0 Mt per Mt alumina	*(IAI, 2015)*
global tailings production	83-238 Mt	*(BRITISH GEOLOGICAL SURVEY, 2018; IAI, 2018)*
other estimates	70 Mt (2007)	*(LIU, LIN, & WU, 2007, P. 255)*
	150 Mt (2016)	*(EVANS, 2016, p. 316)*

Table 15 - Amount of tailings during aluminium production. Made by author.

When comparing absolute numbers, the global iron production is about 10 times larger than aluminium production, and roughly 4 times as many iron tailings are produced compared to aluminium tailings when comparing the calculations based on *BROWN ET AL. (2014)* and *DAS ET AL. (2000)* for iron, and the *BRITISH GEOLOGICAL SURVEY (2018)* and *IAI (2015)* for aluminium. When comparing the highest estimate of bauxite tailings (238 Mt) with the lowest estimate of iron tailings (330 Mt), the difference is still around 100 Mt. However, both iron and aluminium tailings are surpassed by the production of copper tailings.

[ix] Note that the global alumina production was ~40% lower in 2006 (72 Mt), compared to 2016 (119 Mt) *(BRITISH GEOLOGICAL SURVEY, 2018, P. 2; MATOS ET AL., 2015)*.

2.1.8.3 Copper

Global copper tailings production

Although the annual copper production is far lower than iron and aluminium, it generates more tailings in both relative and absolute sense because of its lower ore grades: while iron ore grades are around 50%, and bauxite grades are around 37%, average copper ore grades fall below 1%, meaning that more tailings are produced for each tonne of metal. In *GEO6* by *UNEP* a summary of the current state of the global environment is given. Chapter 4 on 'Cross-Cutting Issues' presents data on the annual copper ore grade, world copper production and copper tailings generation between 1770 and 2020 (see *Figure 8*). In this figure the primary copper production is stated to be around 19 Mt in 2020. The generation of copper tailings is estimated to be around 3,800 Mt in 2020 *(UNEP, 2019)*. This is the reason the subject of RQ2 is copper tailings production.

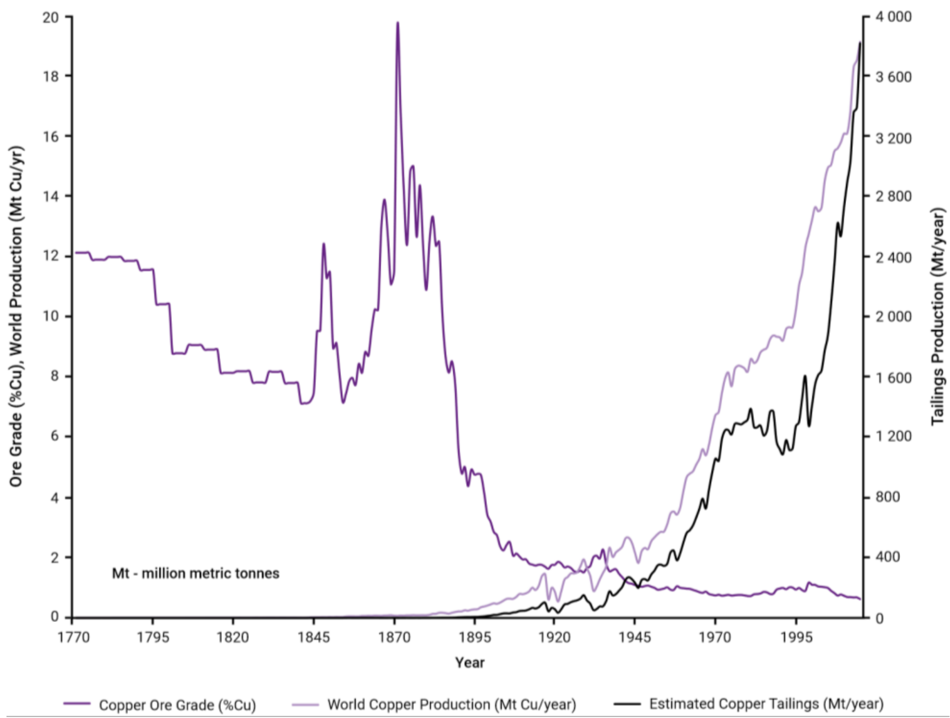

Figure 8 - Global copper ore grade decline, copper production and copper tailings generation (UNEP, 2019, p. 92). Original sources: Ruth (1995); Crowson (2012); Mudd, Weng and Jowitt (2013); Mudd and Jowitt (2016).

3 Method

The research methods that will be used to answer the research questions are a combination of literature research, quantitative data analysis, and a qualitative analysis. In this chapter the methods of each subquestion will be discussed in detail.

3.1 RQ1: To which resources are tailings storage facilities linked?

The first subquestion is answered by combining GRIDA database and USGS MRDS into a new database called GRIDA+. This is done with the software programs Excel and QGIS (an opensource GIS software program).

3.1.1 GRIDA

In 2020 GRIDA created one of the largest open access databases on existing tailings dams. It is based on a survey from the Church of England that was sent to around 700 companies involved in the mining industry. The Church of England has shared data on the responders of the survey in 2019 and again in 2021, see *Table 16*.

	June 17th, 2019	**May 5th, 2021**
# of companies addressed	655	721
Did not respond	453	380
Of which do not own TSFs	-	197
Did respond	202	341
Confirmed ownership of TSFs	77	114
Claimed to not own TSFs	118	188
Not published their disclosure	30	39
# of companies in top 50 mining companies	29	44
% of market capitalisation of top 50	50%	95%
% of market capitalisation global	-	86%
source	*(Church of England, 2019)*	*(Church of England, 2021)*

Table 16 - Response on the CoE tailings survey. Made by author, based on data from Church of England (2019, 2021)

The survey is part of a larger plan to improve tailings management and consists of three phases. Phase 1 is understanding the issue of tailings dam failures and a call to action, phase 2 is the development of a global tailings portal and global industry standard, and phase 3 is the adoption of a global tailings standard, and the creation of an independent global tailings management institute *(Church of England, 2020)*. Based on the results of the survey, a database that was created that includes the following datapoints (see *Table 17 and GRIDA+ database 1.GRIDA*):

#	Datapoint Name
1.	data base_number
2.	company name of the owner
3.	company name of the operator
4.	name of the mine
5.	name of TSF
6.	location (country)
7.	location (latitude)
8.	location (longitude)
9.	status of TSF
10.	year of construction
11.	currently approved design
12.	raise type of dam
13.	current maximum dam height
14.	tailings storage (current)
15.	tailings storage (in 5 years)
16.	year of most recent independent expert review
17.	full and complete relevant engineering records including design, construction, operation, maintenance and/or closure
18.	hazard categorization
19.	classification system
20.	history of stability concerns
21.	do you have internal/in house engineering specialist oversight of this facility? or do you have external engineering support for this purpose?
22.	downstream impact
23.	closure plan in place
24.	long term monitoring included in closure plan
25.	extreme weather secure
26.	notes
27.	link
28.	disclosure origin

Table 17 - Datapoints included in GRIDA database (GRIDA, 2020). Made by author, see GRIDA+ database 1.GRIDA

Although GIRDA is one of the most comprehensive databases on TSFs to date, it does not include the origin of the tailings. Therefore, it is unknown which resources (e.g. iron, aluminium, copper) are linked to each tailings dam. Because the database contains the coordinates of each tailings dam, a global GIS-map was made in QGIS which shows the location of each tailings dam.

3.1.2 Source type hierarchy

The GRIDA data points on this GIS-map have been linked with other sources to find out to which commodities the TSFs are linked. Four types of data sources have been examined. The following hierarchy of reliability and accuracy is used, which will be referred to as the 'source type hierarchy':

I. USGS MRDS hubs - the primary data source used is the United States Geological Survey Mineral Resource Data System (USGS MRDS). With over 300,000 datapoints ('hubs') all over the world this is one of the most comprehensive scientific databases available on mineral deposits, mining activities, and resource processing. The MRDS database includes many details, e.g. the location of the hub, its name and development status, and the primary, secondary, and tertiary commodities that are being produced and/or processed. Therefore, in this study the MRDS is considered to be the most reliable and accurate source of the hierarchy, but only if the data is recent: some of its data is several decades old, so caution is required not to use out-of-date information.

II. Company data - as secondary data source company websites and reports have been used. The data that companies provide is assumed to be accurate and recent but is generally limited in its scope: in most cases only the primary commodities are provided. By-products (i.e. secondary and tertiary commodities), production volumes, and ore types are generally not stated.

III. Scientific literature - for several mines both the USGS MRDS and company websites did not mention their existence and/or the commodities the mine produced were missing. This was the case for a substantial portion of inactive and closed TSFs in Japan[x]. For these TSFs scientific literature was used as source. Papers on geological details of mines are reliable and detailed. However, they are frequently too narrow in their approach to make conclusive claims about the commodities that have been produced in a location, which reduces the accuracy of this type of data source[xi]. Original governmental documents and websites are also included in this category.

IV. Other open sources - in a few cases the three above types of sources did not provide sufficient information on resource data. In these cases other sources have been uses, such as descriptions in OpenStreetMap, news reports, blogs, data aggregation of nearby USGS MRDS hubs, or combinations of these sources.

For many TSFs a combination of several source types has been used, e.g. when a TSF could be matched by name in the USGS MRDS and was also found on a company website. This gave the opportunity to compare data. When a discrepancy between data sources on a TSF was found the source type hierarchy was decisive unless the date of one source was substantially more recent[xii]. In most of such instances this means that the more recent (but simplified) company data was used as primary data source, complemented with older (but detailed) USGS MRDS data.

In the GRIDA+ database the exact references and source types used for each TSFs can be found: see *GRIDA+ database 5.GRIDA+ columns K-N* for the source types that have been used for each GRIDA datapoint, *columns T* for all references to company websites and scientific literature, and *colum N* for the USGS MRDS hub(s) a TSF is linked to (if applicable).

[x] A Japanese mining company was contacted about the commodities linked to their TSFs, but they were not willing to disclose more information than was provided on their website. However, no mention about TSFs could be found other than the pdf-file that was provided to the GRIDA survey. Information and transparency in general are lacking on inactive and closed Japanese TSFs: most inactive mines are not mentioned on the websites of mining companies such as Mitsubishi Materials Corporation, Sumitomo Metal Mining Company, and JX Nippon. This in contrast all open and free Japanese scientific research on geology and mining dating back to the 1950s, which is publicly available on the website of J-STAGE, an 'electronic journal platform for science and technology information in Japan, developed and managed by the Japan Science and Technology Agency' *(J-Stage, 2022)*.

[xi] Take as an example *database_numbers* 1362-1366. *Kase & Yamamoto (1988)* discusse the occurence of copper, zinc, iron, germanium, tin, gold, and silver in the Besshi-deposit, but do not state which of these minerals have been actively mined in this location. Since the deposit has a relatively high copper content (4.77 wt%) the mine was categorized in this study with copper as primary commodity and zinc, iron, germanium, tin, gold, and silver as secondary commidities.

3.1.3 GRIDA+

By combining the GRIDA database with the USGS MRDS and other sources (see *GRIDA+ database 1.GRIDA* and *2.USGS*) a new database was created, which will be referred to as GRIDA+ (+ for the additional data on resource production). The creation of GRIDA+ was accomplished with the use of a GIS-map in QGIS and a data editing in Excel.

3.1.3.1 GIS-map in QGIS

The GRIDA and USGS MRDS database were transferred from their original sources: the USGS MRDS was downloaded from the official website https://mrdata.usgs.gov/mrds/ and the GRIDA database was received on September 3rd 2020 via email contact with GRID-Arendal. Both databases were then imported to QGIS (version 3.14.16-Pi) in the EPSG:4326 - WGS 84 coordinate reference system. As a baselayer OpenStreetMap was used (see *Figure 9*).

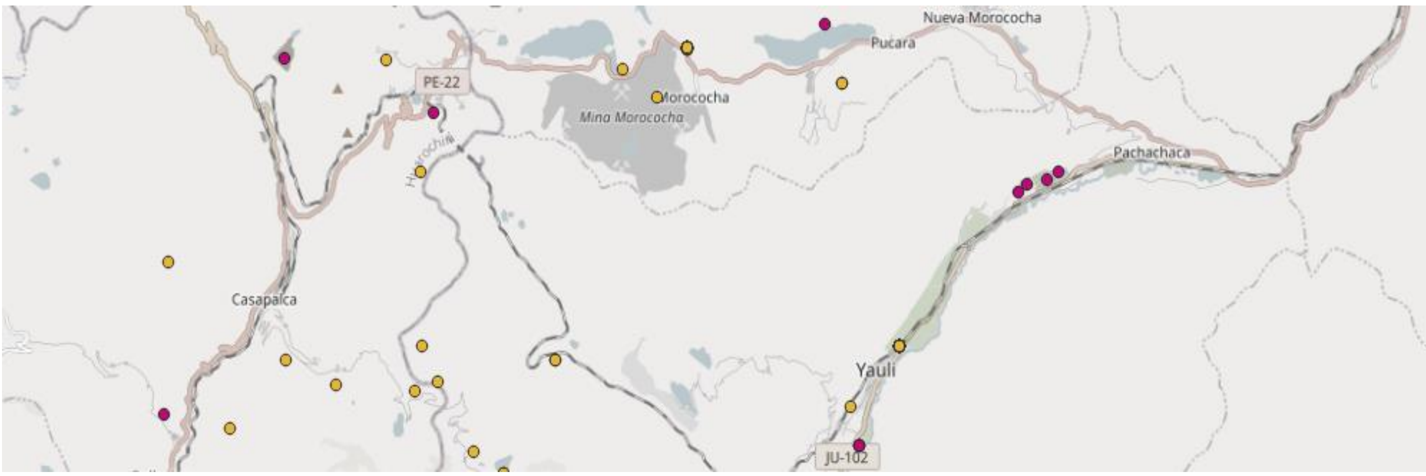

Figure 9 - Screenshot of QGIS: TSFs from GRIDA (purple) and hubs from USGS MRDS (yellow). Made by author.

A vector analysis was performed to find out which GRIDA TSFs could be linked to USGS MRDS hubs based on their location. This was done with the function 'distance to nearest hub (line to hub)' in QGIS. For each GRIDA TSF this function returns the distance to the nearest USGS MRDS hub (see *Figure 10*) [xiii].

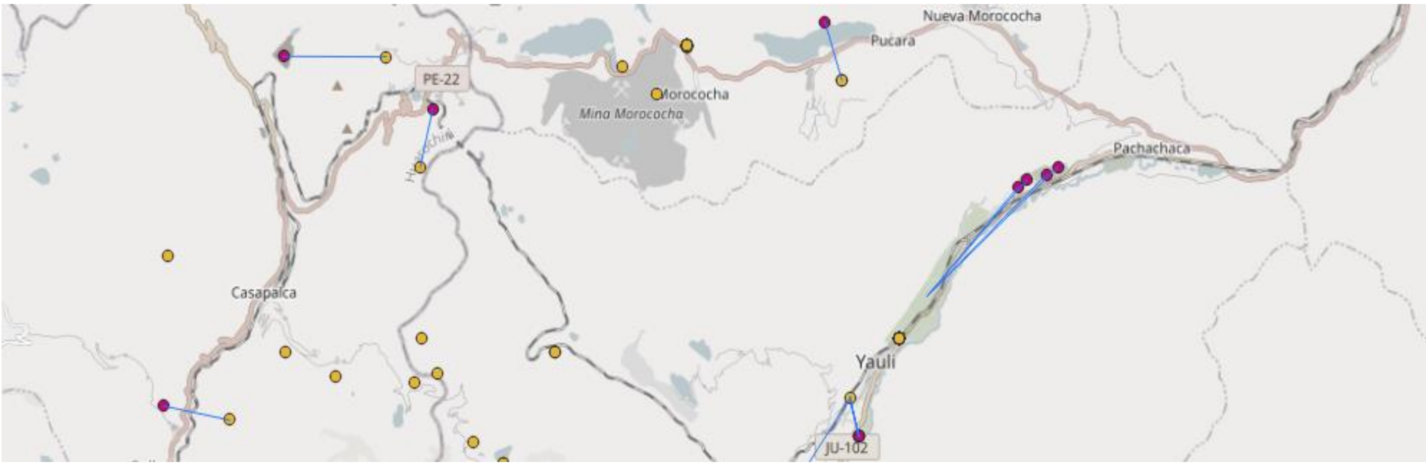

Figure 10 - Screenshot of QGIS: vector analysis of GRIDA TSFs and USGS MRDS hubs. The nearest hub is indicated with a blue line. Made by author.

3.1.3.2 Data in Excel

The GRIDA database complemented with the data from the vector analysis was exported as a csv-file and then imported to Excel. The column with the distance to nearest hub was sorted largest to smallest (see *Table 18* and *GRIDA+ database 3.match (GIS)*).

GRIDA database number	Hub Distance (in km)	USGS MRDS dep_id
162	315.0	10039172
2167	302.6	10039173
30	281.3	60000653
31	281.3	60000653
32	279.5	60000653
2037	248.3	10099588
2121	225.5	10039307
1946	218.5	10255729
...	...	...

Table 18 - Selection of the data returned by vector analysis, with the distance to nearest hub in green. Made by author, see GRIDA+ database 3.match (GIS)

[xiii] The first attempted method of data collection was aggregating the data from all USGS MRDS hubs surrounding a GRIDA TSF. This was done with the function 'distance matrix' in QGIS, which returns the *n* nearest hubs. By aggregating the data from these hubs, it was assumed noise in the USGS MRDS data would be minimized, making the results robust. The result of this distance matrix was imported in Excel and further narrowed down. USGS MRDS hubs >15km distance were regarded too far away to be accurate and discarded. The assumption was that the USGS hub commodities near a GRIDA TSF give a reliable estimation of the origin of the tailings. However, after dozens of results created by this method it showed that the majority of the results were inconsistent with manually checked USGS MRDS and/or company data, because of obsolete data in the MRDS. Because of its unreliable results this method was ultimately abandoned.

The resulting data shows that some GRIDA TSFs are very far away from the nearest USGS MRDS hubs with distances up to 315 kilometres. With a threshold set at 15 kilometres a total of 371 TSFs are cut-off and assumed to be too far away to be reliably linked to USGS MRDS data.

3.1.3.2.1 *Manual check*

For these 371 TSFs the resource data has been manually looked up based on data sources II, III and IV of the source type hierarchy (i.e. company data, scientific research, and other open sources, see). During this manual check the resource data of 611 other TSFs could also be added because on many company websites lists of other mines that also occur in GRIDA were available (see *Figure 11*).

Figure 11 - Screenshot of RioTinto's company website showing their operations per country and mine. Made by author.

3.1.3.2.2 *Matching by name*

After the manual check GRIDA TSFs within a 15 kilometre range from USGS MRDS hubs remain. In both the GRIDA and USGS MRDS database the names of the TSFs and hubs are given, so they can be matched by name. This was done in Excel by using the function '*conditional formatting*' > '*duplicate values*', see *GRIDA+ database 3.match (NAME)*. This method gave a positive outcome for 332 TSFs that could be linked this way[xiv]. When information on a TSF was already manually found, the data was compared and complemented with the USGS MRDS data based on the source type hierarchy.

3.1.3.2.3 *Manual check of remaining TSFs*

The downside of the name matching method is that only exact matches can be found. Because of writing errors, spelling variations, and differences because of intertranslation (e.g. from the Japanese or Cyrillic writing system to English) potential matches have been missed. Moreover, not all TSFs in GRIDA are present in USGS MRDS. Therefore, the remaining TSFs have been manually looked up. First in QGIS to see if they could be manually matched by name

[xiv] The process of matching name included an additional step by manually checking if the coordinates of the USGS TSF and the USGS MRDS hub correspond. The reason for this is that there are multiple sites with the same name, especially in Spanish and English speaking countries.

with USGS MRDS hubs because of slight spelling discrepancies, then by using the source type hierarchy by searching in company data (II), scientific papers (III), and other open sources (IV).

3.1.3.3 Errors in coordinates
In so far possible errors concerning coordinates in the GRIDA+ database have been corrected, *see GRIDA+ database 5.GRIDA+ column G & H*. These errors in the coordinates were for example spotted when TSFs were located in the middle of the ocean, or in another country than indicated (see *see GRIDA+ database 5.GRIDA+ column F*). In total 38 errors have been identified. These errors were fixed, and the resources linked to the related TSFs were manually checked. The reason for correction and the sources it is based on can be found in *GRIDA+ database 5.GRIDA+ column T & O*. In general, the errors can be categorized into three types:

- *Missing coordinates*. For 22 TSFs no coordinates were present in the GRIDA database.
- *Mistakes related to positive and negative coordinates*. This placed 15 TSFs in the wrong location:
    - in 14 cases the minus symbol was missing (in 10 cases for latitude, in 4 cases for longitude)
    - in 1 case the minus symbol was mistakenly added for the latitude
- *Incorrect coordinates*. For 1 TSF incorrect coordinates were provided.

3.2 RQ2: How will the renewable energy transition affect future copper tailings production?
The second subquestion is answered by putting the results of subquestion 1 in perspective of expected future developments. These future developments are based on two IEA report 'The Role of Critical Minerals in Clean Energy Transitions' *(International Energy Agency, 2021b)* and 'Net Zero by 2050 - A Roadmap for the Global Energy Sector' *(International Energy Agency, 2021a)*. In these reports the annual demand for critical materials for the clean energy transition are given. The forecast consists of three scenarios up to 2040 called STEPS, SDS, and NZE.

3.2.1 The SDS, STEPS, and NZE scenarios
The IEA present three scenarios: the Stated Policies Scenario (STEPS), the Sustainable Development Scenario (SDS), and the Net-Zero Emissions Scenario (NZE). STEPS assumes an continuation of the status-quo and indicates 'where the energy system is heading based on a sector-by-sector analysis of today's policies and policy announcements' *(International Energy Agency, 2021b, p. 7)*. SDS assumes that the Paris Agreements are implemented and describes a 'pathway that meets in full the world's goals to tackle climate change', which means that the climate will stabilize at 'well below 2°C global temperature rise' *(International Energy Agency, 2021b, p. 8)*. The NZE scenario assumes a complete transition to renewable energy and describes 'what is needed for the global energy sector to achieve net-zero CO_2 emissions by 2050' *(International Energy Agency, 2021a, p. 47)*

These three scenarios have been used in this study because the IEA is a reliable scientific institution and STEPS, SDS, and NZE provide a realistic bandwidth of possible outcomes. This is essential because 'the largest source of demand variability comes from uncertainty around the stringency of climate policies' *(International Energy Agency, 2021b, p. 8)*. STEPS is a credible baseline of future developments in the energy sector based on existing policies, SDS is a middle way based on current ambitions, and NZE is a realistic upper limit. From each of the three scenarios the annual metal demand over time as calculated by the IEA will be used.

3.2.2 Copper: analysis of an essential critical material

The IEA report on critical materials is mainly focused on cobalt, copper, lithium, nickel, and rare earth elements (REE) *(INTERNATIONAL ENERGY AGENCY, 2021b, p. 43)*. Cobalt, lithium, and REE are each not feasible for a further analysis because there is a lack of records on their TSFs in GRIDA+ (see Table 19 and *GRIDA+ database 6.RQ1 A2-B29*).

Material	# of TSFs in GRIDA+
Cobalt	4
Copper	282
Lithium	5
Nickel	56
REE	11

Table 19 - Number of TSFs in GRIDA+ for each of the 5 critical materials in 2021 IEA report. Made by author, see GRIDA+ 6.RQ1 A2-B29

For nickel there is adequate data available in GRIDA+ (a total of 56 recorded TSFs). However, a tailings-to-metal ratio of nickel could not be found in scientific literature. This is likely because other metals such as copper, PGE, chromium, and cobalt (or varying combinations of these metals) are found as by-product in nickel mines. This makes it difficult to reliably assess which share of the tailings that are generated should be attributed to nickel.

This leaves copper as the only remaining critical material from the IEA, with 282 TSFs available in GRIDA+. Copper currently is a key metal for electric systems and will remain so throughout the renewable energy transition. Its properties such as low electrical resistivity make it a material for which no good alternatives can be found. In the case of copper it is possible to make a reliable estimate on the generation of tailings, because copper generally is the primary commodity that is extracted from the ore, apart from smaller amounts of other metals, e.g. gold, silver, nickel, lead, and zinc. Therefore, the assumption is made that the tailings stored in the 282 copper TSFs in GRIDA+ can be attributed to copper production. In order to calculate how much copper tailings will be generated in the future the following data is required:

- Copper recycling rate and primary copper demand
- Copper ore grades and smelting efficiency
- Copper tailings-to-metal ratio

3.2.3 Copper recycling rates and primary copper demand

In this section the demand for primary (i.e. newly mined) copper is calculated by subtracting the amount of secondary (i.e. recycled) copper from the total copper demand. The IEA report provides the total copper demand for 2020, 2030, and 2040 in the STEPS and SDS scenarios, in a datafile that was downloaded from its original source *(IEA, 2021)* and imported to *GRIDA+ database 11.RQ2 I12-AD35*. The recycling rate of 18% is taken from the same report *(INTERNATIONAL ENERGY AGENCY, 2021b, p. 176)*, see *GRIDA+ database 11.RQ2 AF9*. Based on the total copper demand and the recycling rates of copper, the demand for primary copper is calculated for each of the three scenarios, see *GRIDA+ database 11.RQ2 I12-AD35*.

3.2.4 Copper ore grades and smelting efficiency

In the next section the historic and future copper ore grades and copper smelting efficiency are discussed. These are all found in literature: the copper ore grades in the period 1900 to 1999 come from *GORDON (2002, P. 99)*, 2010-2019 from *MUDD & WENG (2012)* as cited in *CALVO, MUDD, VALERO, & VALERO (2016, P.2)*, and 2020-2069 from detailed model mean estimates in *NORTHEY ET AL. (2014)*, see *GRIDA+ database 11.RQ2 V50-AF67*.

The copper ore grade gives us the theoretical minimum of tailings that is produced. However, the extraction of copper from the ore is never exhaustive, meaning that some of the copper will remain in the ore and end up in the tailings. This level of extraction is expressed as the smelting efficiency. The copper smelting efficiencies between 1900 and 1999 are based on *GORDON (2002, P. 99)*, and the smelting efficiency for 2000-2019 comes from *NORTHEY ET AL. (2014)*, see *GRIDA+ database 11.RQ2 W50-W67*. With the copper ore grades and smelting efficiency the total tailings-to-metal ratio can be calculated in the next section.

3.2.5 Copper tailings-to-metal ratio

The last step is calculating the tailings that are generated for this amount of primary copper. For this we need to know the tailings-to-metal ratio (T/M). T/M involves the weight of tailings that is generated for each weight unit of primary copper endproduct. Calculating the tailings-to-metal ratio is based on the smelting efficiency, ore grade, and the type of copper mineral in a formula presented by *GORDON (2002, p. 98)*, see *GRIDA+ database 11.RQ2 AA61-AA67*. Three assumptions are made when calculating the tailings-to-metal ratio for copper:

- All copper comes from the principal copper mineral chalcopyrite ($CuFeS_2$), which contains 34% copper by weight.
- The fraction of the copper lost to the tailings is assumed to be so small that it can be ignored.
- The amount of tailings is considered to be equal to the amount of gangue in the ore.

Based on these assumptions *GORDON (2002)* presents an equation to calculate the T/M, see *Equation 2*.

$$(1/E)[(1/G) - (1/0.34)] = T/M$$

E	Smelting efficiency
G	Ore grade
34%	Cu content of chalcopyrite by weight %
T/M	Tailings-to-metal ratio

Equation 2 – method to calculate the tailing-to-metal ratio of copper (GORDON, 2002, p. 98)

4 Results

4.1 RQ1: To which resources are tailings storage facilities linked?

The result of combining the GRIDA database with the USGS database and other data is a new database that will be referred to as GRIDA+ (+ for the additional data on commodities). GRIDA+ contains 1938 TSFs and including their primary and – in some cases – secondary commodities. To make the database more useful for further analysis the commodities are categorized. These categories are primarily based on the USGS MRDS 'Mineral deposits of specific types':, i.e. lead/zinc, copper/nickel, PGE/nickel/chromium, REE/niobium, phosphate, chromite, gold, potash. Combined with remaining commodities found in the GRIDA+ database this has led to the following 27 resource categories, see *Table 20*.

Resource category	Based on
aluminium	GRIDA+
boron	GRIDA+
chromite	USGS MRDS – MINERAL DEPOSITS OF SPECIFIC TYPES
coal	GRIDA+
cobalt	GRIDA+
copper	GRIDA+
diamond	GRIDA+
ferrovanadium	GRIDA+
fluorine-fluorite	GRIDA+
gold	USGS MRDS – MINERAL DEPOSITS OF SPECIFIC TYPES
iron	GRIDA+
lead, zinc	USGS MRDS – MINERAL DEPOSITS OF SPECIFIC TYPES
lithium	GRIDA+
manganese	GRIDA+
mercury	GRIDA+
molybdenum	GRIDA+
niobium, REE	USGS MRDS – MINERAL DEPOSITS OF SPECIFIC TYPES
oil sand	GRIDA+
perlite	GRIDA+
PGE, nickel, chromium	USGS MRDS – MINERAL DEPOSITS OF SPECIFIC TYPES
phosphate	USGS MRDS – MINERAL DEPOSITS OF SPECIFIC TYPES
potassium	USGS MRDS – MINERAL DEPOSITS OF SPECIFIC TYPES
silver	GRIDA+
tin	GRIDA+
titanium	GRIDA+
tungsten	GRIDA+
uranium	GRIDA+
zirconium	GRIDA+

Table 20 - resource categories in GRIDA+ and their origin (made by author)

It should be noted that perfect categories do not exist. Some categories overlap, e.g. chromium is found together with PGE and nickel according to the USGS but is also found in combination with iron as chromite/ferrochrome according to data in the USGS MRDS. The same goes for nickel, which is part of the MRDS category *PGE, nickel, chromium,* but is also found together with copper. Copper in turn is frequently discovered in combination with many other metals. For example, in Japan volcanogenic massive sulphide (VMS) deposits can be found, which are rich in copper, lead, and zinc in addition to substantial amounts of gold and silver *(SHANKS & THURSTON, 2012)*. This begs the question how mines that extract all of these metals should be categorized. Based on information given by company websites, categorization is not determined by the mass of the metal that is produced, but usually by the total value of the metals produced. However, the market value of metals is heavily dependent on fluctuations in supply & demand and the level of extractive technologies. In theory this could cause a mine to be defined as a gold mine in one year, and defined as a copper mine in another year, even though nothing fundamental may have changed in its production processes and/or ore grades. Reservations about the accuracy of these resource categories should therefore be made.

4.1.1 Resource categories

The results of the categorization can be found in *Figure 12*. Most TSFs in the database are the result of gold mining (26%), followed by copper (15%) and aluminium (13%). Combined, these three metals are responsible for over 50% of all TSFs in the GRIDA+ database.

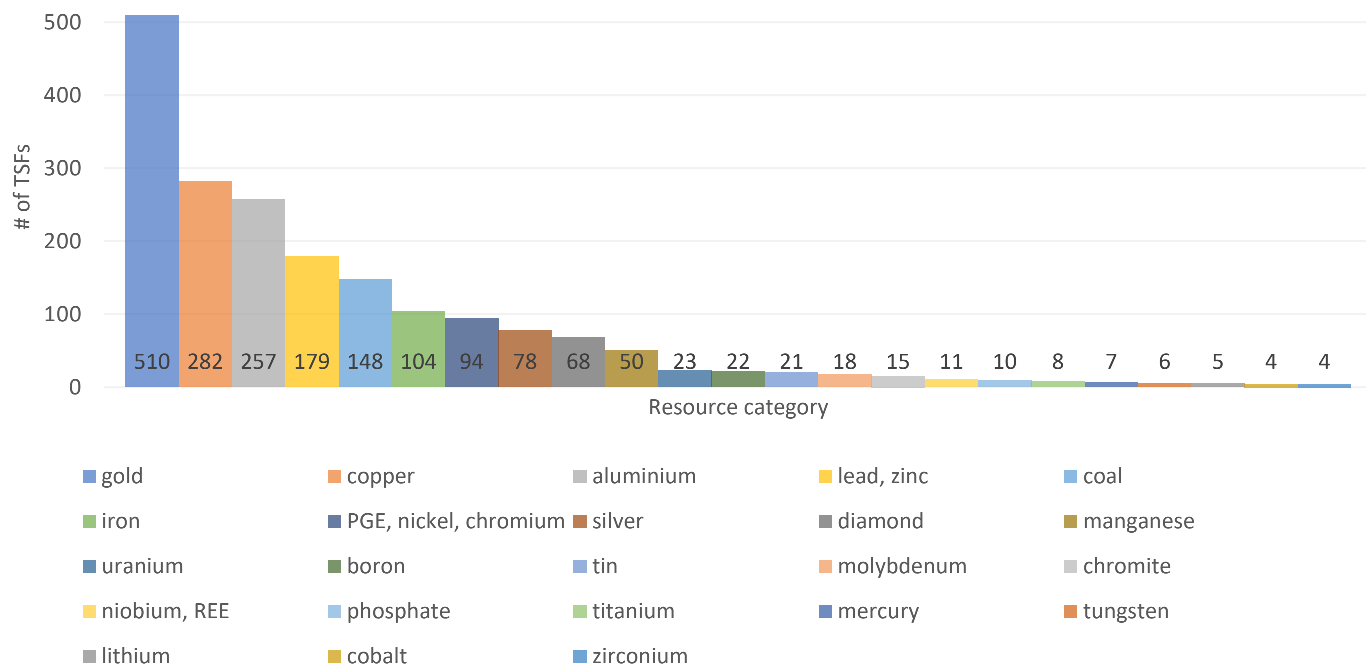

Figure 12 – Number of TSFs in GRIDA+ categorized by resource. Made by author, see GRIDA+ 6.RQ1 A2-B29

The 10 largest resource categories are responsible for over 90% of TSFs. These are gold, copper, aluminium, lead-zinc, coal, iron, PGE-nickel-chromium, silver, diamond, and manganese. For simplicity and robustness the analyses in the following chapter will be limited to the TSFs of these 10 resource categories.

4.1.2 Current and planned storage

Below a description of the adjustments of the current and the planned storage can be found.

The original data for 'current_tailings_storage in m3' in GRIDA was edited so that the values NA, N/A, UNKNOWN, are all set to empty. The same was done for 'planned_storage_5_years in m3', except when a value (other than NA, N/A, UNKNOWN, an empty cell, or 0) was set for the current OR the planned tailings storage. In this study it is assumed that tailings dams are not drained or emptied, unless active reclamation is going on, so the only times a 0 in the planned storage is accepted, is when the status category is set to *reclamation*. In other cases the current storage (if available) was used for the planned 5-year storage, because at minimum the current storage volume can be expected if no reclamation takes place, see *Table 21* for examples.

original data			*adjusted data*	
current_tailings storage in m3 (2020)	**planned_storage 5_years in m3 (2025)**	**status: category**	**current_tailings storage in m3 (2020)**	**planned_storage 5_years in m3 (2025)**
N/A	NA			
Unknown	N/A			
	0			0
28000	Unknown		28000	28000
5300	N/A		5300	5300
Unknown	21000		21000	21000
15200	0	active	15200	15200
12000	0	reclamation	12000	0

Table 21 - Examples of how tailings storage volume was edited in GRIDA+, with changed values in orange. Made by author, see GRIDA+ 5.GRIDA+ AM-AQ

The adjustment of the data has a small effect on the growth of the total amount of tailings in all resource categories: without the adjustments the total 5-year volume growth is 24%. With the adjustments it is 27% (see *Table 22*). This difference comes from the change in the 5 years planned storage, which increases 2.24% in the adjusted data.

	2020	2025	Growth (in %)
Total tailings volume	44,903	55,711	+24%
Total tailings volume ADJUSTED	44,925	56,961	+27%
Change (in %)	+0.05%	+2.24%	

Table 22 – total 5-year growth rates of tailings based on original GRIDA data and adjusted data, in million m^3*. Made by author, see GRIDA+ 7.RQ1 B41-H41.*

However, the adjustment has a minor to substantial effect on the 5-year storage volume of specific resource categories, particularly silver (see *Table 23*). The silver tailings storage volume changes from a 3% decline to an increase of 9%. Other growth rates of resource categories that change are copper (+2% point), gold (+5% point), iron (+3% point), lead, zinc (+2% point).

resource category	growth 2020-2025 ORIGINAL	growth 2020-2025 ADJUSTED	difference (in % point)
aluminium	23%	24%	0%
coal	11%	11%	0%
copper	25%	27%	+2%
diamond	11%	11%	0%
gold	30%	35%	+5%
iron	22%	25%	+3%
lead, zinc	3%	5%	+2%
manganese	33%	33%	0%
PGE, nickel, chromium	28%	28%	0%
silver	-3%	9%	+12%
total	+24%	+27%	+3%

Table 23 – 5-year tailings storage volume growth rates. Made by author, see GRIDA+ 7.RQ1 A17-D28

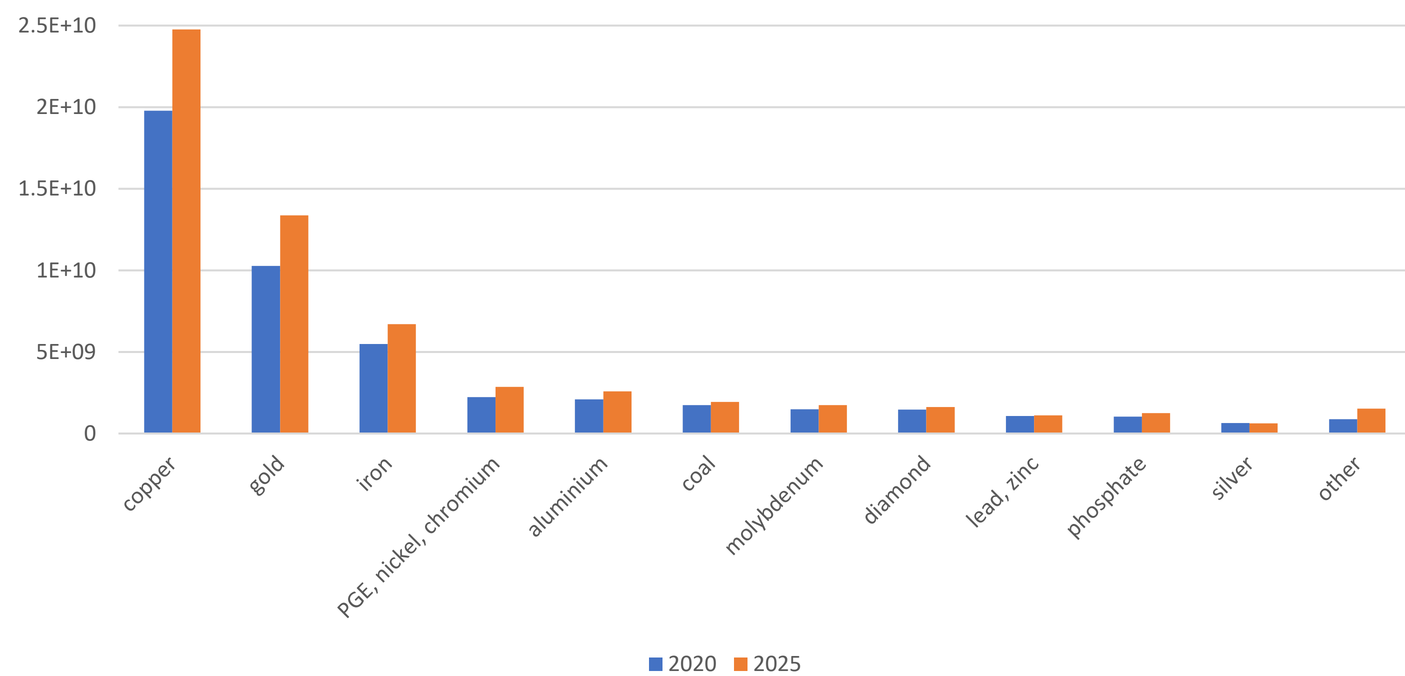

Figure 13 - TSF total storage volume in m³ in 2020 and 2025. Made by author, see GRIDA+ 10.RQ1 E16-G28.

Figure 13 - TSF total storage volume in m3 in 2020 and 2025 shows the total tailings volume categorized by the 10 largest resource groups. It distinguishes between the 2020 storage volume and the planned 2025 storage volume. In some categories, the planned tailings volume growth in 5 years is considerable: for 6 resource the rate is more than 20% (i.e. aluminium, copper, gold, iron, manganese, and PGE-nickel-chromium), see *Table 24*. The largest growth rate of 73% can be found in the 'other' category, which consists of the 17 remaining resource categories. This is mainly caused be high growth rates seen in manganese (+33%), oil sand (+409%), and niobium/REE (+82%).

Resource category	Tailing volume 2020 (in million m^3)	Tailings volume 2025 (in million m^3)	Tailings volume growth (in %)
aluminium	2,096	2,592	+24%
coal	1,761	1,964	+11%
copper	19,788	25,216	+27%
diamond	1,457	1,617	+11%
gold	10,275	13,885	+35%
iron	5,479	6,839	+25%
lead, zinc	1,078	1,132	+5%
manganese	123	163	+33%
PGE, nickel, chromium	2,222	2,850	+28%
silver	642	698	+9%
other	885	1532	+73%
manganese	123	164	+33%
oil sand	110	558	+409%
niobium/REE	106	193	+82%
total	44,925	56,961	+27%

Table 24 - Planned tailings volume growth in 5 years, per resource group (made by author, see GRIDA+ 7.RQ1 A30-D42)

Although there are almost twice the number of gold TSFs compared to copper TSFs (see *Figure 12*), the total volume of copper tailings is almost twice as large as gold (see *Table 24*) meaning that copper TSFs are on average around 4 times larger in volume than gold TSFs. This is because copper is the third largest base metal after iron and aluminium, and has relatively low ore grades.

4.1.3 Tailings dam height

According to *(Robertson, 2011, p. 5)* the likelihood of a dam failing is 'somewhat proportional to its height', making it interesting to see what the dam height differences are for each resource category. *Figure 14* shows the average height of the tailings dams, and the highest individual dam in each resource category. Tailings dams in the gold and copper categories can be especially high (above 200 and 250 meters respectively). Other high dams are found in the iron, lead-zinc, and silver categories with a maximum height of around 150 meters. However, the average height shows that in general much lower dams are used, with an average dam height below 50 meters for all resource categories.

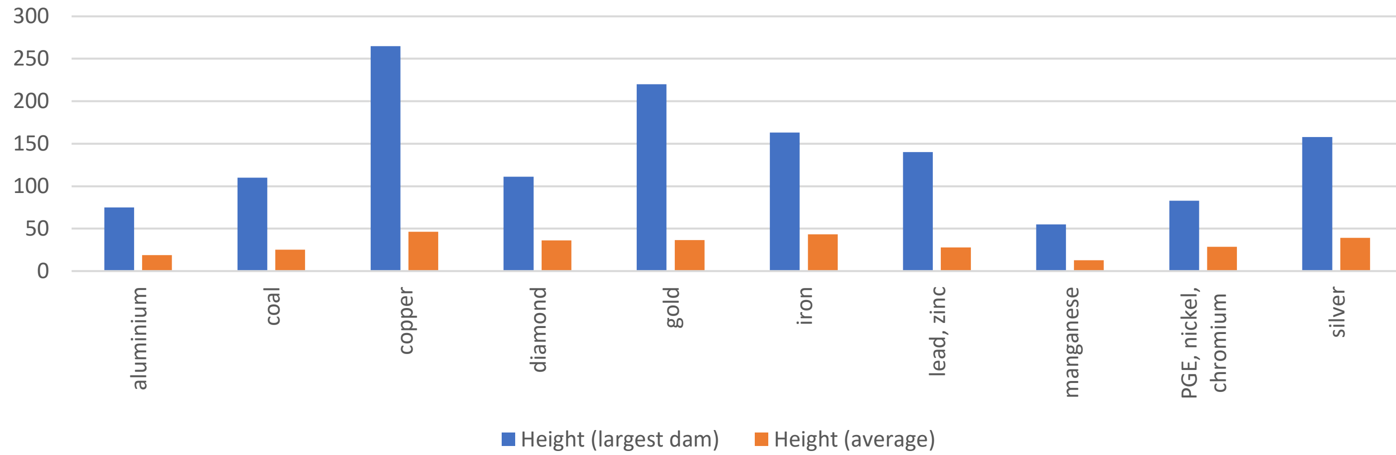

Figure 14 - Highest and average TSF dam height (in meters) per resource category (made by author, see GRIDA+ 7.RQ1 A84-C95)

4.1.4 TSF status

Another variable in the GRIDA database is the status of the TSF, meaning whether it is still being used, abandoned, under construction, etcetera. Again, the results of the survey have been categorized for clarity: the 17 different answers giving by mining companies have been merged into 5 categories, being under construction, active, inactive, closed, and reclamation. Below a description of each category is given:

- Construction — TSF is in the design or construction phase
- Active — TSF is actively used for disposal of tailings
- Inactive — TSF is not actively used, but also not formally closed according to the definition of closed
- Closed — TSF is closed, meaning that a ‘noted approved closure plan was fully implemented or the closure plan is in the process of being implemented’. This plan is ‘developed and approved by the relevant local government agency, and key stakeholders were involved in its development’ (“Disclosure Letter to the Extractive Industry,” 2019, p. 3)
- Reclamation — TSF is being used for remining or the land is reclaimed for other purposes.

The categorized status of the TSFs per resource group can be found in *Figure 15*.

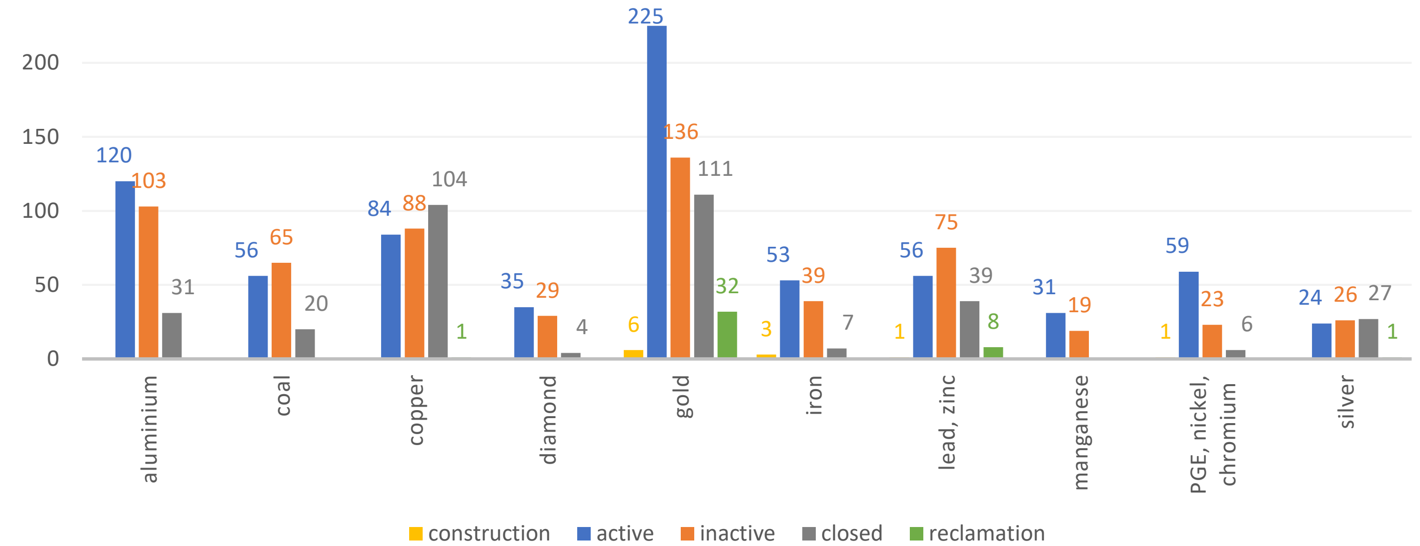

Figure 15 - Categorized status of TSFs per resource group (made by author, see GRIDA+ 7.RQ1 A3-G15)

The inactive category could be described as a TSF management *limbo*[xv] because these TSFs are neither actively used, nor officially closed. Because inactive TSFs are not actively used or officially closed down, we could speculate that they may be less likely to be properly maintained and more prone to failure. Research on failures in Europe indicates that inactive dams are more likely to fail than officially closed dams *(Azam & Li, 2010; Rico, Benito, Salgueiro, et al., 2008)*. A large discrepancy between inactive and closed facilities could further indicate that there are challenges in the end-of-life-phase of TSFs for these resource groups. The largest discrepancy exists in aluminium, coal, diamond, and PGE-nickel-chromium mining: all these three resource groups have over 3 times as many inactive TSFs compared to officially closed TSFs. Additionally, in manganese mining there are zero officially closed TSFs in the GRIDA+ database.

Reclamation is possible when improved technology and market prices make reprocessing of tailings economically viable *(Vitti & Arnold, 2022)*. The graph shows that reclamation is only happening in a minority of TSFs, and in only three resource groups: primarily in gold, and some in lead-zinc and silver[xvi]. The GRIDA+ database contains a few TSFs that are in the design or construction phase, of which half are found in the gold category.

4.1.5 Tailings dam type

As discussed before, an important variable in TSF safety is the type of dam that is being used. Generally speaking upstream dams are most susceptible to failures. Centreline dams are wider and heavier, and therefor safer than upstream dams. Downstream dams are considered the most save, since these dams have the highest width and mass relative to their height (see *Figure 5*). When looking at the GRIDA data in *Figure 16* it can be seen that over the years

[xv] Latin for border or edge (latindictionary.io, 2022)

[xvi] Note that these three resource groups have considerable overlap in mining

the number of upstream dams being build has been relatively stable, apart from a peak in the 1990s and a following decline in the 2000s and 2010s. In contrast, the number of centreline and downstream dams have gradually grown.

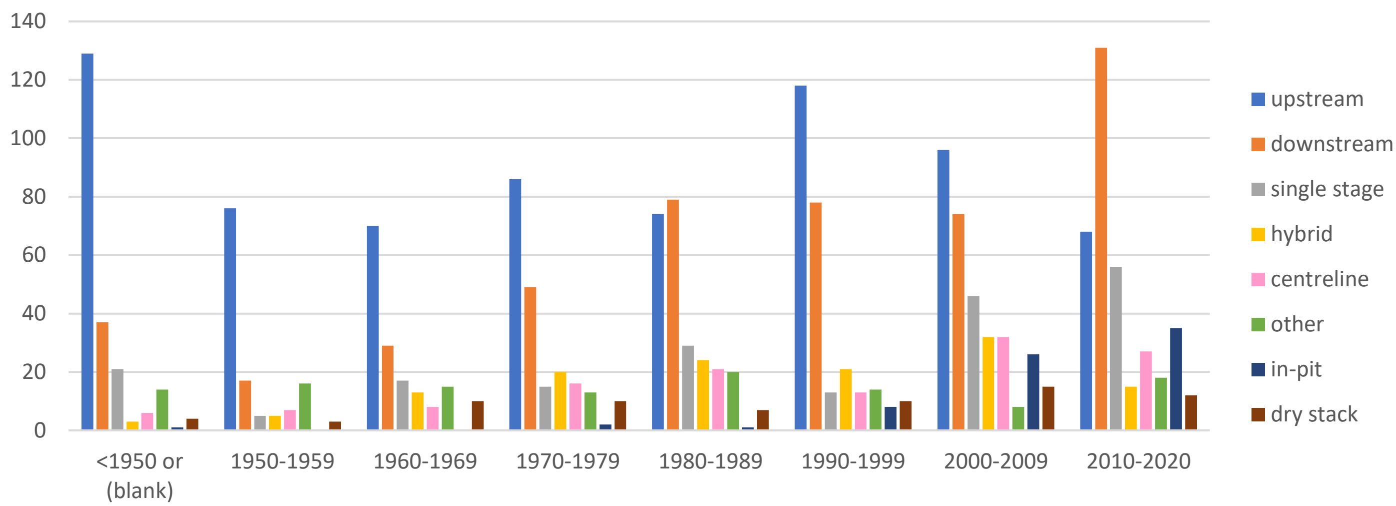

Figure 16 - TSF type of dam, based on year of construction (made by author, see GRIDA+ 7.RQ1 A67-K77)

Combined with the resource data we can see which types of dames are used within each resource category, and if there are certain industries where upstream dams are more prevalent, see *Figure 17* for the relative proportion of each dam type within a resource category, and *Figure 18* for the absolute number. Both figure have been made by filtering the data based on resource category and dam type, see *GRIDA+ 7.RQ1 A47-K59*. The most notable results are:

- For each resource category there is a large variety in dam types being used.
- Upstream dams are one of the most used dam types for every resource, especially in aluminium, copper, PGE-nickel-chromium, and silver production (all over 40% of the total dams). The second most used dam are downstream dams, except in aluminium production
- For each resource, upstream and downstream dams combined cover around 50% of the dams (or more). The only exception is manganese, which mostly uses centreline dams.
- Manganese is the only resource that uses a lot of centreline dams, apart for minor use in copper and gold production, and occasional use in other commodities.
- Almost 50% of aluminium tailings dams are single stage, which is a method that is relatively uncommon, except for some use in manganese and iron mining.
- Dry stacking is almost exclusively found in diamond and some in coal mining.
- In-pit storage is becoming more common in the last 30 years (see *Figure 16*) but is only used in coal, iron, gold, diamond and some copper mining.
- The unknown, other, and hybrid dams combined make up 10 to 20% of the dams in almost all resource categories, with the exception of aluminium and diamond.

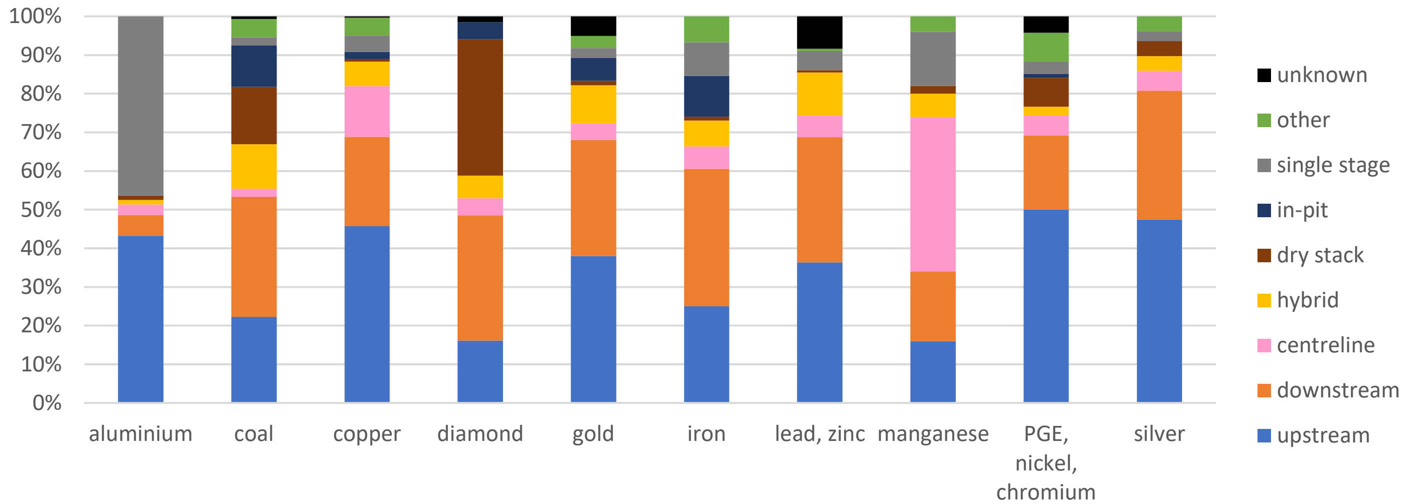

Figure 17- TSFs dam types by resource category, in percentages (made by author, see GRIDA+ 7.RQ1 A47-K59)

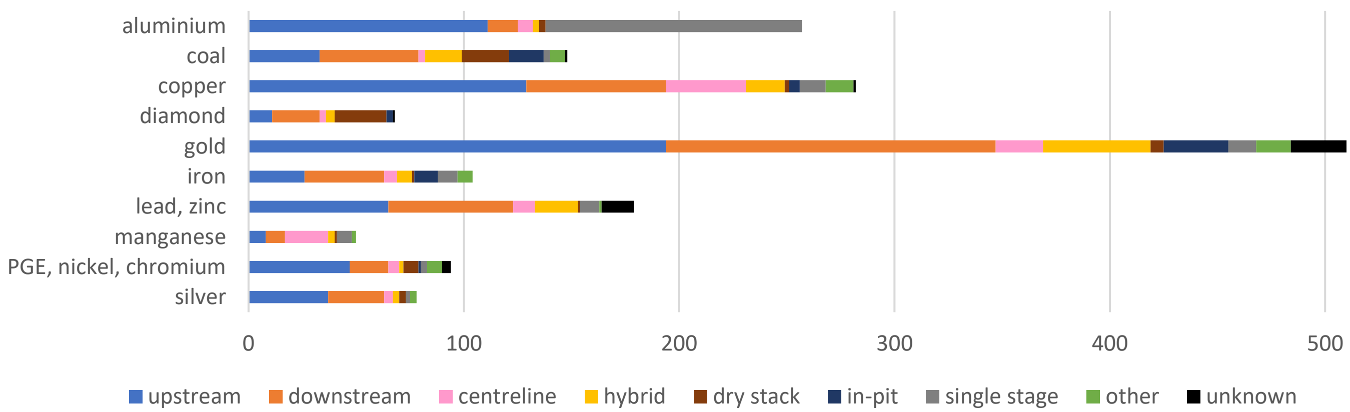

Figure 18 - TSFs dam types by resource category, in absolute numbers (made by author, see GRIDA+ 7.RQ1 A47-K59)

4.1.6 Stability concerns, engineering records, and weather security

Another variable in the GRIDA survey concerns safety and stability concerns, see *Figure 19*:

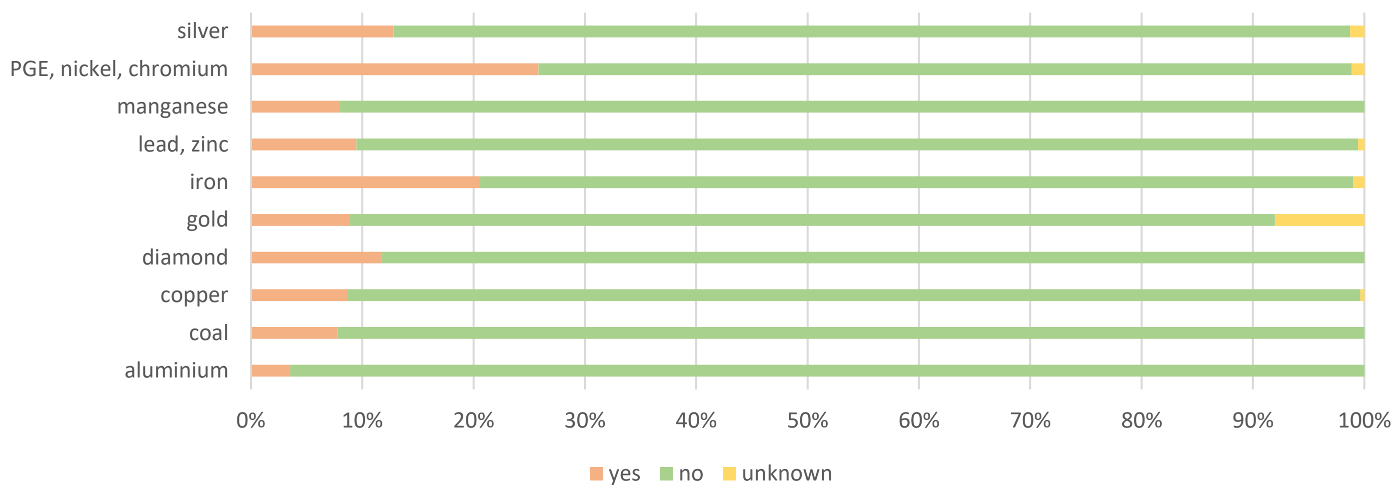

Figure 19 - GRIDA survey question 'Does the dam have a history of stability concerns?' (made by author, see GRIDA+ 7.RQ1 A116-D127)

- In most resource categories around 10% of the TSFs have a history of stability concerns, meaning that for the majority of dams it is claimed that there are no stability concerns.
- There are two resource categories that score substantially worse on stability concerns, being pge-nickel-chromium (25%) and iron (20%).
- For relatively many TSFs in the gold category the stability concern is said to be unknown. Other industries are claiming to be more certain about stability concerns.

In *Figure 20* the presence of detailed engineering records can be found. Combined with *Figure 19* these results indicate motives for concern: companies claim that for 90% of dams there is no history of stability concerns. However, *Figure 20* shows that for most categories 10% to 30% of TSFs are missing detailed engineering records. If there is a blind spot because of missing or incomplete engineering records, it follows that there is no reason for stability concerns. However, it is impossible to make a reliable estimation of the stability of a dam (*Figure 19*) if engineering records of a dam is missing or incomplete (*Figure 20*). The highest discrepancy can be found in the manganese category: for almost half of the TSF engineering records are incomplete or missing, while it is claimed that less than 10% of TSFs have a history of stability concerns. Other categories that score relatively poor in both figures are silver, iron and diamond.

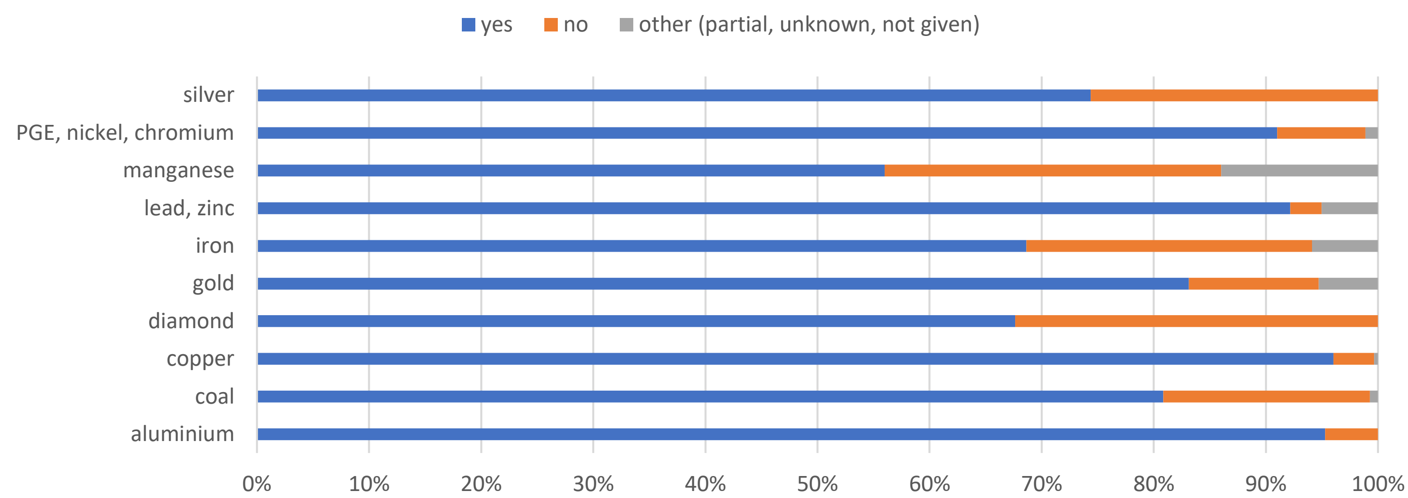

Figure 20 – GRIDA survey question 'Are detailed engineering records of the TSF present?' (made by author, see GRIDA+ 7.RQ1 A134-D145)

Another variable on safety is the weather secure of the dam, see *Figure 21*. Especially in gold, silver, coal, and to a lesser extend PGE-nickel-chromium mining there is reason for concern about the weather security of dams.

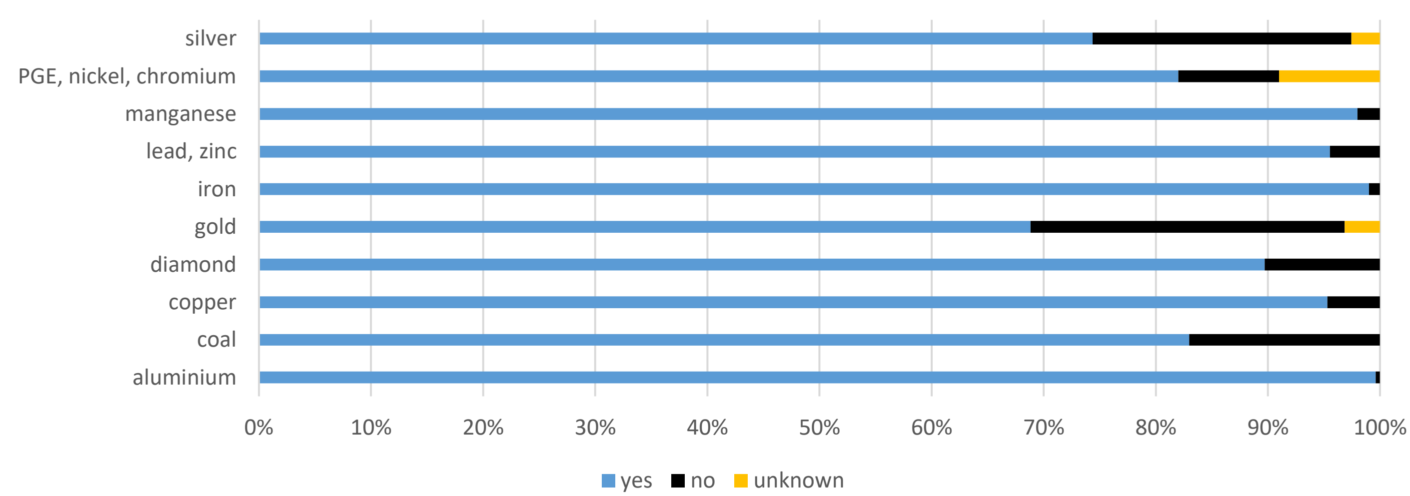

Figure 21 - GRIDA survey question 'Are the TSFs weather secure?' (made by author, see GRIDA+ 7.RQ1 A150-D161

Figure 22 shows that in some resource categories there is a large diversity in classification systems, e.g. gold, manganese, and PGE-nickel-chromium. Only few TSFs do not fall under a classification system. In some resource categories the majority of TSFs fall under the same classification system, e.g. the Canadian Dam Association (CDA) in copper, lead-zinc, and silver, SANS 10286 in coal mining, and ANCOLD in manganese mining.

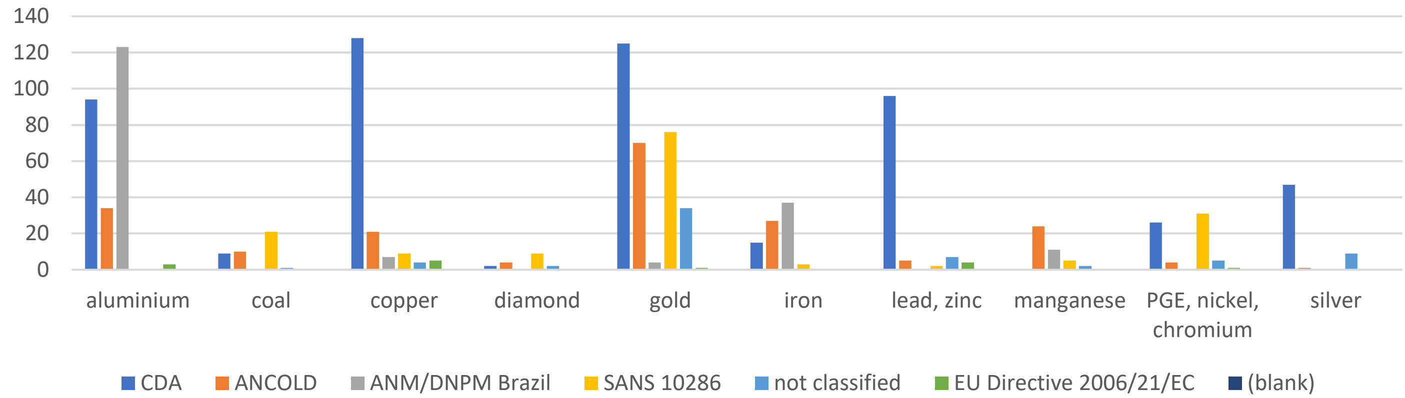

Figure 22 - TSF Classification systems (made by author, see GRIDA+ 7.RQ1 A167-H178)

4.1.7 Copper tailings

Figure 23 shows the companies, and the number of copper TSFs they have in their ownership portfolio. GRIDA distinguishes between companies based on disclosure origin of the survey, the owner of the TSF, and the operator of the TSF, which are usually the same. If the 'owner' or 'operator' was missing form GRIDA without further details, the owner was assumed to be the main operator, and vice versa (operator is taken as owner). If no data was given on 'owner' or 'operator', the company responsible for the disclosure was set as owner.

The graph shows the relationship between number of TSFs per company, and the current storage of copper tailings as percentage of the total copper tailings volume in the database. 11 companies are responsible for 79% of the copper tailings volume, and 47% of TSFs in the database. Three companies own just one, but relatively large copper TSF, for example KGHM Polska Miedz S.A. that owns the earlier mentioned Żelazny Most TSF (see *Figure 6*), which is the fifth largest copper TSF in the GRIDA+ database.

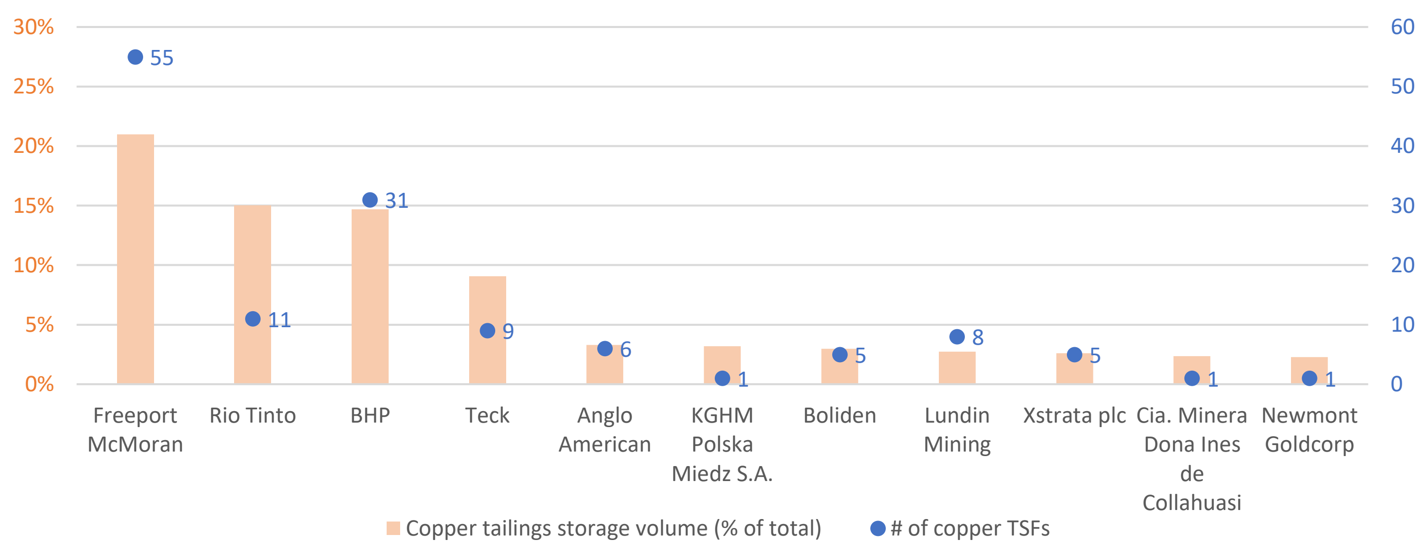

Figure 23 - Copper tailings volume per company as percentage of total, including # of TSFs (made by author, see GRIDA+ 9.RQ1 H4-J14)

Figure 24 indicates that 90% of copper tailings are located in the Americas, with the top-5 countries with the largest volumes of all located in this region.

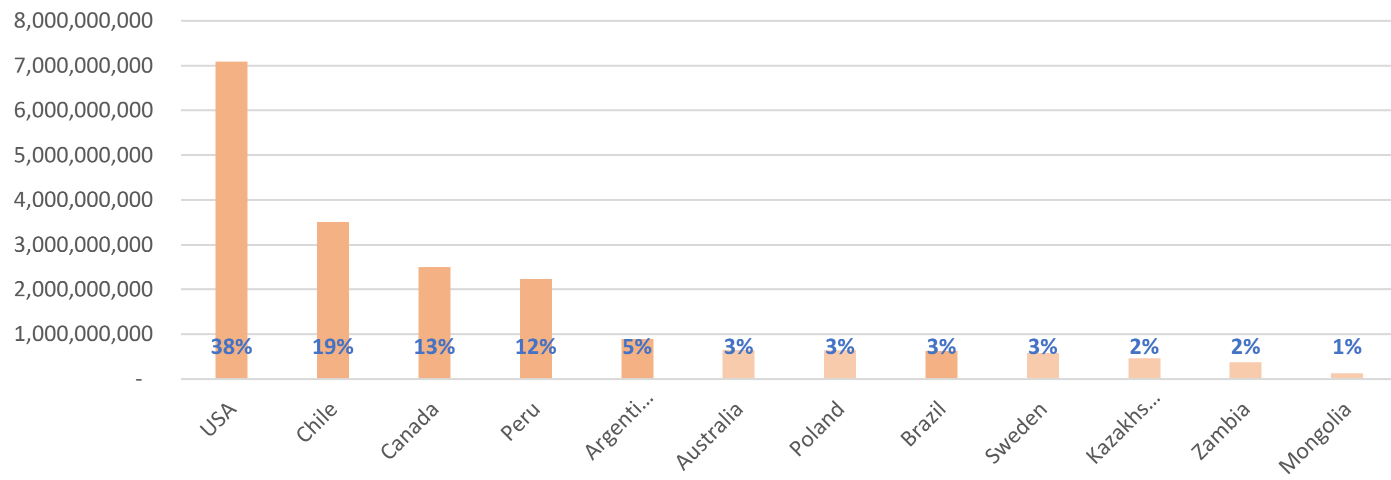

Figure 24 - Copper tailings volume per country, in m3 (made by author, see GRIDA+ 9.RQ1 S3-U14)

4.2 RQ2: How will the renewable energy transition affect copper tailings production until 2040?

In this chapter the results of RQ1 will be discussed in light of the release of a report by the International Energy Agency (IEA) on critical materials. Based on the data presented in this report a forecast of the future production of copper tailings will be given.

In May 2021 the IEA released a *World Energy Outlook* special report titled *The Role of Critical Minerals in Clean Energy Transitions (2021)*. In this report the growing demand for critical minerals such as copper, lithium, nickel, cobalt, and rare earth elements is discussed. This increase in demand is mainly caused by the global transition from carbon based to clean energy systems to eliminate greenhouse gas emissions. Clean energy systems such as solar panels, wind turbines, and electric vehicles (EVs) have a relatively high mineral intensity compared to their fossil fuel counterparts. This means that the future energy system will shift from being fuel intensive to material intensive. This shift could be 'fast and unexpected and, if unmanaged, [...] can critically strain the supply chains of critical materials that, by definition, have their own limits to supply-chain resilience' *(Sprecher & Kleijn, 2021)*. The IEA gives a similar word of warning and expresses its concern for 'price volatility, geopolitical influence and even disruptions to supply' of key minerals for clean energy *(International Energy Agency, 2021b, p. 1)*.

However, it should be noted that this increase in mineral mining will be temporary. When sufficient amounts of iron, aluminium, copper, lithium, and other metals have been mined the economic system will be saturated with these materials. At the EoL of energy systems these materials can be reused and recycled. Metals can be virtually recycled indefinitely if sufficient thought has been put in the application of these materials: life cycle thinking during the design of products and energy systems is therefore crucial.

The challenges that go hand in hand with the growing demand for critical minerals are not limited to geopolitics and fluctuations in price, supply, and demand. Although there is no immediate shortage of copper - the reserves are almost 40 times as large as the annual production (*INTERNATIONAL ENERGY AGENCY, 2021b, p. 123*) - present investment plans are not sufficient to keep up with the growing copper demand. The output of copper mines that are currently under construction and in production are expected to lack behind the estimated demands from STEPS and SDS soon after 2024 *(INTERNATIONAL ENERGY AGENCY, 2021b, p. 119)*. This means that on a more fundamental level several challenges await, such as the rapid upscaling of existing projects and the exploration of new mining locations. A final challenge is the safe disposal of increasingly growing amounts of tailings as a result of the growing mineral demand. This is the topic of the next section, where an estimation of the future tailings production is given.

4.2.1 IEA scenarios: STEPS and SDS

The IEA report 'The Role of Critical Minerals in Clean Energy Transitions' is the basis of a forecast of the future copper tailings production. The report presents two scenarios: the Stated Policies Scenario (STEPS) and the Sustainable Development Scenario (SDS). STEPS indicates 'where the energy system is heading based on a sector-by-sector analysis of today's policies and policy announcements' (International Energy Agency, 2021b, p. 7). SDS describes a 'pathway that meets in full the world's goals to tackle climate change in line with the Paris Agreement', which means a pathway that will stabilize our climate at 'well below 2°C global temperature rise' *(INTERNATIONAL ENERGY AGENCY, 2021b, p. 8)*. The Net-Zero Emissions (NZE) scenario is 'consistent with limiting the global temperature rise to 1.5 °C' *(INTERNATIONAL ENERGY AGENCY, 2021a, p. 47)*.

The scope of the report is predominantly focused on 5 materials (see *P.43*):

- Cobalt
- Copper
- Lithium
- Nickel
- Rare earth elements (Neodymium, Dysprosium, Praseodymium, Terbium, others)

Of these 5 materials cobalt, lithium, and REE will not be further analysed in this study because there is a lack of records on the tailings and TSFs of these metals in the GRIDA+ database (see *Table 25*).

For nickel there is sufficient data available in GRIDA+ (a total of 56 recorded TSFs). However, because it is often mined in combination with other metals such as PGE, chromium, cobalt, and copper (or varying combinations of these metals), it is difficult to assess which share of the tailings can be attributed to nickel. Moreover, a straightforward tailings-to-metal ratio of nickel could not be found in scientific literature.

Resource	# of TSFs in GRIDA+
Cobalt	4
Copper	282
Lithium	5
Nickel	56
REE	11

Table 25 - TSFs of IEA (2021b) critical materials in GRIDA+ (made by author, see GRIDA+ 6.RQ1 A2-B29)

This leaves copper, of which the GRIDA+ database contains 282 TSFs. Copper is a metal that is essential for electric systems: of the $454 billion revenue of the top-40 mining companies in 2020 around $122 billion is ascribed to copper production *(PwC, 2021, p. 5)*. This vital role of copper will persist throughout the sustainable energy transition because solar PV, wind energy and EVs are significantly more copper intensive per MW than their fossil and nuclear counterparts *(International Energy Agency, 2021b, p. 26)*. Moreover, it is possible to make a reliable estimate on copper tailings production, because copper is generally the bulk of the material extracted from the ore (apart from lesser amounts of other metals, such as gold or silver). Therefore, we can assume that the tailings in these TSFs in GRIDA+ can be in majority attributed to copper production.

To make a forecast of the future generation of copper tailings, data on the following variables is required:

1. Copper demand — section *4.2.2*
2. Copper recycling rate — section *4.2.3*
3. Copper ore grades and smelting efficiency — section *4.2.4*
4. Copper tailings-to-metal ratio — section *4.2.5*

4.2.2 Copper demand

The copper demand is based on the above-mentioned IEA report on critical materials. Depending on the scenario, the IEA expects a two- to three-fold increase in the copper demand for renewable energy systems between 2020 and 2040 (see *Table 26*). Depending on the scenario, this will lead to an increase in the total annual copper demand of 31% (STEPS) to 38% (SDS) in 2040 compared to 2020.

	2020	2030	2040	
STEPS - renewables demand	5,715	8,007	10,001	+75%
STEPS - total demand	24,000	28,000	31,500	+31%
SDS - renewables demand	5,715	10,705	15,147	+165%
SDS - total demand	24,000	30,500	33,000	+38%

Table 26 - Annual copper demand in 2020, 2030, and 2040 - total demand and share of renewables (in Kton) and % growth (International Energy Agency, 2021b). See GRIDA+ 11.RQ2 I12-AD35.

4.2.3 Copper recycling rate

The copper demand is supplied by the mining of new, virgin copper (a.k.a. primary copper), or by the recycling of used materials (secondary copper). Because no tailings are produced in the recycling process of copper, the expected share of secondary copper should be subtracted from the total copper demand. It is important to note that there are two different indicators of recycling levels:

- *EOL recycling rates*

  The end-of-life recycling rate is the fraction of disposed copper that is being recycled (in contrast to e.g. landfilling). The global EOL recycling rate of copper is around 45% *(International Energy Agency, 2021b, p. 34)*.

- *Recycling input* or *recycled content rate*

The recycled content rate is the fraction of secondary copper sources in the total supply of material. It is defined by the IEA as the 'share of secondary production in total refined product consumption' *(INTERNATIONAL ENERGY AGENCY, 2021b, p. 176)*. The IEA states that the 2021 recycled content rate of copper is around 17 to 18%.

The importance of more and better recycling practices is emphasized by the IEA, because there is room for improvement. Potential sources for recycling are among others remining of copper tailings, scrap from manufacturing and fabrication, and end-of-life products *(INTERNATIONAL ENERGY AGENCY, 2021b, p. 176)*.

For this calculation only the recycling input rate is relevant. In the last decade (2010-2019) the recycling input remained steady at around 16 to 19%, as 'improved recycling activities have only managed to keep up with [the] demand growth [of copper]' *(P.176)*. No clear estimates on future copper recycling input could be found in literature. However, the increasing use of high-tech alloys leads to 'superior functionalities' but also increasingly difficult and 'energy-intensive recycling pathways' *(INTERNATIONAL ENERGY AGENCY, 2021b, p. 176)*. This is also the case for copper, leading to 'increasing amount[s] of more complex scrap' *(SAMUELSSON & BJÖRKMAN, 2014, p. 85)*. Therefore, it is assumed that the recycling input will remain at 18% between 2020-2040, see *GRIDA+ database 11.RQ2 AF9*. For the production of primary and secondary copper in 2020, 2030, and 2040 in both the STEPS and SDS scenario based on the 18% recycling input of copper see *Table 27.*

	2020	2030	2040
STEPS - total demand	24,000	28,000	31,500
secondary copper	4,320	5,040	5,670
primary copper	19,680	22,960	25,830
SDS - total demand	24,000	30,500	33,000
secondary copper	4,320	5,490	5,940
primary copper	19,680	25,010	27,060

Table 27 - Share of primary and secondary copper (in Kton) based on 18% recycling input (INTERNATIONAL ENERGY AGENCY, 2021b), made by author, see GRIDA+ 11.RQ2 I12-AD35.

4.2.4 Copper ore grades and smelting efficiency

In this section the ore grades and smelting efficiency of copper are applied in the calculation.

4.2.4.1 Copper ore grades

Globally, metal ore grades are declining. The main cause brought forward in scientific literature is the depletion of the highest grade ores: in the past mining locations with the highest metal content have been exploited first causing the lower grade ores to remain *(DOLD, 2014, p. 643; NORGATE & JAHANSHAHI, 2010, p. 65)*. Historical data shows that in several countries the decline of copper ore grades has been steep. In Australia, Canada and the United States of America the copper ore grades (in % Cu) all dropped below 1% in 2005, while they used to be 10% (Australia, 1885), 4% (Canada, 1885), and 2% (USA, 1910) *(Giurco et al., 2010, p. 28)*. Halfway the 19th century copper ore grades where even higher, with an estimated global average of 15-20% *(Sverdrup et al., 2014, p. 163)*.

A further decline of the copper ore grades is expected. *Mudd (2009)* - while focusing on the Australian situation – expects this decline not to be as rapid as before, but states that there is 'no real prospect of [ores] ever returning to the higher grades of the past' *(p.119)*. *Northey, Mohr, Mudd, Weng, & Giurco (2014)* discuss copper grades in the same light as 'peak oil'[xvii] and also anticipate a further decline, although slower than in the past. *Crowson (2012)* states that a 'peak copper' approach is too simplistic and that multiple other factors play a role in copper production related to economy, metal prices, technological progress, and other factors. *Sverdrup et al. (2014)* take into account such factors, e.g. market price and recycling rates, and anticipate the production of copper to peak around 2034. They estimate the supply of copper to dry up 'sometime after [the year] 2400' *(p.158)*. Similar to the IEA, they emphasize the vital importance of upscaling copper recycling.

The decline in copper ore grades will have several effects on the environmental impact of copper mining. First, it has a direct effect in the form of higher embodied energy. This is caused by the increase in energy required for hauling, loading and processing of the ores *(Norgate & Haque, 2010)*. Secondly, lower grades lead to higher stripping ratios and thus higher amounts of waste per unit of copper. This will result in 'a higher tonnage of tailings' for each unit of copper produced *(Adiansyah et al., 2015, p. 1050)*. Consequently, this will bring about growing numbers and/or larger tailings ponds and further increase the pressure on existing ponds. The link between this mining metric and large tailings dam failures has been discussed in literature, see e.g. *Bowker & Chambers (2015)*. In *section 4.2.7* of this chapter a more in-depth description of this topic is given.

[xvii] Peak oil is a hypothesis on oil production that predicts that oil production roughly takes the shape of a symmetric bell curve. It gave an accurate prediction of conventional oil production in the United States, which peaked in 1971. Peak oil has become an 'well accepted idea' *(de Almeida & Silva, 2009, p. 1267)*. It is also being applied to oil production on a global scale *(Bardi, 2009)* and other commodities such as minerals (see e.g. *Prior, Giurco, Mudd, Mason, & Behrisch, 2012*). However, the original theory did not consider the introduction of new technologies: the United States currently is one of the largest oil producers in the world due to the introduction of fracking to produce shale oil *(International Energy Agency, 2019, p. 4)*.

In *Table 28* the copper ore grades *G* are given for each decade. *G* is defined as 'the weight of copper per unit weight of ore' and is expressed as a percentage *(GORDON, 2002, p. 99)*. The data is based on historic data on ore grades from *GORDON (2002)*, recent ore grades from *CALVO, MUDD, VALERO, & VALERO (2016)*, and a forecast based on *NORTHEY ET AL. (2014)*. The copper ore grade for 2000-2009 is calculated by averaging the ore grades from 1990-1999 and 2010-2019. The data shows that the average copper ore grade will decline with 0.02% per decade after 2010-2019 and drop another 0.05% after 2060 to an average copper ore grade of less than 0.5%, see *GRIDA+ database 11.RQ2 V50-AF67*.

decade	ore grade G (%)	source
1900-1909	3.610%	*(GORDON, 2002)*
1910-1919	2.580%	
1920-1929	1.820%	
1930-1939	1.830%	
1940-1949	1.080%	
1950-1959	0.880%	
1960-1969	0.730%	
1970-1979	0.670%	
1980-1989	0.640%	
1990-1999	0.650%	
2000-2009	0.635%	calculated
2010-2019	0.620%	*(CALVO ET AL., 2016)*
2020-2029	0.600%	*(NORTHEY ET AL., 2014)*
2030-2039	0.580%	
2040-2049	0.560%	
2050-2059	0.540%	
2060-2069	0.490%	

Table 28 - Historic and future global copper ore grades in %, made by author, based on (CALVO ET AL., 2016; GORDON, 2002; NORTHEY ET AL., 2014). See GRIDA+ database 11.RQ2 V50-AF67.

4.2.4.2 Copper smelting efficiency

The extraction of copper from ore is never exhaustive, which meaning that some of the copper will eventually will end up in the tailings *(GORDON, 2002, p. 93)*. The smelting efficiency (or *recovery rate*) indicates how much of the copper that is contained in the ore is extracted as endproduct after milling and smelting. It is defined as 'the ratio of copper metal made to copper contained in the ore' *(GORDON, 2002, P. 99)*. The smelting efficiency *E* is expressed as a percentage, see *Table 29*.

The historical data in this table comes from *GORDON (2002)*. The more recent data for 2000-2009 and 2010-2019 comes from *NORTHEY ET AL. (2014)*. In their calculations they used a smelting efficiency of 85% for the year 2010. No scientific literature with forecasts of the future smelting efficiency of copper could be found. Since the smelting efficiency has remained constant at 85% since the 1970s, in this study it is assumed that this number will be accurate for the coming decades up to 2069.

decade	smelting efficiency E (%)	sources
1900-1909	60%	*(GORDON, 2002)*
1910-1919	60%	
1920-1929	85%	
1930-1939	88%	
1940-1949	92%	
1950-1959	92%	
1960-1969	94%	
1970-1979	85%	
1980-1989	85%	
1990-1999	85%	
2000-2009	85%	*(NORTHEY ET AL., 2014)*
2010-2019	85%	
2020-2029	85%	derived
2030-2039	85%	
2040-2049	85%	
2050-2059	85%	
2060-2069	85%	

Table 29 - Smelting efficiency of copper (made by author, based on GORDON, 2002 and NORTHEY ET AL., 2014). See GRIDA+ 11.RQ2 V50-AF67.

Plotting the data on the ore grade *G* (%) and smelting efficiency *E* (%) in a graph gives *Figure 25*.

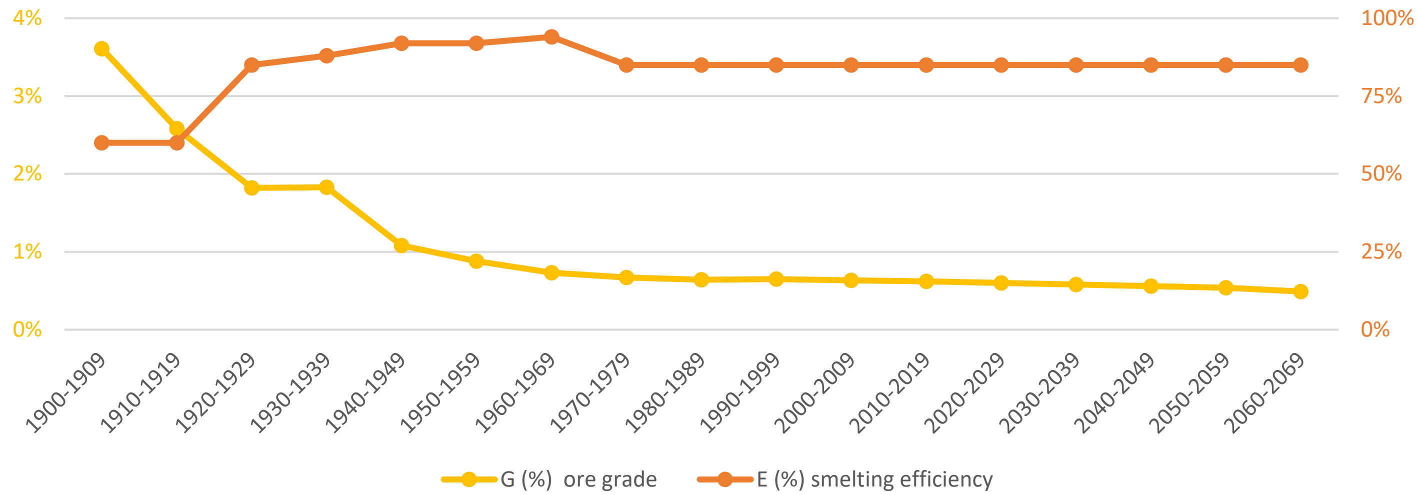

Figure 25 - Ore grades and smelting efficiency of copper, from 1900 to 2069 (made by author, based on CALVO ET AL., 2016; GORDON, 2002; MUDD & WENG, 2012; NORTHEY ET AL., 2014). See GRIDA+ 11.RQ2 V50-AF67.

4.2.5 Copper tailings-to-metal ratio

As described in the previous section, the copper ore grades have worsened in the past century and will gradually decline further in the coming decades. In order to give calculate the future generation of copper tailings one last variable is required: the copper tailings-to-metal ratio (T/M). With the equation provided by *GORDON (2002, p. 98)* a forecast of the tailings-to-metal ratios up to 2060-2069 is made (see *Table 30*) by using the data for *E* (from *Table 29*) and *G* (from *Table 28*).

decade	smelting efficiency *E* (%)	ore grade *G* (%)	tailings to metal *T/M*
1900-1909	60%	3.610%	41
1910-1919	60%	2.580%	60
1920-1929	85%	1.820%	61
1930-1939	88%	1.830%	59
1940-1949	92%	1.080%	97
1950-1959	92%	0.880%	120
1960-1969	94%	0.730%	143
1970-1979	85%	0.670%	172
1980-1989	85%	0.640%	180
1990-1999	85%	0.650%	178
2000-2009	85%	0.635%	182
2010-2019	85%	0.620%	186
2020-2029	85%	0.600%	193
2030-2039	85%	0.580%	199
2040-2049	85%	0.560%	207
2050-2059	85%	0.540%	214
2060-2069	85%	0.490%	237

Table 30 - Smelting efficiency, ore grades, combined, and T/M ratio between 1900-2069 (made by author, see GRIDA+ 11.RQ2 AA61-AA67)

For completeness, the colours of the data in *Table 30* indicate the source of the data:

- The 1900 to 1999 ore grades, smelting efficiencies and T/M ratios are from Gordon (2002, p. 99)
- The smelting efficiency for 2000-2019 comes from Northey et al. (2014)
- The copper ore grades for the 2020-2069 period are based on detailed model mean estimates[xviii] from Northey et al. (2014).
- The copper ore grade for the period 2010-2019 comes from Mudd & Weng (2012), as cited in Calvo, Mudd, Valero, & Valero (2016, p.2).
- The data in grey is calculated or derived:
    - The smelting efficiencies *E* for 2020-2069 are derived from Northey et al. (2014).
    - The copper ore grade *G* for 2000-2009 (0.635%) is derived by averaging the Northey et al. (2014) and Gordon (2002) data of the preceding and subsequent decade.
    - The T/M ratios for 2000-2069 are calculated based on a formula from Gordon (2002, p.99) and the smelting efficiency *E* and ore grade *G*.

In *Figure 26* and *Figure 27* the tailings-to-metal ratio of copper from 1900 until 2069 (from *Table 30*) is plotted in a graph.

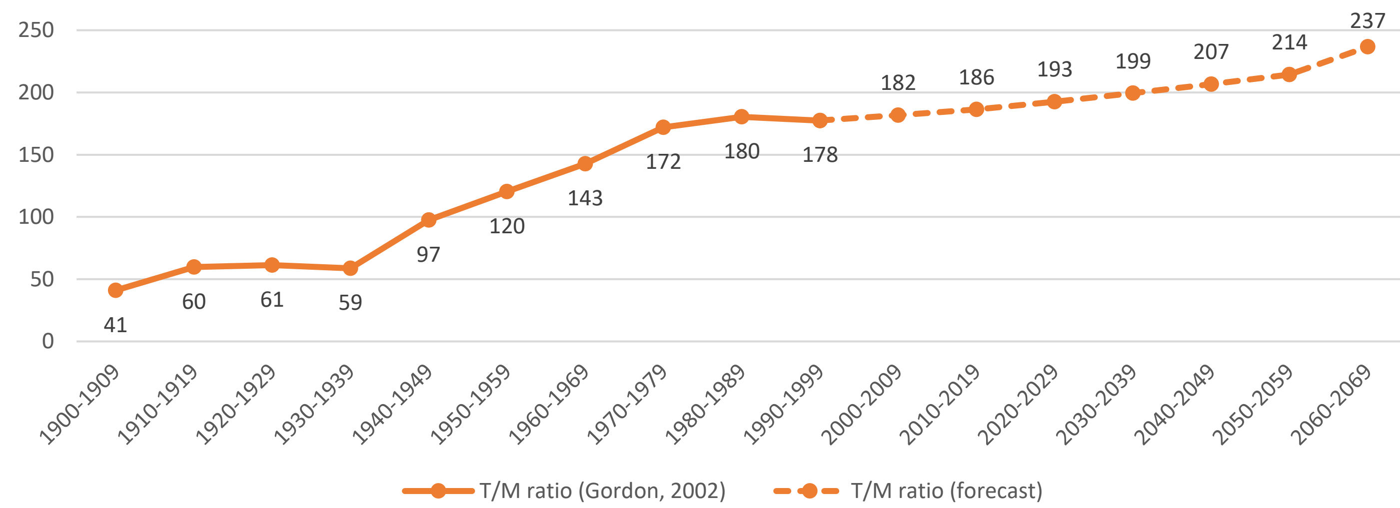

Figure 26 – Forecast of tailings to metal ratio of copper, 1900-2069. Made by author, partly based on Gordon (2002), see See GRIDA+ 11.RQ2 V50-AF67.

[xviii] Based on historic production data and model outputs for Australia, Canada, Chile, China, Democratic Republic of Congo, Peru, Spain, United States of America, and United Kingdom *(Northey et al., 2014, p. 194)*.

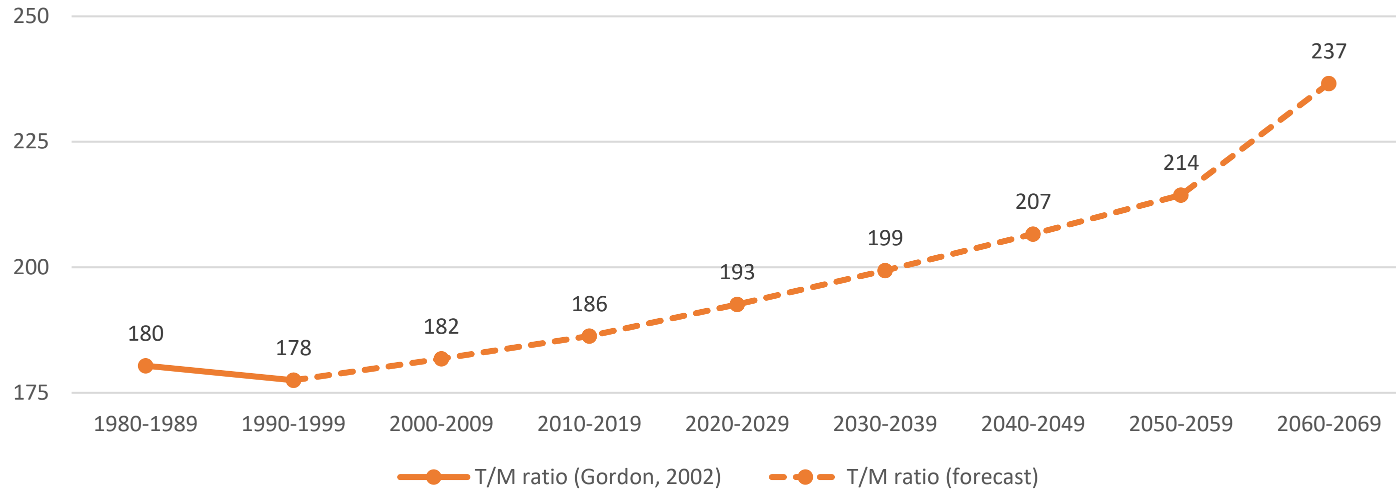

Figure 27 – Forecast of tailings-to-metal ratio of copper, 1980-2069. Made by author, partly based on GORDON *(2002), see See GRIDA+ 11.RQ2 V50-AF67.*

4.2.6 Forecast of copper tailings generation until 2040

4.2.6.1 STEPS and SDS scenarios

Based on the copper ore grades and processing efficiency a forecast of the future tailings-to-metal ratio (T/M) is calculated. By multiplying the T/M with the future copper demand from the STEPS and SDS scenarios (while correction for recycling rates), an estimation of future copper tailings production is made, see *Figure 28* and *Figure 29*.

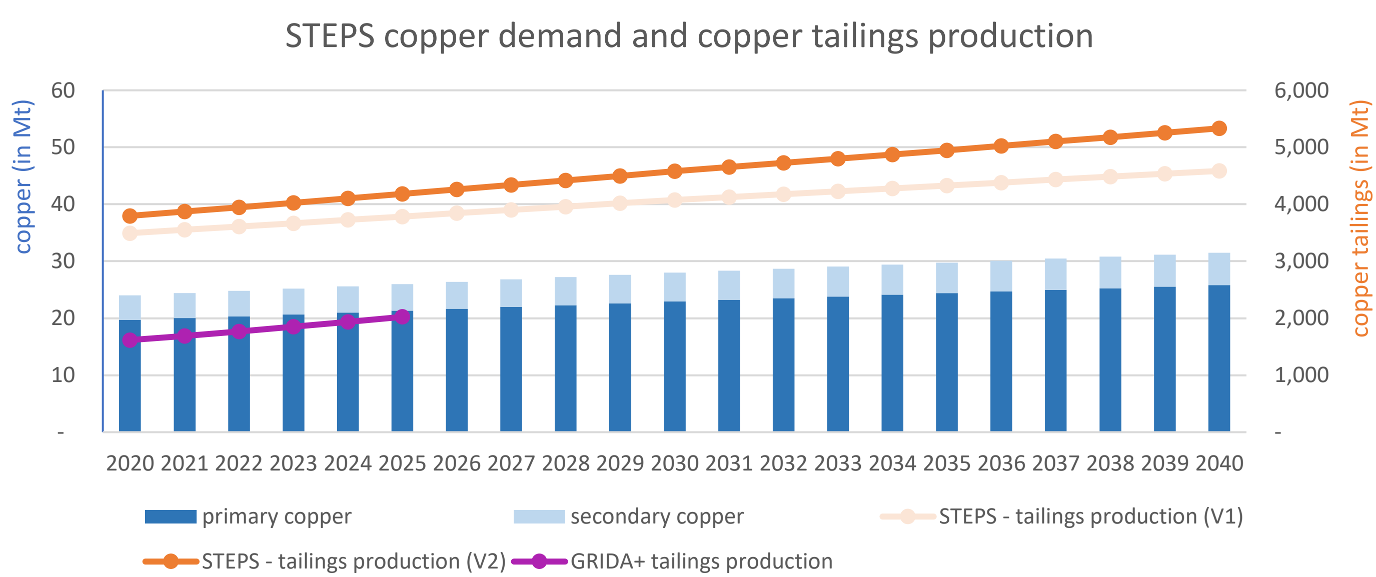

Figure 28 - Copper tailings production forecast in STEPS, including GRIDA+ estimate. Made by author, see GRIDA+ 11.RQ2 I12-AF39.

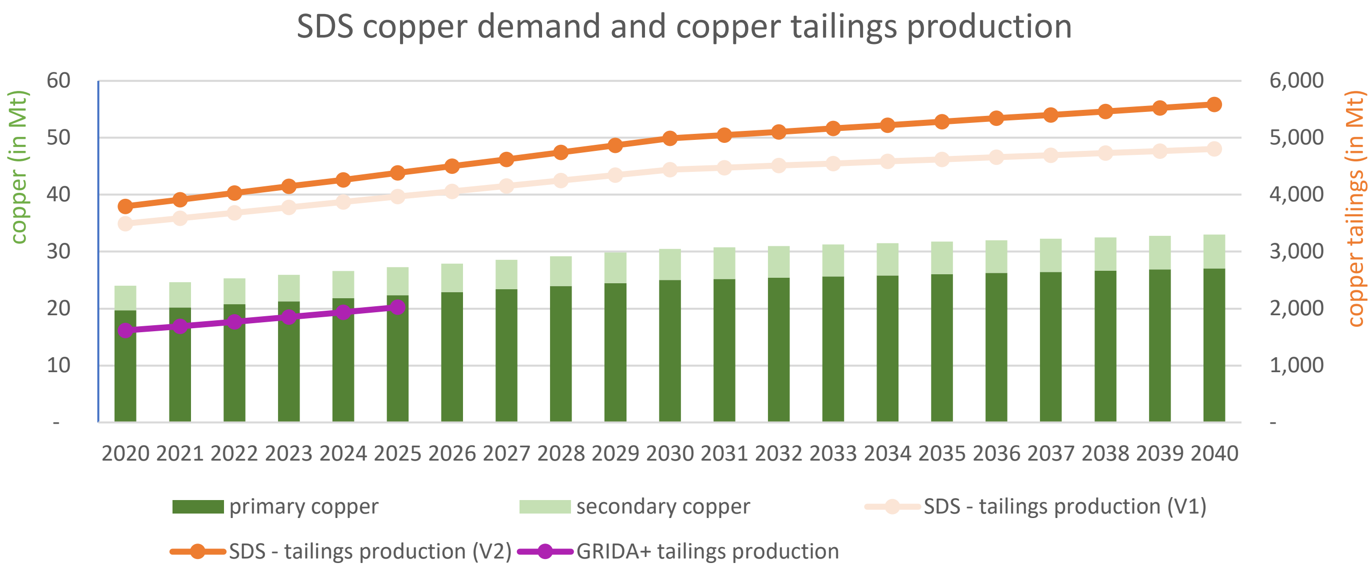

Figure 29 - Copper tailings production forecast SDS, including GRIDA+ estimate. Made by author, see GRIDA+ 11.RQ2 I12-AF39.

Two forecasts of tailings production are mentioned in *Figures 28 & 29*, named V1 and V2. V1 is a simple calculation based on the static 177.5 T/M ratio as mentioned in *Gordon (2002)*. V2 is the comprehensive calculation based on the T/M ratios from *Figure 27* that takes into account declining ore grades as described in this chapter. The difference between these two calculations shows the substantial effect that declining ore grades will have on copper tailings production: the drop in ore grades will lead to 14% higher tailings production in 2040 compared to 2020 in both the STEPS and SDS scenario, see *GRIDA+ 11.RQ2 AF17 & AF25*.

Additionally, the line described as 'GRIDA+ tailings production' is the copper tailings production until 2025 as estimated by the responding companies from the GRIDA survey. The growth line indicates that the companies in GRIDA anticipate a level of growth of tailings that is much higher than the results of STEPS and SDS: when assuming linear growth based on this data, demand for copper tailings storage would be 120% higher in 2040 compared to 2020 (compared to 41% in STEPS and 47% in SDS).

Figure 30 and *Figure 31* are summaries of *Figure 28* and *Figure 29*.

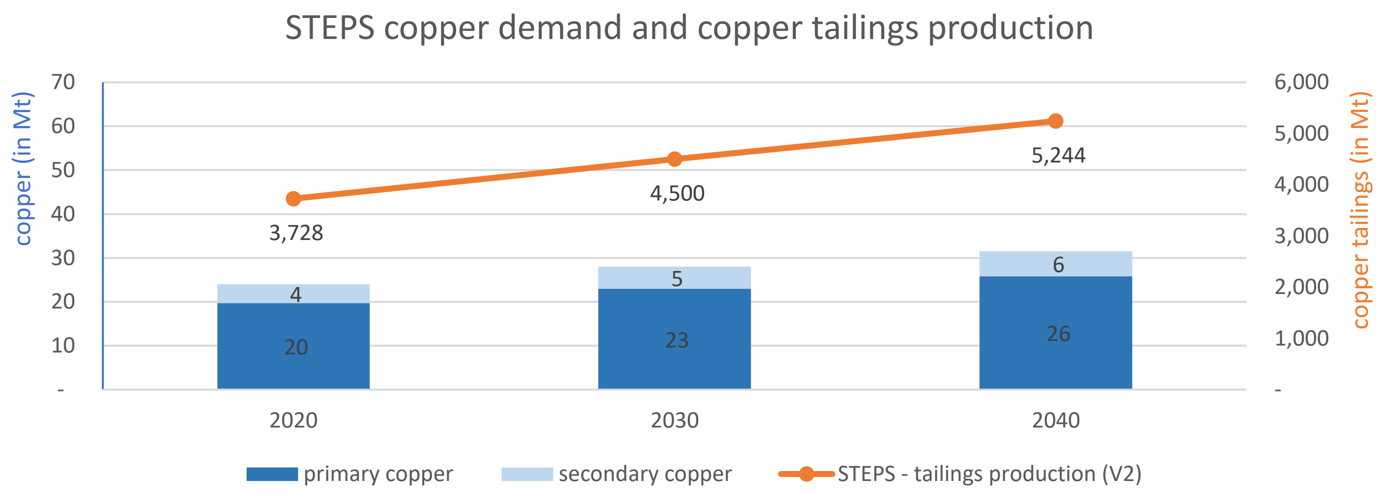

Figure 30 – Annual copper demand and tailings generation in the STEPS scenario, 2020-2040, in Mton. Made by author, see GRIDA+ 11.RQ2 I12-AF39.

In the STEPS scenario a 31% increase in annual copper demand is expected between 2020 and 2040 (from 24 Mt to 32 Mt). This will lead to an estimated annual copper tailings production of 5,244 Mt, which is 41% higher than 2020, see *GRIDA+ 11.RQ2 I12-AF39*.

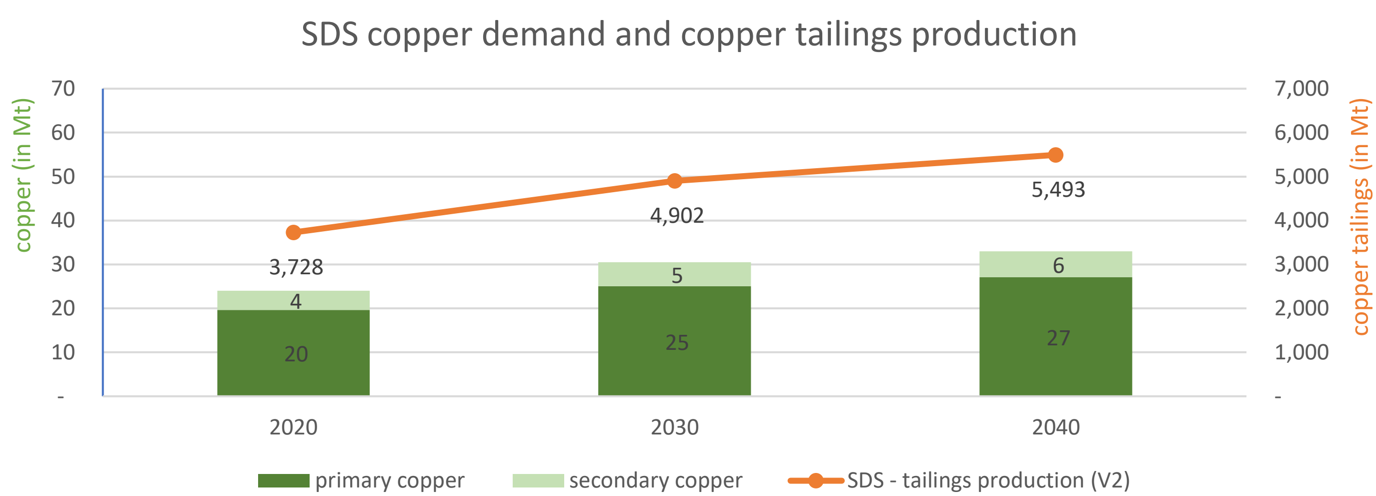

Figure 31 – Annual copper demand and tailings generation in the SDS scenario, 2020-2040, in Mton. Made by author, see GRIDA+ 11.RQ2 I12-AF39.

In the SDS scenario a 38% increase in annual copper demand is expected between 2020 and 2040 (from 24 Mt to 33 Mt). This will lead to an estimated annual copper tailings production of 5,493 Mt, which is 47% higher than 2020, see *GRIDA+ 11.RQ2 I12-AF39*.

4.2.6.2 NZE scenario

In 2021 another IEA report was released named 'Net Zero by 2050 - A Roadmap for the Global Energy Sector'. This report discusses pathways to a completely carbon free energy system, based on a net-zero emissions scenario (NZE). This is the most recent and IEA scenario and is based on net zero carbon emissions in 2050, and therefor goes further than STEPS and SDS. However, the quantification of the metal demand in the NZE scenario is not as extensive compared to STEPS and SDS *(International Energy Agency, 2021b)*. The IEA states that in the NZE scenario 'the total market size of copper, cobalt, manganese and various rare earth metals grows almost sevenfold between 2020 and 2030' *(International Energy Agency, 2021a, p. 23)*. However, the total copper demand in the NZE scenario is not provided; only the copper demand for renewable energy is given, which is rated about 50% higher compared to the SDS scenario in 2040 (15,147 Kt versus 22,720 Kt), see *Table 31* and *GRIDA+ 11.RQ2 I12-AF39*.

The renewable energy transition has a direct influence on the copper demand of other industries. Because it is too complex to quantify this influence for this study an estimation of the total copper demand in NZE is made. In this study it is assumed that the copper demand from other industries (i.e. the total demand minus renewables demand) remains the same in NZE as in SDS. Based on this assumption the copper demand in NZE will be 36 Mt in 2030 and 40 Mt in 2040, see *GRIDA+ 11.RQ2 I12-AF39*. This will lead to an estimated annual copper tailings production of 6,658 Mt, which is 79% higher than 2020, see *Figure 32*. For a side-by-side comparison of the annual primary and secondary copper demand and tailings production in the STEPS, SDS, and NZE scenarios, see *Table 31*.

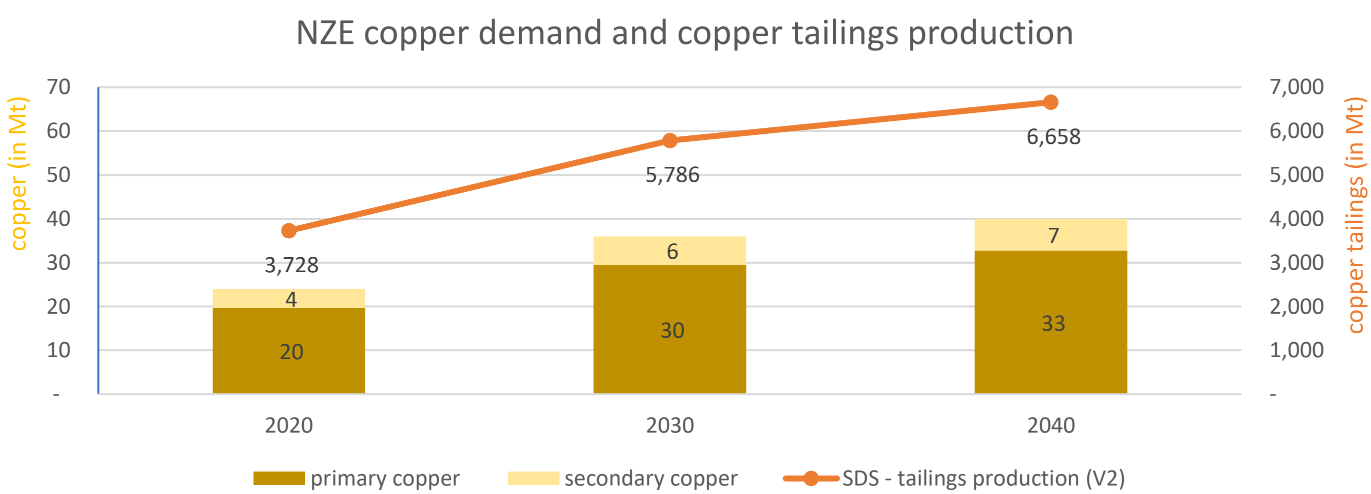

Figure 32 - Annual copper demand and tailings generation in the NZE scenario, 2020-2040, in Mton. Made by author, see GRIDA+ 11.RQ2 I12-AF39.

year	2020	2030	2040	
T / M ratio copper	189	196	203	
STEPS - renewables demand	5,715	8,007	10,001	
STEPS - total demand	24,000	28,000	31,500	
secondary copper	4,320	5,040	5,670	
primary copper	19,680	22,960	25,830	
STEPS - tailings production (V2)	3,728,488	4,500,134	5,243,534	+41%
SDS - renewables demand	5,715	10,705	15,147	
SDS - total demand	24,000	30,500	33,000	
secondary copper	4,320	5,490	5,940	
primary copper	19,680	25,010	27,060	
SDS - tailings production (V2)	3,728,488	4,901,932	5,493,226	+47%
NZE - renewables demand	5,715	16,057	22,720	
NZE - total demand	24,000	36,000	40,000	
secondary copper	4,320	6,480	7,200	
primary copper	19,680	29,520	32,800	
NZE - tailings production (V2)	3,728,488	5,785,887	6,658,455	+79%

Table 31 – Annual copper demand and tailings production in the STEPS, SDS, and NZE scenario, in Kton. Made by author, see GRIDA+ 11.RQ2 I12-AF39.

The density of copper tailings 'sands and slimes' (i.e. solids and liquids) combined is estimated to be 1.78 ton/m³ *(SHAMSAI ET AL., 2007, p. 594)*, which equals to over 3.5 billion m³ of copper tailings annually in NZE in 2040 (6,658,000,000 tonnes / 1.78 = 3,740,000,000 m³). See *Table 32* for different units depicting this volume of tailings.

3,740,000,000 m³ is equal to

- 54 million 40ft shipping containers — (2 TEU, 67.6 m³)
- 130 million 20ft shipping containers — (1 TEU, 33.2 m³)
    - 4500x Ever Ace (largest container ship) — (23,992 TEU capacity)
        - >12x Every Ace capacity every day
    - 2,5x the Shanghai Harbour throughput — (43.50 million TEU in 2020)
    - 7x the Rotterdam Harbour throughput — (14.35 million TEU in 2020)
- 66% of annual crude oil production — (2021)
    - 23,000 million barrels of copper tailings — (159-liter barrels)
        - 110 million barrels — (daily crude oil production 2021)
        - 34,226 million barrels — (annual crude oil production 2021)
- 7x the Żelazny Most TSF current capacity — (634 million m³)
- 3,5x the Żelazny Most TSF maximum capacity — (1,100 million m³)

Table 32 – The volume of the 2040 NZE annual copper tailings production in other units of volume (made by author)

4.2.7 Implications for copper tailings dams and tailings dam failures

The developments causing this increase in tailings production are described as the 'modern mining metric'. This metric is the coming together of the falling ore grades, technological advances in mining and processing in combination with economies of scale, and declining real prices (i.e. prices adjusted for inflation) of most metals such as copper *(Bowker & Chambers, 2011)*. The implication for future copper production is that falling copper ore grades cause scaling, which means that larger amounts of material need to be mined and processed to keep up with demand. Technological advances in extraction make processing of lower ore grades economically viable, and the declining real price of copper since the 1900s has further accelerated upscaling of copper mines *(Kelly et al., 2018)*. However, it should be noted that this trend of declining real prices was halted in the last two decades when copper prices exploded to near all-time highs *(Mudd, 2009a)*. The price of copper will increase when the copper demand further grows, which could lead to re-opening of copper mines depending on its profitability based on the copper grades of accessible ore and market price *(Aguirregabiria & Luengo, 2015)*. This is problematic, because the practice of temporarily closing and re-opening of mines during price surges has been suspected as a risk factor in tailings dam failures *(Bowker & Chambers, 2017)*.

The modern copper mine metric will also affect the total number and size of tailings dams. According to *Pietrzyk & Tora (2018)* the current copper resources and mines have an adequate capacity. However, because of declining ore grades in many copper mines they emphasize the need for new 'high-class copper ore deposits […] to meet the growing global demand for copper' (*p.9*). This indicates that the growing demand for copper will be covered by upscaling existing mines and mining from newly explored deposits, meaning that in the long term the storage of copper tailings will be mainly fulfilled by enlarging and construction new TSFs. However, rapid construction and upscaling of dams has been explicitly stated as a cause for tailings dam failures *(Azam & Li, 2010)*.

5 Discussion and Conclusion

5.1 Answering research questions

Historically, there has been a disbalance between costs and safety in tailings dam management. Hence, tailings dam failures are not caused by technical difficulties, but are the result of poor planning, limited construction guidelines, inadequate management and maintenance, and a general lack of attention for safety. This has caused numerous tailings dam failures in the last decades, which have led to thousands of casualties, large scale environmental and ecological destruction, and billions of dollars in damages. Although the absolute frequency of tailings dam failures has been declining, the severity of failures has gone up due to the growing demand for minerals, combined with a decrease in ore grades, advancing extractive technologies, and the ever-expanding economies of scale in the mining industry. Below the two research questions of this study will be answered.

5.1.1 RQ1: To which resources are tailings storage facilities linked?

In this study 1936 TSFs have been linked to 27 different resource categories. Of these TSFs 90% are linked to 10 resource categories: gold, copper, and aluminium, followed by lead-zinc, coal, iron, PGE-nickel-chromium, silver, diamond, and manganese. In volume, these 10 categories contain 93% of the tailings, of which the top 3 (copper, gold, and iron) contains 74%. The findings reveal that copper plays a prominent role in tailings production, as it alone contributes to approximately 41% of the total tailings volume reported in GRIDA+.

Furthermore, GRIDA+ shows that copper TSFs are among the largest in the world, both in pond capacity and dam height: while the average dam of a copper TSF is just below 50 meter high, the largest dam reaches over 250 meters high. A reason for concern is that copper TSFs are not only big, but also have the highest rates of upstream dams, while historical data shows that these types of dams have the highest failure rates. Moreover, almost one third of copper TSFs are inactive, making them more prone to failure compared to officially closed dams. On the other hand, copper TSFs score relatively well on stability concerns, the presence of engineering records, and extreme weather security compared to other resources categories.

5.1.2 RQ2: How will the renewable energy transition affect copper tailings production until 2040?

This study illustrates that storage of tailings in TSFs remains a major challenge in the mining industry and will be more so in the future. According to GRIDA+ data the tailings storage volume of aluminium, copper, gold, iron, manganese, and PGE-nickel-chromium TSFs is expected to grow with more than 20% between 2020 and 2025. We have zoomed in further on this development by forecasting the global generation of copper tailings until 2040. This was done based on copper demand data from the IEA, while taking into account recycling rates, ore grades, the smelting efficiency, and the tailings-to-metal ratio based.

The annual copper demand will increase with 31% in STEPS, 38% in SDS, and 67% in NZE. The copper ore grades will further decline from the current 0.60% to 0.49% in the 2060s. The recycling rate of copper is assumed to remain stable at 18%, and so is the smelting efficiency at 85%. The tailings-to-metal ratio of copper will degrade, going from the current 193:1 to 237:1 in the 2060s. Combined these developments will cause the annual copper tailings production in 2040 to be much higher than in 2020:

Inn volume the copper tailings production will increase from 3,728 million m^3 in 2020 to 5,243 Mt (STEPS), 5,493 Mt (SDS), and 6,658 Mt (NZE) in 2040. This is an increase of 40% in the STEPS scenario, 47% in the SDS scenario, and 79% in the NZE scenario. This increase is primarily caused by the growing copper demand and to a lesser extent by declining ore grades. In volume, the annual tailings production in NZE is estimated at 3,740 million m^3, which in is equivalent to 66% of the annual global volume of crude oil production.

5.2 Limitations of the study

5.2.1 GRIDA and GRIDA+ database

A foundational aspect of this study is the GRIDA database. Currently, GRIDA is the most up-to-date and complete open access TSF databases, although it does not include all TSFs that exist in the world. There are some points of interest about the accuracy and representativity of the data and the GRIDA database in general, that work through in GRIDA+. First, there is no version history of the database, so it is not clear which of the two statements provided by the Church of England in *3.1.1* applies to the version of the database as used in this study. Secondly, no data or sources have been provided on how the percentage of market capitalization was established. GRIDA claims that a 86% percentage of the market is covered in the database, while *BOWKER (2020, para. 10)* states that GRIDA 'represent[s] less than 10% of the world mine tailings portfolio'. Although the metrics they use are not the exact same, an 8-fold difference cannot be accurate. Noteworthy is the absence of China in GRIDA, despite its significance in the mining industry for various metals and its domination in REEs *(ILANKOON ET AL., 2022)*. Consequently, the claim that 86% as measured by global market capitalization is covered in the database seems implausible due to this gap in data. Moreover, by providing market capitalization it is suggested that there is a strong relation between company size and number of TSFs or tailings volume in their portfolio. Although this seems apparent, this claim is not further substantiated by GRIDA. It could well be the case that, for example, companies sell off their TSFs to subsidiaries or companies specialized in tailings management, or that TSFs become state owned after mining companies leave or go bankrupt. This brings us to a third point: no governments have been contacted about TSF ownership, which are consequently missing from GRIDA. That governments are expected to own TSFs can be illustrated through Canada, where a quarter of the uranium TSFs are owned by the (regional) government or governmental organisations *(LLRWMO, 2012, p. 57)*. Moreover, governmental organisations could also be contacted about information on TSFs in their countries, take for example in Brazil, where TSFs are registered and regulated under a 2010 law *(KAMINO ET AL., 2020; UNEP, 2010)*.

Lastly, GRIDA is based on open survey question, which gives room for interpretation because no objective means to measure variables are given, e.g. 'Is the dam extreme weather secure?'. It also makes answers with a social-desirability bias more likely, e.g. 'Does the dam have a history of instability concerns?'. Such terms have a very broad meaning when they are not further defined or specified. Furthermore, closed questions are asked, while the answers should contain further clarification to be usable, e.g. 'Is there a closure plan in place for this dam?'. A plan could be one handwritten sheet of paper, or a comprehensive third-party report that describes the technical, financial, legal, environmental, and social aspects concerning dam closure. These problems stated above are amplified because companies are not required to give evidence or additional commentary on the answers they provide.

5.2.2 Tailings are completely attributed to copper, not to secondary commodities

For this study it is assumed that company data on mines and commodities are reliable. This appears to be so for the primary commodities when USGS MRDS and company data was available and could be compared. However, on secondary commodities company data is in many cases incomplete or missing, in contrast to data from the USGS MRDS and scientific literature. This makes the GRIDA+ resource data lacking on secondary commodities, although this had no effect on the results of the primary resource data.

When looking at the copper resource category there are 54 (out of 283) TSFs that solely rely on company data, of which half (27 TSFs) are claimed to only produce copper without any secondary products. Because of the lack of reporting of secondary commodities on company websites up to 10% of the primary copper TSFs could contain tailings from secondary commodities that are currently not mentioned in the database. These secondary commodities affect the assumption that tailings from copper TSFs can be fully attributed to copper. According to the results of SQ1 there are at least 182 (out of 283) primary copper TSFs linked to mines that besides copper also produce secondary commodities such as gold, silver, lead, zinc, and molybdenum, and to a lesser extent cobalt, uranium, cadmium, selenium, tellurium, arsenic, nickel, bismuth, tin, and tungsten, see *GRIDA+ 5.GRIDA+ column P*. This means that the copper tailings should be partly attributed to these secondary metals. Because the data on the types of secondary commodities is incomplete, and production quantities of commodities are absent in GRIDA+, it is unclear to what extent.

The uncertainty surrounding allocation of tailings in relation to secondary commodities works the other way around as well. The results of SQ1 and SQ2 on copper tailings in GRIDA+ are based on 283 TSFs that contain copper as primary commodity. However, in total 493 TSFs contain copper tailings to some degree, meaning that 210 TSFs have copper as a secondary commodity. For the sake of simplicity and the lack of production data these TSFs have been excluded from further analysis in this study.

5.2.3 Risks associated with inactive dams

In this study it is suggested that inactive dams are potentially more dangerous than closed dams. Although there is sufficient data that active dams are more at risk of failure than closed dams, evidence that inactive dams are more at risk than closed dams, is limited apart from research focusing on Europe, see *Chapter 2*. However, by the definitions given in GRIDA inactive dams lack behind in plans, attention towards stakeholders, and approval from relevant government agencies compared to officially closed dams, see *section 4.1.4*. Since there is a high correlation between the absence of such factors and risk of failure, it is conceivable that there is an additional risk related to inactive dams compared to officially closed dams. This study is a first step in understanding which resource industries have a high share of inactive dams. Further research should be conducted to make further claims about the risk of this category of TSFs.

5.2.4 Copper demand, recycling rates and copper smelting efficiency

Future copper tailings production is dependent on copper demand, recycling rates, copper smelting efficiency, and ore grades. The NZE scenario by the IEA the annual copper demand is estimated to be 40Mt in 2040, but this could be an underestimation. Examples of other, less detailed, estimates for the global copper demand in 2040 are 40-80 Mt *(SCHIPPER ET AL., 2018, figs. 1 & 2)* and 35-50 Mt *(ELSHKAKI ET AL., 2016)*. This means that the IEA – even in the most copper intense NZE scenario - has made a relatively conservative estimation of the copper demand, and copper tailings production could potentially be up to 2 times higher than calculated in this study.

In this study the recycling rate is assumed to remain 18%, but literature suggests that if strong efforts are made this could increase, e.g. to 40-50% in the case of the EU *(CIACCI ET AL., 2020)*. Such an increase in global copper recycling would reduce the demand for primary copper, thereby lowering tailings production associated with primary copper production. Also, copper smelting efficiency was kept at 85%, for lack of recent data. We could speculate that the smelting efficiency goes down conjointly with the decline in copper ore grades. Since the drop in ore grades between 2020 and 2040 leads to 14% higher tailings production in both the STEPS and SDS scenario, tailings production could be much higher if the smelting efficiency deteriorates.

Finally, the copper tailings-to-metal ratio in this study is calculated up to 2060-2069, but the forecast of copper tailings production is limited to 2040. The reason for this is that the IEA does not provide estimates beyond this year. When new data beyond 2040 is published in the future, the copper tailings forecast could be extended up to 2060-2069 based on the data and methods from this study.

5.3 Energy transition, mitigation of impacts, and policy recommendations

This study shows that there are additional risks associated with the growing extraction of metals caused by the energy transition. The large demand growth of key minerals could not only lead to severe price fluctuations and supply volatility but may also lead to rapid upscaling of production. More metal demand will lead to more extraction, and thus more tailings generation. This puts additional stress on already existing TSFs, and hurried and ill planned construction of new TSFs more probable. Combined with potentially higher metal prices this could make mines with low-ore grades profitable again, which could further inflate tailings-to-metal ratios. Without intervention to break with the status-quo, this will lead to more and bigger TSFs and a higher frequency and increased severity of tailings dam failures. In the case of copper, mining locations are nearing or at their peak output, making the exploration and exploitation of new mining locations necessary to fulfil the future copper demand. The construction of new mines and thus new TSFs in currently unaffected locations poses risks for human health and ecosystems if done without careful consideration.

These future risks are in stark contrast with the attention from the mining industry. Less than halve of the addressed companies for GRIDA responded, and the absence of TSFs in China from the database will become of increasing concern in the future as it further strengthens its dominance on strategic resources. Moreover, initiatives such as the WMTF database are in danger of being terminated because of the lack of funds, although a mere couple of hundred thousand dollars is annually needed to maintain their work. The fact that a multibillion-dollar industry is not funding such projects shows that the topic of tailings dam failures is still not taken as seriously as should be. To mitigate these challenges three policy recommendation are brought forward:

1. Commitment to copper recycling and limiting copper demand.
   Rapid implementation of the principles of circular economy, with particular emphasis on improving copper recycling rates. To minimize the growing demand for copper policymakers should adopt measures that restrict copper demand and increase copper recycling, since more than half of EoL copper is currently being wasted. This entails promoting life cycle thinking during the design of products, implementing policies that promote and improve recycling technologies, and prioritizing the allocation of available copper resources by taking into account the most essential and efficient applications.
2. Inclusion of tailings dam failures in Life Cycle Assessments (LCAs)
   Life Cycle Assessments plays a role in determining the environmental impact of materials and products. By incorporating tailings dam failures into LCAs their effects can be taken into consideration when comparing the environmental impacts of the resources the mining industry produces. This would also emphasize the additional benefit of recycled copper compared to primary copper.
3. Stimulating the formulation and implementation of an industry standard on tailings management.
   Industry, companies, and policymakers should approach copper as a heterogeneous product by prioritizing the use of copper sourced from mines that demonstrate safe and effective tailings management practices.

5.4 Academic relevance

This study is based upon data(bases) from scientific literature and has built upon them. *GRIDA (2020)* made a database on global TSFs based on a survey; this study has expanded it into GRIDA+ by adding primary commodity data in the form of 27 resource categories. *Gordon (2002)* calculated copper tailings-to-metal-ratios until 2000; this study builds upon this and forecasts the copper tailings-to-metal ratios until the 2060s. *UNEP (2019)* calculated the copper tailings production until 2020, in this study a forecast up to 2040 is made based on the STEPS, SDS, and NZE scenarios from the IEA.

5.5 Further research

Further research should prioritize enhancing the records of current and historical occurrences of tailings dam failures. In addition, research should be done to examine the failure rate within the timeframe of 2000-2023 to determining whether failures rates of tailings dams have increased or not.

Furthermore, the GRIDA(+) database should be expanded and refined through the acquisition of annual production data, and the inclusion of secondary commodities. Other entities such as governments should be incorporated in the GRIDA survey, and particular attention should be given to China due to its significant positions in the global resources industry. Moreover, it is imperative that variables are defined and specified, and that the claims that companies make about their TSFs is substantiated by evidence.

A similar methodology could be employed to explore other metals than copper. Example of metals that are anticipated to experience far higher growth levels in the future compared to copper are lithium, graphite, cobalt, nickel, manganese, molybdenum, or REEs.

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Appendix 1: 33 most cited papers on tailings dam failures

Papers that have been used in this study are in green, papers that have not been used are in orange (in most cases because of their limited scope to single incidents).

1. *(Grimalt et al., 1999)* Grimalt, J.O., Ferrer, M., MacPherson, E.
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2. *(Rico, Benito, Salgueiro, et al., 2008)* Rico, M., Benito, G., Salgueiro, A.R., Díez-Herrero, A., Pereira, H.G.
   Reported tailings dam failures. A review of the European incidents in the worldwide context
   (2008) Journal of Hazardous Materials, 152 (2), pp. 846-852. Cited 166 times.
3. *(Simón et al., 1999)* Simón, M., Ortiz, I., García, I., (...), Dorronsoro, C., Aguilar, J.
   Pollution of soils by the toxic spill of a pyrite mine (Aznalcollar, Spain)
   (1999) Science of the Total Environment, 242(1-3), pp. 105-115. Cited 142 times
4. *(Macklin et al., 2003)* Macklin, M.G., Brewer, P.A., Balteanu, D., Coulthard, T.J., Driga, B., Howard, A.J., Zaharia, S.
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8. *(Pastor et al., 2002)* Pastor, M., Quecedo, M., Fernádez Merodo, J.A., Herrores, M.I., González, E., Mira, P.
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10. *(Azam & Li, 2010)* Azam, S., Li, Q.
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11. (Blight, 1997) Blight, G.E.
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12. *(Chandler & Tosatti, 1995)* Chandler, R.J., Tosatti, G.
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    Catastrophe revisited - Disastrous flow failures of mine and municipal solid waste
    (2005) Geotechnical and Geological Engineering, 23(3), pp. 219-248. Cited 34 times
16. *(Bird et al., 2008)* Bird, G., Brewer, P.A., Macklin, M.G., Balteanu, D., Serban, M., Driga, B., Zaharia, S.
    River system recovery following the Novaţ-Roşu tailings dam failure, Maramureş County, Romania
    (2008) Applied Geochemistry, 23 (12), pp. 3498-3518. Cited 32 times.
17. *(Davies, 2002)* Davies, M.P.
    Tailings impoundment failures are geotechnical engineers listening?
    (2002) Geotechnical News 20(3), pp. 31. Cited 28 times
18. *(Jeyapalan et al., 1983a)* Jeyapalan, J.K., Duncan, J.M., Seed, H.B.
    Analyses of flow failures of mine tailings dams
    (1983) Journal of Geotechnical Engineering, 109 (2), pp. 150-171. Cited 27 times.
19. *(Shakesby & Whitlow, 1991)* Richard A. Shakesby, J. Richard Whitlow
    Failure of a mine waste dump in Zimbabwe: Causes and consequences
    (1991) September 1991, Volume 18, Issue 2, pp 143–153. Cited 27 times
20. *(Domènech et al., 2002)* Domènech, C., Ayora, C., De Pablo, J.
    Sludge weathering and mobility of contaminants in soil affected by the Aznalcollar tailings dam spill (SW Spain) (2002) Chemical Geology, 190(1-4), pp. 355-370. Cited 25 times
21. *(Schoenberger, 2016)* Schoenberger, E.
    Environmentally sustainable mining: The case of tailings storage facilities
    (2016) Resources Policy, 49, pp. 119-128. Cited 25 times
22. *(Harder & Stewart, 1996)* Harder Jr., L.F., Stewart, J.P.
    Failure of Tapo Canyon tailings dam
    (1996) Journal of Performance of Constructed Facilities, 10 (3), pp. 109-114. Cited 21 times.
23. *(Wei et al., 2013)* Wei, Z., Yin, G., Wang, J.G., Wan, L., Li, G.
    Design, construction and management of tailings storage facilities for surface disposal in China: Case studies of failures
    (2013) Waste Management and Research, 31(1), pp. 106-112. Cited 21 times.
24. *(Okusa & Anma, 1980)* Okusa, S., Anma, S.
    Slope failures and tailings dam damage in the 1978 Izu-Ohshima-Kinkai earthquake
    (1980) Engineering Geology, 16 (3-4), pp. 195-224. Cited 20 times.
25. *(Grangeia et al., 2011)* Grangeia, C., Ávila, P., Matias, M., da Silva, E.F.
    Mine tailings integrated investigations: The case of Rio tailings (Panasqueira Mine, Central Portugal)
    (2011) Engineering Geology, 123(4), pp. 359-372. Cited 19 times
26. *(Vick, 1996)* Vick, S.G.
    Tailings dam failure at Omai in Guyana
    (1996) Mining Engineering, 48 (11), pp. 34-37. Cited 19 times.

27. *(Sammarco, 2004)* Sammarco, O.
A tragic disaster caused by the failure of tailings dams leads to the formation of the Stava 1985 foundation
(2004) Mine Water and the Environment, 23 (2), pp. 91-95. Cited 16 times.
28. NOT AVAILABLE ONLINE Robinsky, E.I.
Tailings dam failures need not be disasters - the Thickened Tailings Disposal (TTD) system
(1999) CIM Bulletin, 92 (1028), pp. 140-142. Cited 16 times.
29. *(Fourie, 2009)* Fourie, A.
Preventing catastrophic failures and mitigating environmental impacts of tailings storage facilities
(2009) Procedia Earth and Planetary Science. 1(1), pp. 1067-1071. Cited 14 times
30. *(Petticrew et al., 2015)* Petticrew, E.L., Albers, S.J., Baldwin, S.A., (...), Selbie, D.T., Vagle, S.
The impact of a catastrophic mine tailings impoundment spill into one of North America's largest fjord lakes: Quesnel Lake, British Columbia, Canada
(2015) Geophysical Research Letters, 42(9), pp. 3347-3355. Cited 13 times
31. *(Agurto-Detzel et al., 2016)* Agurto-Detzel, H., Bianchi, M., Assumpção, M., Schimmel, M., Collaço, B., Ciardelli, C., Barbosa, J.R., Calhau, J.
The tailings dam failure of 5 November 2015 in SE Brazil and its preceding seismic sequence
(2016) Geophysical Research Letters, 43 (10), pp. 4929-4936. Cited 12 times.
32. *(Q. M. Li et al., 2009)* Li, Q.-M., Zhang, X.-K., Wang, Y.-H., Zhang, B.-Y.
Risk index system and evaluation model for failure of tailings dams
(2009) Shuili Xuebao/Journal of Hydraulic Engineering, 40 (8), pp. 989-994. Cited 12 times.
33. *(Hatje et al., 2017)* Hatje, V., Pedreira, R.M.A., De Rezende, C.E., Schettini, C.A.F., De Souza, G.C., Marin, D.C., Hackspacher, P.C.
The environmental impacts of one of the largest tailings dam failures worldwide
(2017) Scientific Reports, 7 (1), art. no. 10706. Cited 11 times.

Appendix 2: Literature search results

Below the results and search terms of the literature research on the most cited scientific articles on tailings dam failures can be found. The search terms are chronologically sorted: each following search term only displays the additional results that have been found (i.e. literature that has not been found before with other search terms). The resulting literature is sorted by the number of citations from high to low.

Tailings dam failures are typically referred to by these terminology, but often different words are used to address the same type of incidents. Therefor a list of the different search terms was used.

First, the construction itself is referred to in different ways:

- *tailings dyke* (*El-Ramly, Morgenstern, & Cruden, 2003*)
- *tailings pond* (*Rico et al., 2008*)
- *tailings impoundment* (*Yin et al., 2011*)
- *mine waste dump* (*Pastor et al., 2002*)
- *tailings storage facility* (*Wei, Yin, Wang, Wan, & Li, 2013*)

Secondly, there are several ways to address the failures of these constructions

- *accident* (*Grimalt, Ferrer, & MacPherson, 1999*)
- *disaster* (*Robinsky, 1999*)
- *spill* (*Guadiamar et al., 2003*)

All the above-mentioned terms have been used in the literature search in *Scopus*. No limitations on the date range, document type, and access type were applied. Its function to sort scientific articles based on the number of citations was used to find the most cited papers on tailings dam failures. In this study the term *tailings storage facility* (TSF) will be used.

When it is mentioned that '0 additional result(s)' have been found this means that either:

- the search term did not return results OR
- the search term did not return relevant results OR
- the search term only returned previously found papers

(tailings AND dam AND failure) in the TITLE-ABS-KEY [TOO MANY results]

Using this search term dozens of frequently cited papers come up. However, the results are broad, leading to cluttering of papers that are only remotely linked to the topic of tailings dam failures. Thus, more specific search terms are needed to find relevant literature.

(tailings AND dam AND failure) in the TITLE [20 results]

1. Rico, M., Benito, G., Salgueiro, A.R., Díez-Herrero, A., Pereira, H.G.
   Reported tailings dam failures. A review of the European incidents in the worldwide context
   (2008) Journal of Hazardous Materials, 152 (2), pp. 846-852. Cited 166 times.
2. Macklin, M.G., Brewer, P.A., Balteanu, D., Coulthard, T.J., Driga, B., Howard, A.J., Zaharia, S.

The long term fate and environmental significance of contaminant metals released by the January and March 2000 mining tailings dam failures in Maramureş County, upper Tisa Basin, Romania
(2003) Applied Geochemistry, 18 (2), pp. 241-257. Cited 115 times.

3. Rico, M., Benito, G., Díez-Herrero, A.
Floods from tailings dam failures
(2008) Journal of Hazardous Materials, 154 (1-3), pp. 79-87. Cited 99 times.
4. Kossoff, D., Dubbin, W.E., Alfredsson, M., Edwards, S.J., Macklin, M.G., Hudson-Edwards, K.A.
Mine tailings dams: Characteristics, failure, environmental impacts, and remediation
(2014) Applied Geochemistry, 51, pp. 229-245. Cited 82 times.
5. Pastor, M., Quecedo, M., Fernádez Merodo, J.A., Herrores, M.I., González, E., Mira, P.
Modelling tailings dams and mine waste dumps failures
(2002) Geotechnique, 52 (8), pp. 579-591. Cited 77 times.
6. Fourie, A.B., Blight, G.E., Papageorgiou, G.
Static liquefaction as a possible explanation for the Merriespruit tailings dam failure
(2001) Canadian Geotechnical Journal, 38 (4), pp. 707-719. Cited 67 times.
7. Azam, S., Li, Q.
Tailings dam failures: A review of the last one hundred years
(2010) Geotechnical News, 28 (4), pp. 50-53. Cited 56 times.
8. Van Niekerk, H.J., Viljoen, M.J.
Causes and consequences of the merriespruit and other tailings-dam failures
(2005) Land Degradation and Development, 16 (2), pp. 201-212. Cited 35 times.
9. Chandler, R.J., Tosatti, G.
The Stava tailings dams failure, Italy, July 1985
(1995) Proceedings of the Institution of Civil Engineers: Geotechnical Engineering, 113 (2), pp. 67-79. Cited 35 times.
10. Jeyapalan, J.K., Duncan, J.M., Seed, H.B.
Investigation of flow failures of tailings dams
(1983) Journal of Geotechnical Engineering, 109 (2), pp. 172-189. Cited 35 times.
11. Bird, G., Brewer, P.A., Macklin, M.G., Balteanu, D., Serban, M., Driga, B., Zaharia, S.
River system recovery following the Novaţ-Roşu tailings dam failure, Maramureş County, Romania
(2008) Applied Geochemistry, 23 (12), pp. 3498-3518. Cited 32 times.
12. Jeyapalan, J.K., Duncan, J.M., Seed, H.B.
Analyses of flow failures of mine tailings dams
(1983) Journal of Geotechnical Engineering, 109 (2), pp. 150-171. Cited 27 times.
13. Harder Jr., L.F., Stewart, J.P.
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(1996) Journal of Performance of Constructed Facilities, 10 (3), pp. 109-114. Cited 21 times.
14. Okusa, S., Anma, S.
Slope failures and tailings dam damage in the 1978 Izu-Ohshima-Kinkai earthquake
(1980) Engineering Geology, 16 (3-4), pp. 195-224. Cited 20 times.
15. Vick, S.G.
Tailings dam failure at Omai in Guyana
(1996) Mining Engineering, 48 (11), pp. 34-37. Cited 19 times.

16. Sammarco, O.
    A tragic disaster caused by the failure of tailings dams leads to the formation of the Stava 1985 foundation
    (2004) Mine Water and the Environment, 23 (2), pp. 91-95. Cited 16 times.
17. Robinsky, E.I.
    Tailings dam failures need not be disasters - the Thickened Tailings Disposal (TTD) system
    (1999) CIM Bulletin, 92 (1028), pp. 140-142. Cited 16 times.
18. Agurto-Detzel, H., Bianchi, M., Assumpção, M., Schimmel, M., Collaço, B., Ciardelli, C., Barbosa, J.R., Calhau, J.
    The tailings dam failure of 5 November 2015 in SE Brazil and its preceding seismic sequence
    (2016) Geophysical Research Letters, 43 (10), pp. 4929-4936. Cited 12 times.
19. Li, Q.-M., Zhang, X.-K., Wang, Y.-H., Zhang, B.-Y.
    Risk index system and evaluation model for failure of tailings dams
    (2009) Shuili Xuebao/Journal of Hydraulic Engineering, 40 (8), pp. 989-994. Cited 12 times.
20. Hatje, V., Pedreira, R.M.A., De Rezende, C.E., Schettini, C.A.F., De Souza, G.C., Marin, D.C., Hackspacher, P.C.
    The environmental impacts of one of the largest tailings dam failures worldwide
    (2017) Scientific Reports, 7 (1), art. no. 10706. Cited 11 times.

(tailings AND dam AND accident) in the TITLE-ABS-KEY [0 additional results]

(tailings AND dam AND disaster) in the TITLE-ABS-KEY [0 additional results]

(tailings AND dam AND spill) in the TITLE-ABS-KEY [2 additional results]

1. Hudson-Edwards, K.A., Macklin, M.G., Jamieson, H.E., Brewer, P.A., Coulthard, T.J., Howard, A.J., Turner, J.N.
   The impact of tailings dam spills and clean-up operations on sediment and water quality in river systems: The Ríos Agrio-Guadiamar, Aznalcóllar, Spain
   (2003) Applied Geochemistry, 18(2), pp. 221-239. Cited 88 times
2. Domènech, C., Ayora, C., De Pablo, J.
   Sludge weathering and mobility of contaminants in soil affected by the Aznalcollar tailings dam spill (SW Spain)
   (2002) Chemical Geology, 190(1-4), pp. 355-370. Cited 25 times

(tailings AND dam) in the TITLE-ABS-KEY [TOO MANY results]

Using this search term dozens of frequently cited papers come up. However, the results are broad, leading to cluttering of papers that are only remotely linked to the topic of tailings dams. Thus, more specific search terms are needed to find relevant literature.

(tailings AND dyke AND failure) in the TITLE-ABS-KEY [1 additional result]

1. Blight, G.E.
   Destructive mudflows as a consequence of tailings dyke failures
   (1997) Proceedings of the Institution of Civil Engineers: Geotechnical Engineering 125(1), pp. 9-18. Cited 41 times

(tailings AND dyke AND accident) in the TITLE-ABS-KEY [0 additional results]

(tailings AND dyke AND disaster) in the TITLE-ABS-KEY [0 additional results]

(tailings AND dyke AND spill) in the TITLE-ABS-KEY [0 additional results]

(tailings AND pond AND failure) in the TITLE-ABS-KEY [0 additional results]

(tailings AND pond AND accident) in the TITLE-ABS-KEY [1 additional result]

1. Pollution of soils by the toxic spill of a pyrite mine (Aznalcollar, Spain)
   Simón, M., Ortiz, I., García, I., (...), Dorronsoro, C., Aguilar, J.
   (1999) Science of the Total Environment, 242(1-3), pp. 105-115. Cited 142 times

(tailings AND pond AND disaster) in the TITLE-ABS-KEY [0 additional results]

(tailings AND pond AND spill) in the TITLE-ABS-KEY [0 additional results]

(tailings AND impoundment AND failure) in the TITLE-ABS-KEY [0 additional results]

(tailings AND impoundment AND accident) in the TITLE-ABS-KEY [0 additional results]

(tailings AND impoundment AND disaster) in the TITLE-ABS-KEY [1 additional result]

1. Petticrew, E.L., Albers, S.J., Baldwin, S.A., (...), Selbie, D.T., Vagle, S.
   The impact of a catastrophic mine tailings impoundment spill into one of North America's largest fjord lakes: Quesnel Lake, British Columbia, Canada
   (2015) Geophysical Research Letters, 42(9), pp. 3347-3355. Cited 13 times

(tailings AND impoundment AND spill) in the TITLE-ABS-KEY [1 additional result]

1. Grangeia, C., Ávila, P., Matias, M., da Silva, E.F.
   Mine tailings integrated investigations: The case of Rio tailings (Panasqueira Mine, Central Portugal)
   (2011) Engineering Geology, 123(4), pp. 359-372. Cited 19 times

(tailings AND failure) in the TITLE-ABS-KEY [2 additional results]

1. Davies, M.P.
   Tailings impoundment failures are geotechnical engineers listening?
   (2002) Geotechnical News 20(3), pp. 31. Cited 28 times
2. Fourie, A.
   Preventing catastrophic failures and mitigating environmental impacts of tailings storage facilities
   (2009) Procedia Earth and Planetary Science. 1(1), pp. 1067-1071. Cited 14 times

(tailings AND accident) in the TITLE-ABS-KEY [1 additional result]

1. Grimalt, J.O., Ferrer, M., MacPherson, E.
   The mine tailings accident in Aznalcollar
   (1999) Science of the Total Environment, 242(1-3), pp. 3-11. Cited 288 times

(tailings AND disaster) in the TITLE-ABS-KEY [0 additional results]

(tailings AND spill) in the TITLE-ABS-KEY [0 additional results]

(mine AND waste AND dump AND failure) in the TITLE-ABS-KEY [1 additional result]

1. Richard A. Shakesby, J. Richard Whitlow
   Failure of a mine waste dump in Zimbabwe: Causes and consequences
   (1991) September 1991, Volume 18, Issue 2, pp 143–153. Cited 27 times

(mine AND waste AND dump AND accident) in the TITLE-ABS-KEY [0 additional results]

(mine AND waste AND dump AND disaster) in the TITLE-ABS-KEY [1 additional result]

1. Blight, G.E., Fourie, A.B.
   Catastrophe revisited - Disastrous flow failures of mine and municipal solid waste
   (2005) Geotechnical and Geological Engineering, 23(3), pp. 219-248. Cited 34 times

(mine AND waste AND dump AND spill) in the TITLE-ABS-KEY [0 additional results]

(tailings AND storage AND facility AND failure) in the TITLE-ABS-KEY [1 additional result]

1. Wei, Z., Yin, G., Wang, J.G., Wan, L., Li, G.
   Design, construction and management of tailings storage facilities for surface disposal in China: Case studies of failures
   (2013) Waste Management and Research, 31(1), pp. 106-112. Cited 21 times

(tailings AND storage AND facility AND accident) in the TITLE-ABS-KEY [0 additional results]

(tailings AND storage AND facility AND disaster) in the TITLE-ABS-KEY [1 additional result]

1. Schoenberger, E.
   Environmentally sustainable mining: The case of tailings storage facilities
   (2016) Resources Policy, 49, pp. 119-128. Cited 25 times

(tailings AND storage AND facility AND spill) in the TITLE-ABS-KEY [0 additional results]