How to Determine Financial Guarantees of Water Treatment for Mine Closure: A Summary of Affecting Factors

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Abstract

Water treatment at mine closure stage can require a considerable amount of money and resources. These costs should be considered already at the planning stage as part of the closure plan. Setting adequate financial guarantees is essential to mitigating the potential environmental impacts of mines, and to ensuring a positive mine legacy. This paper sums up information on factors affecting the determination of financial guarantees of water treatment for mine closure.

Keywords: Mine water, mine closure, mine water treatment, closure plan

Introduction

Financial guarantees to cover closure and post-closure measures are essential for minimizing the long-term environmental impacts of mines. Planning of closure measures is initiated even before mining operations start. The closure plan is updated throughout the life cycle of the mine. The adequacy of the closure measures must be ensured during the closure phase by means of monitoring.

Determination of suitable water treatment technologies at different closure phases considering changes in mine water amount and quality, as well as estimation of treatment period length, is used for estimating the post-closure water treatment costs. The estimated cost is the minimum monetary amount of financial guarantees concerning water treatment at mine closure.

There are many factors affecting the determination of financial guarantees of water treatment for mine closure. This paper provides a comprehensive summary of knowledge of these factors, which include variation in mine water amount and quality during different stages of mine closure and post-closure, suitable water management and treatment technologies during mine closure, and investment and operational costs related to these technologies.

Water Amount and Quality Changes During Mine Closure

Water fraction quantity and quality can vary considerably between mines. In addition, even within the mining area, water fractions of very different quality and quantity can be formed. Operational stage water streams often consist of e.g., mine dewatering water, concentration plant process water which transfers to tailings management facility, and seepage and run-off water from tailings and waste rock deposition areas. The geological characteristics of the pit walls and waste areas, as well as the contact time with water, impacts the formed mine water quality. Chemical reactions such as sulfide minerals oxidation and acid production, as well as carbonate minerals neutralization have an effect on mine water quality. Weathering and fragmenting of rock also influence mine water quality as physical phenomena.

Usually, the amount and quality of water fractions change towards mine closure as mine operations are run down. Process water and tailings production stops at concentration plant and mine dewatering water pumping typically stops and mine is flooded. This leads to mine overflows after mine is filled with water. The amount of seepage is reduced, and the quality improved by covering the waste rock and tailings.

The water fractions that need to be managed and treated in the closure phase are mainly leachate from extractive waste areas. Additionally, there might be need for process water management and treatment in the beginning of mine closure. Overflow from the pit lake, if water is not stratified sufficiently, may also trigger a need for water treatment even decades after termination of mine operations.

Suitable Water Management and Treatment Technologies

During the mine closure phase, suitable techniques for water management and treatment shall be selected on a case-by-case basis, applying best available techniques (BAT) (Garbarino *et al.* 2018). At different stages of closure, the needs of water management and treatment usually change, as the amount and quality of water fractions may vary.

Water quality can be affected by the water management methods. Primarily, the formation of environmentally harmful leachate should be prevented, for example by means of covering structures for waste areas and collecting seepage and run-off from waste areas by means of pumping and drains. Also, clean surface waters should be diverted from waste areas to prevent their contamination.

Water and loading balance modelling is a tool used for water management planning. With water and loading balance model the amounts of mine waters formed, their potential environmental load, need and capacity for water treatment, and the dimensioning of water transfer structures and other water management structures can be assessed.

Only, if preventing of water contamination is not possible nor sufficient from environmental risk management perspective, water should be treated before discharge into the environment. The selection of a suitable water treatment method depends, among other things, on the sensitivity of the receiving water body and the quality and quantity of formed water fractions. Water treatment technologies can be classified as passive that utilise natural water flow along with natural chemical and biological processes, and active that require continuous maintenance, monitoring, and chemicals addition. Also, semi-passive water treatment technologies (Kleinmann *et al.* 2023), such as occasionally adding amendments to enhance otherwise passive treatment processes, are widely used and applicable for post-closure water treatment.

Active mine water treatment technologies such as lime precipitation or coagulation are capable of removing many of the potential pollutants from mine affected water. In the closure phase, active treatment is typically applied, for example, during active closure stage, but also in longer term if required. Passive, or semi-passive, methods are preferred in cases where there is a minor or precautionary need and the emission has already been minimized by primary means, such as covering structures. Passive treatment as polishing treatment for example on wetlands is common, but wetlands' pollutant removal efficiency is limited and affected by temperature. Often after mine closure, water treatment will continue with the technology that was in use during the mine's operational phase as long as necessary, considering the environmental risks and impacts (Garbarino *et al.* 2018).

Water Management Costs

The costs of water management during closure phase consist of e.g. cover structures, pipelines, drains, ponds, pumping stations, and disassembling of existing water management systems. The water management costs are site-specific and depend on many factors (fig. 1).

Cover structures for each waste area need to be designed individually as each waste area has its own unique geochemical, and geotechnical features as well as material balance. Thus, the costs of cover structures can vary a lot. The costs presented below do not include VAT. The estimated unit cost of cover structures varies between 7.3–21.6 €/m2 depending on the cover layer materials, and the thickness of cover layers (Laakso *et al.* 2022). The use of synthetic films or geotextiles as part of the cover structure elevates the costs compared to cover structures built with solely natural materials.

Mine flooding can last for decades. The formation of pit lake can be accelerated by

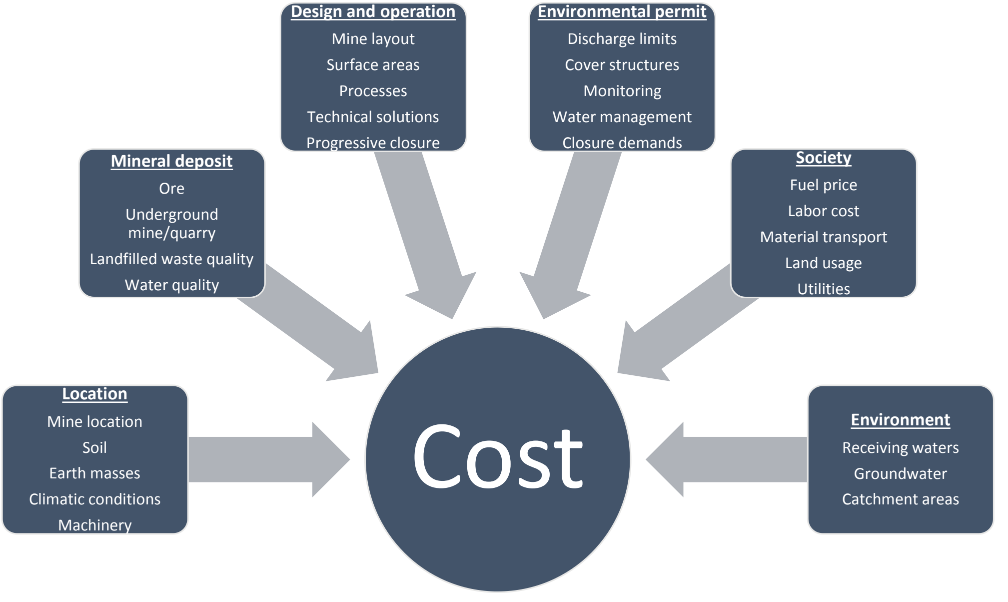

Figure 1 *Factors Affecting the Cost of Closure Measures (from Laakso* et al. *2022).*

directing leachate into open pit mine. At closure stage, the existing water management structures are utilized when possible. However, new pipelines may need to be assembled. The estimated investment unit cost for pipelines varies between 20–500 €/m for pipes, and 70–250 €/m for earth construction works (Laakso *et al.* 2022). In some cases, there might be need for new pumping stations. The estimated investment cost of new pumping station can vary between 10 000–100 000 € (Laakso *et al.* 2022). The water management systems also need maintenance, which results in operational costs.

Water Treatment Costs

The costs of water treatment during the closure phase are affected by, among other things, the chosen water treatment technologies, and the length of the treatment period (fig. 1). Water treatment plants built during the operational phase of the mine can be used during the closure phase, but the use of active treatment plants require maintenance. If the water treatment plant comes to the end of its service life but the quality of environmental discharges is not yet sufficient, it may be necessary to use temporarily, for example, container treatment plants.

In active water treatment, maintenance costs consist of, e.g., equipment maintenance and possible renewal and renovation of buildings. Active water treatment also requires external energy, chemicals, and operating personnel. Because of this, switching from active water treatment to passive methods is preferably done during the closure phase, if the water quality allows.

The costs of passive water treatment methods can include, e.g., earth construction costs, remediation costs, and monitoring costs. As an example, the construction costs of constructed wetlands usually consist of costs derived from excavation works, earth mass movement, insulating structures, and planting of vegetation. However, the operating time of a wetland is limited, and, over time, substances bound to the field can be leached out of it. Because of this, it is possible that the wetland will have to be remediated to prevent leaching. This results in addition of re-construction costs and disposal costs of contaminated soil material.

It is difficult to generalise the costs of water treatment, as the chemical composition of the water, such as pH and concentrations of harmful substances, affect the costs (Sveriges geologiska undersökning 2017).

***Table 1** Indicative Estimates of CAPEX and OPEX of Water Treatment (from Laakso* et al. *2022*

Treatment method	CAPEX	OPEX	Source
Overland-flow wetland	0.14 €/m^2	moderate	AFRY Finland Oy design data 2019
Aerobic wetland	3–30 €/m^2	moderate	Garbarino *et al*. 2018
Anaerobic wetland	20–350 €/m^2	moderate	Garbarino *et al*. 2018
Settling pond	17–90 €/pond-m^3	moderate	AFRY Finland Oy design data 2018-2021
Lime precipitation, field set	930 € per m^3/h design flow	0.02–1.3 €/m^3	AFRY Finland Oy design data 2017-2021
Lime precipitation, plant	5 200-22 000 € per treatment capacity m^3/h	0.02–1.3 €/m^3	Garbarino *et al*. 2018; INAP 2014
Coagulation, plant	3 900 € per m^3/h design flow	Similar cost as lime precipitation	AFRY Finland Oy design data 2019-2021

Table 1 summarizes estimated indicative values of investment and operational costs (CAPEX = Capital expenditure and OPEX = Operational expenditure) of water treatment (VAT excluded).

Estimation of the Length of Water Treatment Period

The length of water treatment period is a key parameter in evaluating financial guarantees of water treatment for mine closure. There are several approaches for the determination of the length of water treatment period. The suitable approach needs to be selected case by case considering the special features of the mine and the available initial information.

The length of the active water treatment period is usually determined with means of modelling. Modelling of mine water quality and quantity should be done as part of the closure planning. For geochemical modelling purposes, representative sampling and laboratory testing of wastes and pit walls are needed. The accuracy level of the emission modelling, as well as the closure plan, will evolve as the mining project progresses. (ICMM 2019) Modelling can also be used after assessment of post-closure emissions to determine the dispersion of mine discharges on the receiving water body. This model will feed to post-closure environmental impact assessment work, which outcome will iteratively feedback to selecting sufficient closure measures. The improved closure methods can be, e.g., modifications of water treatment, improved cover structures for waste areas, or directing leachate into open pit mine.

In some cases, there may be a need for temporal water treatment that is tied to a change in the amount of water rather than change in the water quality. This can be the case, for example, in a slurry deposition tailings area, where water table gradually lowers after the end of production. In the initial phase of drying, the amount of leachate is at its maximum and decreases over time. On certain stage after closure, residual emissions could be on environmentally acceptable level and water treatment could be terminated.

One option for determining the length of the post-closure active water treatment period is to determine the theoretical replacement time of the pore water in the mining waste area. This approach can be well suited, for example, if importance of some factor during production to the mine waste area water quality is overruling the effect of the waste's characteristics. Such factor can be, for example, process water or a factor related to explosives.

The need for water treatment can also be related to the progress of the implementation of closure works, for example, particularly impervious cover structures can be assessed to prevent the interaction of mining waste with its environment to such an extent, that the water treatment can be run down at completion of the cover structures.

Future trends

Progressive mine closure has become more common, especially at waste rock areas (ICMM 2019). Progressive mine closure means that some closure measures are done already during operational period of the mine.

The goal is to reduce the amount of waste formed in mining, which also decreases the amount of waste impacted water and closure costs. The amount of environmentally harmful leachate generated from waste areas could be reduced already during the production phase by sorting and selective processing of mining waste, and by diversion of unimpacted waters. This would increase costs during operation but could reduce costs at the closure. (Garbarino *et al.*, 2018)

On tailings management and management of active water treatment sludges formed on mine sites, dry stacking is gaining favour in comparison to slurry deposition. The advantage of dry stacking is a smaller surface footprint compared to slurry deposition, decreased seepage volumes, and enhanced possibilities for progressive closure. All these factors decrease the post-closure water treatment costs and offer benefits for improved post-closure environmental risk management.

Conclusions

At the early stage of mine closure, the active water treatment technology used during mine operation could be suitable for discharge water treatment. However, the goal is to replace the active treatment with passive or semi-passive, less resource intensive, treatment as soon as the water quality allows it. Passive treatments need also certain amount of maintenance. When the water management measures are at a stage where water quality reaches the set requirements, also passive treatment can be terminated. As part of the closure plan, it is recommended to model mine water quantities, qualities, and environmental discharges until stabilized post-closure stage in order to evaluate the environmental impacts and to select sufficient closure measures related to water management and treatment. The cost estimate of water treatment will then assist on setting sufficient financial guarantees.

This paper describes factors affecting the financial guarantees of water treatment and can help to find a suitable water treatment method, or combination of water treatment methods, in mine closure phase. The information presented on this paper can be used as a reference point in estimation of water treatment costs during closure phase.

Acknowledgements

The findings of this paper are based on the study that was part of the Finnish governmental project Scope Expansion of Financial Guarantees in Mining: Influence on Environmental Protection and Costs. The project was financed by the Finnish Government's analysis, assessment, and research activities and was based on the aim to improve environmental protection in mining by developing provisions on financial guarantees.

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