



**Geospatial Analysis and Overview of Tailings Storage Facilities in  
Kazakhstan: A Case Study of Varvara Tailings Storage Facility**

By

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## Originality Statement

I, Akbota Kairat, hereby affirm that this submission is my original work and, to the best of my knowledge, it does not include any materials previously published or authored by another individual, nor does it contain significant portions of material that have been accepted for the conferment of any other degree or diploma at Nazarbayev University or any other educational institution, except where appropriate acknowledgement is provided in the thesis.

All contributions to the research from collaborators at Nazarbayev University or other institutions are explicitly recognized in the thesis.

I declare that the intellectual content of this thesis is solely my own, save where support from others in the project's design, conception, style, presentation, or language expression is acknowledged

Signed on: 01.04.2025.

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## Abstract

Tailings Storage Facilities (TSFs) are essential to mining operations but pose ongoing environmental and structural risks. This study investigates the Varvara TSF in northern Kazakhstan using geospatial analysis of Sentinel-2 and Landsat 8 satellite imagery from 2019 to 2024. Spectral indices including NDWI, mNDWI, and NDVI were applied to detect changes in the supernatant water pond and wet tailings, both of which are critical indicators of facility stability. The results reveal a consistent expansion of the water pond, with its proximity to the dam infrastructure raising concerns, especially during spring flood events. The spatial extent of water and tailings was highly responsive to fluctuations in precipitation and temperature, highlighting the vulnerability of the facility to climatic variability. The study further critiques the limitations of traditional slurry-based tailings management under such environmental stressors. Despite improvements introduced after the 2016 dam incident, the findings emphasize the need for adaptive strategies, including real-time satellite monitoring, adoption of dewatered tailings technologies, and stronger containment measures. Additionally, the absence of a comprehensive national TSF inventory hampers effective risk governance in Kazakhstan. This research advocates for improved regulatory frameworks and sustained monitoring to ensure safer and more resilient tailings management.

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# 1. Introduction

The mining industry serves as a fundamental component of the global economy, supplying essential minerals required for diverse sectors such as construction, energy, and technology. Mining operations can indeed have significant environmental impacts, with one of the most challenging issues being the management of tailings — the waste generated from the extraction of valuable minerals. Tailings Storage Facilities (TSFs) are engineered to contain these byproducts; however, they frequently face significant failures that result in severe environmental consequences and disturb communities.

Recent studies highlight TSFs as major factors in mining disasters; catastrophic failures such as those in Brazil in 2015 and 2019 demonstrate the potential for extensive ecological harm and loss of life (Wang et al., 2022; Carneiro & Fourie, 2019). Improper management can lead to water pollution and habitat destruction, as hazardous substances from these facilities may be released into surrounding ecosystems (Cacciuttolo et al., 2023).

The growing expectation of sustainable practices has raised awareness regarding the necessity for enhanced tailings management strategies that prioritise environmental protection and community safety (Cacciuttolo & Atencio, 2022). In light of the increasing demand for minerals, the mining industry must confront its environmental legacy and adopt more responsible operational practices, carefully evaluating the risks associated with tailings and other mining activities (Vargas & Pulido, 2022).

## 1.1. Background Information

TSFs play a crucial role in the management of mine tailings, and the waste materials produced during ore processing. In Kazakhstan, the mining sector is a prominent industry, functioning as a cornerstone of the national economy, yet it also poses considerable environmental challenges. The primary approach to managing tailings consists of transporting them as slurries using hydraulic methods, which is preferred due to its cost-effectiveness. The slurries are subsequently placed in TSFs, specifically engineered to contain and stabilise the waste materials.

An exemplary instance of this type of facility is the Varvara TSF, managed by Solidcore Resources. Solidcore Resources (previously known as Polymetal JSC) is acknowledged for its

dedication to sustainable and safe mining practices; however, the dependence on traditional tailings storage techniques presents significant risks, such as the possibility of dam wall failures, seepage of hazards and overtopping events. The necessity for thorough monitoring and analysis of these facilities has grown significantly, especially considering the effects of climate change and extreme weather occurrences, like the floods that took place in northwestern Kazakhstan in spring 2024. These occurrences highlight the susceptibility of TSFs to shifts in environmental conditions and the imperative for flexible management approaches.

Geospatial analysis has developed into a significant method for evaluating alterations in TSFs over time, offering valuable insights into their structural integrity and environmental effects. This investigation centres on the Varvara TSF, with the objective of assessing its development from 2019 to 2024, particularly regarding the sedimentation pond and its vulnerability to external influences. By employing advanced remote sensing techniques, it is possible to monitor sedimentation patterns, assess the ecological health of surrounding areas, and inform better management practices to mitigate risks associated with tailings storage.

## **1.2. Problem Statement**

The conventional slurry method of tailings storage is more economical but presents two major hazards: dam overtopping and dam wall failure. The aforementioned risks are particularly significant for the Varvara TSF, which underpins the operations of the Varvara gold-copper mine in northern Kazakhstan, operated by Solidcore Resources. The mine is a crucial asset in the region and depends significantly on the TSF for the storage of tailings generated during ore processing. Established in the early 2000s, the facility is integral to the site's waste management operations. Nonetheless, its history of dam failure in 2016 and its location in a region susceptible to extreme weather events augment its susceptibility.

Recent floods in the Kostanay region in 2024 could put at risk the stability of TSFs due to climate-related disasters. Notwithstanding Solidcore's reputation for sustainable mining practices, the company's dependence on conventional TSFs underscores the imperative for comprehensive evaluations of these structures. A comprehensive geospatial analysis of Varvara TSF over a five-year duration can yield critical insights into the impact of these risks on the pond and its related infrastructure, along with recommendations for improved management strategies.

Moreover, there is a notable gap in studies addressing the structural stability, geotechnical design, and hydrological performance of TSFs in the country. Majority of the literature on TSFs in Kazakhstan is focused on the environmental concerns and ecological footprint of tailings. Therefore, limited attention has been given to the risks of overtopping, failure due to changing climatic conditions or operational pressures. This lack of research limits the development of proactive risk mitigation and monitoring strategies in Kazakhstan's mining sector.

### **1.3. Research Objectives**

This study seeks to answer the following research question: How have the spatial and hydrological characteristics of the Varvara Tailings Storage Facility evolved between 2019 and 2024, and what do these changes reveal about the facility's structural integrity, environmental vulnerability, and the effectiveness of current management practices under variable climatic and operational conditions in Kazakhstan?

Based on the this question, this study aims to achieve the following objectives:

- To conduct a detailed geospatial analysis of the sedimentation pond at the Varvara TSF during a five-year period (2019-2024), identifying spatial and temporal changes in structure and composition.
- To make an overview of TSFs in Kazakhstan to contextualize the case study within the broader landscape of tailings management challenges in Kazakhstan.
- To assess the production rates and their correlation with the TSF dynamics for the study period.
- To evaluate the influence of unstable weather conditions, specifically fluctuations in precipitation, temperature and water level changes, on the TSF and its supernatant process water pond, with an emphasis on critical hydrological and environmental consequences.
- To create concrete recommendations for improving the safety, efficiency, and sustainability of tailings management methods at the Varvara site, while aligning them with current industry standards and best practices applied around the world.

## 1.4. Scope of Work

This research examines the spatial and temporal dynamics of the Varvara TSF in Kazakhstan from 2016 to 2024. The study seeks to evaluate surface alterations in wet tailings and supernatant water ponds utilizing remote sensing methods, particularly through the examination of Sentinel-2 and Landsat-8 satellite imagery. The research additionally integrates hydrological and meteorological data, such as precipitation, temperature, and river water levels, to investigate relationships between environmental variables and TSF behavior over time.

This study encompasses a national overview of TSFs in Kazakhstan, derived from a 2021 mapping endeavor by the United Nations Economic Commission for Europe (UNECE), in addition to site-level analysis, to position the Varvara case study within the broader framework of national tailings management practices and trends

The scope includes assessing the Varvara TSF's design, water management, structural integrity, and environmental monitoring, utilizing data from independent audit reports and company disclosures. However, the study does not include geotechnical modeling, tailings composition analysis, or financial evaluation of tailings management practices. Chemical pollution is recognized but not prioritized; the focus is on physical stability, hydrological interactions, and monitoring TSF dynamics using remote sensing.

## 2. Literature Review

### 2.1 What are tailings?

The mining industry is closely associated with environmental changes that may be inherently destructive. Substantial volumes of soil and rock are excavated, with a portion treated to extract valuable minerals, while the remainder is deemed waste and abandoned. This waste left after the processing is known as tailings. Having low economic value, tailings are the residual byproducts or waste materials left over after the extraction of valuable minerals and metals from ore in mining and mineral processing. Depending on the mining operation, the minerals extracted, and the techniques used, tailings - which comprise finely crushed rock particles, water, and residual chemicals from the extraction process - may vary greatly (Lottermoser, 2010; Spitz & Trudinger, 2019). It is known that the volume of tailings produced by mines mirrors the volume of raw material processed. This statement is explained by the fact that the volume of waste produced constitutes around 97–99% of the entire ore processed. The generated concentrate, in turn, constitutes only about 1–3 percent (Adiansyah et al., 2015). On a global scale, tailings are produced at a projected rate of 5 to 14 billion tonnes each year (Schoenberger, 2016). Moreover, according to some studies, the mining sector is the largest generator of waste globally, yielding over 65 billion tonnes per year (Jones & Boger, 2012). Consequently, it is essential to acknowledge that waste materials and tailings are a matter of critical importance and constitute the primary sources of environmental risks associated with the mining industry.

### 2.2. How are tailings generated?

Tailings are produced in the mining sector as a byproduct of the extraction of valuable minerals from ore. The process encompasses multiple critical steps, each contributing to the creation and management of tailings. The following is a comprehensive description of the process by which tailings are produced, encompassing the phases from excavation to deposition (inspired by the MB GeoTech's (2022) video lecture):



Figure 1. Stages of the tailings production process (MB GeoTech, 2022)

**1. Excavation**

Excavation constitutes the initial phase of mining, during which ore is taken from the earth. Excavation does not immediately produce tailings; rather, it prepares the raw material (ore) that will ultimately yield tailings following subsequent processing. The ore is conveyed to processing facilities for later phases. The primary goal of excavation is to recover ore, but waste materials (overburden, non-valuable rock) begin to accumulate. The quantity of ore extracted directly affects the volume of tailings produced afterwards. Extensive mining operations, particularly in copper and gold extraction, can produce several hundred thousand tonnes of ore daily, resulting in comparable quantities of tailings (Lottermoser, 2007; Blight, 2010; Mudd, 2007).

**2. Crushing**

Subsequent to extraction, the ore is subjected to crushing, which diminishes it to smaller, simpler-to-handle fragments. The main objective, as in almost all of the mining process, is to extract the valuable minerals from the adjacent rock. This phase employs crushers, such as jaw crushers, cone crushers, or gyratory crushers, to fragment the ore into smaller pieces. Crushing produces waste consisting of fine particles and large fragments. While the majority of the material remains classified as ore at this juncture, the procedure facilitates the production of material that will ultimately constitute the tailings after the

extraction of valuable minerals. Crushing is an energy-demanding process, and the efficiency of this phase directly influences the size and properties of the subsequently produced tailings. The finer the material, the more prone it is to producing tailings during later processing.

### **3. Grinding**

After crushing, grinding is the next most important step in separating the useful minerals from the unwanted gangue. In order to separate minerals effectively in subsequent stages, grinding mills (such as ball mills and SAG mills) grind the ore into a fine slurry. The effectiveness of the procedure dictates the quantity of ore that can be treated and the amount of energy used. After crushing, the material is ground into a slurry that includes both valuable minerals and non-valuable gangue. Tailings are generated at a higher rate with finer grinding. The majority of the tailings are physically produced during the grinding process, which separates the desired minerals from the waste rock and gangue. Sophisticated tailings storage methods are necessary for the management of fine-grained tailings because of their increased water content and smaller particle size.

### **4. Concentration & Separation**

In order to recover important minerals, the finely powdered slurry is subjected to concentration and separation processes. Some common approaches are:

- Flotation, which involves using chemical reagents and air bubbles to separate precious minerals from waste (Ritcey, 2005);
- Leaching is where chemicals such as cyanide or sulphuric acid are used to dissolve the target metals (e.g., gold or copper), leaving behind waste (Hudson-Edwards et al., 2011).

At this point, the valuable concentrate (ranging from 1-3%) is separated from the tailings, which are significantly bigger in volume.

### **5. Thickening**

Thickening is the process that decreases the water content of tailings before disposal, minimizes the volume of slurry to be managed, and enhances water recovery. In extensive thickeners, solid particles precipitate to the base while water is extracted and reused. Paste and thickened tailings constitute a highly concentrated slurry (70 wt%), typically derived from the dewatering of normal 20–30 wt% tailings slurry. Dewatering

significantly influences the thickening efficacy of tailings slurry. Following thickening, tailings continue to possess a significant moisture content, although the volume of free water is reduced. This facilitates the management of tailings during transportation and deposition.

The water extracted during thickening is repurposed in the mining process, enhancing water efficiency and mitigating environmental effects.

## **6. Transport**

Tailings are conveyed to their ultimate storage sites by diverse methods based on their characteristics and site conditions. The physical characteristics of the tailings, including particle size and moisture content, affect the transportation technique. Prevalent techniques encompass ([Tailings.info](#), n.d.):

Slurry Transportation:

- Pumped Pipeline Systems that employ centrifugal or positive displacement pumps.
- Gravitational Pressure Systems: Employs gravity when the storage location is situated below the processing facility, occasionally requiring energy dissipation strategies.
- Channel Launder Systems: Concrete channels designed for low-density slurries, inappropriate for high-density tailings.

Moist Cake (Filtered Tailings):

- Conveyors: Utilised for the conveyance of tailings containing less than 18% moisture to dry stack plants. Available options comprise plough systems and radial stackers.
- Trucks: Appropriate for low-tonnage tasks or challenging terrains.

Transport does not produce tailings but is an essential operational phase in their management. The physical attributes of tailings, particularly particle size and moisture content, affect the energy and infrastructure required for their safe transportation.

## 7. Deposition

Deposition entails the placement of tailings in TSFs for extended storage which includes extensive surface impoundments known as tailings dams. The impoundments function as specialised sedimentation lagoons designed to capture fine-grained waste leftovers and spent process water (Lottermoser, 2007). The characteristics and significance of TSFs will be examined in the following section.

### 2.3. How are tailings handled?

Tailings management includes several strategies, including containment in constructed dams, dry stacking, backfilling, and alternative alternatives such as marine or riverine disposal and recycling. Each approach differs regarding expense, environmental danger, water consumption, and storage capacity (Lottermoser, 2007; Kossoff et al., 2014).

The predominant method is the utilization of tailings dams, where slurry is deposited to settle, permitting the reclamation of water for reuse. Thickened or paste tailings serve as alternatives that diminish water content, enhance stability, and minimize spatial requirements. Backfilling transfers tailings into excavated voids to reinforce subterranean structures, while antiquated methods such as riverine and marine disposal are predominantly discontinued because of their significant ecological repercussions. Recycling tailings into construction materials presents possible environmental and economic advantages, although it is not viable for all varieties.

A comprehensive evaluation of various strategies, encompassing mechanisms, advantages, and limits, is presented in **Table 1** according to Lottermoser (2007):

**Table 1.** Summary of various tailings management and storage methods (recreated after Lottermoser, 2007)

Method	General Description	Tailings Storage Mechanism	Advantages	Disadvantages	Source
Tailings Dams	Large impoundments that store tailings as slurry in surface	Tailings settle as solids in the dam; water evaporates or is recycled.	- Large storage capacity - Can accommodate huge amounts of waste - Recycles water	- Risk of catastrophic dam failures - High environmental risk from leaks	Lottermoser, 2007

	facilities.			- Expensive to maintain
Thickened Discharge	Tailings are thickened (usually to 40–70% solids) to reduce water content before disposal.	Spread in layers; less water to manage than slurry.	<ul style="list-style-type: none"> <li>- Smaller land footprint</li> <li>- Reduced water usage</li> <li>- Improved stability</li> <li>- Good for water-scarce regions</li> </ul>	<ul style="list-style-type: none"> <li>- Pipe blockage risk</li> <li>- Pipe corrosion and leakage</li> <li>- Expensive equipment required</li> <li>- Liquefaction risk in seismic areas</li> </ul>
Dry Stacking	Tailings are mechanically dewatered (filtered) to produce a dry, stackable material.	Stacked on a lined, engineered surface without forming a pond or dam.	<ul style="list-style-type: none"> <li>- No need for dam structure</li> <li>- Minimal water content</li> <li>- High geotechnical stability</li> <li>- Good for arid regions with small winds</li> </ul>	<ul style="list-style-type: none"> <li>- High capital cost (filters, transport systems)</li> <li>- Dust control required</li> <li>- Less suitable for high-tonnage or fine tailings</li> <li>- Wind erosion of fine particles</li> <li>- Dust generation</li> </ul>
Backfilling	Tailings are placed back into mined-out areas such as underground voids.	Pumped or placed into underground stopes or pits, often mixed with cement.	<ul style="list-style-type: none"> <li>- Minimizes surface impact</li> <li>- Helps stabilize underground workings</li> <li>- Reduces tailings on the surface</li> </ul>	<ul style="list-style-type: none"> <li>- Expensive</li> <li>- Limited capacity (only handles some tailings)</li> <li>- Potential groundwater contamination</li> </ul>
Riverine and Lacustrine Disposal	Tailings are discharged directly into rivers or lakes.	Tailings are carried downstream, settling based on particle size.	<ul style="list-style-type: none"> <li>- Low initial cost</li> <li>- Suitable for remote locations</li> </ul>	<ul style="list-style-type: none"> <li>- Severe environmental damage to rivers/lakes</li> <li>- Long-term ecological harm</li> <li>- Banned in many countries due to environmental risks</li> </ul>
Marine Disposal	Tailings are discharged into the deep sea (below biologically active zones).	Settles on the ocean floor, reducing interaction with marine ecosystems.	<ul style="list-style-type: none"> <li>- Minimal oxidation (no acid mine drainage)</li> <li>- Saves land space</li> </ul>	<ul style="list-style-type: none"> <li>- Potential long-term harm to deep-sea ecosystems</li> <li>- Strict regulations</li> <li>- Difficult to monitor</li> </ul>

Recycling	Tailings are repurposed into other products like construction materials.	Tailings are processed and used in industrial applications.	<ul style="list-style-type: none"> <li>- Reduces waste</li> <li>- Generates additional revenue</li> <li>- Lowers environmental footprint</li> </ul>	<ul style="list-style-type: none"> <li>- Not all tailings can be recycled</li> <li>- Requires additional processing and investment</li> <li>- May not always be cost-effective</li> </ul>	
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### 2.4. Tailing Storage Facilities

The data in [Table 1](#) demonstrate that tailings management approaches may be classified into two main categories. The initial category, encompassing tailings dams, thickening discharge, and backfilling, is predominantly concerned with waste storage, known as Tailing Storage Facilities (TSFs). The second group, consisting of riverine and lacustrine disposal, marine disposal, and recycling, tackles waste management by disposal or transformation into diverse byproducts. Currently, the first method of the first category is most common worldwide, especially among major companies in the developed world; the buildings that come out of it are usually called "tailings ponds" or "tailings dams" ([Kossoff et al., 2014](#)). TSFs are typically covered with water to prevent dust formation and acid mine drainage by reducing oxidation. This can lead to the misconception that TSFs function like conventional water dams. However, the key distinction is that TSFs are designed to store waste from mining operations, while water dams are built to store and regulate water. Additionally, TSFs are dynamic structures that expand over time to accommodate more tailings, unlike water dams, which are generally built in a single phase. The construction materials also differ: TSFs are usually made from mine waste such as earth and rock, while water dams can be constructed from earth, rock, concrete, and other materials ([What Are Tailings Storage Facilities | BHP, n.d.](#)).

As it was mentioned above, tailings dams are generally built with locally sourced materials, in contrast to water-retention dams that frequently utilize concrete. The initial dam segment is often constructed using locally obtained soil; however, waste rock and tailings are also commonly applied in the construction process. Rather than constructing the structure to its full capacity initially, interim retaining embankments are erected and elevated as storage requirements grow.

Upon completion of the original structure, the embankments may be elevated utilising one of three techniques: upstream, vertical (center-line), or downstream. In upstream raising, additional material is incorporated into the existing dam, whereas centerline raising entails placing material right atop the current embankment. Downstream raising, conversely, entails the incorporation of additional material beyond the impoundment. Among these approaches, upstream raising is the most economical, as it necessitates fewer construction materials (Kossoff et al., 2014; Lottermoser, 2007). The key differences between these embankment types are shown below in **Table 2:**

**Table 2.** Essential differences between the three types of tailings embankment raising method

Type of Embankment	Description	Material Placement	Economics	Typical Use	Sources
Upstream Raising	Additional material is added to the existing dam.	Added material is incorporated into the dam.	Most economical; requires fewer materials.	Suitable for areas where space is limited upstream.	Kossoff et al., 2014; Lottermoser, 2007; MB GeoTech, 2022; What Are Tailings Storage Facilities   BHP, n.d.
Vertical (Center-Line) Raising	Material is placed directly on top of the current embankment.	Material is stacked vertically on the embankment.	Moderate cost; depends on existing structure.	Often used when stability is a concern.	
Downstream Raising	Additional material is placed beyond the impoundment.	Material is added further away from the embankment.	Typically more expensive due to greater material needs.	Used when increased stability is needed, or space permits.	

The selection of embankment elevation technique is contingent upon site factors and financial constraints. Upstream is the most cost-effective option, ideal for constrained resources or scarce materials. Centerline provides a compromise between stability and space, whereas downstream - albeit costlier - is favored when optimal stability and extensive space are accessible. Each method possesses distinct advantages and should be chosen according to the individual requirements of the project.

## 2.5. Analysis of common TSF failures and their causes

TSF failures are complicated, multilayered phenomena influenced by a variety of design, operational, regulatory, and environmental variables. While various failure mechanisms exist, they all share a similar thread: governance failings, which are frequently compounded by external conditions and internal technical flaws. The following is a detailed summary of failure causes based on key literature.

### 1. Governance and regulatory failures.

According to the [Global Tailings Review \(2020\)](#), operational and regulatory governance shortcomings are major factors in TSF events. Inadequate monitoring of key performance metrics required for safe facility management frequently results in failure. Inadequate regulatory enforcement, poor operator training, and failures to account for increasing environmental or operational hazards are examples of governance failings. Even the most well-designed TSFs cannot substitute for ongoing mismanagement and a lack of control.

### 2. Overtopping

Overtopping is one of the most catastrophic failure modes, which occurs when a TSF's water storage capacity is exceeded owing to severe storms, quick snowmelt, or operational disruptions. Without proper spillways, water overflows the embankment, causing significant erosion and potentially precipitating a complete collapse. [Davies \(2002\)](#) observed that overtopping is the predominant failure mode for inactive TSFs, but [Rico et al. \(2008\)](#) ascribed around 25-35% of global TSF failures to extreme weather events, a risk worsened by climate change. Historical instances, such as the 2000 Baia Mare spill in Romania, demonstrate overtopping's severe implications, which include poisoning of streams and downstream ecosystems. Overtopping happens when water surpasses a dam's design capacity, causing erosion of the dam's crest and eventual failure. This scenario is commonly worsened by extreme weather events, such as excessive rainfall or rapid snowmelt, which can overwhelm the dam's capacity to handle inflows. According to research, the most prevalent cause of dam breaches is overtopping by excess water, which can erode the downstream slope and result in catastrophic failures ([Stastka et al., 2018](#); [Chovan et al., 2021](#)). The Sermo Dam case study exemplifies this issue, as excessive precipitation played a substantial role in the dam's failure ([Sumira, 2023](#)). Furthermore, the risk

of overtopping is increased in TSFs due to their frequently unpredictable and poorly controlled water levels, demanding strong monitoring and management techniques to prevent such incidents (Cacciuttolo & Cano, 2023).

### **3. Foundation Failures.**

Weak or unstable soil and rock foundations under TSFs pose severe vulnerabilities. According to [Global Tailings Review \(2020\)](#) and [Lottremoser \(2007\)](#), incorrect geotechnical estimates of the foundation's load-bearing capacity frequently result in structural instability. This failure mode is especially important in facilities subjected to high pressures from embankment weight or rapid dam rises, as demonstrated in the 1998 Los Frailes event in Spain.

### **4. Piping and seepage.**

Excessive seepage through the embankment or foundation might cause internal erosion known as piping. This process causes cavities in the structure, compromising its integrity and potentially resulting in rapid, uncontrolled tailings releases. While piping is more typical in water reservoirs, it has also been observed in TSF failures. [Kossoff et al. \(2014\)](#) demonstrated how insufficient seepage control measures aggravate this risk, as erosion impairs structural integrity.

### **5. Slope failures and liquefaction.**

Slope instability is a common cause of TSF collapses, especially in plants that use tailings for embankment building. According to the [Global Tailings Review \(2020\)](#) and [Lottremoser \(2007\)](#), slope failures occur because of insufficient compaction or material strength. In rare circumstances, saturated tailings experience liquefaction, a sudden loss of strength caused by dynamic forces like earthquakes, mine blasting, or heavy machine vibrations. The 1985 Veta de Agua failure in Chile, as well as other comparable instances, demonstrate how seismic liquefaction may transform stable structures into catastrophic risks.

### **6. Rapid Dam Raising**

Raising the height of upstream dams too soon causes significant internal pore pressures, reducing structural stability. [Lottremoser \(2007\)](#) gave an example of the 1980 Tyrone dam catastrophe in the United States, in which rushed dam construction resulted in collapse. This failure scenario

emphasises the dangers associated with operational haste and insufficient hydrological modelling.

### **7. Seismic Activity & Earthquakes**

Seismic occurrences greatly increase shear stress and pore pressure within TSFs, frequently resulting in liquefaction or slope failure. [Davies and Martin \(2009\)](#) recorded over 100 upstream tailings dam breaches induced by seismic activity, emphasising the importance of strong geotechnical design and site-specific seismic hazard evaluations.

### **8. Extreme meteorological events.**

Unusual rainfall, snowmelt, and flooding are increasingly being recognised as key causes of TSF instability. [Rico et al. \(2008\)](#) discovered that extreme weather events cause a considerable number of failures, particularly in locations with shifting climatic trends. Poor water management methods, such as failing to maintain appropriate freeboard or installing diversion canals, amplify the effects of extreme occurrences.

### **9. Inactive TSFs**

Abandoned and inactive tailing dams with poor maintenance are more prone to overtopping, seepage, and erosion. [Kossoff et al. \(2014\)](#) highlighted the stabilising impact of spontaneous cementation in inactive impoundments, which increases resistance to liquefaction over time. However, previous instances demonstrate that abandoned structures that have not been maintained are disproportionately vulnerable to collapse.

### **10. Structural and operational deficiencies**

Structural failures due to design defects, combined with operating shortcomings such as insufficient water balance control, are common causes of TSF occurrences. [The Global Tailings Review \(2020\)](#) stated that even well-designed TSFs are susceptible if operations do not adjust to changing conditions, such as increased tailings volumes or water inputs.

## 11. Dam Wall Failure

Dam wall failure can be caused by a variety of factors, including internal erosion, structural deficiencies, and external stresses like seismic activity. Internal erosion, often known as piping, is a significant failure mechanism in dams in which water travels into the structure, degrading materials and potentially causing collapse. According to studies, piping accounts for around 31% of dam collapse, emphasising the significance of adequate seepage control techniques (Adams et al., 2012). Furthermore, phenomena such as differential settlement and wetness deformation might impair the dam wall's structural integrity, resulting in cracks and seepage paths (Zhou et al., 2022).

In conclusion, failures of TSFs arise from a confluence of elements, significantly affected by external conditions including meteorological events, engineering difficulties, and human error. Due to the potentially grave repercussions of such failures for all stakeholders, mining corporations must prioritise preventive actions. Allocating time, money, and effort towards thorough planning and risk mitigation techniques is significantly more advantageous than responding to the human, environmental, and financial consequences that arise after a failure.

## 2.6. Best Practices and Global Standards in Tailings Management

Efficient tailings management is fundamental to sustainable mining practices, especially in light of increasing governmental oversight and elevated societal demands for environmental stewardship and corporate social responsibility. The International Council on Mining and Metals (ICMM) has established extensive global standards and recommendations that prioritize a life-cycle approach to TSFs, assuring safety, environmental sustainability, and social responsibility (ICMM, 2025). These standards emphasize essential elements including site selection, design optimization, operational controls, risk assessment, and closure planning, all of which mitigate the probability of catastrophic failures (Franks et al., 2021).

The basis of ICMM's Global Industry Standard on Tailings Management (GISTM) is the mitigation hierarchy, which prioritizes risk reduction through tailings volume minimization, enhanced storage methods, and ongoing monitoring (Adiansyah et al., 2015). The

implementation of optimal engineering practices - such as filtered tailings, paste backfilling, and dry stacking - has demonstrated success in mitigating the likelihood of tailings dam failures, while simultaneously improving water recovery and diminishing environmental contamination hazards (Blight, 2022).

The Environmental and Social Impact Assessment (ESIA) approach is a fundamental element of contemporary tailings management. The ESIA framework is intended to comprehensively assess, forecast, and alleviate the environmental and socio-economic effects linked to TSF development (Cacciuttolo & Atencio, 2022). An effectively executed ESIA incorporates stakeholder consultations, guaranteeing transparency, accountability, and conformity with community expectations (Bainton & Holcombe, 2018). In addition to regulatory compliance, Environmental and Social Impact Assessments (ESIAs) assist mining corporations in preserving their social license to operate (SLO) by integrating indigenous knowledge, resolving public apprehensions, and enhancing long-term community ties (Owen et al., 2020).

Optimal practices in TSF management also encompass the implementation of sophisticated tailings disposal techniques. Thickened Tailings Disposal (TTD) and Dry Stacking have been extensively adopted in arid regions like Chile, Australia, and South Africa to improve water conservation, minimize dam footprint, and alleviate the hazards associated with dam failures (Cacciuttolo & Pulido, 2022). Responsible mining companies are increasingly favoring these alternative technologies, despite their higher capital intensity, due to their improved geotechnical stability and environmental resilience.

Moreover, periodic performance assessments and independent audits are essential for facilitating adaptive management and continual enhancements in TSF safety requirements. The ICMM framework requires consistent risk evaluations, continuous monitoring, and regular third-party audits to improve openness and accountability (ICMM, 2025). Progress in remote sensing technology, geospatial data analysis, and machine learning applications has enhanced the capacity to identify early indicators of tailings dam instability, so aiding in the prevention of probable failures before they develop into disasters (Franks et al., 2021).

In conclusion, the incorporation of optimal techniques and internationally acknowledged standards in tailings management is crucial for guaranteeing the sustainable and responsible operation of the mining industry. Mining businesses may mitigate ecological degradation, maintain safety standards, and cultivate trust with local populations by adopting ICMM-aligned frameworks, employing novel disposal methods, and completing thorough environmental and social impact assessments. As regulatory frameworks grow, connecting industry practices with scientific progress and international standards will be crucial in developing a resilient and environmentally sustainable mining sector.

## 2.7. Previous Researches on TSFs in Kazakhstan

In the last twenty years, Kazakhstan's mining sector has undergone substantial expansion, propelled by increased exploitation of key resources including uranium and several base and rare metals. This development has significantly enhanced the country's economic progress, yet it has also highlighted concerns regarding the environmental and operational sustainability of mining practices, especially in relation to the management of TSFs ([Atakhanova & Azhibay, 2023](#); [Atakhanova et al., 2024](#)). A significant segment of the current study on TSFs in Kazakhstan concentrates on the environmental repercussions of mining activities, particularly the pollution of soil and water in areas impacted by both historical and continuing extraction operations. Uranium tailings in Northern Kazakhstan exhibit heightened levels of toxic compounds, including arsenic, radium, and uranium, which pose a considerable risk to adjacent aquifers and ecosystems ([Nygymanova et al., 2021](#); [Baubekova et al., 2021](#)).

Comparable problems have been observed in Southern Kazakhstan, where remnants from a former lead smelting facility have resulted in extensive dissemination of heavy metals - specifically lead, cadmium, and zinc - into the tailings and neighboring soils, significantly affecting the local environment ([Toishimanov et al., 2023](#)). The threat transcends local limits, exemplified by the 1964 Ak-Tyuz Mine disaster, in which seismic activity instigated a disastrous tailings spill that polluted rivers flowing into Kazakhstan, thereby underscoring the transboundary and enduring consequences of TSF mismanagement ([Severinenko et al., 2023](#)). The ramifications of this contamination are both ecological and socio-economic, impacting

public health and agriculture. Research indicates that the buildup of heavy metals in agricultural soils jeopardizes food safety, diminishes agricultural output, and endangers biodiversity (Zhyrgalova et al., 2024; Zhang et al., 2019).

Although the environmental dimensions of tailings management are thoroughly examined in the literature, a notable deficiency in study pertains to the stability and structural integrity of TSFs in Kazakhstan. Limited research offers a comprehensive assessment of TSF design resilience, geotechnical reliability, hydrological load responses, or long-term capacity management. The absence of such studies creates a significant gap in the comprehension of TSF safety, particularly regarding climate change, heightened precipitation variability, and the escalating risk of overflow or dam failure. In a nation with a history of perilous tailings and escalating mining operations, the lack of stability-oriented research constrains stakeholders' capacity to execute predictive maintenance plans and risk mitigation frameworks.

This study on the Varvara TSF aims to fill this gap by analyzing the geographical and environmental dynamics of the facility, as well as its hydrological balance, structural design characteristics, and adherence to optimal TSF management standards. This study employs remote sensing, climatic data analysis, and geospatial modeling to enhance the assessment of tailings facilities in Kazakhstan, providing insights that are presently underrepresented in the literature.

## 3. Case Study: Varvara Mining Site and TSF

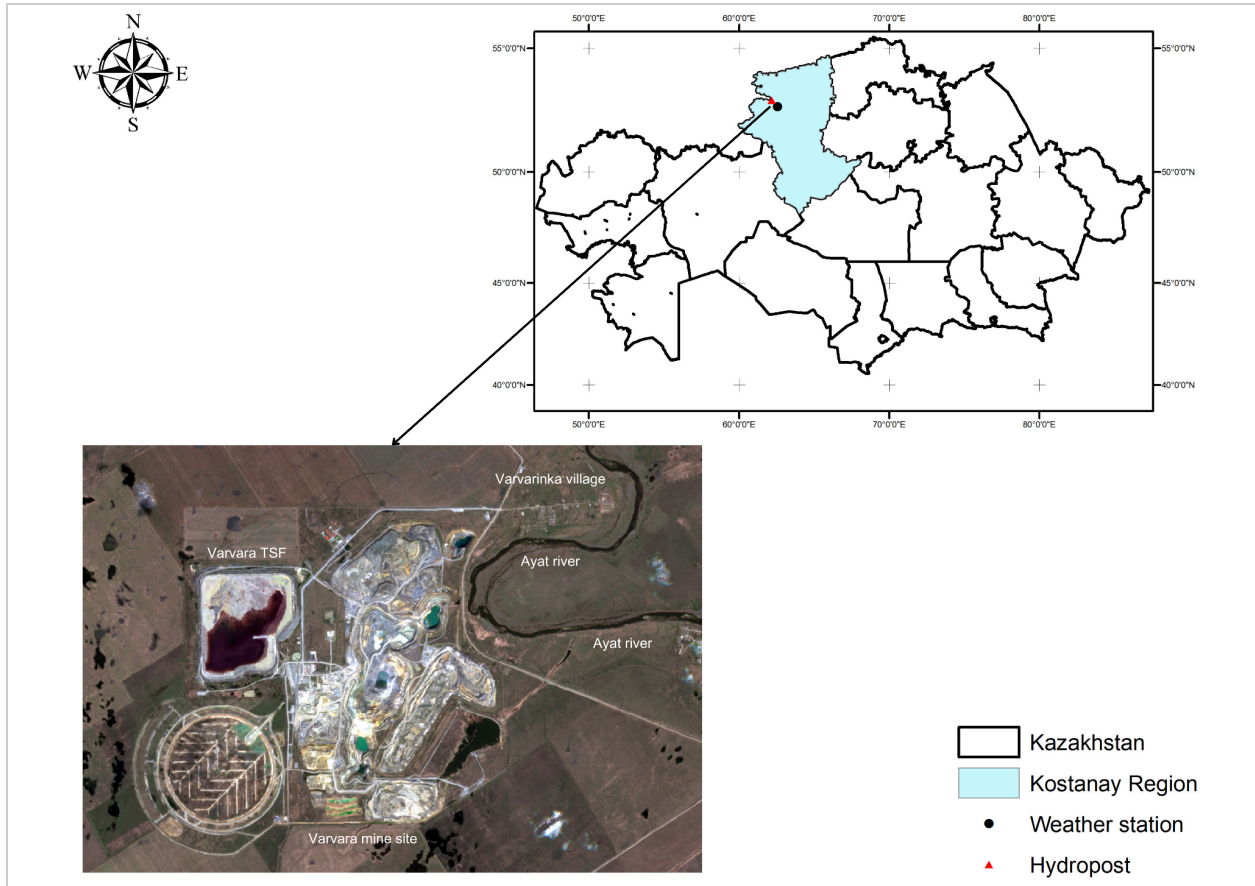
### 3.1. Study Area and Background

**Table 3** below highlights the primary geographical, operational, and production-related characteristics of the Varvara and Komar mining operations, both entirely owned by Solidcore Resources. These values represent the latest data available as of 2023, encompassing production output, resource estimations, and anticipated mine lifespan (Solidcore Resources, 2024).

**Table 3.** Key Operational and Resource Characteristics of the Varvara Mine Site (Solidcore Resources, 2024)

Category	Details
Geographical Area	Kostanay Region, Kazakhstan, N 52°57'26", E 62°07'23"
Ownership	Entirely owned by Solidcore Resources
Operations	Includes the Varvara and Komar mines
Mining and Processing	Open-pit mining; 3.2 Mtpa leaching (gold ore), 1.0 Mtpa flotation (copper ore)
Resources and Reserves	2.0 million oz Au eq reserves (1.2 g/t); 1.0 million oz Au eq resources (1.5 g/t)
Employee Count	1,410 (as of 2023)
2023 Production Data	169 Koz Au eq; 2.8 Mt ore mined; \$1,189 cash cost/oz Au eq
Mine Life	Expected to continue until 2042 (Solidcore Resources, 2024)

The composite image below in **Figure 2** depicts the spatial view of Varvara mine site with TSF, the neighboring Varvarinka village, and the proximate Ayat River, acquired from Sentinel-2 satellite data from Google Earth Engine. The upper inset map locates the site within Kazakhstan, emphasizing the Kostanay Region in blue. A red triangle designates the hydrological post on the Ayat River, while a black circle signifies the Tobol weather station; both were obtained from KazHydroMet’s hydrological and meteorological databases. These stations supply critical meteorological and hydrological data, which are subsequently utilized to examine and correlate environmental dynamics surrounding the TSF. The administrative boundaries of Kazakhstan were sourced from the AmeriGEOSS dataset (USGEO, 2023).



**Figure 2.** Spatial view of Varvara Mining Site ([Google Earth Engine](#))

### 3.2. Historical Background

The Varvara deposit, identified in 1981, is situated within the Urals Fold Belt. Mining commenced in 2006, following its initial development by European Minerals Corporation, with the processing plant becoming operational in 2007. In 2009, Solidcore Resources acquired the asset and commenced a turnaround strategy that encompassed revised mine design, enhanced extraction methodologies, and superior grade control.

In 2016, Solidcore purchased the Komarovskoye deposit for \$100 million to provide high-grade open-pit ore for the Varvara processing hub, substituting lower-grade feedstock and augmenting yearly gold production by about 70 Koz at diminished cash costs ([Solidcore Resources, 2024](#)).

### 3.3. Ecological Context

The Varvara and Komar sites are situated in the Kostanay region, distinguished by its level topography, many rivers, and more than 5,000 lakes (Figure 2). The nearest river to Varvara is the Ayat, about 7 kilometres distant. The region encompasses many ecosystems, comprising pine woods, grasslands, and shrublands. The climate of the region is continental, with temperatures varying from -30°C in winter to 30°C in summer, with annual precipitation ranging from 240 to 350 mm (Blackmore, 2022).

### 3.4. Geological and Mineralogical Processes

The Varvara deposit features intricate gold-copper skarn mineralisation inside fault zones. Chalcopyrite and bornite are the principal copper minerals, but gold exists both in its native state and within sulphide compounds. Mineralisation is categorised into four distinct types:

- Primary gold (low copper): Leach the ore.
- Primary copper-gold: Float ore.
- Oxide gold (low copper): Leach the ore.
- Copper-gold oxide: Currently stockpiled.

Mineralisation in Komarovskoye is found along fault zones characterised by steeply dipping quartz-carbonate metasomatites. The deposit exhibits low-sulfide quartz gold mineralisation with an oxidation depth ranging from 30 to 50 meters (Solidcore Resources, 2024).

### 3.5. Mining Operations

The gold extraction process, depicted in Figure 3 as a block flow diagram, follows a straightforward approach that utilizes cyanide for gold recovery. The cyanide used on-site is procured through a certified supply chain (Blackmore, 2022).

Mining operations at Varvara and Komar utilise traditional open-pit truck-shovel and drill-and-blast techniques. The existing life-of-mine plan is projected to continue until 2042, with possible extensions contingent upon exploration and pit expansion. Varvara's processing facility functions with two circuits:

- Leach Circuit: Processes ore containing less than 0.2% copper, yielding gold doré by carbon-in-leach (CIL) methodology. Capacity: 3.2 million tonnes per year.
- Flotation Circuit: Processes ore containing more than 0.2% copper, yielding a gold-copper concentrate. Capacity: 1.0 million tonnes per annum.

The facility additionally processes third-party gold quartz-sulfide ore to enhance capacity utilisation (Blackmore, 2022; Solidcore Resources, 2024).

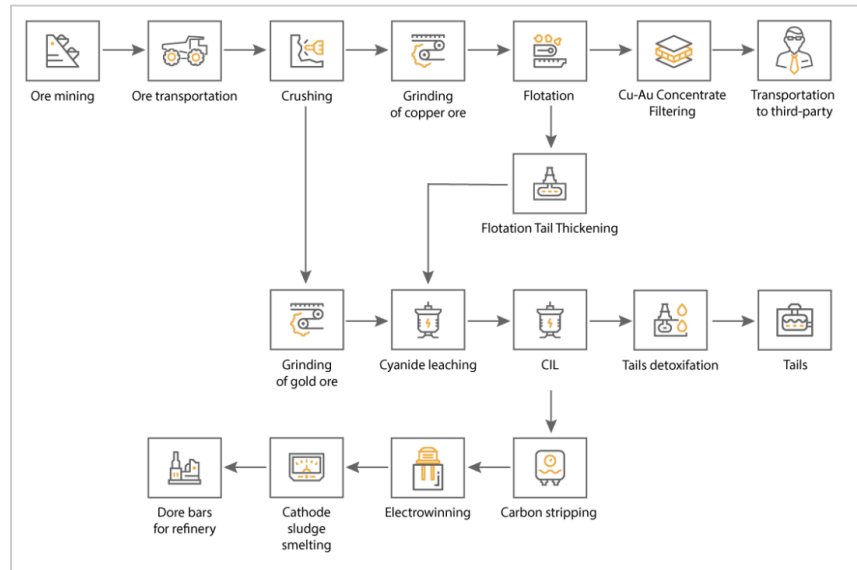


Figure 3. Varvara Block Flow Diagram for Flotation and Leaching Circuit (Blackmore, 2022)

### 3.6. The source of tailings and environmental risks

Tailings at the Varvara TSF are the outcome of cyanide-based leaching and flotation of gold-copper ores. The presence of sulfide minerals such as chalcopyrite and bornite in the tailings raises the risk of acid production and heavy metal leaching under oxidizing conditions, potentially leading to acid mine drainage (AMD). If not controlled effectively, this geochemical process has the potential to mobilize hazardous metals and pose long-term hazards to groundwater quality. Cyanide utilized in processing is managed in accordance with the International Cyanide Management Code, with detoxification lowering WAD cyanide levels to less than 0.5 mg/L before tailings disposal. While no cyanide is discharged into surface water, the possibility of groundwater contamination is reduced through HDPE liner, return water circuits, and regular borehole monitoring. In accordance with Kazakhstan's subsoil and

environmental legislation, a liquidation plan has been implemented, which includes equipment detoxification and the safe disposal of cyanide-contaminated materials (Blackmore, 2022).

### **3.7. Geotechnical Considerations and Structural Stability of the TSF**

The Varvara TSF is constructed as a ring-dyke embankment raised in six stages. Initially, the dam was raised using the upstream method, with each phase built partially on previously deposited tailings. However, following a structural incident, the design was revised in 2017 to implement a downstream raising approach, which provides enhanced stability by placing new embankment material on undisturbed foundations.

A critical geotechnical factor influencing the facility's stability is the use of fine-grained local materials - primarily loam and soil - as embankment fill. These materials possess relatively low shear strength and higher susceptibility to erosion and deformation compared to rock-fill, increasing the importance of robust design and monitoring. To address these risks, downstream phases incorporated a geomembrane shield to minimize seepage and a drainage system to control pore water pressure and hydraulic gradients.

The dam geometry also contributes to stability, with a 12-meter-wide berm, 1:3 upstream slope, and 1:1.5 downstream slope. Despite these measures, an independent review by SRK Consulting in 2021 identified a lack of sufficient geotechnical data on the foundation soil's strength and behavior, particularly under the normal seismic loading conditions of the region. In response, further engineering and geological investigations were scheduled to assess the foundation and improve the understanding of its long-term performance (Polymetal International PLC, 2023).

The current Factor of Safety (FoS) for the TSF is 1.205, slightly above the national minimum of 1.20 for high-risk structures. Although this indicates nominal compliance, the narrow margin underscores the need for continued geotechnical assessment, particularly as the facility expands and operates in a seismically active zone.

### 3.8. Monitoring Methods Employed at the Varvara TSF

According to Blackmore (2022), Varvara TSF uses a systematic approach to monitoring that combines environmental supervision, technical controls, and routine inspections. Every twelve hours, pipelines, valves, pump stations, and indications of seepage or erosion are all the subject of operational checks. Standardized checklists and prompt reporting procedures help these.

A drainage system comprising headers, pumps to control pore water pressure, and pipe drains is used to manage seepage. The monitoring strategy recommends the use of instruments like piezometers and slope stability modeling, even though instrumentation is not covered in detail in reports.

In order to identify cyanide or seepage-related effects, environmental surveillance involves routine sampling from monitoring boreholes and nearby soils. CCTV and real-time alerts are employed to provide additional control in high-risk areas, such the cyanide mixing zone. The TSF's operational safety and compliance are further supported by regular emergency response drills and current contingency plans.

### 3.9. Evolution and Risk Management

The evolution of the Varvara TSF reflects a shift from reactive to adaptive risk management, particularly following the 2016 northern embankment failure, which led to a permanent transition from upstream to downstream raising. Since then, risk mitigation strategies have included structural reinforcements, enhanced monitoring systems, and regular third-party audits.

Figure 4 illustrates the facility's location and the infrastructure potentially affected in the event of dam failure.

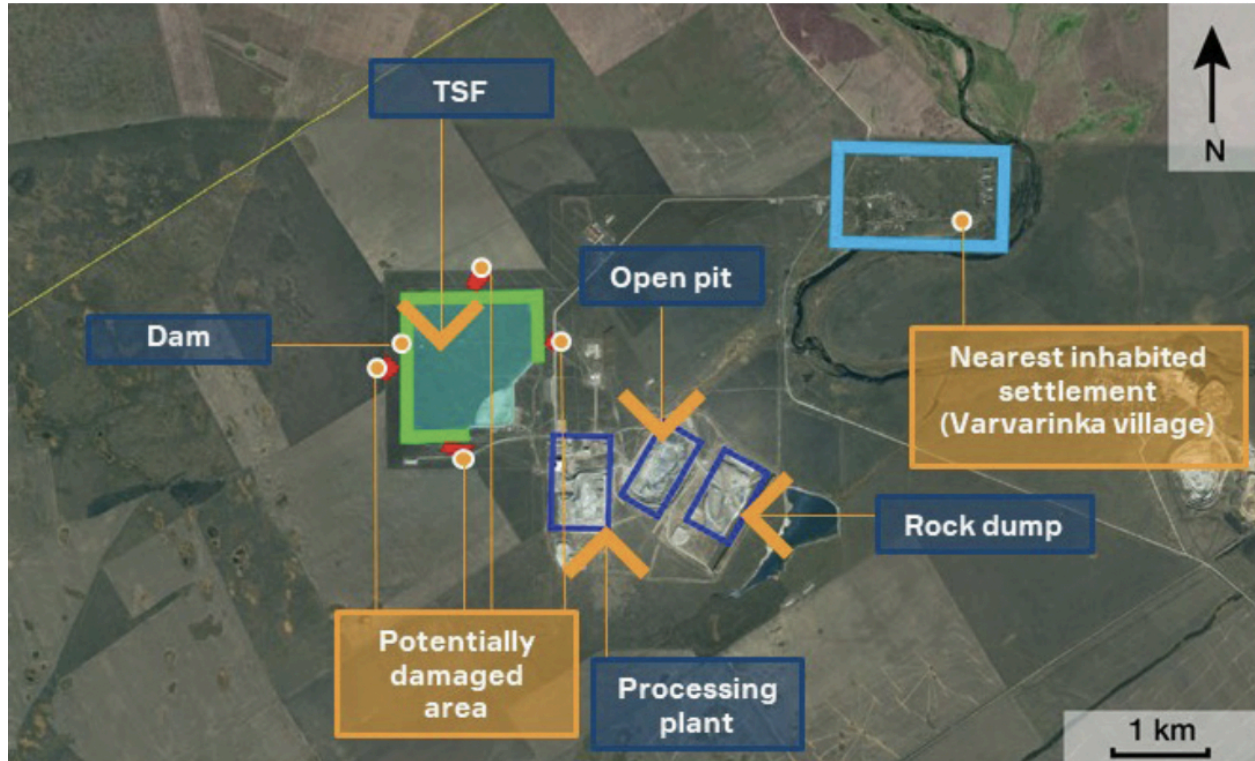


Figure 4. Varvara TSF location and it's affected areas in case of dam failure (Polymetal International PLC, 2019)

In line with its classification as a high-risk facility under the Global Industry Standard on Tailings Management (GISTM), the TSF is subject to ongoing operational improvements. Recent updates have focused on climate resilience, capacity extensions, and long-term planning. According to Solidcore Resources, the TSF is expected to remain operational until 2042 (Polymetal International PLC, 2019; Polymetal International PLC, 2021; Polymetal International plc, 2022; Polymetal International PLC, 2023; Solidcore Resources, 2024).

A thorough analysis of annual TSF management reports from the past five years established a robust foundation for identifying significant events and important operational changes in TSF's timeline. Reports from Polymetal International PLC for the years 2019, 2021, 2022 and 2023 were examined, revealing the major findings presented in Table 4 below:

**Table 4.** Key Events and Developments in the Operational History of the Varvara TSF (2016–2023)

<b>Year</b>	<b>Key Event</b>	<b>Description and Implications</b>
2016	Dam Collapse & Design Shift	Northern embankment failure on September 14 led to no casualties but exposed flaws in upstream raising. Resulted in shift to downstream raising for all future stages. Reinforcement measures included a rock-fill buttress and installation of real-time monitoring systems.
2019	Capacity Expansion & Operational Maturity	Completion of four construction phases; elevation reached 18 m. Company implemented drainage systems, geomembrane linings, and achieved a safety factor of 1.205 (with 1.2 being a minimum for this kind of facility). Capacity rose to 33.87 million m <sup>3</sup> with a 2024 forecast of 43.49 million m <sup>3</sup> . Environmental risks remained low due to remote location.
2020	No Data Available	No report or monitoring data was published for this year, resulting in a gap in the TSF’s documented development.
2021	Structural Enhancements & Safety Upgrades	TSF raised to 22 m. Safety surveys prompted new berms and improvements to linings. Freeboard of 1.5 m introduced. Normative FoS was stable around 1.205. Advanced drainage and water management systems integrated to mitigate overtopping and seepage.
2022	Independent Audit & Data-Driven Adjustments	External SRK audit revealed soil stability data gaps. Further engineering assessments followed. Impoundment volume reached 35.34 million m <sup>3</sup> . Projected capacity of 43.49 million m <sup>3</sup> by 2025. Emergency plans and environmental risk assessments updated; damage repair costs estimated at \$1.6 million. FoS remained the same.
2023	Climate Resilience & Strategic Planning	Continued safe operation at 35.34 million m <sup>3</sup> . Proposed capacity extensions to maintain use until 2036 (but it was afterwards increased to the year 2042 in 2024). Design adapted to climate extremes with 2 m freeboard. Enhanced sediment control and water recovery implemented. Audits confirmed compliance with GISTM and national regulations.

## 4. Methodology

### 4.1. Methodology Overview

This research employs a two-phased methodology to assess the condition of TSFs in Kazakhstan focusing on the case of the Varvara TSF. The initial phase offers a country-specific evaluation derived from the 2021 UNECE digital TSF map and further research sources. As the UNECE data was solely accessible in a visual format, relevant data was manually collected and organized into a structured dataset. This facilitated the identification of patterns in TSF distribution, capacity, and related dangers, providing a statistical and descriptive overview of the current TSF landscape in Kazakhstan, which had not been comprehensively investigated before.

The second portion concentrates on a geographical case study of the Varvara TSF. This investigation employs remote sensing methodologies and geospatial instruments - specifically Google Earth Engine (GEE) and ArcGIS - to examine the temporal and spatial dynamics of the site. Focus is directed on observing environmental alterations, prospective risks, and seasonal water accumulation patterns. Collectively, these two phases provide a comprehensive overview and a detailed examination, creating the basis for evaluations of Kazakhstani TSFs' safety and environmental consequences.

In addition, this research incorporates analysis of climatic and hydrological data obtained from KazHydroMet, including annual precipitation and temperature changes recorded at the Tobol Station, as well as water level measurements at the Ayat River point, to support the interpretation of geospatial analysis results for the Varvara TSF.

Furthermore, data were extracted from the Integrated Annual Reports of Solidcore Resources spanning 2009 to 2023 to assess the link between fluctuations in TSF dynamics and the quantities of ore produced and processed at the mine site during the study period.

## **4.2. Overview of TSFs in Kazakhstan: A Country-Level Assessment**

Efficient management of TSFs is essential for reducing environmental hazards and guaranteeing the sustainability of mining activities. Notwithstanding the sector's significance in Kazakhstan, comprehensive analyses of TSFs are in short supply.

In 2021, the United Nations Economic Commission for Europe (UNECE) initiated a pilot project to map and evaluate all TSFs in Kazakhstan, therefore addressing this deficiency. The computerized map encompassed essential data including location, capacity, pollutants, water hazard categorization, operating condition, seismic and flood threats, dam safety, and the Tailings Hazard Index (THI). The data was not initially organized for statistical analysis.

For this study, pertinent data were manually retrieved and organized into a structured spreadsheet to enable national-scale analysis. The initial phase aims to deliver a comprehensive assessment of TSFs in Kazakhstan, emphasizing their distribution, operating status, capacity, and potential risk concerns.

This analysis establishes the basis for the subsequent phase of the project - a targeted geospatial investigation of the Varvara TSF - and aids in contextualizing wider trends and issues in tailings management nationwide.

## **4.3. A Case Study Approach: Geospatial Analysis of Varvara TSF**

Remote sensing has become an essential tool in the study of TSFs, largely because satellite products are often the only open-access sources of historical data - especially in remote or hard-to-access regions. In countries like Kazakhstan, where many TSFs are located far from urban centers and ground-based monitoring is limited, satellite imagery offers a practical and scalable solution. It enables consistent, long-term observation of landscape changes and potential environmental risks through broad spatial coverage and frequent revisit cycles, making it a highly suitable method for assessing TSF conditions over time.

Numerous studies underscore the effective utilization of remote sensing in the monitoring of TSFs. [Cacciuttolo & Cano \(2023\)](#) illustrated the application of multispectral photography in differentiating supernatant water ponds from adjacent tailings, offering essential insights on pond stability and spill danger. [Thomas et al. \(2019\)](#) utilized InSAR techniques to identify minor ground deformations surrounding TSFs, facilitating the early detection of dam collapse. [Li et al. \(2020\)](#) demonstrated that tailings ponds may be precisely delineated by remote sensing classification techniques, hence improving TSF inventory mapping. [Turgeon et al. \(2013\)](#) underscored the significance of historical satellite data for monitoring the long-term development of tailings impoundments and comprehending its environmental effects.

The general flow of the proposed methodology for this study was adapted from [Cacciuttolo & Cano \(2023\)](#) and [Xia et al. \(2019\)](#). These authors identified that supernatant-processed water ponds and wet tailings are two separate elements within TSFs, each fulfilling unique functions in mining waste management. Ponds of processed supernatant water are created from the water that separates from the tailings during the mineral processing step. This water generally collects on the surface of the tailings and is distinguished by its comparatively low sediment content. The management of these ponds is essential, as improper control may lead to overtopping and environmental pollution issues. Conversely, wet tailings denote the fine-grained, water-saturated substance that persists following the extraction of precious minerals. Wet tailings possess elevated moisture levels and may contain toxic chemicals, rendering their care crucial for environmental safeguarding. The identification of wet tailings frequently uses spectral indices, which differentiate them from supernatant water and vegetation by examining their distinct spectral fingerprints. A step-by-step explanation of the applied methodology is provided in Sections 4.3.1 to 4.3.3.

### **4.3.1. Data Acquisition and Preprocessing**

#### 4.3.1.1 Sentinel-2 and Landsat-8 Data Selection in Google Earth Engine

To analyze the temporal changes in Varvara TSF, Sentinel-2 Level-2A and Landsat 8 imagery was obtained via Google Earth Engine (GEE). Sentinel-2 data is widely used for environmental monitoring due to its high spatial and temporal resolution ([Drusch et al., 2012](#)).

The study focused on the spring hydrological period (from 1st of March to 31st of May) between years 2019 and 2024, as this timeframe aligns with the snowmelt season, during which surface water levels rise rapidly and the pond typically reaches its annual maximum. Also, a Landsat imagery from 2016 was analyzed to examine changes in the dynamics of the Varvara TSF, particularly in response to the TSF failure that was mentioned in [Section 3](#) and occurred on September 14, 2016. Sentinel-2 imagery (10-20 m resolution) was used for years 2019–2024, while Landsat 8 (30 m resolution) was used for 2016, all corresponding to the spring season (March 1st–May 31st). The detailed information on resolution of each band from both Landsat and Sentinel imagery services are presented below in [Table 5](#).

[Table 6](#) explains the preprocessing steps applied in GEE to ensure the quality and consistency of Sentinel-2 and Landsat-8 imagery used in this study. These steps include cloud filtering, temporal compositing, masking of unwanted atmospheric effects, and selection of key spectral bands for further analysis.

**Table 5.** Preprocessing parameters applied to satellite imagery in GEE

<b>№</b>	<b>Preprocessing Step</b>	<b>Description</b>
1	Cloud Cover Threshold	Only images with less than 5% cloud coverage were retained.
2	Temporal Compositing	A median composite was generated for each year to reduce atmospheric variability and improve feature visibility.
3	Cloud, Snow, and Shadow Masking	Quality Assessment bands were used to exclude pixels affected by clouds, shadows, and snow.
4	Spectral Band Selection	Bands B3 (Green), B4 (Red), B8 (NIR), and B11 (SWIR1) were extracted for further analysis in ArcGIS for the calculation of indexes.

**Table 6.** Description and resolution of Sentinel-2 and Landsat 8 bands used for index calculation

<b>Band</b>	<b>Description</b>	<b>Sentinel-2 Resolution</b>	<b>Landsat 8 Resolution</b>	<b>Sources</b>
B3 (Green)	Green reflectance, distinguishes clear and muddy water, highlights oil and vegetation, and reflects green light	10 m	30 m	

	strongly while still showing man-made features.			Sentinel Hub, n.d.; U.S. Geological Survey, n.d.
B4 (Red)	Red reflectance, reflects well from dead foliage, helping identify vegetation, soil, and urban areas, but poorly from live plants and water.	10 m	30 m	
B8 (NIR)	Near-infrared, used for the classification of vegetation	10 m	30 m (Band 5)	
B11 (SWIR1)	Short-wave infrared, effective for assessing soil and vegetation moisture and distinguishing between various vegetation types.	20 m	30 m (Band 6)	

The details of the bands used for index calculation are presented in [Table 6](#) above. These bands were selected based on their sensitivity to vegetation, water, and soil characteristics, which are essential for effective remote sensing analysis in this study. Thus, preprocessed Sentinel-2 and Landsat-8 images were exported in GeoTIFF format for subsequent processing in ArcGIS software (version 10.6.1).

### 4.3.2. Image Processing and Index Calculation

#### 4.3.2.1 Calculation of Spectral Indices

In this study, spectral indices were calculated using ArcGIS software (version 10.6.1) and the Raster Calculator tool to classify water bodies and wet tailings in the TSF. The classification criteria were based on methodologies outlined in previous studies, particularly the work of [Xia et al. \(2019\)](#), who used the combined criteria  $mNDWI > NDVI$  and  $EVI < 0.1$  to detect **water surfaces**. This combination was specifically designed to mitigate the interference of vegetation and soil in water detection, where the  $mNDWI > NDVI$  criterion isolates water features, and  $EVI < 0.1$  further reduces the impact of vegetation.

Building on this approach, [Cacciuttolo & Cano \(2023\)](#) applied the same index combination to detect **wet tailings** within TSFs. In their work,  $mNDWI > NDVI$  was used to identify areas with

high moisture content (wet tailings), and the  $EVI < 0.1$  criterion was applied to further reduce the influence of vegetation, ensuring more accurate detection of the supernatant water and wet tailings in TSFs.

In this study, the  $mNDWI > NDVI$  and  $EVI < 0.1$  criteria were initially used to identify wet tailings. However, due to the high noise and variability in the EVI values, it became impractical to consistently apply the  $EVI < 0.1$  condition across the study period. As a result, only the  $mNDWI > NDVI$  criterion was used for wet tailings detection to ensure consistency and reliability. The presence of water was identified by calculating the NDWI.

- **Water Surface Detection**

The Normalised Difference Water Index (NDWI) developed by [McFeeters \(1996\)](#) is used to identify supernatant water ponds in the TSF. NDWI was computed utilising Sentinel-2 bands B3 (green) and B8 (near-infrared, NIR) according to the subsequent equation:

$$NDWI = \frac{(Green - NIR)}{(Green + NIR)}$$

The output is expected to vary from -1 to 1, with values exceeding 0 signifying the existence of a water pond. Median pixel values were computed for the three-month interval (March-May) for each year to mitigate environmental noise and capture consistent hydrological signals. This strategy guaranteed a precise depiction of water availability during the crucial snowmelt and flood period, consistent with techniques outlined in prior research.

- **Wet tailings detection**

Wet tailings were detected with the application of two spectral indices:

- Modified Normalised Difference Water Index (mNDWI) proposed by [Xu \(2006\)](#) emphasises aquatic features by minimising the influence of soil and vegetation. It was estimated using Sentinel-2 bands B3 (green) and SWIR1 (shortwave infrared), according to the following equation:

$$mNDWI = \frac{(Green - Swir1)}{(Green + Swir1)}$$

- Normalised Difference Vegetation Index (NDVI) established by [Rouse et al. \(1973\)](#), differentiates vegetation from other terrestrial surfaces. It was calculated using Sentinel-2 bands B8 (near-infrared, NIR) and B4 (red), applying equation below:

$$NDVI = \frac{(NIR - Red)}{(NIR + Red)}$$

Both mNDWI and the NDVI generate values ranging from -1 to 1. An mNDWI output value greater than 0 signifies the presence of water, with elevated values indicating denser or more concentrated water regions. Likewise, NDVI values beyond 0 indicate the existence of vegetation, and values below 0 pertain to non-vegetated regions, including bare soil or water.

#### 4.3.2.2. Reclassification and Raster Conversion

To refine wet tailings detection, the “Reclassify” (Spatial Analyst) tool within ArcGIS software was used to segment the raster into five classes. Only the 5th class, corresponding to  $mNDWI > NDVI$  or  $NDWI > 0$ , was retained for further analysis. This reclassified raster was then converted to a polygon shapefile using the “Raster to Polygon” tool, enabling accurate area measurements.

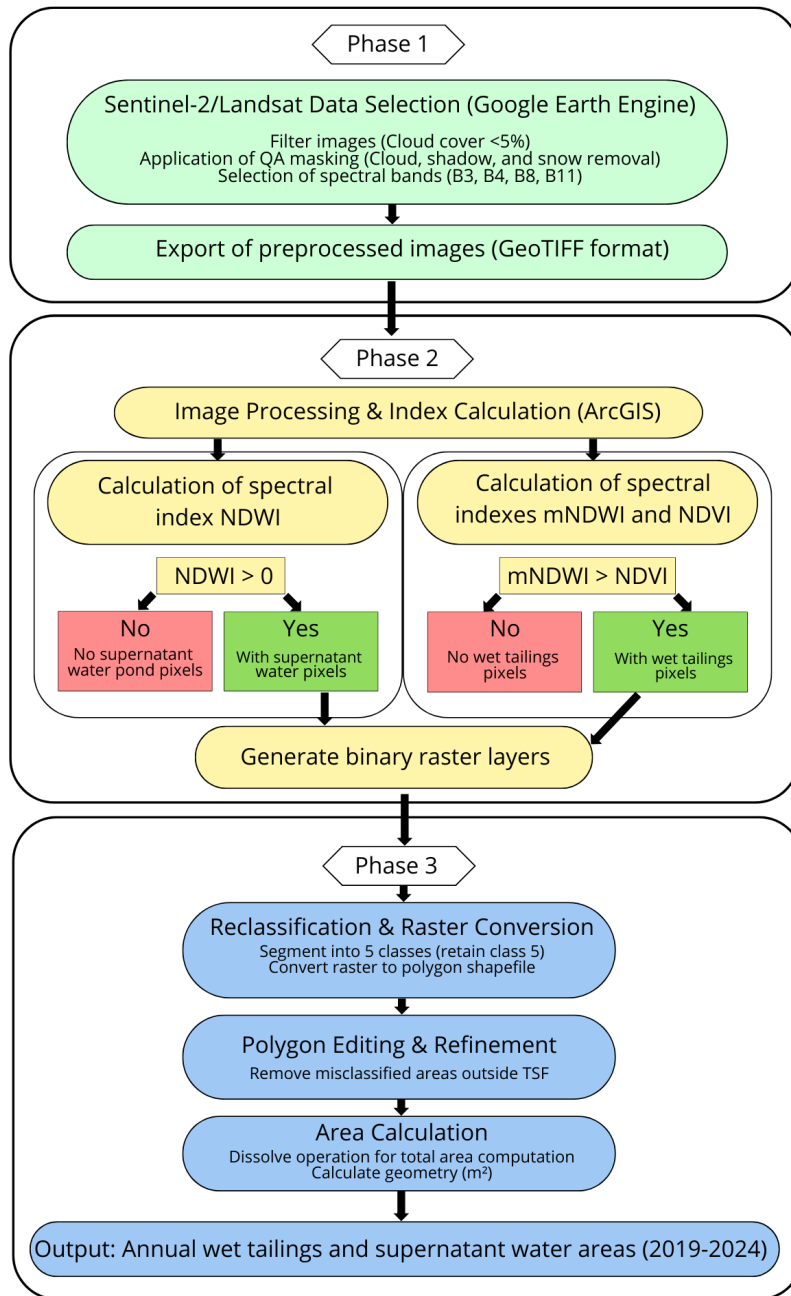
### 4.3.3 Area Computation and Spatial Analysis

#### 4.3.3.1. Post-Classification Processing and Area Estimation

The generated polygons were manually refined to remove misclassified areas outside the TSF boundaries by selecting and retaining only the Pond/Wet Tailings polygons, removing unrelated features, and saving the edits upon completion.

To obtain an aggregate measurement of wet tailings and water-covered areas, all individual polygons were merged into a single "Total Area Pond/Wet Tailings" shapefile using the grid code (5) as the grouping criterion through a “Dissolve” operation. A new "Area" field was then created in the attribute table, and the “Calculate Geometry” tool was used to compute area values in square meters. Since raster data offers pixel-based classifications, converting them to vector-based polygon features was essential for accurate area computation. The final output provided annual area estimations of wet tailings for the study period, enabling spatial trend analysis over time.

The **Figure 5** below shows the flowchart summarizing the satellite image processing workflow for assessing supernatant water ponds and wet tailings at the Varvara TSF using Sentinel-2 and Landsat remote sensing data. The methodology is adapted from [Cacciuttolo & Cano \(2023\)](#) and [Xia et al. \(2019\)](#).



**Figure 5.** Flowchart of satellite imagery processing process workflow performed on Varvara TSF

## 4.4. Incorporation of Climatic and Hydrological Data

To enhance the geospatial analysis of the Varvara TSF, this study integrated climatic and hydrological data obtained from KazHydroMet, Kazakhstan's national hydrometeorological service. The information was sourced from the official meteorological and hydrological databases, as well as the interactive map of hydrological monitoring stations available on the KazHydroMet website (*KazHydroMet, n.d.-a, KazHydroMet, n.d.-b*). These datasets included daily records of precipitation, river water levels, and air temperature, which are essential for understanding environmental variability and potential risks surrounding the TSF.

Precipitation and air temperature data were obtained from the Tobol weather station located in the Kostanay Region (Code: KZ-KUS), while river water level measurements were sourced from the Ayat River hydrological monitoring point (Post-code: 12032) within the Tobol-Torgai Basin, as recorded in the hydrological database (**Figure 2**). These two monitoring sites were selected due to their geographic proximity to the Varvara mining site and their relevance in assessing local climatic and hydrological conditions.

KazHydroMet defines water level as the elevation of the water surface relative to a fixed benchmark, measured in centimetres at automated hydrological stations. This parameter is key to evaluating seasonal fluctuations in river discharge and potential interactions with mining infrastructure. Precipitation, recorded in millimetres, reflects water accumulation from various atmospheric sources including rain, snow, and fog, and is logged twice daily.

Air temperature, another key environmental variable, is measured in degrees Celsius (°C) at a standardized height of 2 meters above the surface to avoid ground influence. Due to atmospheric turbulence, values are averaged over a short interval (3–5 minutes) to produce a reliable reading.

All data were provided in daily format. Each value was manually collected and compiled into a unified dataset, after which annual average statistics were calculated. This method enabled the tracking of interannual variability and supported comparisons with wet tailings and water pond dynamics observed via geospatial analysis between 2019 and 2024. Due to data limitations, water level measurements were only available up to 2022, excluding the two most recent years from analysis.

Annual precipitation and Ayat River water level values serve as key indicators of natural water inflow, evaporation rates, and potential seepage effects, all of which directly influence TSF stability and water balance. The inclusion of these variables provided valuable environmental context to interpret spatial and temporal patterns at the Varvara TSF.

#### **4.5. Mining Production Data Collection**

To investigate the potential relationship between mining activity and changes in the Varvara TSF, production data from the Solidcore's Varvara mining facility were systematically collected from the company's Integrated Annual Reports spanning the period from 2009 to 2023. This period aligns with the acquisition of the deposit and ensuing operational advancements. Key performance indicators - specifically, ore mined, ore processed, gold produced, copper produced, and waste generated - were manually collected and consolidated into a comprehensive dataset. This organized table will facilitate the examination of relationships between geographical alterations in the TSF and the intensity of mining activities during the study period. All reports were obtained from Solidcore's official website.

### **5. Results**

This section outlines the results obtained from the complex methodological framework employed in this investigation. The analysis commences with a comprehensive national assessment of TSFs throughout Kazakhstan, utilizing data derived from the UNECE digital TSF map and additional sources to elucidate patterns in spatial distribution, storage capacity, and associated concerns. The emphasis next switches to the Varvara TSF case study, wherein geospatial analysis employing Sentinel-2 imagery and GIS tools clarifies the temporal and spatial alterations in wet tailings and supernatant ponds from 2019 to 2024. These dynamics are further elucidated through the incorporation of climatic and hydrological records from KazHydroMet, notably precipitation, temperature, and river water level data, to ascertain environmental impacts on TSF behavior. Furthermore, production-related data from Solidcore Resources are analyzed to investigate connections between operational outputs and variations in the TSF area. Collectively, our

findings seek to provide a comprehensive understanding of TSF conditions, enhancing broader dialogues on environmental monitoring and tailings management in Kazakhstan.

## 5.1. National Overview of TSF in Kazakhstan based on UNECE map

The UNECE (2021) pilot project aimed at enhancing TSF safety in Central Asia involved the mapping and assessment of all identified TSFs in Kazakhstan. The dataset comprised parameters like location, capacity, pollutants, operational condition, seismic and flood threats, and the THI. The data, first displayed visually, was manually retrieved from the UNECE TSF map, systematically organized into a table (see Appendix A), and evaluated to identify significant trends and attributes of TSFs nationwide.

### 5.1.1. Principal Findings

Kazakhstan possesses 121 TSFs, with 94 currently operational, 2 repaired, and 25 decommissioned. The mean storage capacity is 23.7 million cubic meters, with the minimum facility at 0.002 million m<sup>3</sup> (LLP "Taraz Metallurgical Plant", Section 4) and the maximum at 595.394 million m<sup>3</sup> (Conserved TMF of Zhezkazgan Dressing Plants 1 and 2, LLP "Kazakhmys Corporation"). TSFs are classified according to their storage capacity as follows:

- Small (<10 million m<sup>3</sup>): 88 establishments
- Medium (10–50 million m<sup>3</sup>): 19 establishments
- Facilities over 50 million m<sup>3</sup>: 12 establishments
- Unspecified capacity: 2 establishments

The oldest TSF in Kazakhstan, the Balkhash Dressing Plant, operated by "PO Zhezkazgantsvetmet," a subsidiary of LLP "Kazakhmys Corporation," has been in operation since 1937. The latest at the moment of the creation of the map was TSFs at LLC "Bakyrchik" GDP commenced operations in 2018. In total:

- **40 TSFs** were commissioned in the last 30 years (1995–present).
- **79 TSFs** were established before 1995.
- **2 TSFs** have no recorded commissioning data.

### 5.1.2. Structural Attributes

The crest width varies from 0.01 m to 20 m, with a mean of 8 m. when in comes to the embankment material, 73 of all TSFs utilize non-rock embankments, 34 employ rock embankments, and 14 have unspecified data.

### 5.1.3. Geographical Dispersion

The geographical allocation of TSFs is as follows:

- Zhambyl (34) and East Kazakhstan (29) contain over fifty percent of all TSFs, indicative of their substantial mining legacies.
- Additional significant regions include: Karagandy (19), North Kazakhstan (10), Turkistan (9), Pavlodar (8), Aktobe (6), Kostanay (4), Almaty (1), and Mangystau (1).

Consequently, East Kazakhstan possesses abundant polymetallic reserves, including copper, lead, zinc, gold, silver, and rare earth elements. Zhambyl is recognized for its phosphate, uranium, and polymetallic ores, featuring numerous facilities from the Soviet period.

### 5.1.4. Risk Evaluation

The Tailings Hazard Index (THI) is a screening instrument utilized to evaluate the hazard potential of various TSFs. It integrates five essential parameters - total tailings capacity, toxicity of stored substances, management status, exposure to natural hazards (e.g., floods, earthquakes), and dam safety (FoS) - into a singular indicator. The THI facilitates the prioritization of TMFs for monitoring and resource allocation by identifying those with elevated risk levels (ICPDR, 2020). Based on the overall score, TSFs are categorized into low, medium, or high hazard classifications:

- Low hazard: Facilities characterized by limited capacity, non-toxic or less toxic materials, stable conditions, and well-maintained structures with minimal exposure to natural risks.
- Medium hazard: Facilities exhibiting moderate capacity or toxicity, or situated in areas with some hazard exposure. These TSFs necessitate regular monitoring but are not deemed critical.

- High hazard: Facilities with substantial volumes, highly toxic contents, inadequate management or abandoned status, and/or significant exposure to environmental risks. These require immediate attention due to their potential for severe consequences in the event of failure.

The THI evaluation of Kazakhstani TSFs' indicates:

- 58 TSFs pose a medium-level hazard.
- 41 TSFs are classified as low-risk.
- 19 TSFs have a high hazard rating.

3 TSFs present transboundary risks - located within 15 km of an international border or within transboundary water catchment areas.

### 5.1.5. Varvara TSF on the map

Based on UNECE (2021), the Varvara TSF, launched in 2008, has a documented design capacity of 7.4 million m<sup>3</sup>. The material predominantly comprises waste generated from the processing of copper-gold ores, comprising compounds such as cyanides, iron oxide, aluminum oxide, and copper. The plant is designated as active and has a moderate THI score of 9.87. The TSF is constructed with a non-rock embankment that has a crest width of 11 meters. Data from Solidcore Resources (2021) reveal a markedly greater actual impoundment volume of 29,962,829 m<sup>3</sup>, indicating a divergence between reported capacity and operational reality.

The UNECE map designates the Varvara TSF with a water hazard classification and a flood risk level of 2. However, the foundation for this grade is not explicitly delineated, and the ramifications of such a classification remain ambiguous. In common risk rating systems, a level 2 may denote moderate risk; however, additional confirmation from UNECE is required for precise interpretation.

Moreover, the UNECE map misplaced the Varvara TSF (see Figure 6 below), indicating a significant deficiency in the national tailings facility inventory. Conversely, Figure 2 (Section 3) displays correct satellite imagery of the site, and dependable operating data from Solidcore Resources will provide a more comprehensive evaluation in later parts.

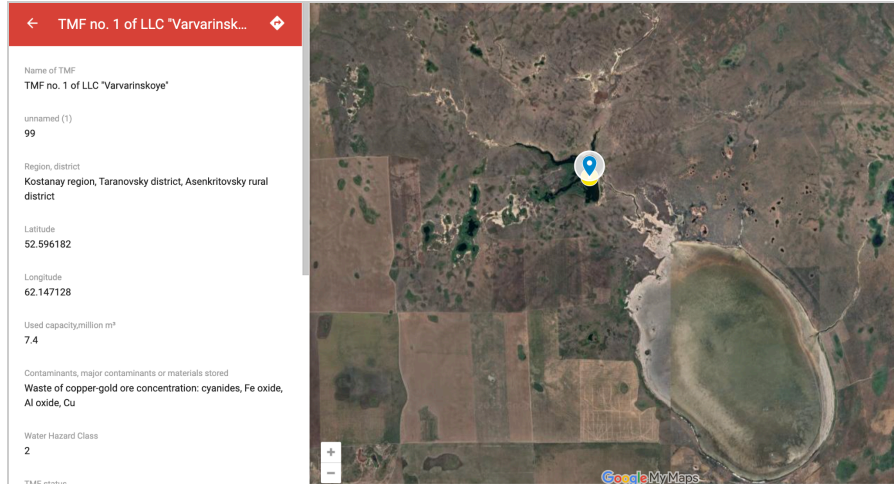


Figure 6. Misrepresentation of Varvara TSF location on the UNECE TSF Map (UNECE, 2021)

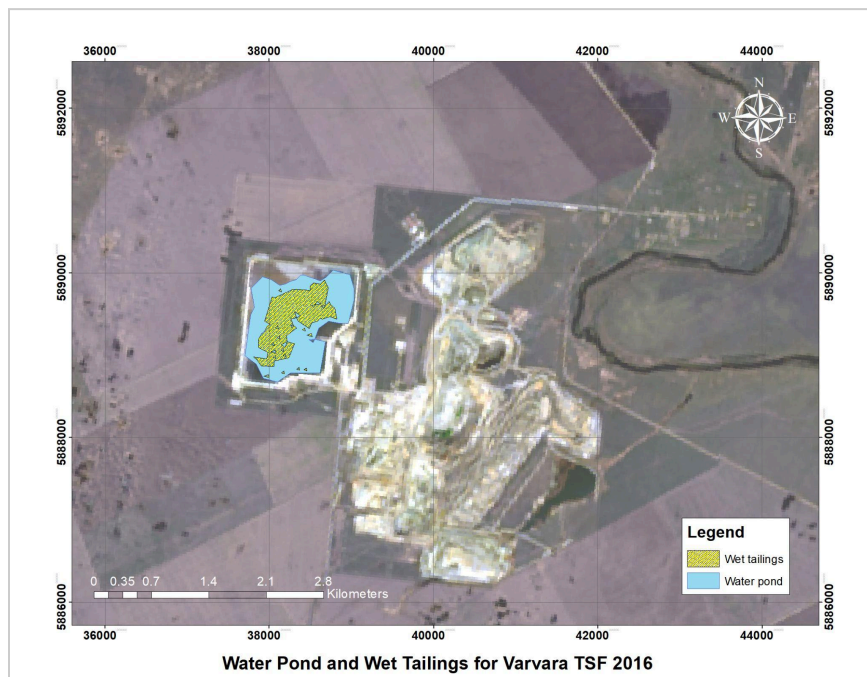
## 5.2. Spatial Analysis on dynamics of Wet Tailings and Processed Water Ponds in Varvara TSF

This research applied spectral indices to spatially identify supernatant water and wet tailings at the Varvara TSF. The Normalised Difference Water Index (NDWI) was employed to locate surface water bodies by examining reflectance disparities between green and near-infrared (NIR) bands. The Modified Normalised Difference Water Index (mNDWI) and Normalised Difference Vegetation Index (NDVI) were utilized to differentiate saturated tailings from surrounding dry regions. The Enhanced Vegetation Index (EVI) was initially evaluated but then was excluded due to unreliable outcomes. The geographic outputs (Figures 7–13) depict the distribution of water ponds and wet tailings within the TSF for the study period, facilitating visual evaluation of seasonal variations and hydrological dynamics within the impoundment. These visualizations not only reveal the presence and movement of water and tailings zones over time but also allow for assessing whether the water pond remains at a safe distance from the dam structure - an essential factor in evaluating the facility's stability and environmental safety. The blue regions denote water ponds, whilst the yellow regions signify wet tailings, providing a distinct visual distinction within the plant. The indices' values were evaluated throughout time (see Table 7), although the results specifically illustrate intra-annual spatial changes rather than temporal trends. Significantly, image data from 2016, obtained from Landsat with a lower spatial resolution (30

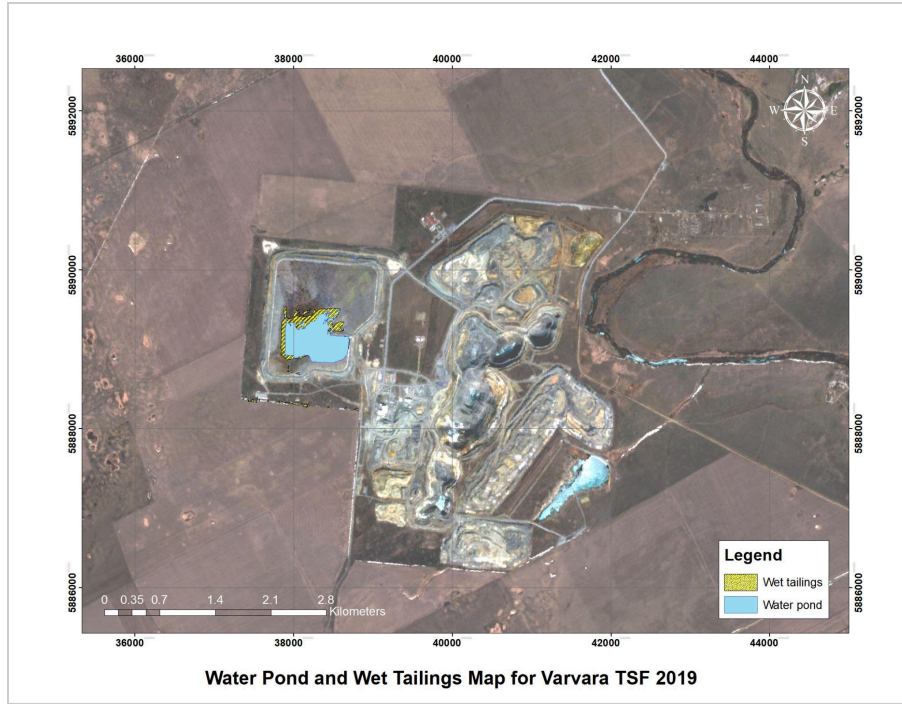
m), produced more pronounced spectral values. Conversely, the more stable results in subsequent years are attributable to the enhanced spatial resolution (10-20 m) of Sentinel data, which facilitates more accurate distinction of saturated zones and improves the geographic dependability of the categorization.

**Table 7.** Temporal Variation of Spectral Index Values (NDWI, NDVI, mNDWI) for the Varvara TSF (2016–2024)

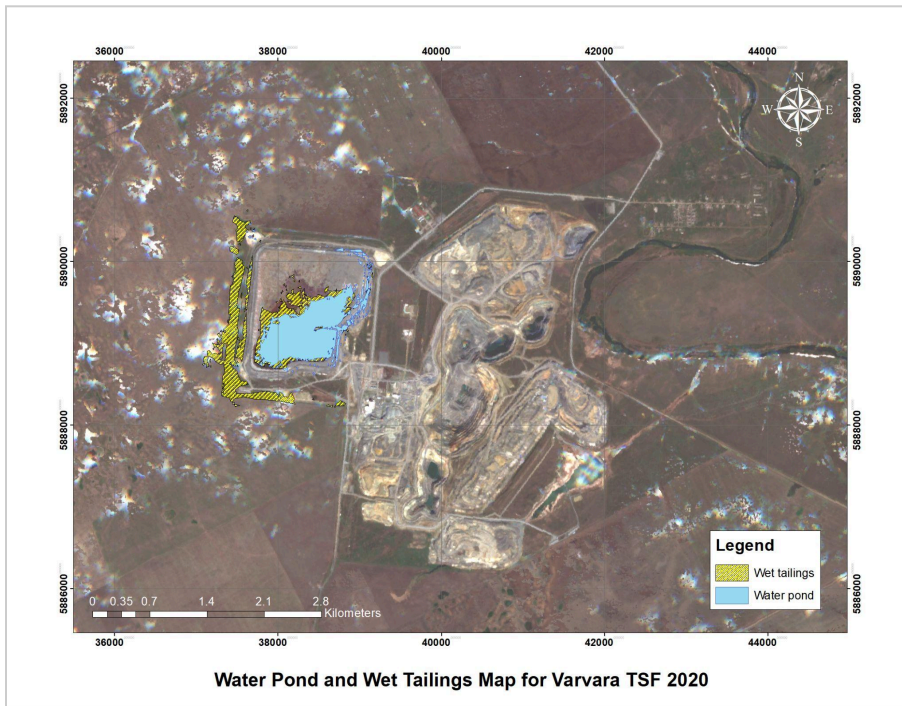
Year	NDWI		NDVI		mNDWI	
	Highest value	Lowest Value	Highest value	Lowest Value	Highest value	Lowest Value
<b>2016</b>	1.17219	-0.898855	0.904431	-2.65449	0.988832	-0.949974
<b>2019</b>	0.419242	-0.613585	0.487018	-0.315511	0.9122	-0.692287
<b>2020</b>	0.41701	-0.52053	0.47211	-0.271274	0.88633	-0.554714
<b>2021</b>	0.237549	-0.396229	0.37491	-0.144549	0.797838	-0.383048
<b>2022</b>	0.258644	-0.403115	0.387399	-0.135987	0.858205	-0.519669
<b>2023</b>	0.569151	-0.552986	0.490972	-0.394748	0.844439	-0.68291
<b>2024</b>	0.612529	-0.626239	0.65748	-0.461846	0.792193	-0.65093



**Figure 7.** Identification of Wet Tailings and Processed Water Ponds Using NDWI, MNDWI, and NDVI for 2016



**Figure 8.** Identification of Wet Tailings and Processed Water Ponds Using NDWI, MNDWI, and NDVI for 2019



**Figure 9.** Identification of Wet Tailings and Processed Water Ponds Using NDWI, MNDWI, and NDVI for 2020

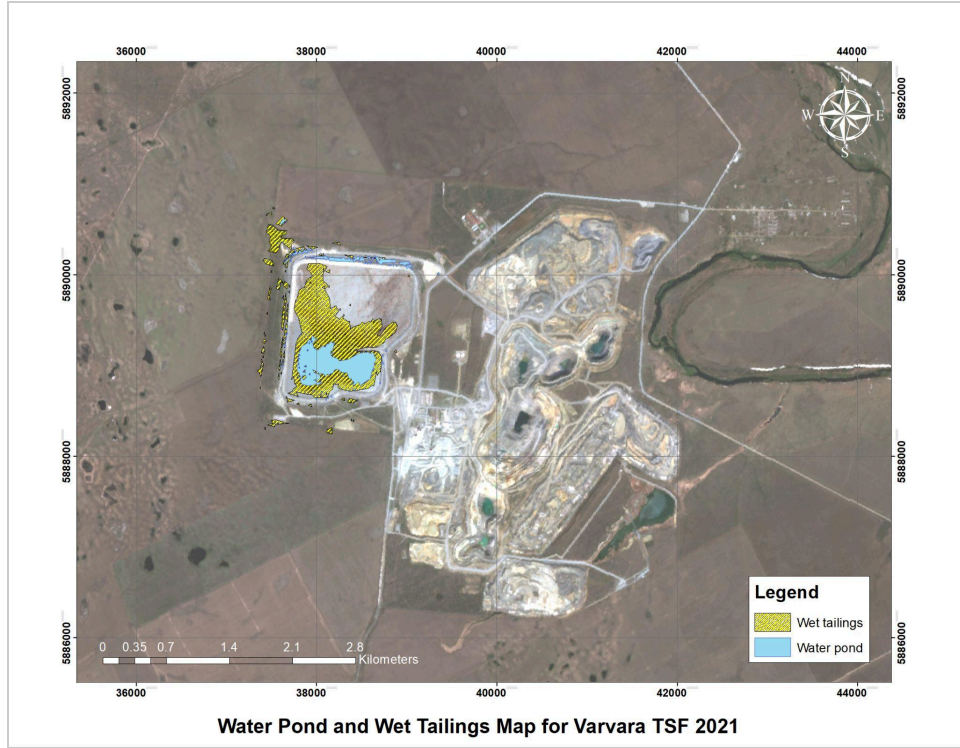


Figure 10. Identification of Wet Tailings and Processed Water Ponds Using NDWI, MNDWI, and NDVI for 2021

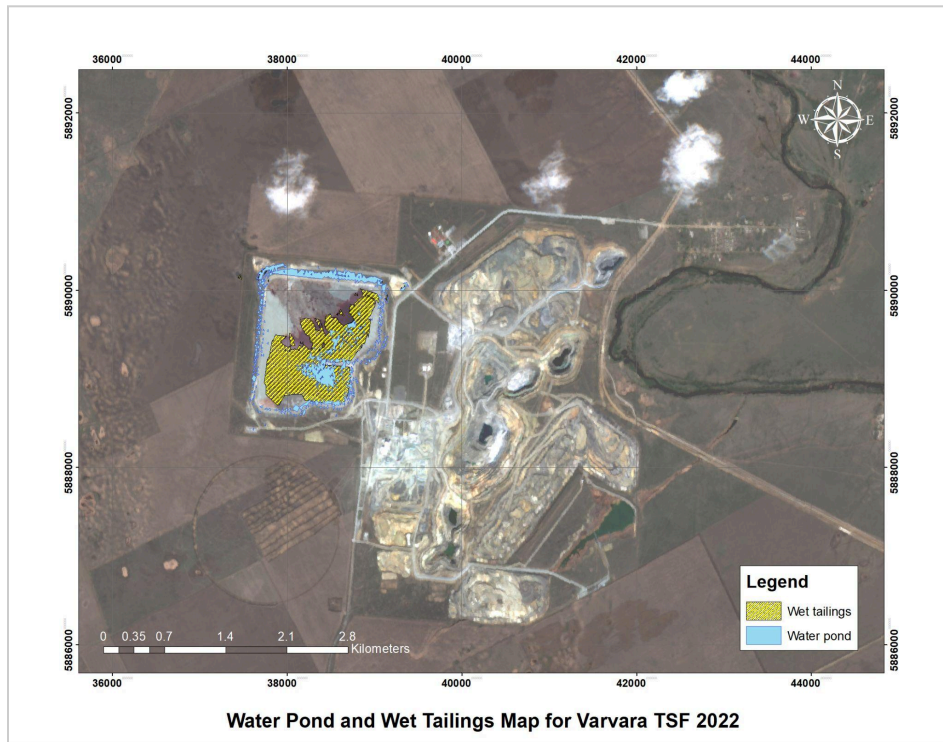


Figure 11. Identification of Wet Tailings and Processed Water Ponds Using NDWI, MNDWI, and NDVI for 2022

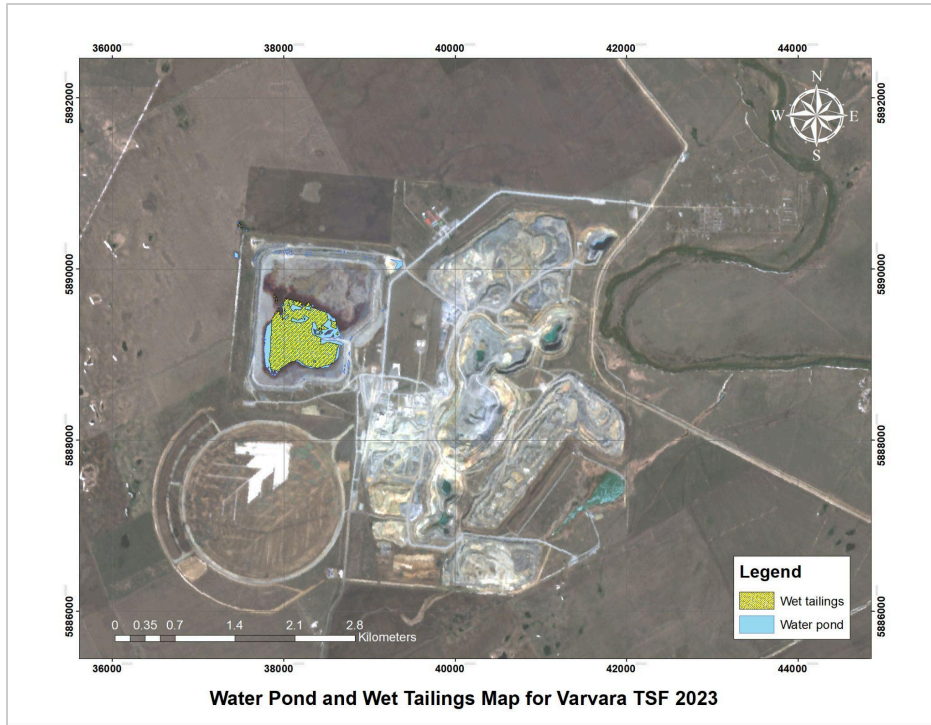


Figure 12. Identification of Wet Tailings and Processed Water Ponds Using NDWI, MNDWI, and NDVI for 2023

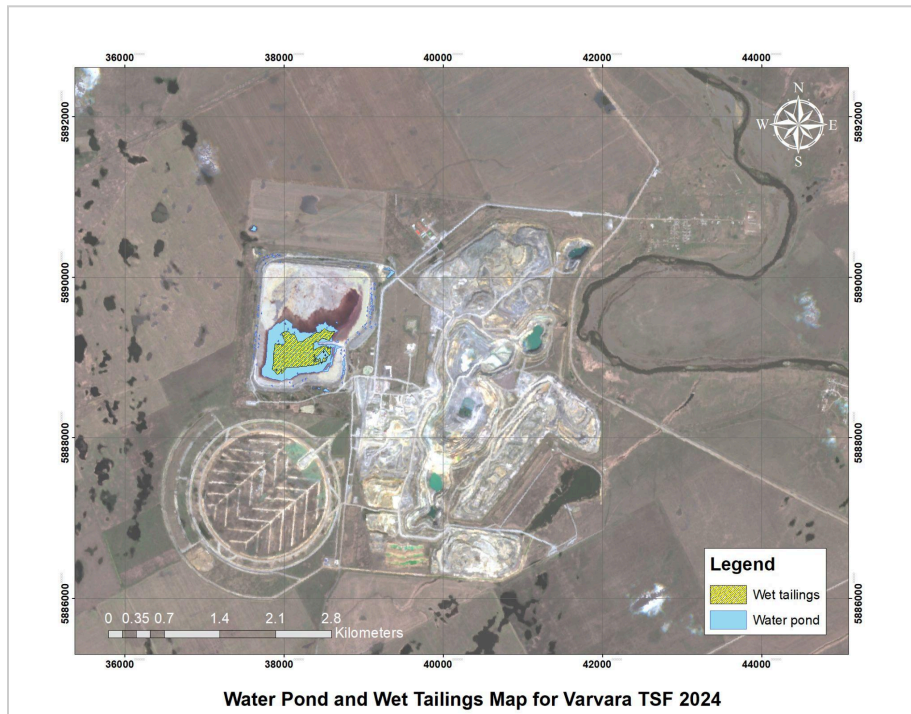


Figure 13. Identification of Wet Tailings and Processed Water Ponds Using NDWI, MNDWI, and NDVI for 2024

**Table 8** illustrates the temporal variations in the extents of wet tailings and the supernatant water pond within the Varvara TSF from 2016 to 2024. The data reveals significant fluctuations in the wet tailings area, which initially covered 462,290 m<sup>2</sup> in 2019. It expanded substantially by 161.7% to reach a peak of 1,209,544 m<sup>2</sup> in 2020. Following this maximum, a steady decline is observed, with the area contracting by 13% to 1,052,010 m<sup>2</sup> in 2021, followed by a further 18.2% reduction to 860,230 m<sup>2</sup> in 2022. The most substantial decreases occurred between 2022 and 2023, with the wet tailings area shrinking by 48.2% to 445,144 m<sup>2</sup>, followed by another 47.3% loss from 2023 to 2024, resulting in a final area of approximately 234,730 m<sup>2</sup>. This represents a total decline of 80.6% from its peak in 2020, indicating significant changes in deposition patterns, compaction, or operational adjustments.

**Table 8.** Summary of Wet Tailings and Water Pond Area Changes at Varvara TSF (2016–2024)

Year	Wet Tailings Area (m <sup>2</sup> )	Water Pond Area (m <sup>2</sup> )	Total Area of Pond and Tailings (m <sup>2</sup> )	Key Observations
2016	456,630	1,207,392	1,207,392	Dam failure: excessive water accumulation led to structural instability
2019	462,290	334,990	468,931	Baseline measurement
2020	1,209,544 (+161.7%)	669,875 (+100.3%)	1,286,340 (+174.37%)	TSF expansion, high water retention
2021	1,052,010 (-13%)	291,939 (-56.4%)	1,088,280 (-15.39%)	Possible water removal efforts
2022	860,230 (-18.2%)	294,779 (+1%)	1,037,508 (-4.67%)	Stable year, minor fluctuations
2023	445,144 (-48.2%)	564,214 (+91.4%)	576,500 (-44.43%)	Potential seepage or reduced extraction
2024	234,730 (-47.3%)	524,839 (-7.1%)	525,043 (-8.91%)	Continued wet tailings decline

A similar fluctuating trend is evident in the water pond area. Initially measuring 334,990 m<sup>2</sup> in 2019, it increased by 100.3% to 669,875 m<sup>2</sup> in 2020. It then experienced a substantial 56.4%

decrease to 291,939 m<sup>2</sup> in 2021, followed by a minor 1% increase to 294,779 m<sup>2</sup> in 2022. In 2023, the water pond expanded considerably by 91.4% to 564,214 m<sup>2</sup>, before slightly decreasing by 7.1% to 524,839 m<sup>2</sup> in 2024.

Notably, the inclusion of the 2016 dataset was intentional, as it corresponds to a documented dam failure at the Varvara TSF on September 14, 2016, despite falling outside the primary study period of 2019–2024. At that time, the wet tailings area was 456,630 m<sup>2</sup>, while the water pond covered 1,207,392 m<sup>2</sup> - the largest recorded in the dataset. By comparing the 2016 conditions with later years, we can better understand the relationship between excessive water accumulation and potential failure risks. This comparison aids in predicting TSF behavior under critical conditions and provides valuable insights into stability thresholds and water management strategies.

These fluctuations highlight dynamic changes in water retention and tailings deposition, likely influenced by operational factors such as tailings disposal methods, water management strategies, or seasonal hydrological conditions. The pronounced reduction in wet tailings volume since 2020 suggests a shift in deposition techniques or improved compaction, while the variability in the water pond area may reflect changes in water balance within the TSF, possibly driven by precipitation, evaporation, or active water extraction. Continuous monitoring of these trends is essential for assessing potential stability concerns and ensuring effective environmental management at the facility.

**Figure 14** below presents the measured changes in the extent of wet tailings and supernatant water ponds within the Varvara TSF from 2019 to 2024. In the figure, 'A' denotes the area, with blue indicating the water pond and yellow representing wet tailings.

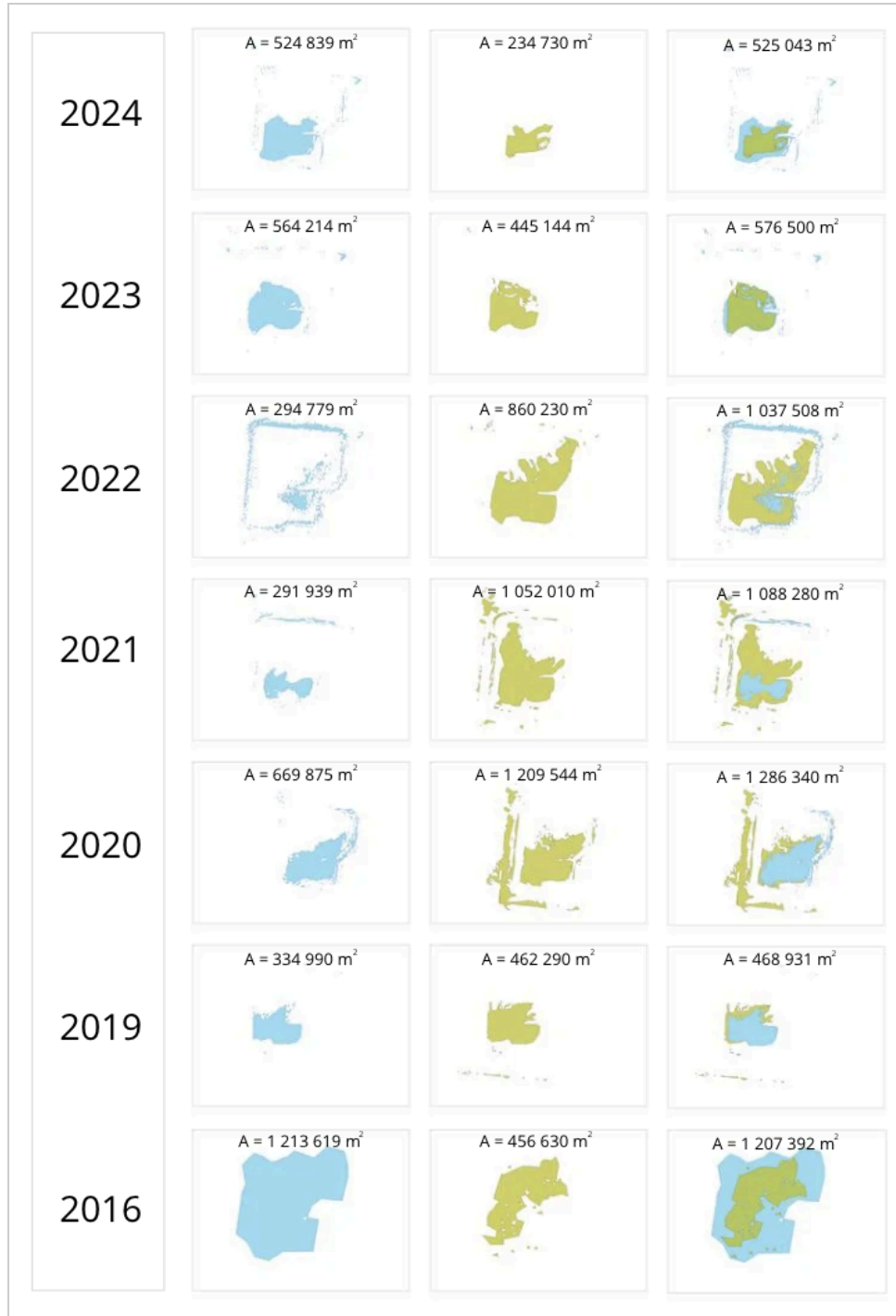


Figure 14. Areal changes of Wet Tailings and Processed Water Ponds within the Varvara TSF between 2019 and 2024

### 5.3. Production at Varvara Mining Site

**Table 9** outlines the yearly production outputs of the Varvara mining operation from 2009 to 2023. Essential indicators cover ore extraction, ore processing, gold and copper output, and waste generation quantities. During this 15-year span, the Varvara site has undergone substantial expansion in both volume and efficiency.

The volume of ore extracted rose from 844 Kt in 2009 to 2,834 Kt in 2023, indicating a 235% growth. The processed ore increased significantly from 510 Kt to 3,898 Kt, representing a 664% rise. Gold production exhibited a significant transformation, escalating from 13 Koz in 2009 to 169 Koz in 2023, representing a 1200% rise. Copper output reached its zenith in 2011 at 6,915 tonnes but was no longer reported after 2017.

An significant operational transition was observed in 2016, characterized by a persistent trend in which ore processed surpassed ore mined. This modification signifies the incorporation of the Komarovskoye (Komar) deposit, which was formally integrated into the Varvara hub in the same year 2016. As Komar lacks its own processing facilities, it is verified that its ore is transported to and processed at the Varvara plant. As a result, all tailings produced from Komar's ore are deposited to the Varvara TSF.

Subsequent infrastructure enhancements, notably railway expansions in 2015 and 2017, facilitated improved ore transport efficiency ([Solidcore Resources, 2015](#); [Solidcore Resources, 2017](#)). Construction of a new TSF commenced in 2020 to improve storage capacity and environmental safety, and is currently ongoing ([Solidcore Resources, 2020](#)). These operational patterns underscore the Varvara site's evolution as a centralized regional processing hub. The heightened ore throughput and waste production emphasize the necessity of effective tailings management, which is elaborated upon in the subsequent section.

**Table 9.** Solidcore Resources' production outputs of Varvara mining site for years 2009-2023 (from Solidcore Resources Integrated Annual Reports for 2009-2023)

Year	Ore Mined (Kt)	Ore Processed (Kt)	Gold Produced (Koz)	Copper Produced (tonnes)	Waste Produced, (Kt)
------	----------------	--------------------	---------------------	--------------------------	----------------------

2009	844	510	13	1,053	3,396
2010	3,411	3,076	78	4,003	21,955
2011	3,983	3,473	92	6,915	Not reported
2012	3,609	3,647	101	6,567	Not reported
2013	2,008	3,676	107	4,841	Not reported
2014	3,985	3,664	98	1,631	Not reported
2015	4,068	3,457	68	827	Not reported
2016	3,203	3,120	80	839	Not reported
2017	3,243	3,269	123	1,411	Not reported
2018	3,138	3,642	142	Not specified	Not reported
2019	3,943	3,663	149	Not specified	Not reported
2020	2,812	3,745	159	Not specified	40,600
2021	3,624	3,879	197	Not specified	42,000
2022	3,857	3,951	211	Not specified	43,300
2023	2,834	3,898	169	Not specified	40,700

### 5.4. Meteorological and Hydrological Data

The meteorological and hydrological data gathered from 2014 to 2024 provide essential insights into the environmental parameters that may affect the Varvara TSF dynamics. Comprehensive tables outlining annual variations in precipitation and temperature recorded at the Tobol station are provided in [Appendices B](#) and [C](#). This section highlights only the main findings derived from these datasets, with detailed values available for reference in the appendices. [Table 10](#) displays the annual and monthly precipitation data collected at the Tobol weather station. Precipitation, a critical determinant of TSF behavior, exhibited considerable variation during the study period, with 2020 and 2023 recording the highest amounts at 433.4 mm and 485.5 mm, respectively. The precipitation peaks correlate with significant alterations in the TSF's water pond area and wet tailings dynamics, as outlined in [Table 10](#) in [Section X6](#). The variations in precipitation patterns

are crucial for comprehending the seasonal and annual changes in the TSF's hydrological circumstances.

**Table 10.** Annual and Monthly Precipitation Data at Tobol Weather Station (KazHydroMet), 2014–2024

<b>Yearly Precipitation at Tobol Station, KazHydroMet</b>											
Month Year	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
Annual Precipitation, mm	287.5	377.5	368.1	323.2	309.0	287.3	433.4	219.4	306.7	485.5	469.7
Average Monthly Precipitation, mm	24.0	31.5	30.7	26.9	25.8	23.9	36.1	18.3	25.6	40.5	39.1

The temperature data from the Tobol station, presented in **Table 11**, demonstrate a consistent warming trend over the years, with average annual temperatures increasing by roughly 1°C in the last decade. The temperature fluctuations are intricately connected to changes in regional precipitation patterns, which directly influence TSF stability. For instance, in 2020, there was a notable increase in temperature (5.46°C) and precipitation (433.4 mm), leading to a considerable growth of wet tailings and water pond areas. Details of this correlation will be discussed in the following sections.

**Table 11.** Annual Temperature Changes Data from Tobol Weather Station (KazHydroMet), 2014–2024

<b>Yearly Average Temperature Changes at Tobol Station, KazHydroMet</b>											
Year	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
Yearly Average, °C	3.33	3.85	3.52	3.41	2.09	3.93	5.46	4.33	3.42	5.01	4.01

**Table 12** presents the water level statistics for the Ayat River, documented from 2014 to 2022. These observations indicate the yearly variations in river water levels, which affect the natural water input to the TSF and are essential for assessing flood hazards and seepage potential. During the spring months (March-May), water levels routinely above yearly norms, underscoring the influence of snowmelt and seasonal precipitation on the local hydrology. This seasonal pattern validates the selection of these months for observing TSF dynamics in this research, as it captures the most hydrologically active and influential period of the year.

**Table 12.** Annual and Spring Water Levels at Ayat River Hydropost (KazHydroMet), 2014–2022

Yearly Water Level at Ayat river point, KazHydroMet									
	2014	2015	2016	2017	2018	2019	2020	2021	2022
Annual Average, cm	141	127	130	135	131	122	125	125	118
March-May Average, cm	149	145	143	144	137	130	138	143	136

Thus, these data collectively establish a basis for comprehending the external climatic and hydrological factors that may have affected the TSF dynamics, including the possible effects of increasing temperatures, modified precipitation patterns, and variable water levels. The ensuing study in the Discussion section will examine the relationships between these variables and the observed alterations in the TSF infrastructure.

## 6. Discussion

### 6.1. Production at Varvara Mining Site and its correlation with TSF dynamics

A well-established relationship exists between production volumes and the dynamics of TSFs in mining literature. [Kossoff et al. \(2014\)](#) illustrate that the generation of tailings is directly proportional to ore processing rates, thereby influencing the capacity requirements of TSFs. [Wang et al. \(2014\)](#) demonstrate that production fluctuations influence tailings properties, such as particle size and moisture content, which are crucial for TSF stability and water management. [Carneiro and Fourie \(2019\)](#) present life cycle assessment findings indicating that heightened production contributes to environmental risks associated with tailings, especially in terms of water consumption and the mobility of contaminants. This requires adaptive management strategies for TSF. [Badiozamani et al. \(2019\)](#) provide a mathematical validation of this relationship using production scheduling models that incorporate tailings storage constraints. These studies demonstrate that production rates are critical in determining tailings behavior, necessitating integrated management strategies that align processing outputs with TSF capacity and monitoring systems.

At the Varvara TSF, satellite-derived surface area measurements and operational data indicate that fluctuations in TSF dynamics frequently correspond to alterations in ore processing volumes. The changes and correlations of TSF area with the volume of ore processed at the mine site are shown in [Table 13](#) and [Figure 15](#) below.

**Table 13.** Annual ore production statistics and corresponding spatial changes in wet tailings and water pond areas at the Varvara TSF (2016–2023)

Year	Wet Tailings Area (m <sup>2</sup> )	Water Pond Area (m <sup>2</sup> )	Total Area of Pond and Tailings (m <sup>2</sup> )	Ore Mined (Kt)	Ore Processed (Kt)	Gold Produced (Koz)
2016	456,630	1,213,619	1,207,392	3,203	3,120	80
2019	462,290	334,990	468,931	3,943	3,663	149

2020	1,209,544 (+161.7%)	669,875 (+100.3%)	1,286,340 (+174.37%)	2,812 (-28.68%)	3,745 (+2.24%)	159
2021	1,052,010 (-13%)	291,939 (-56.4%)	1,088,280 (-15.39%)	3,624 (+28.89%)	3,879 (+3.58%)	197
2022	860,230 (-18.2%)	294,779 (+1%)	1,037,508 (-4.67%)	3,857 (+6.44%)	3,951 (+1.86%)	211
2023	445,144 (-48.2%)	564,214 (+91.4%)	576,500 (-44.43%)	2,834 (-26.49%)	3,898 (-1.34%)	169

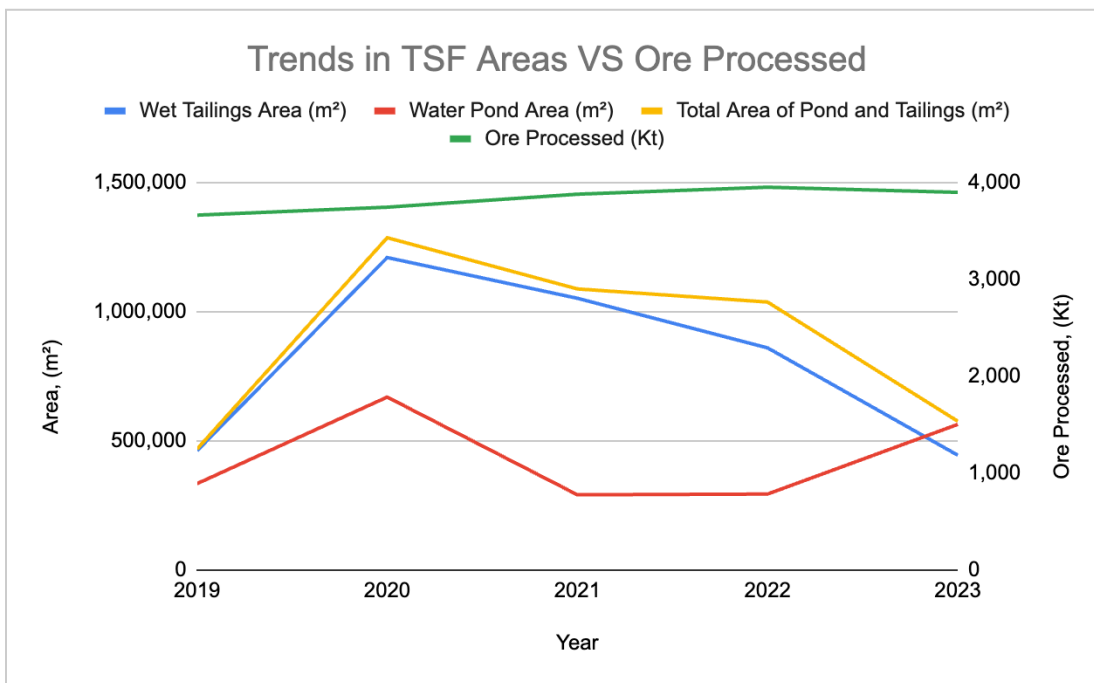


Figure 15. Trends in TSF Changes and Ore Processed at Varvara Mining Site (2019–2023)

From Table 13 and Figure 15 it can be noted that the processing volumes have usually risen throughout the years, from 3,120 Kt in 2016 to 3,951 Kt in 2022, reflecting comparable alterations in TSF surface areas. The most substantial increase in wet tailings area occurred in 2020, totaling 1,209,544 m<sup>2</sup>, coinciding with a considerable ore processing volume of 3,745 Kt. This year also recorded the biggest total surface area of pond and tailings (1,286,340 m<sup>2</sup>), reflecting a direct correlation between the TSF footprint and heightened processing activity.

From 2021 to 2023, there was a progressive reduction in both wet tailings and water pond areas, despite consistently high ore processing rates of roughly 3,900 Kt per year. In 2023, despite processing 3,898 Kt of ore - one of the biggest volumes recorded - the wet tailings area fell significantly to 445,144 m<sup>2</sup>, reflecting a 48.2% reduction from 2022. This inverse trend indicates that elements outside processing volume, such as enhanced tailings dewatering techniques, elevated solids concentration, or modifications in TSF management tactics, may have significantly contributed to the reduction of the spatial extent of tailings deposition and ponding. The significant rise in water pond area in 2023 (+91.4%) after two years of loss may suggest seasonal or climatic factors (e.g., heightened precipitation) or alterations in water management strategies within the TSF. This rise coincided with a significant decrease in wet tailings area, indicating a possible redistribution of free water or a modification in tailings discharge behavior. The correlation coefficient calculations based on the [Table 13](#) and [Figure 15](#) values indicate that:

- Wet Tailings Area and Ore Processed: 0.10 (very weak positive)
- Water Pond Area and Ore Processed: -0.22 (weak negative)
- Total Area of Pond and Tailings and Ore Processed: 0.26 (weak positive)

These results suggest **weak correlations** between ore production and TSF areas at Varvara. The low correlation between wet tailings area and ore processed indicates that factors like dewatering practices or TSF management likely influence tailings area. Similarly, the negative correlation with water pond area suggests that changes in water management or climate conditions, rather than ore processing, may play a role. It is important to note that estimation of correlation coefficients typically requires at least 30 data points for a robust analysis. Therefore, these results should be confirmed by future research with additional data points.

While the specifics of water management at Varvara TSF remain undisclosed, the company's infrastructure, as detailed in [Blackmore's \(2022\)](#) audit report, comprises standard pipes for slurry transfer and water return, high-pressure pumping systems, and flow control valves. These systems conform to industry standards yet restrict external visibility into site-specific processes. Furthermore, the lack of output statistics for 2024 limits additional analysis of previous patterns.

In summary, although a general association between production quantities and TSF expansion is evident, recent variations highlight the impact of operational enhancements, climatic fluctuations, and internal management practices on TSF stability and water balance.

## **6.2. Correlation with the climatic changes (particularly precipitation, water level and floodings)**

### **6.2.1. The Influence of Climate Variability on Hydrology and TSFs**

In Kazakhstan, where dynamic interactions among precipitation patterns, water levels, and flood regimes are evident, climate change has become a critical issue for water resource management. Changing precipitation patterns and a warming climate are expected to have substantial environmental consequences, including increased water scarcity and shifts in hydrological cycles. [Yessenzholov et al. \(2024\)](#), for example, report a steady warming trend in Kazakhstan, with temperature increases of 0.31 °C per decade from 1950 to 2020 and 0.28 °C per decade from 1941 to 2011. [Kakabayev et al. \(2023\)](#) further support this trend, showing that the average annual air temperature anomaly from 2012 to 2021 was +6.61 °C - more than 1 °C above the climatic norm - with particularly high temperatures recorded between 2017 and 2021.

Alongside increasing temperatures, hydrological data reveal that Kazakhstan's annual precipitation in 2021 fell to 85.5% of its long-term average, with regional shortfalls between 20% and 40%, underscoring the nation's susceptibility to water scarcity. Future estimates differ; certain climate models predict minor increases in winter and spring precipitation by 2050, but others foresee an overall reduction of up to 11% by 2085 ([Yessenzholov et al., 2024](#)). These alterations, however, are not evenly dispersed across seasons or areas. [Didovets et al. \(2021\)](#) indicate that certain northern catchments may encounter heightened precipitation and river discharge, but southern and mountainous areas are anticipated to suffer considerable losses, especially during summer months, with river flow declines reaching up to 40%. Recent model simulations indicate that Central Asia is expected to see further warming of up to 6.4 °C by the

century's end under high-emission scenarios, accompanied by faster glacier melt and variations in runoff (Fallah et al., 2024).

These climatic changes are already evident through increased frequency and intensity of hydrological extremes. Observational data and modeling studies indicate that the region has undergone a 20% decrease in snow depth over the last 70 years, alongside an increasing frequency of catastrophic flood occurrences, attributed to accelerated snowmelt and heightened rainfall. This trend highlights that, in addition to gradual warming and water scarcity, Central Asia - particularly Kazakhstan - is increasingly vulnerable to climate-induced flood threats (Fallah et al., 2024; Didovets et al., 2021). The changing conditions present significant issues for water resource management, environmental resilience, and industries like mining, where TSFs are especially vulnerable to variations in water intake and seasonal hydrology.

For the mining sector, climate change presents growing difficulties, particularly in the management of TSFs. Mining operations are increasingly exposed to climate-driven hazards such as extreme weather, altered precipitation patterns, and prolonged droughts, while also contributing to greenhouse gas emissions (Lèbre et al., 2020). Heavy rainfall can exacerbate seepage issues and compromise dam stability, increasing the risk of TSF failures. Recent studies indicate that rising temperatures and intensified rainfall accelerate tailings desiccation and enhance the oxidative dissolution of sulfide minerals, thereby heightening the likelihood of acid rock drainage and pollutant mobilization (Labonté-Raymond et al., 2020; Williams, 2008).

Therefore, this section further examines the correlation between key hydrological and meteorological parameters - specifically, precipitation, water levels, and temperature - and the dynamics of the Varvara TSF from 2019 to 2024. The following **Table 14** presents a summary of TSF changes alongside corresponding hydrological and meteorological conditions:

**Table 14.** Annual Variations in TSF Wet Tailings, Water Pond Area, Precipitation, Annual Average Temperature and Ayat River Water Levels

Year	Wet Tailings Area (m <sup>2</sup> )	Water Pond Area (m <sup>2</sup> )	Total Area of Pond and Tailings (m <sup>2</sup> )	Annual Precipitation, (mm)	Annual Average Temperature, (C)	Ayat River Water Level (cm)	Key Observations
2016	456,630	1,213,619	1,207,392	368.1	3.52	130	Excessive water accumulation; dam failure
2019	462,290	334,990	468,931	287.3	3.93	122	Baseline measurement; stable TSF
2020	1,209,544 (+161.7%)	669,875 (+100.3%)	1,286,340 (+174.37)	433.4 (+50.86%)	5.46 (+38.93%)	125 (+2.46%)	TSF expansion, high precipitation, increased water retention
2021	1,052,010 (-13%)	291,939 (-56.4%)	1,088,280 (-15.39%)	219.4 (-49.37%)	4.33 (-20.88%)	125 (0%)	Active water removal; sharp pond reduction
2022	860,230 (-18.2%)	294,779 (+1%)	1,037,508 (-4.67%)	306.7 (+39.81%)	3.42 (-21.01%)	118 (-5.60%)	Stable conditions, minor fluctuations
2023	445,144 (-48.2%)	564,214 (+91.4%)	576,500 (-44.43%)	485.5 (+58.24%)	5.01 (+46.49%)	Data Not Available	Water pond surge; possible seepage or reduced water extraction
2024	234,730 (-47.3%)	524,839 (-7.1%)	525,043 (-8.91%)	469.7 (-3.25%)	4.01 (-19.96%)	Data Not Available	Wet tailings decline, persistent pond levels

Now, it is time to discuss the changes of TSF with the precipitation and water level statistics.

### 6.2.2. Precipitation and Expansion of TSF Water Pond

Precipitation significantly affects the behavior of TSFs, as rainfall directly impacts water retention and deposition patterns. Precipitation may settle on the surface of the tailings deposit, augmenting the volume of the process water pond and modifying tailings beach slopes, resulting in reduced deposition slope values during moist intervals (Cacciuttolo & Cano, 2023). Moreover, contingent upon the tailings deposition strategy, certain regions remain persistently saturated (wet tailings beaches), whereas others desiccate over time (inactive beaches), hence influencing

TSF stability. Figure 16 below shows the changes of yearly precipitation in the region where Varvara TSF located. Overall trend is increasing upwards with more than 150 ml of precipitation increase from the baseline measurements.

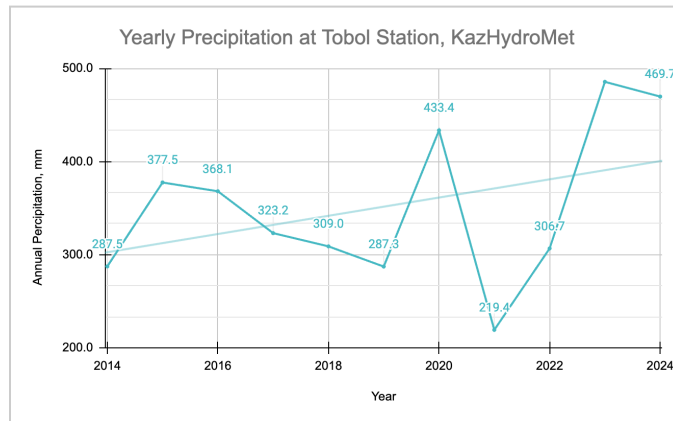


Figure 16. Annual Precipitation Changes at the Ayat River Point between 2014 and 2024, KazHydroMet

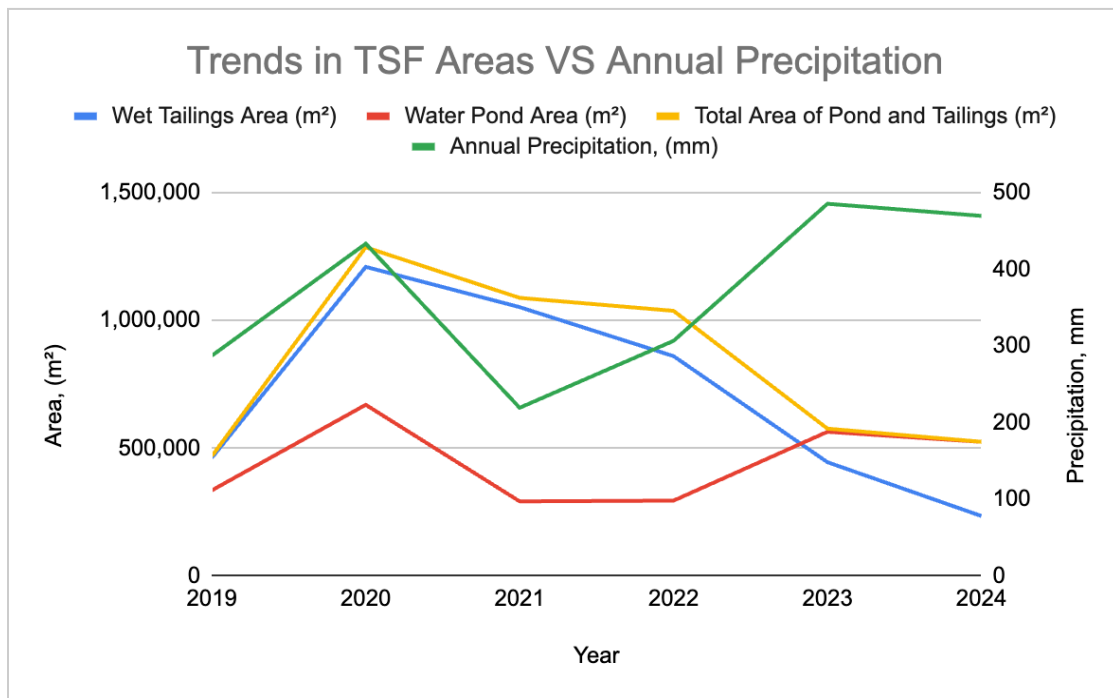


Figure 17. Trends in TSF Changes and Annual Precipitation at Varvara Mining Site (2019–2024)

Figure 17, in turn, depicts the correlation of regional precipitation patterns next to the mining site with area changes of Varvara TSF. A definitive correlation exists between prolonged periods of elevated precipitation and enhanced TSF water retention. In 2020, annual precipitation reached

433.4 mm, coinciding with a 161.7% rise in wet tailings and a 100.3% expansion of the water pond area. In 2023, precipitation increased to 485.5 mm, resulting in a 91.4% enlargement of the water pond, despite a 48.2% decrease in wet tailings, potentially attributable to seepage or insufficient drainage.

In contrast, 2021, the driest year with 219.4 mm of precipitation, experienced a 56.4% decrease in the water pond area, underscoring the significant relationship between rainfall and TSF water accumulation. The correlation analysis reveals a **strong positive relationship** between water pond area and precipitation (correlation coefficient of 0.88), validating that higher rainfall leads to increased water retention in TSFs. This is further supported by the negative correlation between precipitation and wet tailings area (-0.41), indicating that heavy rainfall may cause an increase in water content and a shift in tailings deposition behavior, leading to changes in wet tailings dynamics.

The data confirms that variations in precipitation substantially alter TSF hydrodynamics, influencing water retention and tailings deposition patterns, and impacting structural integrity. As such, water management and dewatering techniques must account for the seasonal and climatic variations in precipitation to ensure TSF stability.

### **6.2.3. Annual Temperature Changes correlations with TSF Dynamics**

In the last ten years, the average temperature at the Tobol station has risen by around 1°C, a notable alteration in light of the prolonged warming trend in Kazakhstan (**Figure 18**). [Yessenzholov et al. \(2024\)](#) documented a consistent temperature increase of 0.31°C each decade from 1950 to 2020, indicating a recent acceleration. This warming trend significantly affects area hydrology, especially concerning precipitation patterns and their influence on TSF stability.

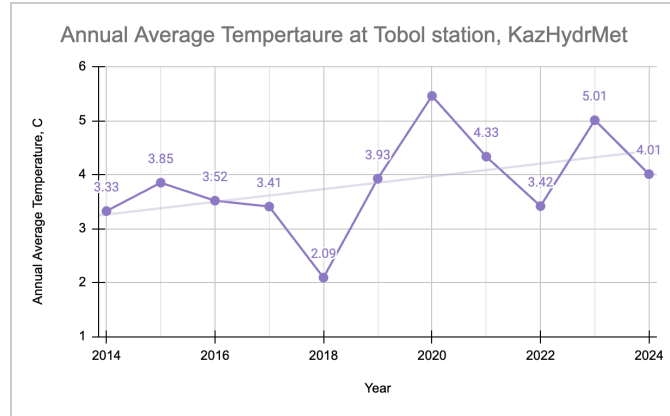


Figure 18. Annual Temperature Changes Data at Tobol Weather Station between 2014 and 2024, KazHydroMet

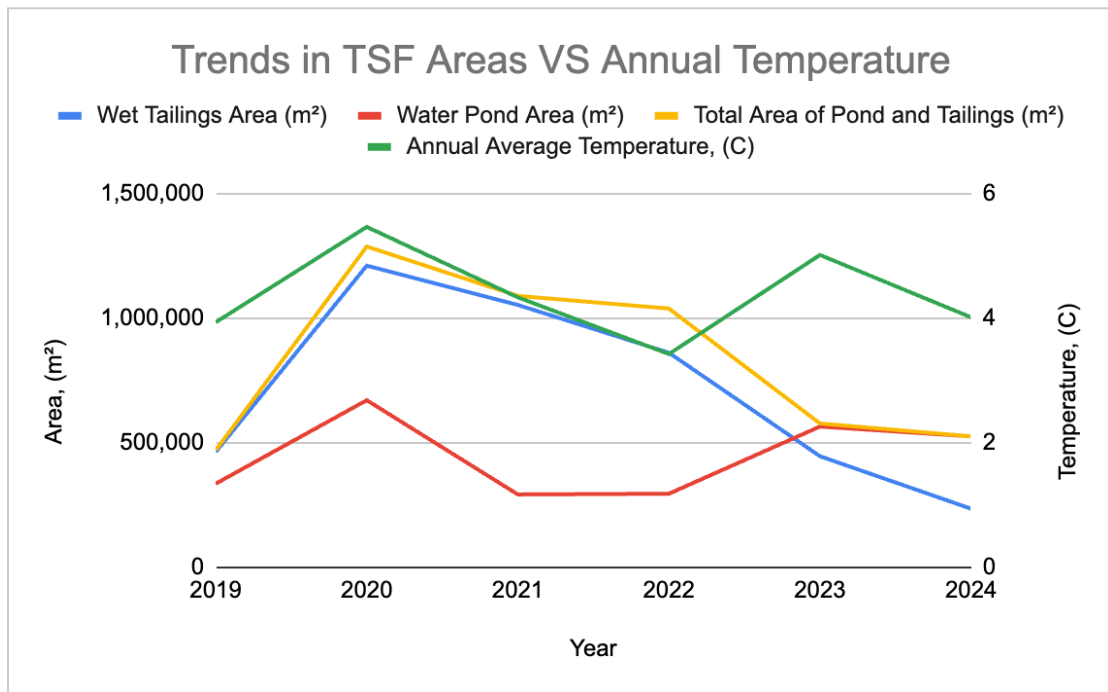


Figure 19. Trends in TSF Changes and Annual Temperature at Varvara Mining Site (2019–2024)

To illustrate the correlation between changes in the TSF's wet tailings and water pond areas with temperature variations, Figure 19 presents the relevant results. Although temperature does not directly govern the dynamics of wet tailings and water ponds, it plays an indirect role through its influence on precipitation levels and evaporation rates. Precipitation remains the primary driver of TSF expansion, with warmer and wetter years correlating with larger areas of water accumulation. However, during drier years, elevated temperatures can increase evaporation rates, leading to a noticeable reduction in the size of water ponds and the saturation of tailings.

Between 2019 and 2020, a temperature increase from 3.93°C to 5.46°C coincided with a 161.7% rise in wet tailings area and a 100.3% expansion of the water pond area, linked to a significant increase in precipitation from 287.3 mm to 433.4 mm. In 2023, a temperature peak of 5.01°C was associated with a 91.4% increase in water ponds, while elevated precipitation (485.5 mm) likely facilitated water retention. In contrast, 2021, with a temperature of 4.33°C and reduced precipitation (219.4 mm), experienced a 56.4% decrease in pond area (Table 14 and Figure 19).

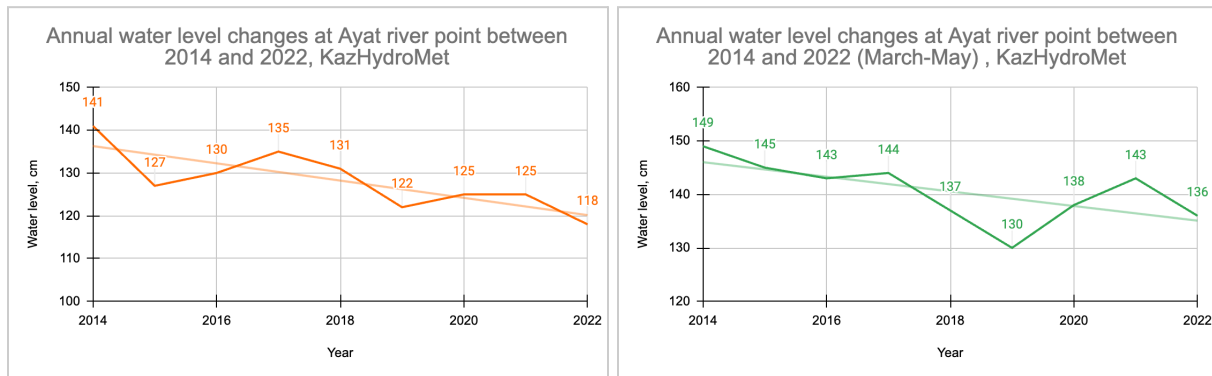
These findings underscore that climate change, via elevated temperatures, results in increased precipitation, thereby enlarging TSF areas and increasing the risk of structural failure. The **weak positive correlation** between temperature and wet tailings area (0.34) and the **strong correlation** with water pond area (0.81) suggest that temperature impacts TSF dynamics more significantly through its influence on water retention rather than direct effects on tailings area. This challenges assumptions about direct temperature-induced water loss and highlights the need for climate-adaptive TSF management strategies to mitigate excessive water retention during rainy years and manage structural weaknesses resulting from increased precipitation.

#### 6.2.4. Ayat River Water Levels and Related Flooding Risks

The Ayat River's water level decreased from 130 cm in 2016 to 118 cm in 2022, indicating a broader regional trend of diminishing water availability (Figure 20). However, TSF dynamics did not consistently align with these variations, suggesting that precipitation and temperature changes played a more significant role in pond expansion than water level. Furthermore, annual water level statistics indicate that measurements taken between March and May are regularly higher than the yearly averages, reinforcing the assumption that this period represents the peak of water abundance in the region. This seasonal rise is largely driven by the rapid melting of accumulated winter snow, which generates a sudden influx of runoff into river systems. Since no direct snowmelt data are available, precipitation and water level records serve as key indicators of these hydrological shifts.

Critically, the combination of heavy precipitation and accelerated snowmelt during spring heightens flood risks, potentially overwhelming river channels and surrounding floodplains. These extreme hydrological events not only threaten regional water infrastructure but also

increase the likelihood of excessive water accumulation within the TSF. Uncontrolled flooding can lead to overtopping, erosion of containment structures, and heightened seepage risks, significantly compromising TSF stability. Given these vulnerabilities, spring represents the most critical period for flood-related hazards, underscoring the need for enhanced water management strategies to mitigate potential failures.



**Figure 20.** Annual and Seasonal Water Level Changes at the Ayat River Point between 2014 and 2022 (KazHydroMet)

The increased awareness over the flooding is justified: in the spring of 2024, Kazakhstan encountered its most severe flooding in 80 years, precipitated by unusually heavy winter precipitation and an anomalously warm March, resulting in quick snowmelt that swamped river systems (Issayev, 2024). The direct effects on the Varvara TFS are uncertain because of data constraints on snowmelt and water level statistics for the years 2023 and 2024. Nonetheless, **Table 14** reveals that the water pond area in 2024 was diminished relative to 2023, implying that floodwaters did not cause substantial pond enlargement. This reduction does not inherently indicate stability, as seepage, erosion, or alterations in water management practices may have affected TFS dynamics. The rising occurrence and severity of climate-induced floods highlight the pressing necessity for adaptive water management techniques to alleviate future risks linked to both excessive rainfall and rapid snowmelt. Especially, taking into account the fact that Varvara mining site is located in the Kostanay region - one of the eight areas in Kazakhstan most susceptible to flooding (KazHydroMet, 2025a).

Alongside diminishing water levels and heightened flooding risks, KazHydroMet's interactive surface water quality data reveal that the Ayat River adjacent to the Varvara TSF exhibits extremely low water quality. A monitoring site along the river is designated as Class 6 (below Class 5 criteria) due to elevated levels of suspended matter, with a recorded value of 39.3 mg/dm<sup>3</sup>, exceeding the background norm of 26.897 mg/dm<sup>3</sup> (KazHydroMet, 2025b). This considerable exceedance of permissible limits indicates substantial contamination, perhaps associated with sediment runoff from the TSF, industrial effluent, or erosion from adjacent mining operations.

### 6.3. Best Practices and Challenges in TSF Management

In response to the rising incidence of TSF failures and their possible environmental and social repercussions, the International Council on Mining and Metals (ICMM) published the Tailings Management: Good Practice Guide (2025), which delineates a thorough framework for the responsible governance of TSFs. The ICMM guidance emphasizes six fundamental pillars - governance and accountability, risk-based design, surveillance and monitoring, climatic resilience, emergency readiness, and sustainable closure—as crucial for attaining enduring safety and sustainability in tailings management.

Simultaneously with these global initiatives, Varvara mine site has been subjected to an independent audit of its cyanide and tailings management, performed by Christine Blackmore, Lead Auditor at Wardell Armstrong International. The Mining Operational Summary Audit Report (Blackmore, 2022), created in compliance with the International Cyanide Management Code (ICMC), provides essential insights into Varvara's tailings and water management policies. The audit primarily examines cyanide management, but it also assesses the structural design of the TSF, overflow mitigation strategies, water reuse regulations, and environmental monitoring systems. Collectively, these components provide a thorough overview of the Varvara TSF's conformity with national standards and international best practices, especially those advocated by the ICMM. The correlation and compliance of Varvara mine site with the best practices navigated by ICMM are presented below in [Table 15](#):

**Table 15.** Comparison of ICMM Tailings Management Best Practices and Varvara TSF Compliance

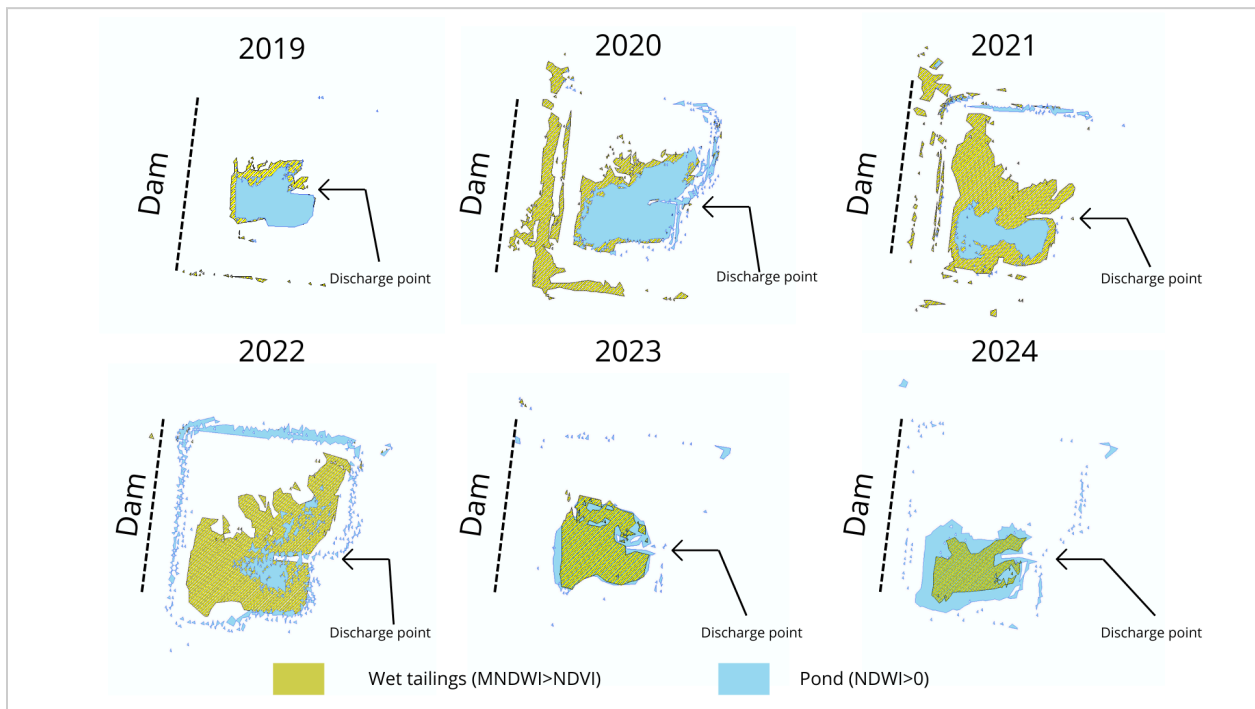
<b>ICMM Good Practice Guideline</b>	<b>Best Practice (ICMM, 2025)</b>	<b>Varvara TSF Practices (Blackmore, 2022)</b>	<b>Compliance</b>
Governance and Accountability	Assign clear accountability at all organizational levels; conduct third-party audits; comply with GISTM.	Appointment of Engineer of Record; QA/QC and CQA protocols before operation; external audit under ICMC.	Yes
Risk-Based Design and Operation	Use site-specific geotechnical and hydrological data; prioritize downstream or centerline construction; design facilities for weather emergency; reduce water content.	Hydraulic modeling ensures crest height margin; two emergency overspill ponds; design shifted to downstream post-2016 dam failure.	Yes
Monitoring and Surveillance	Implement continuous monitoring with piezometers, inclinometers, satellite/LiDAR; conduct routine inspections and independent evaluations.	Real-time monitoring post-2016 dam failure; daily inspections; borehole network; monthly environmental assessments.	Yes
Climate Resilience and Adaptation	Use dynamic water balance modeling; design for extreme rainfall events; integrate long-term climate change scenarios into TSF planning.	Probabilistic hydrological model includes local climate data; seasonal rainfall and freeze-thaw cycles accounted for; no long-term climate projections mentioned.	Partial
Emergency Preparedness	Develop Emergency Response Plan (ERP) with early warning systems, community communication, and coordinated evacuation plans.	Emergency ponds in place; limited mention of full ERP or stakeholder drills.	Partial
Sustainable Closure Planning	Plan for progressive closure from early stages; ensure post-closure stability, monitoring, and financial provisioning.	Closure strategy not detailed in 2022 audit because the mine site is expected to be operating until 2042.	No
Water Management and Reuse	Maximize water reuse; limit new water intake; detoxify effluents before discharge; control seepage.	Water reused in processing; detoxification reduces Weak Acid Dissociable (WAD) cyanide <0.5 mg/L; discharge tested before reintroduction; seepage mitigation with HDPE liners.	Yes

Environmental and Wildlife Monitoring	Implement routine sampling of air, water, soil, biodiversity; use data to detect and mitigate impacts; ensure zero wildlife deaths.	Monthly to semi-annual testing of all major media; no recorded wildlife incidents; data reviewed by in-house ecologist; no major deviations reported.	Yes
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Overall, [Blackmore's \(2022\)](#) audit verifies Varvara TSF's adherence to national safety and international cyanide management standards, consistent with ICMM best practices. Nonetheless, independent oversight might be enhanced. The ICMM prioritizes ongoing expert evaluations, whereas Varvara predominantly depends on regulatory adherence and internal QA/QC (Quality Assurance/Quality Control). Enhancing openness via frequent third-party audits and incorporating climate risk factors will bolster their dedication to sustainable tailings management. Moreover, there is still no formal closure strategy for the Varvara TSF, which is a significant error. Closure planning should start early in the mine's life to ensure long-term stability, environmental remediation, and appropriate financial reserves. Delays in this procedure raise the danger of post-closure consequences and future noncompliance.

To ensure the effectiveness of TSFs, it is crucial to go beyond the global best practices set by ICMM and other organizations and assess the operational aspects and long-term dynamics of these facilities. [Cacciuttolo and Cano \(2023\)](#) conducted a geospatial analysis of six TSFs to determine which facility exhibited the best stability, not just according to reports and standards, but in real-world conditions. According to the authors, TSFs are typically classified according to their tailings discharge methods and the subsequent positioning of the supernatant process water pond, as these elements significantly affect the facility's stability and environmental risk. Tailings management strategies vary in their effectiveness at ensuring TSF stability. In **conservative systems**, tailings are released from the crest or periphery of the dam, forming an elongated beach that strategically places the pond at a secure distance from the dam wall. **Intermediate approaches** discharge tailings along the entire perimeter, centralizing the pond but sometimes allowing it to move closer to the dam. **Non-conservative management** lacks effective beach formation, often resulting in the water pond forming adjacent to the dam, which significantly increases the risk of failure. In the instance of the Varvara TSF ([Figure 21](#)), spatial analysis from 2019 to 2024 reveals that the discharge point is constantly situated not on the dam crest but on the eastern wall of the facility. This layout results in the accumulation of wet tailings surrounding

the discharge zone, creating a beach in that area, while the supernatant pond remains unstable, constantly altering its position and often arriving near the dam. This circumstance contradicts conservative design standards and presents considerable safety issues. The observable presence of water along the dam wall and other containment borders is a concerning sign of possible seepage or inadequate drainage, indicating internal instability. Water in proximity to the structural walls undermines the integrity of the TSF and markedly elevates the danger of dam wall failure. The Varvara TSF has features akin to a **non-conservative tailings management system**, highlighting the imperative for enhanced discharge regulation and structural oversight. Given the site's history - including a previous failure in 2016 - and the inadequate placement of discharge points, Varvara's approach to TSF management appears to fall short of best-practice recommendations.



**Figure 21.** Changes in water pond and wet tailings accumulation with respect to the dam and discharge point over the study period between 2019 and 2024

If we set aside best practices and examine the root cause of TSF failures, it becomes evident that the presence of water in unintended locations within the facility has been the primary factor in almost all recorded incidents throughout mining history. Jeong and Kim (2024) analyzed 147 cases globally and concluded that inadequate water management - including poor drainage,

excessive accumulation, and failure to maintain optimal water levels - compromises the structural integrity of TSFs the most.

Given the significant risks associated with water mismanagement, one may question why a definitive solution has not been widely adopted. In fact, such a solution does exist: thickened discharge and dry stacking (see [Section 2.3](#) and [2.6](#)). Thickened discharge, particularly in the context of tailings management, is a critical process that aims to reduce the water content of tailings to enhance transport efficiency and lower environmental impacts. This process involves thickening tailings to a point where they can be pumped as a viscous slurry, commonly referred to as thickened or paste tailings. One of the primary advantages of thickened discharge is that it significantly increases the stability of the tailings upon deposition, minimizing the risk of water contamination and improving the overall safety of tailings storage facilities ([Javadi et al., 2020](#)). Furthermore, using thickened tailings reduces the volume of water retained in tailings storage, allowing for increased water recovery and recycling back into the process, which is essential in water-scarce regions ([Javadi et al., 2020](#)).

Dry stacking is similarly recognized as a safer and more sustainable alternative to conventional tailings storage. This method dewater tailings, creating a stable, unsaturated material that eliminates the need for water-filled impoundments. As a result, it reduces the facility footprint, enhances water recovery, and significantly lowers the risks of dam failure, liquefaction, and seepage ([Cacciuttolo & Campomanes, 2022](#)). Furthermore, dry stacking minimizes environmental damage by preventing seepage-related contamination and improving stability under seismic conditions ([Wang et al., 2022](#)).

However, both thickened discharge and dry stacking present operational challenges that must be considered for successful implementation. One significant issue with thickened tailings disposal is the propensity for pipe blockages during transport. As the solid concentration increases, the material's yield stress rises, making pipeline transport more difficult. If not properly managed, this can lead to flow disruptions, system downtime, and costly maintenance ([Gao & Fourie, 2015](#); [Cooper & Smith, 2011](#)). Additionally, pipe corrosion and leakage are serious risks, especially when tailings contain chemically reactive substances. These can degrade metal

pipelines, raising concerns over environmental contamination and the need for corrosion-resistant materials or protective coatings (Gao & Fourie, 2015; Thompson, 2017).

In the context of dry stacking, wind erosion is a critical environmental issue. Because the method involves stacking nearly dry tailings in open-air configurations, fine particles are susceptible to becoming airborne under windy conditions. This not only contributes to dust emissions but also poses health and environmental risks in surrounding areas (Dentoni et al., 2021; Furnell et al., 2022). This is especially important for Kazakhstan, where steppe terrain and prevailing winds, particularly in the north and center, create ideal conditions for wind erosion. In such cases, dry stacking becomes less desirable due to the difficulties of maintaining material stability and managing airborne dust. Effective dust reduction methods, such as surface treatments, vegetation cover, or wind barriers, are consequently required, although they may add operational complexity and cost. Furthermore, geotechnical challenges may arise due to variations in moisture content and external climatic factors, which can influence the shear strength and overall stability of the stacked material (Lê & Pabst, 2023; Velten & Gomes, 2020). These operational concerns underscore that while alternative disposal methods are promising, they require rigorous engineering and environmental oversight.

Despite their advantages, thickened discharge and dry stacking remain underutilized due to their high implementation costs and operational disadvantages. These financial and functional constraints explain why many companies continue to favor traditional TSFs, despite their failure risks. Consequently, if the most effective yet costly solutions cannot be widely implemented, it is imperative that mining operations enhance TSF monitoring and management strategies. Given that wet tailings storage requires indefinite structural integrity - because the wet storage of tailings necessitates a dam designed for “forever” - regular maintenance and oversight are crucial. Without these measures, failure is inevitable (Schoenberger, 2016). While the hazards may be less severe than those of radioactive waste, the long-term management of TSFs remains equally critical, particularly in the context of climate change (as discussed in previous sections).

## 6.4. Study Limitations and Data Reliability

Although satellite imagery proved valuable for monitoring surface conditions around the Varvara TSF, several limitations must be acknowledged - particularly those related to spatial resolution and classification accuracy. The Landsat imagery, with a spatial resolution of 30 meters, tends to smooth out fine-scale surface features, which can obscure smaller changes in tailings deposition, erosion channels, or structural deformations. This limitation is especially pronounced in engineered environments like TSFs, where subtle variations can carry significant geotechnical implications (Wang et al., 2019).

In contrast, Sentinel-2 imagery, offering 10–20 meter resolution, provides more granular detail and is better suited for detecting localized surface disturbances and more accurate land cover classification. However, even with improved resolution, spectral confusion can occur - for instance, between tailings, bare soil, and disturbed ground - leading to potential misclassification in supervised or unsupervised analyses (Mazzia et al., 2020; Bamford et al., 2020).

Additional constraints include cloud cover, seasonal variability, and sensor calibration differences, which may impact the temporal consistency and reliability of the datasets. These limitations introduce uncertainty into land cover change detection, especially when remote sensing is not supported by ground-truth verification.

To mitigate these issues, the study prioritized clearer seasonal imagery, applied preprocessing corrections, and cross-referenced satellite-derived patterns with operational and environmental records. TSFs like Varvara are usually located in sensitive or high-risk areas - such as those near population centers, situated in climatically unstable regions, or built on weak geological foundations. These facilities require more detailed and reliable monitoring due to their elevated vulnerability and potential for significant environmental or social consequences in the event of failure. Therefore, future studies in this area would benefit from the use of very high-resolution commercial satellite data and field validation.

Furthermore, it should be mentioned that the estimation of correlation coefficients (Sections 6.1 and 6.2) in this study is based on a limited dataset. Normally, a larger sample size of 30+ data

points is required for more robust statistical analysis. Therefore, the results presented here should be confirmed by future research with additional data points to ensure more reliable conclusions.

## **6.5. Broader Application of Geospatial Monitoring Framework for TSFs**

As outlined in the national TSF inventory results ([Section 5.1](#)), Kazakhstan hosts a significant number of TSFs (121 in total), all of which are situated within arid or semi-arid climate zones. These climatic conditions are characterized by limited precipitation, high evaporation rates, and pronounced temperature fluctuations, which can influence both surface water dynamics and structural stability of tailings storage facilities.

Kazakhstan exhibits a predominantly continental climate, with harsh winters and hot summers - conditions typical of arid and semi-arid regions. Temperatures often plunge well below freezing in winter and exceed 30°C in summer ([Lioubimtseva & Henebry, 2009](#)). These patterns reflect broader climatic trends observed throughout Central Asia, a region that includes Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, and Uzbekistan. This region is largely classified as arid and semi-arid due to consistently high evaporation rates relative to precipitation, making it particularly vulnerable to drought ([Qin et al., 2022](#); [Lioubimtseva & Henebry, 2009](#)). Moreover, the Central Asian climate exhibits significant inter-annual variability, marked by recurring drought and wet cycles driven by large-scale atmospheric processes ([Joyner et al., 2010](#); [Qin et al., 2022](#)). This was demonstrated in the example of Varvara TSF ([Section 6.2](#)), which is extremely responsive to temperature and precipitation variations.

Building on the Varvara case study, this research proposes a generalized geospatial monitoring framework that can be applied to TSFs throughout Kazakhstan and across similarly dry continental regions all over Central Asia. The framework integrates freely available satellite imagery (e.g., Landsat, Sentinel) with meteorological and operational data to identify surface anomalies, monitor tailings deposition, and assess climatic stressors. Periodic change detection analysis can reveal unusual surface wetness or signs of instability, while combining this with temperature and precipitation records helps interpret seasonal and long-term patterns. Facilities

in higher-risk areas - whether due to aging infrastructure, climatic sensitivity, or proximity to communities - can be prioritized using spatial overlays.

The Varvara TSF demonstrates how this scalable and cost-effective monitoring approach can improve site-level awareness and support broader governance of tailings facilities. Implemented at national or regional levels, such a framework could strengthen early warning systems, guide regulatory planning, and foster transboundary collaboration, particularly in areas where on-site inspections are infrequent or constrained by access and resources.

## **7. Conclusions and Recommendations**

This study effectively accomplished its key goals by delivering an extensive geographical analysis of the Varvara TSF from 2019 to 2024. The research utilized remote sensing techniques and climatic-hydrological data to elucidate distinct geographical and temporal patterns in the TSF's wet tailings and supernatant water ponds. The significant enlargement and instability of the water pond, particularly during the spring floods of 2024, highlighted the susceptibility of the TSF to seasonal hydrological stresses and potential hazards of structural failure.

A link was identified between ore production and processing volumes and tailings accumulation, especially during heightened mining activity. Moreover, the study revealed that heightened precipitation and elevated temperatures, consistent with overarching climate patterns in Central Asia, directly affect TSF behavior. These findings underscore the imperative of incorporating environmental variability into TSF design and monitoring systems.

The research filled a significant need in Kazakhstan's mining literature by concentrating on the stability and operating dynamics of TSFs, whereas prior studies primarily highlighted environmental contamination. The incorporation of a national overview of TSFs derived from the UNECE 2021 database further contextualized the Varvara instance within the wider tailings management framework in Kazakhstan.

Based on that, the key recommendations for the Varvara TSF are as follows:

- Institutionalization of mandatory satellite-based monitoring of TSFs across Kazakhstan is essential for the near-real-time detection of alterations in tailings and water pond dynamics. However, limitations in satellite data, such as the coarse spatial resolution of Landsat imagery (30 meters) and potential misclassification in Sentinel-2 imagery due to spectral confusion, should be addressed by using higher-resolution commercial satellite data for more accurate monitoring. These improvements will enhance the detection of fine-scale changes in tailings deposition and surface disturbances.
- Strategically relocate or reengineer discharge points and ponds at the Varvara TSF to enhance the distance from the dam wall and reduce the probability of failure.
- Revise hydrological design standards to address future climate extremes, incorporating increased freeboard margins and upgraded overflow control systems.

And the recommendations applicable at national and international levels are outlined below:

- Establish a comprehensive national TSF registry, leveraging the UNECE mapping initiative, incorporating regular updates, performance evaluations, and publicly accessible data to enhance transparency and facilitate risk communication.
- Perform regular third-party evaluations of TSFs in Kazakhstan, encompassing stability analyses, hydrological modeling, and risk simulations under severe weather scenarios.
- Augment investment in early warning and emergency preparedness systems, particularly for high-risk locations next to towns or vital water bodies.
- Address the study's data limitations by using larger datasets for correlation analysis to validate findings, particularly concerning the impact of temperature and precipitation on TSF behavior.
- Apply the geospatial monitoring framework of this study, combining satellite imagery, meteorological data, and operational records, to other regions (Central Asia) with similar climate conditions for TSF monitoring and regulatory planning, especially where on-site inspections are limited.

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# Appendices

## Appendix A. Structured Analysis of TSFs in Kazakhstan Extracted from UNECE (2021) Map

Number/Order	Name of TSF	Number of TMF on the map	Region (district)	Latitude	Longitude	Chief construction organization	Comments, major construction or materials used	Water Hazard Class	TMF status	Seismic ground and maximum accel.	Flow frequency (100-100)	Factor of safety	Structure material	Depth (m)	Commissioning year	TMF	The range	Region
1	TMF "Kazakhstan 95"	11	Abay region, Khromtau city, 8.5 km to the north	53.2171	68.4870	4.27 Mg, Fe, Si, Ca		2	Active	0.13	1	1.54	concrete	6	2012	11.62	Medium level	Abay
2	TMF "Kazakhstan 95"	12	Abay region, Khromtau city, 8.5 km to the north	53.2428	68.4722	2.8 Mg, Fe, Si, Ca		2	Active	0.13	1	1.18	Rock	8	1986	19.36	Medium level	Abay
3	TMF "Kazakhstan 95"	13	Abay region, Khromtau city, 8.5 km to the north	53.2629	68.5216	2.93 Si, Si, Fe, Al		3	Active	0.13	0	2.79	Non-rock	10	2009	7.3	Low level	Abay
4	TMF "Kazakhstan 95"	14	Abay region, Khromtau city, 8.5 km to the north	53.27196	68.48266	2.07 Mg, Fe, Si, Ca		2	Active	0.13	1	1.25	Rock	8	1987	11.6	Medium level	Abay
5	TMF "Kazakhstan 95"	15	Abay region, Khromtau city, 8.5 km to the north	53.2828	68.55473	2.96 Mg, Fe, Si, Ca		2	Active	0.13	1	1.27	Rock	8	2009	9.96	Medium level	Abay
6	TMF "Kazakhstan 95"	16	Abay region, Khromtau city, 8.5 km to the north	53.29439	68.51722	14.882 Fe, Si, Ca		3	Active	0.13	0	0	Rock	10	2008	10.17	Medium level	Abay
7	TMF "Kazakhstan 95"	17	Abay region, Khromtau city, 8.5 km to the north	53.296162	68.47128	7.4 Fe oxide, Fe oxide, Cu	Water of upper part on permeation concrete	2	Active	0.13	0	2	Non-rock	11	2008	6.87	Medium level	Abay
8	TMF "Kazakhstan 95"	18	Abay region, Khromtau city, 8.5 km to the north	53.29656	68.53722	2.65	Water impregnating water (Fe)	4	Active	0.13	0	0	Rock	8	1972	8.82	Low level	Abay
9	TMF "Kazakhstan 95"	19	Abay region, Khromtau city, 8.5 km to the north	53.28880	68.40389	31.71 Fe oxide, Al oxide	Chert, hydrogels in Fe	4	Active	0.13	0	0	Rock	10	1972	10.49	Medium level	Kostanay
10	TMF "Kazakhstan 95"	20	Abay region, Khromtau city, 8.5 km to the north	53.297102	68.217413	278.2 Fe, Si, Ca	Water of wet magnetic impregnation, Fe, oxides of	4	Active	0.13	0	1.21	Non-rock	8	1984	10.38	Medium level	Abay
11	TMF "Kazakhstan 95"	21	Abay region, Khromtau city, 8.5 km to the north	53.29758	68.22472	0.13	T-20 sand	4	Active	0.01	0	0	Non-rock	8	1984	7.12	Low level	Abay
12	TMF "Kazakhstan 95"	22	Abay region, Khromtau city, 8.5 km to the north	53.21583	68.17012	6.263	Slagging ballings Au	4	Active	0.01	1	1.26	Non-rock	12	2009	9.8	Medium level	Abay
13	TMF "Kazakhstan 95"	23	Abay region, Khromtau city, 8.5 km to the north	53.21324	68.19678	44.051	Technical ballings Au	4	Active	0.01	1	1.26	Non-rock	8	2009	10.65	Medium level	Abay
14	TMF "Kazakhstan 95"	24	Abay region, Khromtau city, 8.5 km to the north	53.20374	68.21084	6.081	Technical water	4	Active	0.01	1	1.16	Non-rock	8	2012	9.78	Medium level	Abay
15	TMF "Kazakhstan 95"	25	Abay region, Khromtau city, 8.5 km to the north	53.20761	71.27189	5.823 Au		4	Active	0.01	0	0	Rock	8	1983	9.77	Low level	Abay, North Kazakhstan
16	TMF "Kazakhstan 95"	26	Abay region, Khromtau city, 8.5 km to the north	52.45643	71.27174	10.918 Au		4	Active	0.01	0	0	Rock	16	1981	10	Medium level	Abay, North Kazakhstan
17	TMF "Kazakhstan 95"	27	Abay region, Khromtau city, 8.5 km to the north	52.5	71.36	15.208 U, Sb		1	Closed	0.01	0	0	Rock	6	1976	12.02	Medium level	Abay
18	TMF "Kazakhstan 95"	28	Abay region, Khromtau city, 8.5 km to the north	52.5	71.34	19.25 U, Sb		1	Active	0.01	0	0	Rock	6	1982	12.39	High level	Abay
19	TMF "Kazakhstan 95"	29	Abay region, Khromtau city, 8.5 km to the north	52.5	71.83	14.16 U, Sb		1	Closed	0.01	0	0	Rock	6	1986	12.15	High level	Abay
20	TMF "Kazakhstan 95"	30	Abay region, Khromtau city, 8.5 km to the north	52.46658	71.23666	6.5 Au		4	Active	0.01	0	0	Rock	8	1982	9.81	Medium level	Abay
21	TMF "Kazakhstan 95"	31	Abay region, Khromtau city, 8.5 km to the north	51.86459	74.30738	66 Au, Ag	Water of upper part permeation Cu, Zn, S	3	Active	0.01	0	0	Non-rock	10	2015	10.95	Medium level	Abay
22	TMF "Kazakhstan 95"	32	Abay region, Khromtau city, 8.5 km to the north	51.47639	78.82778	3.367 Zn, Cu, Fe		3	Active	0.01	0	0	Non-rock	12	1982	10.53	Medium level	Abay
23	TMF "Kazakhstan 95"	33	Abay region, Khromtau city, 8.5 km to the north	52.07778	78.80189	3.911 Au, Ag	2 High hazard	Closed	0.01 (low accel)	0 (No food risk)	0 (Not provided or uncertain)	Non-rock	20	1986	9.6	Medium level	Abay	
24	TMF "Kazakhstan 95"	34	Abay region, Khromtau city, 8.5 km to the north	52.04844	78.85424	2.9 Mg, Cu, Mg, Al	2 High hazard	Active	0.01 (low accel)	0 (No food risk)	0 (Not provided or uncertain)	Non-rock	7	2006	10.38	Medium level	Abay	
25	TMF "Kazakhstan 95"	35	Abay region, Khromtau city, 8.5 km to the north	52.01189	78.82331	2.46 Mg, Ag	2 High hazard	Active	0.01 (low accel)	0 (No food risk)	0 (Not provided or uncertain)	Non-rock	7	2006	10.38	Medium level	Abay	
26	TMF "Kazakhstan 95"	36	Abay region, Khromtau city, 8.5 km to the north	52.26847	77.181424	41.21 Fe, Si, Ca	Slagging oxides of Al, Fe, Si, Ca, Fe	2	Closed	0.01	0	0	Non-rock	10	1984	11.01	Medium level	Abay
27	TMF "Kazakhstan 95"	37	Abay region, Khromtau city, 8.5 km to the north	52.26240	77.28031		Slagging oxides of Al, Fe, Si, Ca, Fe	2	Closed	0.01	0	0	Non-rock	10	1984	11.01	Medium level	Abay
28	TMF "Kazakhstan 95"	38	Abay region, Khromtau city, 8.5 km to the north	52.26240	77.28031		Slagging oxides of Al, Fe, Si, Ca, Fe	2	Closed	0.01	0	0	Non-rock	10	1984	11.01	Medium level	Abay
29	TMF "Kazakhstan 95"	39	Abay region, Khromtau city, 8.5 km to the north	49.78187	84.32893	91.57 Zn, Pb, Cu, Au, Ag	Flotation ballings Fe, Al	2	Active	0.06	0	1.8	Rock	10	1988	11.96	Medium level	Abay
30	TMF "Kazakhstan 95"	40	Abay region, Khromtau city, 8.5 km to the north	53.36166	83.99817	86 Au, Zn, Mn, Cu, Pb		2	Closed	0.07	0	0	Rock	11	1983	10.93	Medium level	Abay
31	TMF "Kazakhstan 95"	41	Abay region, Khromtau city, 8.5 km to the north	53.36466	83.99188	111.8 Au, Zn, Mn, Cu, Pb		2	Active	0.78	0	1.32	Rock	12	1979	13.05	High level	Abay
32	TMF "Kazakhstan 95"	42	Abay region, Khromtau city, 8.5 km to the north	49.78424	83.29337	3.7 Fe	ABR, manganese, quartz	2	Closed	0.6	0	0	Rock	6	1981	10.57	Medium level	Abay
33	TMF "Kazakhstan 95"	43	Abay region, Khromtau city, 8.5 km to the north	53.36339	81.90417	12.301 Ca, Zn, Pb, Au, Ag	Concentration ballings	2	Active	0.36	0	0	Non-rock	8	1980	12.09	High level	Abay
34	TMF "Kazakhstan 95"	44	Abay region, Khromtau city, 8.5 km to the north	53.37896	81.89436	18.765 Ca, Zn, Pb, Au, Ag	Concentration ballings	2	Active	0.36	0	0	Non-rock	8	1980	12.27	High level	Abay
35	TMF "Kazakhstan 95"	45	Abay region, Khromtau city, 8.5 km to the north	53.26813	82.28117	13.888 Ca, Zn, Pb, Au, Ag	Concentration ballings	2	Closed	0.45	0	0	Unfilled	8	1981	11.14	Medium level	Abay
36	TMF "Kazakhstan 95"	46	Abay region, Khromtau city, 8.5 km to the north	53.13031	82.48819	17.153 Ca, Zn, Pb, Au, Ag	Concentration ballings	2	Active	0.54	0	0	Unfilled	8.02	1945	12.24	High level	East Kazakhstan
37	TMF "Kazakhstan 95"	47	Abay region, Khromtau city, 8.5 km to the north	48.5889	78.51028	8.928	Red waste containing iron	4	Active	1.18	1	1	Non-rock	10	2016	11	Medium level	Abay
38	TMF "Kazakhstan 95"	48	Abay region, Khromtau city, 8.5 km to the north	53.32446	81.28049		Cu, Zn, Pb, Au, Ag (Concentration ballings)	2	Active	0.57	0	0	Non-rock	4.5	1983	6.57	Low level	Abay
39	TMF "Kazakhstan 95"	49	Abay region, Khromtau city, 8.5 km to the north	53.31338	82.80277	2.82	Unfilled	1	Active	0.65	0	1.7	Non-rock	8	2011	9.80	Medium level	Abay
40	TMF "Kazakhstan 95"	50	Abay region, Khromtau city, 8.5 km to the north	53.21427	82.81046	2.207	Unfilled	1	Active	0.55	0	1.86	Non-rock	6	1987	10.35	Medium level	Abay
41	TMF "Kazakhstan 95"	51	Abay region, Khromtau city, 8.5 km to the north	53.21075	82.80382	4.16	Unfilled	1	Active	0.65	0	1.43	Non-rock	6	2004	10.62	Medium level	Abay
42	TMF "Kazakhstan 95"	52	Abay region, Khromtau city, 8.5 km to the north	53.21644	82.80396	3.98	Unfilled	1	Active	0.55	0	1.49	Non-rock	6	2014	9.79	High level	Abay
43	TMF "Kazakhstan 95"	53	Abay region, Khromtau city, 8.5 km to the north	53.03844	82.75278	0.4	Slurry T, Mg	4	Closed	0.57	0	0	Non-rock	4.5	1985	7.6	Low level	Abay
44	TMF "Kazakhstan 95"	54	Abay region, Khromtau city, 8.5 km to the north	53.02639	82.78263	0.204	Slurry T, Mg	4	Active	0.57	0	1.72	Non-rock	6.01	1979	7.52	Low level	Abay
45	TMF "Kazakhstan 95"	55	Abay region, Khromtau city, 8.5 km to the north	53.04722	82.78222	0.388	Slurry T, Mg	4	Active	0.57	0	0	Non-rock	4.5	1983	6.57	Low level	Abay
46	TMF "Kazakhstan 95"	56	Abay region, Khromtau city, 8.5 km to the north	53.33835	82.83933	6.4	Cartridge ballings Cu, Zn, Pb, Au, Ag	Water Hazard Class 2	Active		Flow frequency 100-100	Factor of Safety 2.0	Rock	12	Commissioning year 2016	716.8.61	Low level	Abay
47	TMF "Kazakhstan 95"	57	Abay region, Khromtau city, 8.5 km to the north	48.77429	83.88104		Solid waste containing SO <sub>2</sub> , Al <sub>2</sub> O <sub>3</sub> , CaO, Fe <sub>2</sub> O <sub>3</sub> , MgO	4	Active	0.81	0	0	Non-rock	8.5	2006	6.1	Low level	Abay
48	TMF "Kazakhstan 95"	58	Abay region, Khromtau city, 8.5 km to the north	48.77882	81.88888		Waste (slag) and liquid (effluent)	4	Active	0.38	1	1.27	Rock	10	2018	6.27	Low level	Abay
49	TMF "Kazakhstan 95"	59	Abay region, Khromtau city, 8.5 km to the north	48.71182	81.88888		Sludge (solid and liquid) (effluent)	4	Active	0.38	1	1.27	Rock	10	2018	6.58	Low level	Abay
50	TMF "Kazakhstan 95"	60	Abay region, Khromtau city, 8.5 km to the north	53.04145	79.78465	1.088 Mg, Si, Zn, Pb, Cu		2	Active	0.16	0	0	Non-rock	8	2008	10.04	Medium level	Abay
51	TMF "Kazakhstan 95"	61	Abay region, Khromtau city, 8.5 km to the north	53.04281	79.74127	6.038 Pb, Zn, K	Cartridge ballings silica, hydrogels, Cu, Fe, Mg, Ca	2	Active	0.16	0	0	Non-rock	8	2008	9.83	Low level	Abay
52	TMF "Kazakhstan 95"	62	Abay region, Khromtau city, 8.5 km to the north	53.03938	79.74253	5.262 Pb, Zn, K	Cartridge ballings silica, hydrogels, Cu, Fe, Mg, Ca	2	Active	0.16	0	0	Non-rock	8	2008	9.79	Low level	Abay
53	TMF "Kazakhstan 95"	63	Abay region, Khromtau city, 8.5 km to the north	53.0411	79.74381	5.691 Pb, Zn, K	Cartridge ballings silica, hydrogels, Cu, Fe, Mg, Ca	2	Active	0.16	0	0	Non-rock	8	2013	9.82	Medium level	Abay
54	TMF "Kazakhstan 95"	64	Abay region, Khromtau city, 8.5 km to the north	53.04415	79.78202	5.063 Pb, Zn, K	Cartridge ballings silica, hydrogels, Cu, Fe, Mg, Ca	2	Active	0.16	0	0	Non-rock	8	2013	8.83	Low level	Abay
55	TMF "Kazakhstan 95"	65	Abay region, Khromtau city, 8.5 km to the north	53.04277	79.78208	5.063 Pb, Zn, K	Cartridge ballings silica, hydrogels, Cu, Fe, Mg, Ca	2	Active	0.16	0	0	Non-rock	8	2013	8.83	Low level	Abay
56	TMF "Kazakhstan 95"	66	Abay region, Khromtau city, 8.5 km to the north	53.04181	79.78408	5.178 Mg, Si, Zn, Pb, Cu	Cartridge ballings silica, hydrogels, Cu, Fe, Mg, Ca	2	Active	0.16	0	0	Non-rock	8	2017	9.06	Low level	Abay
57	TMF "Kazakhstan 95"	67	Abay region, Khromtau city, 8.5 km to the north	53.04287	79.78404	5.022 Pb, Zn, K	Cartridge ballings silica, hydrogels, Cu, Fe, Mg, Ca	2	Active	0.16	0	0	Non-rock	8	2017	8.34	Low level	Abay

Project ID	Project Name	Location	Coordinates	Area (km²)	Volume (m³)	Material	Status	Start	End	Depth (m)	Height (m)	Speed (m/s)	Notes			
81	Manufacturing plant "Kazakhstan Copper"	Kangarskiy region, Karkaraly industrial zone	49.288708, 75.787891	4.915	10,000	Tailings of polymetallic concentrate: Zn, Cu, Ni, Pb, Fe, Ag, Au, Cd, Co, Mn, Mo, Se, Te, U, V, W, Bi, Br, Ga, Ge, In, Ir, K, Li, Mg, N, Na, Nb, Ni, Pd, Pt, Rb, S, Sb, Sn, Sr, Ta, Tl, Th, U, Zr, Hf, Y, Zn	2 Active	0.01	1	1.28	8	2012	11.89 Medium level			
82	TMF of LLC "Kazakhstan Copper"	Kangarskiy region, Aktogay district, 30 km north of the railway station Aktogay	47.548537, 75.791113	1.422	1,000	Ag, Au, Cu, Ni, Pb, Fe, Ag, Au, Cd, Co, Mn, Mo, Se, Te, U, V, W, Bi, Br, Ga, Ge, In, Ir, K, Li, Mg, N, Na, Nb, Ni, Pd, Pt, Rb, S, Sb, Sn, Sr, Ta, Tl, Th, U, Zr, Hf, Y, Zn	2 Active	0.06	0	0	0	Non-rock	10	2014	12.15 Medium level	
83	TMF of LLC "Kazakhstan Copper"	Kangarskiy region, Zharyn Zaur district, village Achal	47.787075, 75.974741	17.25	10,000	Ag, Au, Cu, Ni, Pb, Fe, Ag, Au, Cd, Co, Mn, Mo, Se, Te, U, V, W, Bi, Br, Ga, Ge, In, Ir, K, Li, Mg, N, Na, Nb, Ni, Pd, Pt, Rb, S, Sb, Sn, Sr, Ta, Tl, Th, U, Zr, Hf, Y, Zn	2 Active	0.01	0	0	0	Non-rock	10	1996	12.20 High level	
84	TMF of LLC "Kazakhstan Copper"	Kangarskiy region, Buldakh district, 10 km north of the village Achal	49.634444, 74.893292	280.0	1,000	Tailings of copper ore concentrate: Cu, Pb, Zn, Ni, Co, Fe, Ag, Au, Cd, Co, Mn, Mo, Se, Te, U, V, W, Bi, Br, Ga, Ge, In, Ir, K, Li, Mg, N, Na, Nb, Ni, Pd, Pt, Rb, S, Sb, Sn, Sr, Ta, Tl, Th, U, Zr, Hf, Y, Zn	3 Active	0.08	0	0	0	Non-rock	12	1937	12.42 High level	
85	TMF of LLC "Kazakhstan Copper"	Kangarskiy region, 8 km to the west of the village Achal	49.018203, 75.961489	1.3	1,000	Pb, Ni, Cu, Ag	2 Active	0.08	0	0	0	Non-rock	8	1995	10.11 Medium level	
86	TMF of LLC "Kazakhstan Copper"	Kangarskiy region, Aktyu district, 6 km from the village Achal	49.64006, 72.899305	8	1,000	Fe, Zn, Pb, Ag	4 Closed	0.01	0	0	0	Non-rock	8	1960	8.78 Low level	
87	TMF of LLC "Kazakhstan Copper"	Kangarskiy region, Aktyu district, 30 km from the village Achal	49.842207, 72.828208	13	1,000	Fe, Zn, Pb, Ag	4 Active	0.01	0	0	0	Non-rock	8	2017	9 Low level	
88	TMF of LLC "Kazakhstan Copper"	Kangarskiy region, Aktyu district, 30 km from the village Achal	49.83071, 73.07144	0.932	1,000	Fe, Zn, Pb, Ag	4 Active	0.01	0	0	0	Non-rock	18.3	2007	7.77 Low level	
89	TMF of LLC "Kazakhstan Copper"	Kangarskiy region, Aktyu district, 30 km from the village Achal	50.017553, 73.028288	14.884	1,000	Fe, Zn, Pb, Ag	2 Active	0.01	0	0	0	Non-rock	9	1993	11.17 Medium level	
90	TMF of LLC "Kazakhstan Copper"	Kangarskiy region, Aktyu district, 30 km from the village Achal	50.218699, 73.07144	11.207	1,000	Fe, Zn, Pb, Ag	3 Active	0.01	1	1.3	8	2013	11.04 Medium level			
91	TMF of LLC "Kazakhstan Copper"	Kangarskiy region, Aktyu district, 30 km from the village Achal	50.018108, 73.018108	19	1,000	Fe, Zn, Pb, Ag	2 Closed	0.01	0	0	0	Non-rock	9	1990	10.28 Medium level	
92	TMF of LLC "Kazakhstan Copper"	Kangarskiy region, Aktyu district, 30 km from the village Achal	49.841191, 73.128315	0.533	1,000	Fe, Zn, Pb, Ag	4 Active	0.01	0	0	0	Non-rock	18.3	1976	8.73 Low level	
93	TMF of LLC "Kazakhstan Copper"	Kangarskiy region, Aktyu district, 30 km from the village Achal	49.238008, 70.731127	0.203	1,000	Mine recycling water	4 Active	0.01	0	1.1	Non-rock	10	2007	9.7 Low level		
94	TMF of LLC "Kazakhstan Copper"	Kangarskiy region, Aktyu district, 30 km from the village Achal	49.273448, 70.198564	0.308	1,000	Sludge of mangan	3 Closed	0.01	0	1.1	Non-rock	10	2007	7.61 Low level		
95	TMF of LLC "Kazakhstan Copper"	Kangarskiy region, Aktyu district, 30 km from the village Achal	49.280136, 70.129134	0.716	1,000	Sludge of lead	2 Active	0.01	0	1.1	Non-rock	10	2000	9.80 Medium level		
96	TMF of LLC "Kazakhstan Copper"	Kangarskiy region, Aktyu district, 30 km from the village Achal	49.277112, 70.141389	0.408	1,000	Sludge of mangan	3 Active	0.01	0	1.1	Non-rock	10	2000	8.86 Low level		
97	TMF of LLC "Kazakhstan Copper"	Kangarskiy region, Aktyu district, 30 km from the village Achal	47.719288, 67.854382	143.847	1,000	Tailings of copper ore concentrate: Cu, Pb, Zn, Ni, Co, Fe, Ag, Au, Cd, Co, Mn, Mo, Se, Te, U, V, W, Bi, Br, Ga, Ge, In, Ir, K, Li, Mg, N, Na, Nb, Ni, Pd, Pt, Rb, S, Sb, Sn, Sr, Ta, Tl, Th, U, Zr, Hf, Y, Zn	2 Active	0.01	1	1.38	13	2008	12.18 High level			
98	TMF of LLC "Kazakhstan Copper"	Kangarskiy region, Aktyu district, 30 km from the village Achal	47.779063, 67.838363	595.296	1,000	Tailings of copper ore concentrate: Cu, Pb, Zn, Ni, Co, Fe, Ag, Au, Cd, Co, Mn, Mo, Se, Te, U, V, W, Bi, Br, Ga, Ge, In, Ir, K, Li, Mg, N, Na, Nb, Ni, Pd, Pt, Rb, S, Sb, Sn, Sr, Ta, Tl, Th, U, Zr, Hf, Y, Zn	2 Closed	0.01	0.01	1.33	13	1964	13.77 High level			
99	TMF of LLC "Kazakhstan Copper"	Kangarskiy region, Aktyu district, 30 km from the village Achal	47.873874, 67.878267	43.874	1,000	Tailings of copper ore concentrate: Cu, Pb, Zn, Ni, Co, Fe, Ag, Au, Cd, Co, Mn, Mo, Se, Te, U, V, W, Bi, Br, Ga, Ge, In, Ir, K, Li, Mg, N, Na, Nb, Ni, Pd, Pt, Rb, S, Sb, Sn, Sr, Ta, Tl, Th, U, Zr, Hf, Y, Zn	2 Active	0.01	0.01	0.2	8	1985	13.84 High level			
100	TMF of LLC "Kazakhstan Copper"	Kangarskiy region, Aktyu district, 30 km from the village Achal	43.527743, 66.541136	2.3	1,000	Waste of hydrochloric acid and treatment of non-ferrous metal ore	3 Closed	0.05	0.01	1	0	Unfilled	0.01	1951	10.36 Medium level	
101	TMF of LLC "Kazakhstan Copper"	Kangarskiy region, Aktyu district, 30 km from the village Achal	43.918879, 66.482443	63.48	1,000	Sludge containing phosphorus	2 Closed	0.08	0.01	0	0	Rock	20	1960	11.8 Medium level	
102	TMF of LLC "Kazakhstan Copper"	Kangarskiy region, Aktyu district, 30 km from the village Achal	42.262214, 68.719168	0.1	1,000	Sludge containing phosphorus	1 Closed	2.7	0.01	0	0	Unfilled	8	1964	11 Medium level	
103	TMF of LLC "Kazakhstan Copper"	Kangarskiy region, Aktyu district, 30 km from the village Achal	42.262214, 68.719168	0.1	1,000	Sludge containing phosphorus	1 Active	2.7	0.01	0	0	Unfilled	8	1964	15.46 High level	
104	TMF of LLC "Kazakhstan Copper"	Kangarskiy region, Aktyu district, 30 km from the village Achal	42.262214, 68.719168	0.1	1,000	Sludge containing phosphorus	1 Active	2.7	0.01	0	0	Unfilled	8	1964	14.20 High level	
105	TMF of LLC "Kazakhstan Copper"	Kangarskiy region, Aktyu district, 30 km from the village Achal	42.262214, 68.719168	0.1	1,000	Sludge containing phosphorus	1 Active	2.7	0.01	0	0	Unfilled	8	1964	14.90 High level	
106	TMF of LLC "Kazakhstan Copper"	Kangarskiy region, Aktyu district, 30 km from the village Achal	42.262214, 68.719168	0.1	1,000	Sludge containing phosphorus	1 Active	2.7	0.01	0	0	Unfilled	8	1964	14.23 High level	
107	TMF of LLC "Kazakhstan Copper"	Kangarskiy region, Aktyu district, 30 km from the village Achal	42.262214, 68.719168	0.1	1,000	Sludge containing phosphorus	1 Closed	2.7	0.01	0	0	Unfilled	8	1964	11 Medium level	
108	TMF of LLC "Kazakhstan Copper"	Kangarskiy region, Aktyu district, 30 km from the village Achal	42.262214, 68.719168	0.1	1,000	Sludge containing phosphorus	2 Rehabilitated	1.53	0.01	0	0	Rock	10	1960	10.89 Medium level	
109	TMF of LLC "Kazakhstan Copper"	Kangarskiy region, Aktyu district, 30 km from the village Achal	43.133205, 70.517211	8.1	1,000	Mine water	4 Active	1.58	0.01	0	0	Unfilled	6	1963	10.91 Medium level	
110	TMF of LLC "Kazakhstan Copper"	Kangarskiy region, Aktyu district, 30 km from the village Achal	42.908708, 71.333066	0.4	1,000	Domestic wastewater and cleaned wastewater	Water Hazard Class 4	Domestic wastewater and cleaned wastewater	0	0	0	0	Unfilled	7	Commissioning year: 1978	10.86 Medium level
111	TMF of LLC "Kazakhstan Copper"	Kangarskiy region, Aktyu district, 30 km from the village Achal	42.860795, 71.328488	0.038	1,000	Clarified fraction of waste of yellow phosphorus production	3 Active	2.73	0.01	1	0	Non-rock	7	1978	10.96 Medium level	
112	TMF of LLC "Kazakhstan Copper"	Kangarskiy region, Aktyu district, 30 km from the village Achal	42.860003, 71.328474	0.032	1,000	Industrial wastewater	4 Active	2.73	0.01	1	0	Non-rock	7	1978	9.51 Low level	
113	TMF of LLC "Kazakhstan Copper"	Kangarskiy region, Aktyu district, 30 km from the village Achal	42.8592, 71.328277	0.05	1,000	Lime-soda sludge	4 Active	2.73	0.01	1	0	Non-rock	7	1991	8.7 Low level	
114	TMF of LLC "Kazakhstan Copper"	Kangarskiy region, Aktyu district, 30 km from the village Achal	42.859145, 71.328264	0.05	1,000	Lime-soda sludge	4 Rehabilitated	2.73	0.01	1	0	Non-rock	7	1991	7.7 Low level	
115	TMF of LLC "Kazakhstan Copper"	Kangarskiy region, Aktyu district, 30 km from the village Achal	42.859145, 71.328264	0.017	1,000	Lime-soda sludge	4 Active	9.41	0.01	1	0	Non-rock	8	1961	4.71 Low level	
116	TMF of LLC "Kazakhstan Copper"	Kangarskiy region, Aktyu district, 30 km from the village Achal	42.85918, 71.328213	0.017	1,000	Lime-soda sludge	4 Active	2.83	0.01	1	0	Non-rock	8	1991	8.23 Low level	
117	TMF of LLC "Kazakhstan Copper"	Kangarskiy region, Aktyu district, 30 km from the village Achal	42.859184, 71.328214	0.038	1,000	Lime-soda sludge	4 Active	2.83	0.01	1	0	Non-rock	8	1978	9.37 Low level	
118	TMF of LLC "Kazakhstan Copper"	Kangarskiy region, Aktyu district, 30 km from the village Achal	42.860225, 71.327136	0.29	1,000	Domestic wastewater and cleaned wastewater	4 Active	2.74	0.01	1	0	Non-rock	7	1978	10.41 Medium level	
119	TMF of LLC "Kazakhstan Copper"	Kangarskiy region, Aktyu district, 30 km from the village Achal	42.91424, 71.891816	0.078	1,000	Waste of yellow phosphorus production	3 Active	2.8	0.01	1	0	Non-rock	9.2	1991	9.88 Medium level	
120	TMF of LLC "Kazakhstan Copper"	Kangarskiy region, Aktyu district, 30 km from the village Achal	71.005581, 0.1	0.1	1,000	Waste of yellow phosphorus production	Water Hazard Class 3	Waste of yellow phosphorus production	0	0	0	0	Unfilled	9.2	Commissioning year: 1991	10 Medium level
121	TMF of LLC "Kazakhstan Copper"	Kangarskiy region, Aktyu district, 30 km from the village Achal	42.858088, 71.328474	0.033	1,000	Waste of yellow phosphorus production	3 Active	2.77	0.01	1	0	Non-rock	8	1991	9.31 Low level	
122	TMF of LLC "Kazakhstan Copper"	Kangarskiy region, Aktyu district, 30 km from the village Achal	42.860482, 71.328435	0.05	1,000	Waste of yellow phosphorus production	3 Active	2.77	0.01	1	0	Non-rock	8	1991	9.7 Low level	
123	TMF of LLC "Kazakhstan Copper"	Kangarskiy region, Aktyu district, 30 km from the village Achal	42.859331, 71.328352	0.038	1,000	Waste of yellow phosphorus production	3 Active	2.78	0.01	1	0	Non-rock	10	1978	10.54 Medium level	
124	TMF of LLC "Kazakhstan Copper"	Kangarskiy region, Aktyu district, 30 km from the village Achal	42.848791, 71.319123	0.016	1,000	Waste of yellow phosphorus production	3 Active	2.78	0.01	1	0	Non-rock	10	1978	10.2 Medium level	
125	TMF of LLC "Kazakhstan Copper"	Kangarskiy region, Aktyu district, 30 km from the village Achal	42.901157, 71.319184	0.016	1,000	Waste of yellow phosphorus production	3 Active	2.88	0.01	1	0	Non-rock	6	1978	10.19 Medium level	
126	TMF of LLC "Kazakhstan Copper"	Kangarskiy region, Aktyu district, 30 km from the village Achal	42.901308, 71.321217	0.016	1,000	Waste of yellow phosphorus production	3 Active	2.88	0.01	1	0	Non-rock	6	1978	10.19 Medium level	
127	TMF of LLC "Kazakhstan Copper"	Kangarskiy region, Aktyu district, 30 km from the village Achal	42.947711, 71.252879	0.28	1,000	Phosphogypsum	4 Active	2.81	0.01	1	1.2	Non-rock	6	1988	10.41 Medium level	
128	TMF of LLC "Kazakhstan Copper"	Kangarskiy region, Aktyu district, 30 km from the village Achal	42.848791, 71.324247	0.32	1,000	Phosphogypsum	4 Active	2.81	0.01	1	1.2	Non-rock	6	1988	10.51 Medium level	
129	TMF of LLC "Kazakhstan Copper"	Kangarskiy region, Aktyu district, 30 km from the village Achal	42.848791, 71.328359	0.4	1,000	Phosphogypsum	4 Active	2.81	0.01	1	1.2	Non-rock	6	1991	9.6 Low level	
130	TMF of LLC "Kazakhstan Copper"	Kangarskiy region, Aktyu district, 30 km from the village Achal	42.848791, 71.328359	0.4	1,000	Phosphogypsum	4 Active	2.81	0.01	1	1.2	Non-rock	6	1991	9.6 Low level	
131	TMF of LLC "Kazakhstan Copper"	Kangarskiy region, Aktyu district, 30 km from the village Achal	42.848791, 71.328359	0.4	1,000	Phosphogypsum	4 Active	2.81	0.01	1	1.2	Non-rock	6	1991	9.6 Low level	
132	TMF of LLC "Kazakhstan Copper"	Kangarskiy region, Aktyu district, 30 km from the village Achal	42.848791, 71.328359	0.4	1,000	Phosphogypsum	4 Active	2.81	0.01	1	1.2	Non-rock	6	1991	9.6 Low level	
133	TMF of LLC "Kazakhstan Copper"	Kangarskiy region, Aktyu district, 30 km from the village Achal	42.848791, 71.328359	0.4	1,000	Phosphogypsum	4 Active	2.81	0.01	1	1.2	Non-rock	6	1991	9.6 Low level	
134	TMF of LLC "Kazakhstan Copper"	Kangarskiy region, Aktyu district, 30 km from the village Achal	42.848791, 71.328359	0.4	1,000	Phosphogypsum	4 Active	2.81	0.01	1	1.2	Non-rock	6	1991	9.6 Low level	
135	TMF of LLC "Kazakhstan Copper"	Kangarskiy region, Aktyu district, 30 km from the village Achal	42.848791, 71.328359	0.4	1,000	Phosphogypsum	4 Active	2.81	0.01	1	1.2	Non-rock	6	1991	9.6 Low level	
136	TMF of LLC "Kazakhstan Copper"	Kangarskiy region, Aktyu district, 30 km from the village Achal	42.848791, 71.328359	0.4	1,000	Phosphogypsum	4 Active	2.81	0.01	1	1.2	Non-rock	6	1991	9.6 Low level	
137	TMF of LLC "Kazakhstan Copper"	Kangarskiy region, Aktyu district, 30 km from the village Achal	42.848791, 71.328359	0.4	1,000	Phosphogypsum	4 Active	2.81	0.01	1	1.2	Non-rock	6	1991	9.6 Low level	
138	TMF of LLC "Kazakhstan Copper"	Kangarskiy region, Aktyu district, 30 km from the village Achal	42.848791, 71.328359	0.4	1,000	Phosphogypsum	4 Active	2.81	0.01	1	1.2	Non-rock	6	1991	9.6 Low level	
139	TMF of LLC "Kazakhstan Copper"	Kangarskiy region, Aktyu district, 30 km from the village Achal	42.848791, 71.328359	0.4	1,000	Phosphogypsum	4 Active	2.81	0.01	1	1.2	Non-rock	6	1991	9.6 Low level	
140	TMF of LLC "Kazakhstan Copper"	Kangarskiy region, Aktyu district, 30 km from the village Achal	42.848791, 71.328359	0.4	1,000	Phosphogypsum	4 Active	2.81	0.01	1	1.2	Non-rock	6	1991	9.6 Low level	



mm												
Average Monthly Precipitation, mm	24.0	31.5	30.7	26.9	25.8	23.9	36.1	18.3	25.6	40.5	39.1	

**Appendix C.** Annual Temperature Changes Data at Tobol Weather Station ([KazHydroMet](#)), 2014–2024

Yearly Average Temperature Changes at Tobol Station, KazHydroMet													
Year/ Month	January	February	March	April	May	June	July	August	September	October	November	December	Yearly Average
2024	-14.8	-14.6	-7.3	10.1	10.9	21.4	20.4	16.9	11.5	4.1	-3.4	-7.1	4.01
2023	-14.6	-14	-2.9	7.6	15.7	19.1	22.7	18.5	12.8	6	0.5	-11.3	5.01
2022	-14.4	-10.6	-10.5	9.3	13	18	21.4	20.3	14.1	3.6	-7.8	-15.4	3.42
2021	-16.1	-14.4	-8.5	6	19.9	21.2	21.6	22.1	10.8	5.1	-5.8	-9.9	4.33
2020	-6.7	-8.5	0.1	7.2	16.8	17.7	22.9	19.6	11.8	5.1	-6.7	-13.8	5.46
2019	-15.9	-15.7	-2.4	5.4	15.4	18.7	22.9	19	10.2	6.9	-7.2	-10.2	3.93
2018	-18.7	-15.8	-10.7	4.2	11.7	16.3	21.8	18.1	13.2	6.1	-5.2	-15.9	2.09
2017	-13.2	-15.2	-7.3	5.4	13.1	18	19.5	20.2	12.3	2.5	-1	-13.4	3.41
2016	-18	-7.9	-4.7	8.4	14.1	18.1	20	22.7	12.4	1.5	-9.3	-15.1	3.52
2015	-14.3	-12.9	-7.6	4.8	14.6	21.8	20	17	13.2	2.5	-5.7	-7.2	3.85
2014	-16	-18.1	-4.4	3.5	17.2	21.2	16.9	21.3	10.6	2.6	-5.6	-9.3	3.33