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Article

Use of Submarine Tailings Disposal as Alternative Tailings Management System

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Abstract: The importance of the mining/milling industry in increasing the growth level and welfare of countries is quite high. However, at the end of mining/milling processes, huge amounts of waste (often known as tails) are inevitably produced that have no economic value and can even be considered dangerous due to some heavy metals they contain. These tails are highly problematic due to both their volume (difficult to manage environmentally) and toxicity (potential to cause acid/leach waters) and need to be handled outside of existing disposal methods. This article presents the effective and sustainable handling and application of tails resulting from the enrichment of copper–zinc ores, which are actively engaged in metallic mining activities in the northeast of Türkiye, with the submarine tails disposal (STD) method. In the mining operation under study, some (~55–60 wt.%) of the tails are employed as underground fill, even though the residual part is disposed of by the STD method. The characterization of ore beneficiation tails, their transportation to the subsea via a pipeline system, and discharge monitoring results are detailed in the present investigation. According to the limitations which are indicated by the Turkish Control of Water Contamination regulation, the concentration of Pb-Cu found in the results was under the allowable limit of 0.05 mg/L. The allowed 2 mg/L limit for Zn was not surpassed mainly by the concentration found in the collected samples. pH values were almost above the allowable limit of pH > 5. The results reveal that the STD technique works quite well as an integrated mine tails method in the mine under study.

Keywords: tails; submarine placement; waste treatment; mining; characterization; monitoring

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1. Introduction

Even though mining activities greatly contribute to the development of modern societies, they also lead inevitably to the formation of bulky sizes of undesirable wastes [1]. It will continue progressively because ore grade decreases from richer–easier to processed ore and becomes increasingly scarce for sustainable/profitable operations [2]. A major drop in the metal content of ores can cause increases in the rate of tails/metal production [3]. If wastes are not properly managed, due to their sheer quantities and toxicities, they may lead to several forms of environmental (air, water, and land) pollution, such as acid/leachate formations [4,5]. There are some methods of tails management which can remove these environmental impacts [6,7]. Tails are usually managed with four key options: (i) disposal into surface tail dams or impoundments [8], (ii) discharge into deep-sea zones or lakes [9], (iii) backfill into underground mined-out voids [10], and (iv) the placement of tails filtered in a self-supporting stack, also known as dry-stacking [11]. One can generally say that many modern mines worldwide employ land-based systems for sustainable tails management [12]. However, there is a feasible alternative (stated as submarine tails disposal (STD), also termed deep-sea or marine tails disposal) to land-based tails disposal methods [13]. This relatively different waste disposal method is much lower in cost than the classical method of storing waste above ground in dams built adjacent to the mine [14]. It is well used in zones with topographies of high seismic activity and landslides and in climates with high rainfall and low sun exposure [15,16]. For this reason, the STD method, as a sustainable, profitable, and effective waste disposal technique, is successfully implemented by some mines worldwide [17,18]. As mentioned by Mining Watch Canada [19], the STD system has a high degree of risk for substantial, unpredicted, and long-term impacts on the deep-sea ecosystem, and the scientific community lacks knowledge on this subject. STD is mostly employed for areas where topographic and climatic manacles are two key hindrances of fabricating a suitable mining waste barrage at the surface. In terms of economy and durability, STD offers an exclusive technique of secure clearance of the process tails created in deep-sea areas. This technique, whose schematic view is presented in Figure 1, consists characteristically of a main tank that collects and discharges tails/dirty water at the mine site, a mixing tank that blends these discharges from the mine with seawater, and a pipeline that finally discharges solid/liquid waste gathered/blended in this tank into the deep point of the sea.

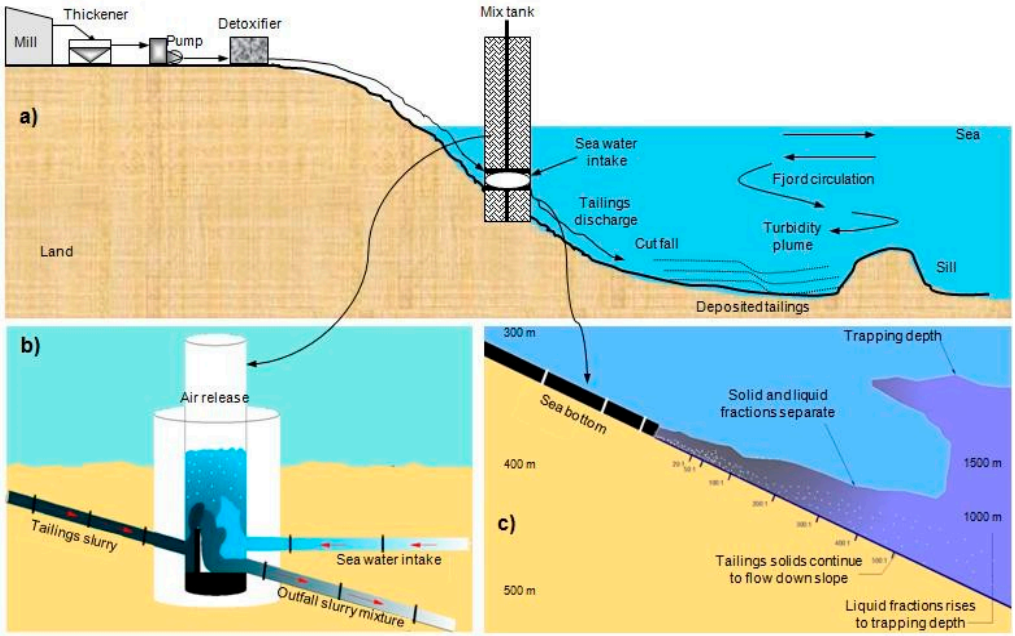

Figure 1. View of (**a**) STD, (**b**) a tank for mixing tail/dirty water, and (**c**) pipe laid at sea's bottom.

Storage of tails via the STD system is indeed considered a more secure way since sulfide-rich minerals such as pyrite are geochemically stable under the deep-sea conditions of the Black Sea [20,21]. This paper explains the aspects and application of the STD system and presents results of the experiments needed for assessing the technique's efficiency. The original contribution of this research is that it analyzes the potential impacts of the STD method by evaluating the data related to the tails' properties in the studied Cu-Zn mine. Therefore, this study focuses on the specific properties of the tails disposed into the submarine by assessing the chemical characteristics, such as pH, metal contents, and total suspended solids. From a general point of view, this study aims to encourage researchers to further investigate the sustainable management of tails and understand its importance for the mining sector's viable progress.

2. Materials and Methods

2.1. Mine's Portrayal

The mining site under study is located in the Black Sea coast of Türkiye. In total, 1.2M tons of ore is extracted from the mine, where the first Cu and Zn concentrates were produced in 1994, to produce approximately 220,000 tons of Cu/Zn concentrate annually. A flotation method is used for ore processing, and the average Cu and Zn grades fed to the milling facility are 3.2% and 6.3%, respectively. While the Cu grade is increased to an average of 20% with a recovery of 76%, the Zn grade is increased to an average of 49% with a recovery of 71%. The Average Cu and Zn recoveries over the last two decades have been 82% and 71%, respectively.

Huge quantities of highly acidic mining waste are created indispensably during mineral processing. Nearly 55% of tails created are driven underground by pumps as backfill, while the remaining tails (45%) are put to sea at a depth of 298 m, 2.85 km away from the land. There are two 7.25 km long pipes (tails and contaminated water) between the mining site, where tails and contaminated water are collected, and the point where they are safely discharged into the sea. Contaminated water consists of dirty water collected in mud pools in underground and aboveground mine sites and water discharged from the upper streams (overflows) of thickeners. The remaining non-functional tails after filling and the existing contaminated waters are thoroughly blended with seawater in the mixing tank built on land near the sea. Since the densities of tails and seawater are different from each other, they are first mixed in this tank and then stored under the sea through pipes laid under the submarine. Figure 2 shows the effective disposal of contaminated waters and fluid tails created from milling operations at the mine site.

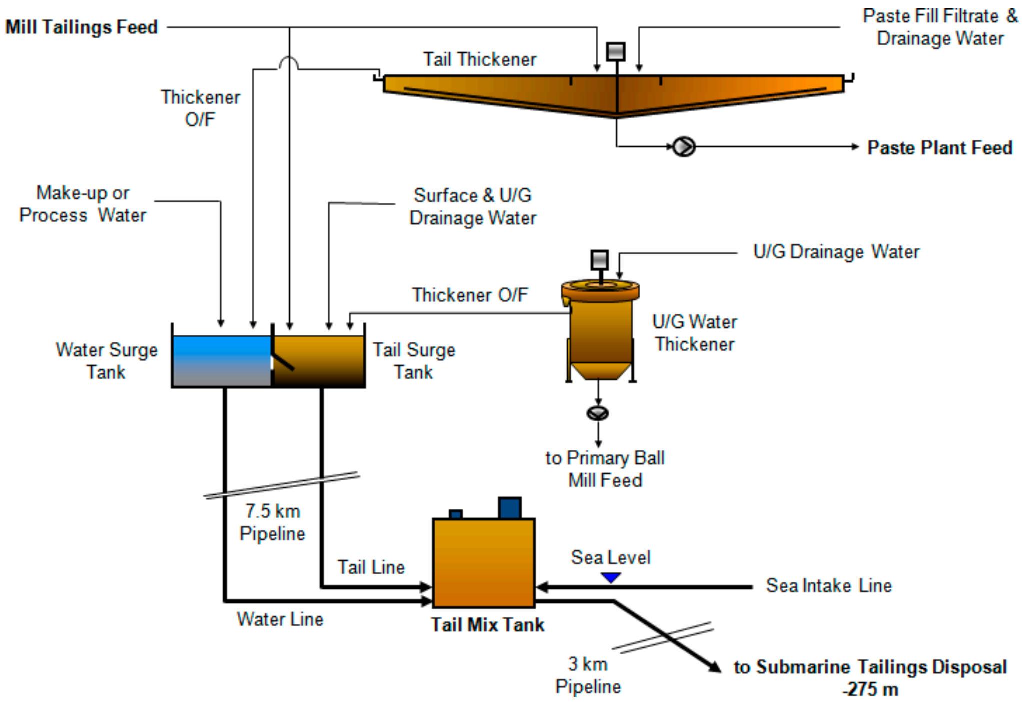

Figure 2. A flowchart of the efficient management of tails and contaminated waters.

2.2. Tails Slurry Characterization

The tails slurry was sized via a Malvern Mastersizer grain sizer (Mastersizer 3000, Malvern Panalytical, Malvern, UK). Figure 3 indicates the tails' particle sizes and scatterings. The tail specimen was categorized as a medium-sized tail. The tail's specific gravity was detected by a helium pycnometer. The specific gravity, specific surface, and pH of the as-received tails are measured to be 3.5, 2.1 m^2/g, and 10, respectively. The as-received tails slurry's rheology was measured via a rotational viscometer, the Rheomat 15T (mettler Toledo, Columbus, OH, USA), at 23 °C and investigated at 30, 35, 40, and 45% dry solids by weight at a pH of 10, as mixed (Table 1). In addition, settling tests were performed at solid concentrations of 15 and 30% dry solids by weight at a pH of 10, as mixed (Table 2).

Note that a 7 mm diameter HDPE (high-density polyethylene) rod, positioned with its lower end at the settled solids' surface, fell hurriedly through the settled solids' layer under its own weight, striking the bottom of the cylinder audibly—indicating that the solids were very softly settled. Very little resistance was felt to the rod's lateral (sideways) movement.

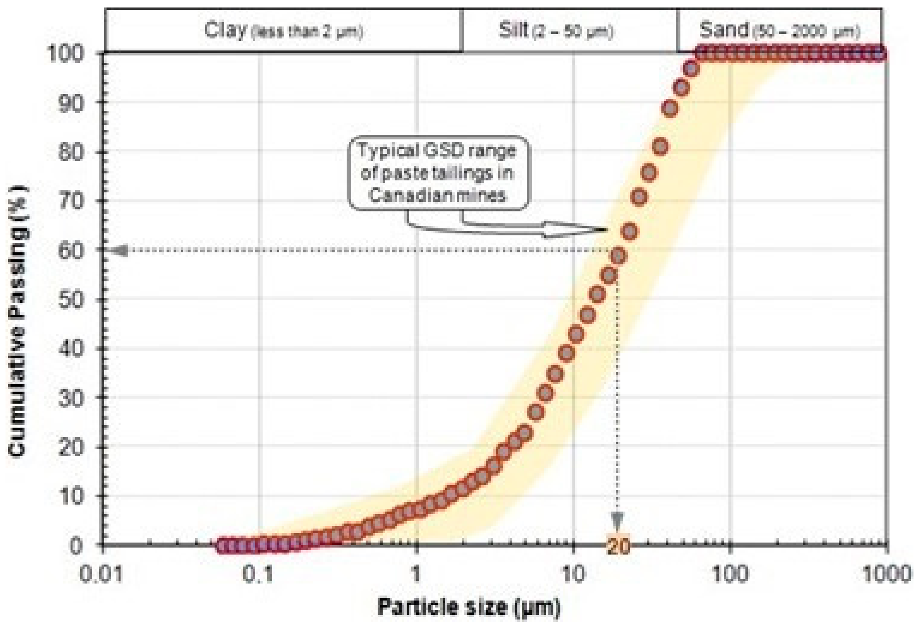

Figure 3. Tails' grain size distribution (GSD), accompanied with common Canadian mine tails.

Table 1. Rheological properties of tails slurry used in the experiments.

Solid Content Cw, wt%	Volume Fraction, ϕsat	Volume Ratio	Viscosity of Slurry/Viscosity of Water	Yield Stress, Pascal
45	0.19	0.23	6.9	3.1
40	0.16	0.19	5.2	1.6
35	0.13	0.15	4.3	1.0
30	0.11	0.12	3.4	0.5

Table 2. Settling properties of tails slurry used in the experiments.

Cw%-Initial	Cw%-Maximum	ϕsat-Initial	ϕsat-Maximum	Max. Settling Velocity, m/h
30	58	0.11	0.28	8.15
15	53	0.05	0.25	17.0

The as-received tails' chemistry is detected via atomic absorption spectrometry (e.g., K_2O, Na_2O, SO_3). Tails are led through iron oxide, Fe_2O_3 (43.7%), and slight masses of silicon dioxide, SiO_2 (10.9%), and aluminum oxide, Al_2O_3 (3.9%), accompanied by trivial sums of Mg, Ca, K, Na, Cr, Mn, and P oxides (<2%). Note that the tails slurry had an LOI value of 27.7%, as FeS_2 is consumed for revealing the high Fe_2O_3 reading.

The polished section was also prepared and displays a sharp contact between two completely different types of ore, as shown clearly in Figure 4. Note that gg stands for gangue minerals. Type I possesses a clastic texture with pyrite (py) in the form of clasts, crystals, layered aggregates, and dissemination. Pyrite is often replaced by chalcopyrite (cp). Sphalerite (sl) and chalcopyrite occur as clasts and irregular patches, as well as a matrix for finely disseminated pyrite. Type II is characterized by a rather massive matrix of sphalerite associated with galena (gn) in the form of irregular inclusions in dimensions ranging from less than 10 microns to a few hundred microns. Sphalerite also bears minute inclusions of chalcopyrite without really being "diseased".

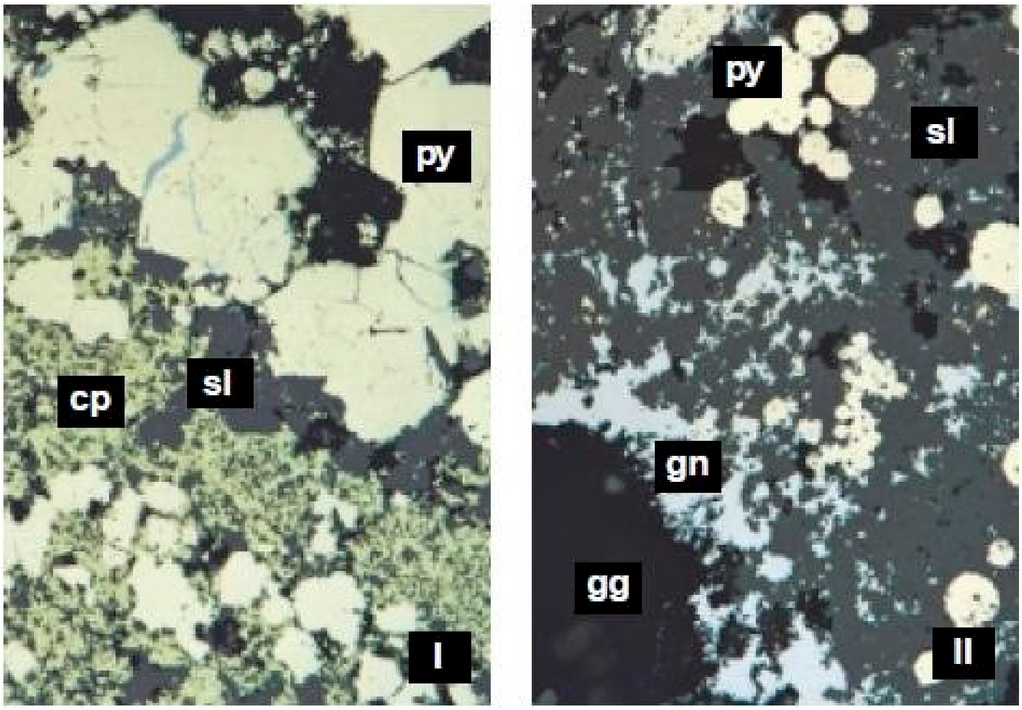

Figure 4. The polished sections of two types of ore samples: I and II.

2.3. Submarine Tails Disposal System

The studied mine's STD system includes (i) a head tank gathering tails and waste water at the mining area; (ii) overland tail pipes from the head tank at the mine site to the shore of the Black Sea (~7.25 km); (iii) an overland waste water pipeline from the head tank at the mine site to the shore of the Black Sea (~7.25 km); (iv) a mix tank near the sea; (v) a pipe laid at the sea's bottom, discharging tails out of the mix tank to 298 m below sea level in the Black Sea (~2.85 km); and (vi) a seawater intake pipeline.

To prevent the mix tank from overflowing and the subsea pipeline from running in slack flow, the mix tank level needs to stay between 2 m and 10 m. With the seawater intake pipeline, the mix tank level stays at 4.3 m. Given that the set point for the mix tank is 4.3 m, the highest throughput available for the submarine tails pipeline is 180 tph at 12.9–13.7% of slurry content. The limiting factor for tails throughput is the maximum flow rate and slurry concentration of the overland tails pipeline. Typical operating slurry concentrations for the overland tails pipeline are from 25 wt.% to 30 wt.%. The maximum solid throughput for the overland tails pipeline at a slurry concentration of 30 wt.% is 122 tph at a 320 m^3/h flow rate. If the flow rate is greater than 320 m^3/h for a throughput of 122 tph, then head tank overflow would occur. In order for the STD system to operate at a throughput greater than 122 tph, a higher slurry concentration would be needed. Table 3 lists the maximum flow rates at the operating slurry concentration of 30 wt.% for overland and submarine pipelines without risk of head and mix tank overflow.

Table 3. Maximum flow rate of both overland and submarine pipelines.

Parameter	Overland Water Pipeline	Overland Tails Pipeline	Submarine Tails Pipeline
Max volumetric flow rate, m^3/h	270	320	1043
Maximum solid throughput, tph	0	122	122
Slurry content at max flow rate, wt.%	0	30	11

2.4. Pipeline Characteristics and STD System Criteria

Table 4 summarizes the pipeline system characteristics for the overland tails, water, and subsea tails pipeline.

Table 4. Overland water, overland tails, and submarine tails pipeline system features.

Parameter	Overland Water Pipeline	Overland Tails Pipeline	Submarine Tails Pipeline
Design solid throughput, tph	180	180	180
Pipeline nominal diameter, inch	14	12	22
Pipeline standard dimensional ratio	17	7	9
Pipe outside dia., mm	356	324	559
Pipe wall width, mm	21	46	62
Pipe inside dia., mm	314	231	435

Operating Velocity: This is defined as the point at which the heaviest particles are no longer fully suspended and begin to accumulate near the bottom of the pipe. Slurry pipelines are operated in a turbulent flow regime to prevent solids from building up on the bottom of the pipe. The velocity of flow within any pipe is detected by maintaining an easily spinning propeller in the pipe section and conducting required tuning. The measurement device of flow is called a turbine flowmeter or sometimes a propeller flowmeter.

Mix Tank Level: Tails and waste water flow from the overland pipelines into the mix tank. From the mix tank, the pressure difference from the outlet of the submarine tails pipeline and the mix tank dictates the submarine tails' flow rate. At high solid contents, the mix tank level will drop below 3 m, which causes seawater to flow into the mix tank via the seawater intake pipeline to keep the mix tank level at 3 m.

Head Tank Level: The overland processing tails and waste water pipelines also operate with a gravity line. Tails and waste water flow from the outlet of head tanks at an elevation of 97 m to the inlet of the mix tank at an elevation of 3 m below sea level. To prevent overflow on the water side of the head tank, there exists a flap valve, which allows water to flow into the tails side of the head tank if the level on the water side is higher.

Slack Flow: Slack flow occurs when the hydraulic gradient line is below the line profile. When this occurs, the pipeline would run partially full for the areas below the line profile. This causes accelerated erosion to the pipeline. To prevent slack flow for the system, additional process water is added in to the head tank for the overland tails pipeline and/or seawater is added into the mix tank via the seawater intake pipeline for the submarine tails pipeline.

2.5. Atomic Absorption Spectrometry and pH Measurement

In the current study, an atomic absorption spectrometer named the Varian AA 240 FS (Agilent Technologies, Santa Clara, CA, USA) flame was used for detecting Cu, Zn, and Pb within tail slurry. They were digested using an HF-HClO4-HNO3 total dissolution technique. The pH of the tail slurries was also detected by a Benchtop pH/ISE M Orion Model 920A tied by a Thermo Orion Triode grouping electrode (Pt-Ag-AgCI, thermo fisher scientific, Waltham, MA, USA).

3. Results and Discussion

3.1. Submarine Tails Pipeline Hydraulic Design Results

Hydraulic models for the overland tails/waste water pipelines and the submarine tails pipeline are built to predict the hydraulic performance of the system. Assuming that the maximum allowable tank height for the mix tank is 10 m, the maximum flow rate for the subsea pipeline at 180 tph is 1264 m^3/h at 12.9%. Given the seawater intake pipeline, the mix tank height is typically 4.3 m with a low of 2 m. Table 5 depicts the submarine tails pipeline's operating range based on the mix tank height of 4.3 to 10 m. At a mix tank height of 10 m, the mix tank is at risk of overflow. At a mix tank height of 4.3 m, the submarine outfall pipeline operates without the need for seawater intake. When the ore processing plant is commissioned, the slurry content cannot be more than 12.9% while operating at a maximum throughput of 180 tph. If the content exceeds this specific value, the level of the mix tank will rise instantly and there will be a risk to storing the tails under the sea in a healthy way. The flow rate allowed in this maximum solid throughput (180 tph) is limited to 1264 m^3 per hour and the flow velocity cannot exceed 2.37 m/s. The optimum values determined in Table 5 should be taken into consideration to ensure that the mixed tank operations and thus the tails produced can be stored safely under the sea. Otherwise, the mill facility will not be able to operate optimally and losses will occur in terms of its recovery, efficiency, and tonnage.

Table 5. Operating range for submarine outfall tails pipeline.

Solid Throughput, tph	Slurry Content, %	Flow Rate, m^3/h	Flow Velocity, m/s	Mix Tank Height, m
180	12.9	1264	2.37	10
180	13.7	1182	2.21	4.3
120	9.9	1131	2.12	10
120	10.7	1037	1.94	4.3
60	6.1	943	1.77	10
60	6.9	824	1.54	4.3
0	0	556	1.04	10
0	0	189	0.35	4.3

Figure 5 depicts the operating range for the submarine outfall tails pipeline. Using the operating range, it is possible to determine the operating data for the submarine tails pipeline at the ideal mix tank heights and solid throughputs. For example, in order for the submarine tails pipeline to operate at a mix tank height of 4.3 m and a solids throughput of 107 tph, the submarine tails pipeline would need 1000 m^3/h of slurry at a 10% weight concentration. Any flow rates (m^3/h) and throughputs (tph) above the mix tank height 10 m line would cause the mix tank to overflow. Any flow rates and throughputs below the mix tank height 2 m line imply the need for seawater dilution to prevent the mix tank from emptying. The section between the two lines represents, obviously, the operating range where the submarine tails outfall pipeline can function without risk of mix tank overflow or the requirement of additional seawater.

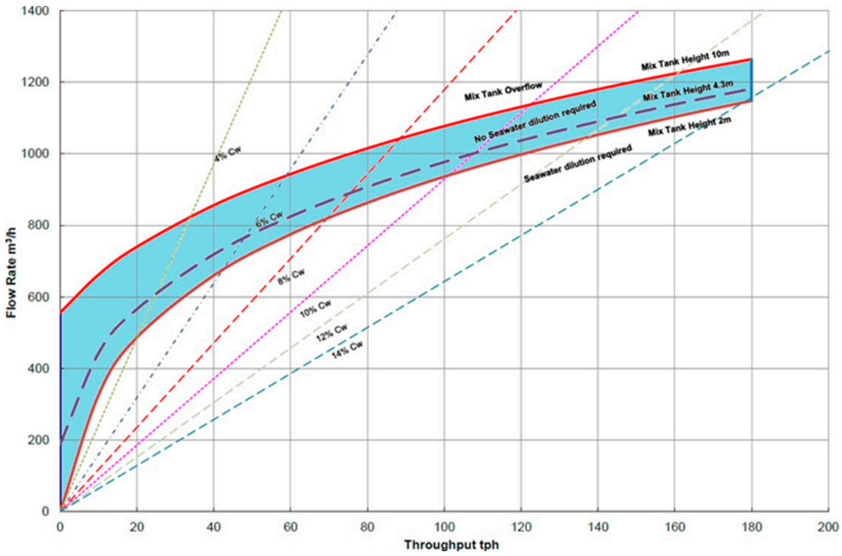

Figure 5. Operating range diagram for submarine tails pipeline.

3.2. Overland Tails Pipeline Hydraulic Design Results

It was assumed that the level of the mix tank would range from 4.3 to 10 m. In addition, it is assumed that the head tank for the overland tails pipeline is approximately 4–5 m in height, giving an additional head of 1 to 3 m to the gravity line. While the overland tails pipeline can operate at a lower head tank level, it is assumed that waste water from the waste water side of the head tank would flow into the overland tails head tank side in order to prevent slack flow. Table 6 depicts the overland tails pipeline operating range. While the ore processing plant operates at a maximum throughput of 180 tph, the slurry content in the overland tails pipeline should not be more than 43.4%, because at this rate, the level of mix tank may overflow and lead to the contamination of tails–waste water, which may be discharged into the environment uncontrollably. In fact, at this maximum solid throughput, the level of head tank within the mill facility reaches 1 m. If the slurry content in the overland tails pipeline drops from 43.4% to 41.8%, then the level of the head tank can rise up to 3 m in height. In order to carry out stable ore processing plant operations in terms of ore recovery, efficiency, and tonnage, the flow rate should not exceed 286 m^3 per hour and the flow velocity should not exceed 1.89 m/s.

Table 6. Operating range for overland tails pipeline.

Solid Throughput, tph	Slurry Content, %	Flow Rate, m^3/h	Flow Velocity, m/s	Head Tank Height, m	Mix Tank Height, m
180	43.4	286.0	1.89	1	10
180	41.8	302.3	2.00	3	4.3
120	30.8	304.3	2.01	1	10
120	29.6	319.5	2.11	3	4.3
60	16.7	315.6	2.09	1	10
60	16.1	330.5	2.18	3	4.3
0	0	326.6	2.16	1	10
0	0	341.4	2.26	3	4.3

Figure 6 depicts the operating range for the overland tails pipeline. Using the operating range, it is possible to determine the operating data for the overland tails pipeline at the maximum and minimum flow rates. For example, given the solid throughput of 180 tph at the maximum flow rate of 302 m^3/h, the slurry content needs to be 41.8%. Any flow rates and throughputs above the maximum flow rate line would cause the head tank to overflow. Any flow rates and throughputs below the minimum flow rate line imply the risk of slack flow in the overland tails pipeline. The section between the two lines represents the operating range where the overland tails pipeline can function without risk of head tank overflow or slack flow.

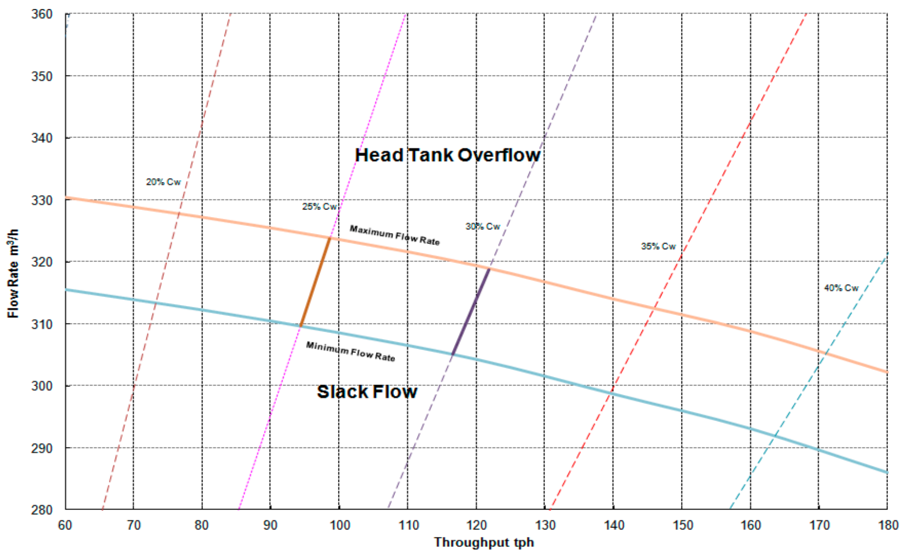

Figure 6. Operating range diagram for overland tails pipeline.

3.3. Overland Waste Water Pipeline Hydraulic Design Results

Figure 7 depicts the operating range for the overland waste water pipeline. Any flow rate above the max. flow rate line would cause the head tank to overflow. Any flow rate below the minimum flow rate line would result in the head tank being emptied by open channel flow for the first section of the overland waste water pipeline. The section between the two lines represents the operating range where the head tank is not at risk of overflow and the overland waste water pipeline is operating with packed flow.

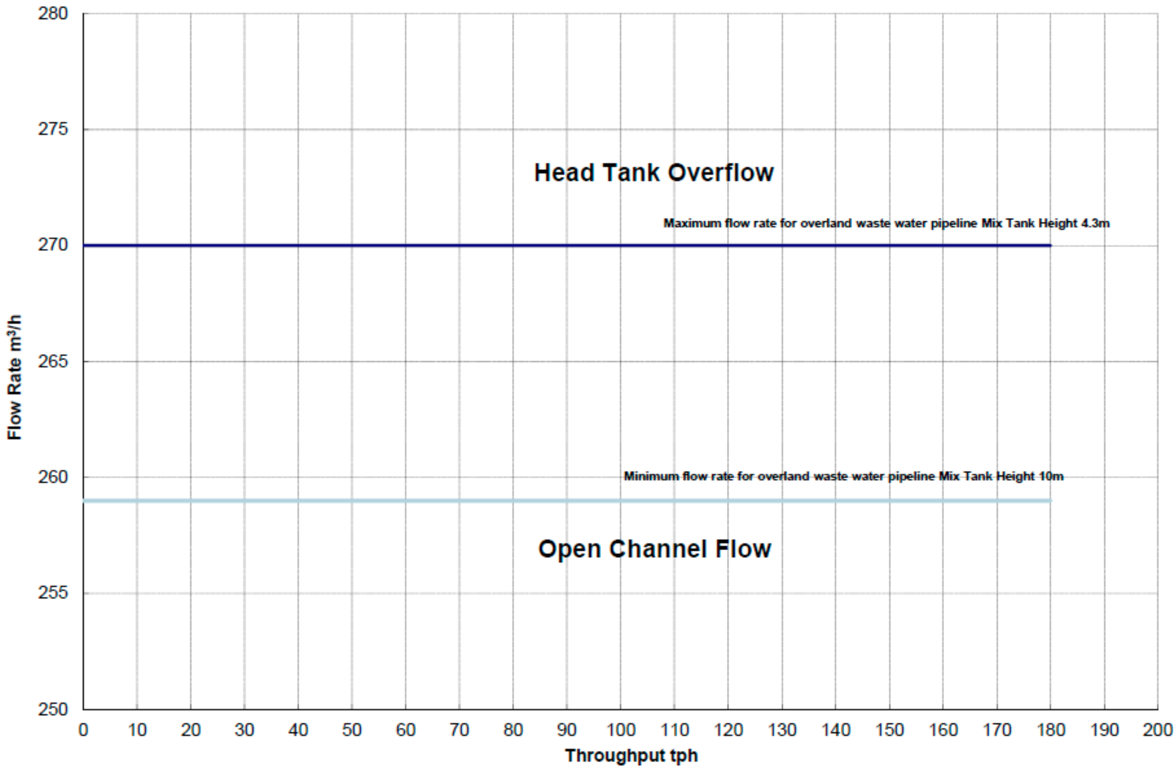

Figure 7. Operating range diagram for overland waste water pipeline.

3.4. Discharging Tails to Sea's Bottom

Figure 8 demonstrates changes in the quantity of mill tails (also employed as STD) produced between 2010 and 2017. The average amount of tails produced in the mill facility between these years was determined as 85,677 tons. Depending on mill tails production, the percentage of tails used as STD varies between 55% and 85%. Automatically drawn from a Yokogawa CS 3000 distributed control system (DCS) used in the mill plant, this amount reflects the cumulative amount of tails disposed undersea through the STD technique. The system has three key stations: engineering, operator, and field control. Through this system, the operator is able to monitor, control, start-up, and shut-down the actual plant operations, including paste backfill and tails management facilities. An average of 49% of tails are delivered using overland tails and submarine outfall pipelines undersea as tails disposal. The mine uses both the STD technique as a unique tails management option and paste backfill in which tails are mixed with cement first and then delivered underground for filling. Between 2010 and 2017, a total of more than 7 million tons of tails are produced and almost 3.5 million tons of them are delivered undersea for STD, as revealed clearly in Figure 8.

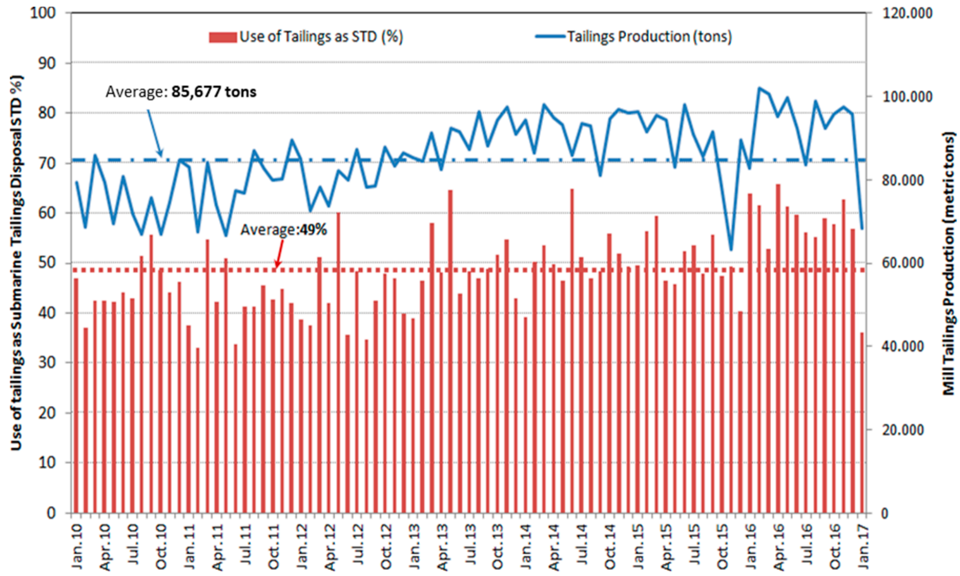

Figure 8. Disposal of mine tails undersea using submarine tails placement system.

3.5. Tails Discharge Monitoring Results

Samples are collected from the mix tank right before the generated tails are delivered undersea as disposal. These samples are brought to the assay laboratory for pH and some heavy metal analyses. Figure 9a shows the change in pH of waste water samples collected between 2010 and 2017. The results indicate clearly that the pH of all samples is higher than 5, which reflects the allowable limit. The mean pH value is 10, showing an effect of the lime added to copper–zinc circuits in the studied mine as a pH modifier. In a similar manner, the concentration of lead (Pb) was assessed for the same time period. The results indicate that samples' Pb values were under the permissible limit of 0.05 mg/L (Figure 9b). In addition, copper (Cu) concentrations were under the permissible limit of 0.05 mg/L (Figure 9c). Zinc (Zn) concentrations are found to be scattered in the collected samples and were under an allowable limit of 2 mg/L (Figure 9d). One can overall say that sulfidic minerals (Cu/Zn/Pb) are not as steady in undersea dipping settings. Releasing heavy metals from sulfidic ores exposed to dipping settings has been witnessed in both laboratory- and field-scale testing. There are some signs that great chloride dosage can augment sulfides' corrosion.

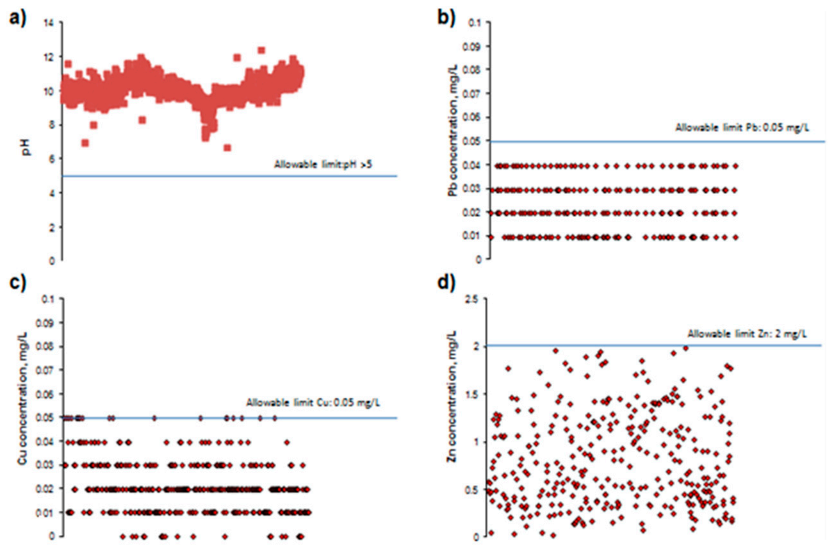

Figure 9. Change in pH (**a**), lead (**b**), copper (**c**), and zinc (**d**) concentrations over time.

4. Conclusions

This paper presents the use of submarine tails disposal (STD) as an alternative tails management system. STD provided a unique technique in terms of stability and economy for the safe disposal of process wastes to the bottom of the sea. The limiting factor for tails throughput is the maximum flow rate and slurry concentration of the overland tails pipeline. At a slurry concentration of 30 wt.%, the overland tails pipeline can operate at a maximum throughput of 122 tph at 318.8 m^3/h without risk of head tank overflow. The main restriction on the STD system is the total flow rate of the overland pipelines without head tank overflow. To prevent head tank overflow, the overland tails pipeline flow rate must run between 302.3 and 341.4 m^3/h. It must be emphasized that for the overland tails pipeline to process high solid throughput, high slurry concentrations are required. This may be an issue since the waste water side of the head tank has a flap valve, which enables excess waste water to flow into the overland tails side of the head tank. While this prevents the water side of the head tank from overflowing, this also dilutes the slurry concentration of the overland tails pipeline. A lower solid throughput or less waste water disposal is thus needed for optimal STD system operation. As a result, the STD system can be advantageously used as alternative tails management in most modern mines.

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