Chapter 6
Waste Management in the Gold and Silver Industry

V. I. Lakshmanan, R. Roy, and B. Gorain

Sustainable development is strategic for mining companies. In the late 1998, nine of the world's largest mining companies took an initiative to examine the role of the minerals sector in contributing to sustainable development and how that contribution could be enhanced. This initiative was called the Global Mining Initiative. Through the World Business Council for Sustainable Development (WBCSD), the International Institute for Environment and Development (IIED) was given the contract to undertake a scoping study in May 1999. The scope of this study was to understand the global challenge of sustainable development facing the mining sector and to propose the scope of a 2-year project to explore the role of mining sector in sustainable development. Following the scoping study, the IIED undertook a 2-year independent process of research and consultation project, which was named the Mining, Minerals and Sustainable Development Project (MMSD). The project was carried out between 2000 and 2002, and a final report was published in 2002. In its final report, a set of guiding principles for sustainable development was detailed as shown in Table 6.1 (MMSD 2002a).

In the environmental sphere, the minimization of waste and environmental damage was described as a guiding principle. In this chapter, the methods of waste management in gold mining are described starting with a description of how waste is generated in mining projects.

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Table 6.1 Sustainable development principles (MMSD 2002a)

Economic sphere	1. Maximize human well-being 2. Ensure efficient use of all resources, natural and otherwise, by maximizing rents 3. Seek to identify and internalize environmental and social costs 4. Maintain and enhance the conditions for viable enterprise
Social sphere	1. Ensure a fair distribution of the costs and benefits of development for all those alive today 2. Respect and reinforce the fundamental rights of human beings, including civil and political liberties, cultural autonomy, social and economic freedoms and personal security 3. Seek to sustain improvements over time; ensure that depletion of natural resources will not deprive future generations through replacement with other forms of capital
Environmental sphere	1. Promote responsible stewardship of natural resources and the environment, including remediation for past damage 2. Minimize waste and environmental damage along the whole of the supply chain 3. Exercise prudence where impacts are unknown or uncertain 4. Operate within ecological limits and protect critical natural capital
Governance sphere	1. Support representative democracy, including participatory decision-making 2. Encourage free enterprise within a system of clear and fair rules and incentives 3. Avoid excessive concentration of power through appropriate checks and balances 4. Ensure transparency through providing all stakeholders with access to relevant and accurate information 5. Ensure accountability for decisions and actions, which are based on comprehensive and reliable analysis 6. Encourage cooperation in order to build trust and shared goals and values 7. Ensure that decisions are made at the appropriate level, adhering to the principle of subsidiarity where possible

6.1 Waste Generation in Mining

Waste generated during mining and processing of ores consists of waste rock and tailings. Waste rock consists of the overburden and mine development rock (UNEP 2002). Overburden refers to the soil and rock that covers an ore body. Overburden is removed during surface mining to access the ore body. The overburden ratio or stripping ratio is the ratio of the weight of overburden excavated to the weight of ore excavated. Surface mining typically generates 8–10 times more waste rock compared to underground mining (Das and Choudhury 2013). Mine development rock is part of host rock that contains the ore body and is removed during underground mining to access the ore body. Waste rock contains economically insufficient amount of metals and is typically stored in waste rock dumps. The objective of a sound mining plan is to minimize the amount of waste rock that needs to be removed from the host rock.

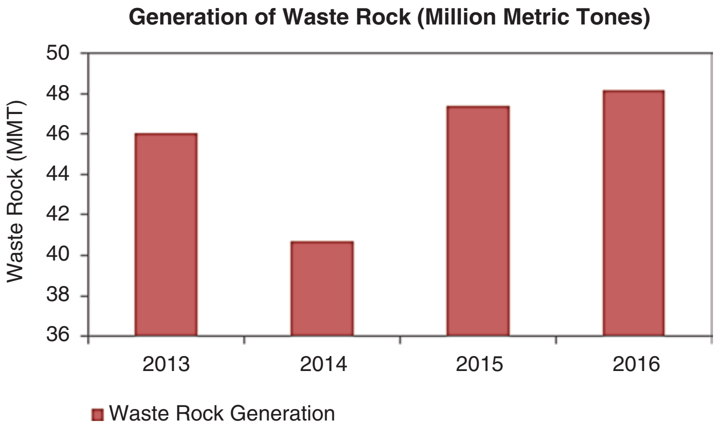


Fig. 6.1 Waste rock generated during Barrick operations

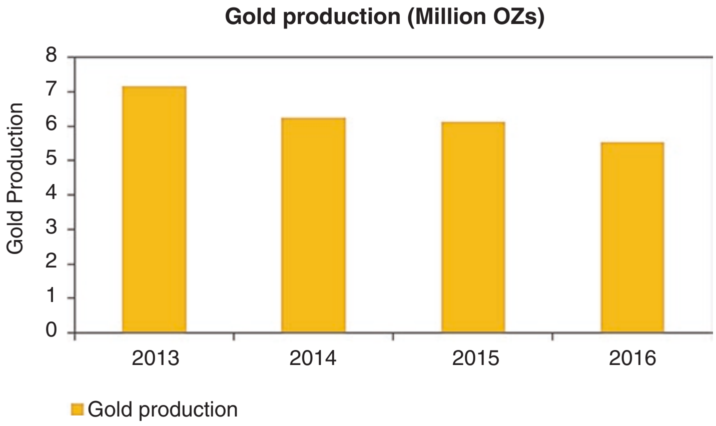


Fig. 6.2 Gold production at Barrick

Since the data on global generation of waste rock due to gold processing is not available, a rough estimate of the amount of waste rock generated for the production of a unit amount of gold can be obtained by analysing the data provided by Barrick Gold Corporation, one of the largest gold mining companies in the world, for its operations. Figures 6.1 and 6.2 show the amount of waste rock generated and amount of gold produced by Barrick between 2013 and 2016, respectively. This data on gold production and waste rock generation is listed in Table 6.2, where a column has been added to show the amount of waste rock generated per unit gold production. The amount of waste rock generated per year has been increasing since 2014, while the amount of gold produced per year has been decreasing since 2013. Waste rock generated per ounce of gold produced has been continuously increasing and was 8.73 tons per ounce of gold in 2016 for Barrick operations (Barrick 2018a, 2018b).

Table 6.2 Generation of waste rock for Barrick operations

Year	Gold produced (million ozs)	Waste rock generated (million tons)	Waste rock generated/gold produced (tons/oz)
2013	7.166	46.037	6.42
2014	6.249	40.721	6.52
2015	6.117	47.387	7.75
2016	5.517	48.183	8.73

6.2 Waste Generation in Processing

After the ore is mined, the rock can be crushed and heap leached or ground and leached depending on the ore grade and chemistry. For heap leaching, crushed ore may be placed in heap leach facilities (HLFs), where the ore is irrigated with process solutions for the recovery of precious metals. The processing of ground ores generates tailings or waste material left after the precious or value metals have been extracted. Mine tailings consist of remaining ground ore and associated process water containing dissolved metals and ore processing reagents. The amount of tailings generated by a mine can be approximately equal to the amount of ore processed for gold and copper-gold ores, considering that the metal content in ore is low. As an example, a mine treating 200,000 ton of copper ore per day produces nearly 200,000 ton of tailings per day (MMSD 2002b).

As tailings are generated from the processing of ground ore, tailings contain a wide range of particle size fractions. Tailings consist of coarse mine waste, fine clays, flotation tailings, chemical precipitates and slimes. Tailings are stored in engineered tailings storage facilities (TSFs). These facilities need to be carefully designed taking into consideration the physical, chemical and mineralogical characteristics of the tailings along with Geotech considerations of the infrastructure. The failure of these tailings storage facilities can lead to serious environmental problems in the affected areas.

According to one study, 14 billion tons of tailings were produced by the mining industry in 2010 (Jones and Boger 2012). To get a rough estimate of the amount of tailings generated for the production of a unit amount of gold, Fig. 6.3 shows the amount of tailings generated during Barrick operations between 2013 and 2016. Table 6.3 shows tailings generation, gold production and the amount of tailings generated per unit gold production for this time period. Tailings generated have been decreasing since 2014. However, as shown in Fig. 6.2, the gold production by Barrick has also been decreasing during this time period. To normalize the effect of the amount of gold production, tailings generated per ounce of gold produced has been shown in Table 6.3, and this ratio has also been decreasing since 2014 and was 27.40 tons per ounce of gold in 2016 for Barrick (2018a).

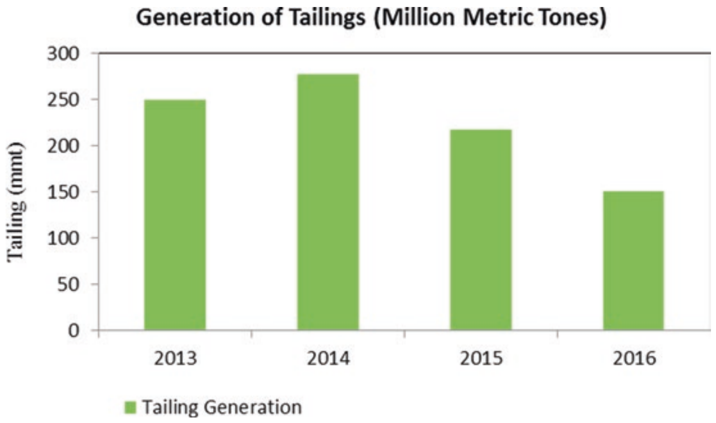


Fig. 6.3 Tailings generation for Barrick operations

Table 6.3 Generation of tailings for Barrick operations

Year	Gold produced (million ozs)	Tailings generated (million tons)	Tailings generated/gold produced (tons/oz)
2013	7.166	249.662	34.84
2014	6.249	276.675	44.28
2015	6.117	217.987	35.64
2016	5.517	151.145	27.40

Figure 6.4 combines the data on waste rock and tailings shown in Figs. 6.1 and 6.3, respectively, and shows the amount of total waste generated for Barrick operations between 2013 and 2016. Table 6.4 shows total waste generated, gold production and total waste generated per unit gold production. Total waste generated per ounce of gold produced has been decreasing since 2014 as the tailings generated per ounce of gold produced has been decreasing since 2014. The amount was 36.13 tons of total waste generated per ounce of gold produced in 2016 for Barrick (Barrick 2018a).

Even though the amount of total waste has been decreasing per unit of gold produced, it is still a huge number. The main reason for the generation of huge amount of waste generated per ounce of gold produced is the low grade of gold ores. The average grade of gold ores has been falling over the years. Between 1830 and 1900, the average grade of gold ore was around 20 g/ton and in 2000; it had dropped to around 3 g/ton (Muller and Frimmel 2010). Gold mining companies are processing lower grades of ore as the higher-grade ores are getting depleted. Table 6.5 shows the average grade of gold ores at Barrick operations. In 2016, the average grade of gold at major mines owned by Barrick was lower than 4 g/ton. There are many gold miners, including Barrick, that are processing gold ores having less than 1 g/ton of gold. One troy ounce of gold is equal to 31.10 g. Thus, for an ore containing 1 g/ton of gold, over 31 tons of tailings is generated per troy ounce of gold even at 100% recovery of gold. Thus, it has become very important to properly manage the waste generated by gold mining

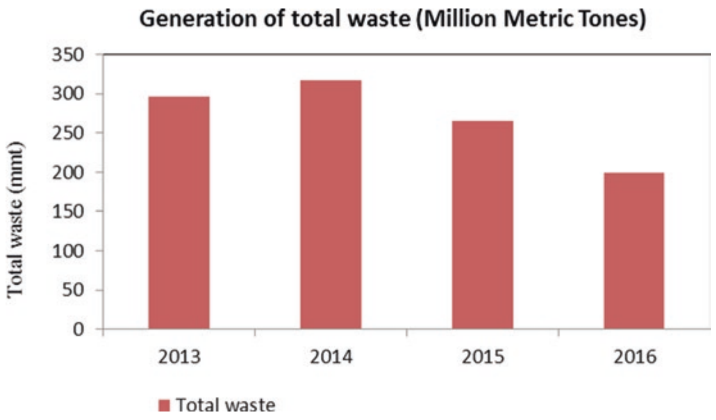


Fig. 6.4 Total waste generated during Barrick operations

Table 6.4 Total waste generated during Barrick operations

Year	Gold produced (million ozs)	Total waste (million tons)	Total waste generated/gold produced (tons/oz)
2013	7.166	295.699	41.26
2014	6.249	317.396	50.79
2015	6.117	265.374	43.38
2016	5.517	199.328	36.13

Table 6.5 Average ore grade at Barrick operations (Barrick 2018b)

Year	Ore grade (g/ton) at Goldstrike	Ore grade (g/ton) at Cortez	Ore grade (g/ton) at Pueblo Viejo	Ore grade (g/ton) at Lagunas Norte	Ore grade (g/ton) at Veladero
2013	5.01	2.59	6.14	1.06	0.94
2014	6.28	1.34	5.53	0.99	1.00
2015	6.01	1.73	4.94	1.02	0.82
2016	3.55	2.11	2.93	1.86	0.83

operations as the storage of waste is taking up a huge amount of space and creating a large environmental footprint.

6.3 Waste Disposal and Management

As discussed above, the waste from mining operations consists of waste rock and tailings. The disposal and management of waste rock and tailings is described in this section.

6.3.1 Waste Rock Management

Waste rock that does not present a risk to the environment due to leakage of harmful chemicals can be disposed in many ways. It can be placed in waste rock storage facilities till the facility is full and then covered with soil for growing plants and trees. Open pits or underground tunnels can also be filled with waste rock, if no environmental concerns are present. Non-reactive waste rock can also be used as construction material for road beds or tailing dams. Depending on the composition of waste rock, it may be susceptible to acid rock drainage (ARD) and/or metals leaching (ML) into the surrounding soil and water sources. Reactive waste rock can be encapsulated within non-reactive waste rock to minimize the chance of ARD and/or ML.

6.3.1.1 Acid Rock Drainage and Metals Leaching

The drainage of acid, metal or sulphates results from the oxidation of sulphide minerals due to the exposure to air or water. It is described by several terms such as acid rock drainage (ARD), acid mine drainage or acid and metalliferous drainage (AMD), mining influenced water (MIW), saline drainage (SD) and neutral mine drainage (NMD). Based on the composition of the mineral and ambient conditions, the drainage could be acidic or neutral and may contain heavy metals. Depending on the pH of the resulting solution, the drainage is classified as acid rock drainage (ARD), neutral mine drainage (NMD) or saline drainage (SD). Table 6.6 shows the difference between different types of drainages. Figure 6.5 shows the sources, pathways and receiving environment for acid rock drainage.

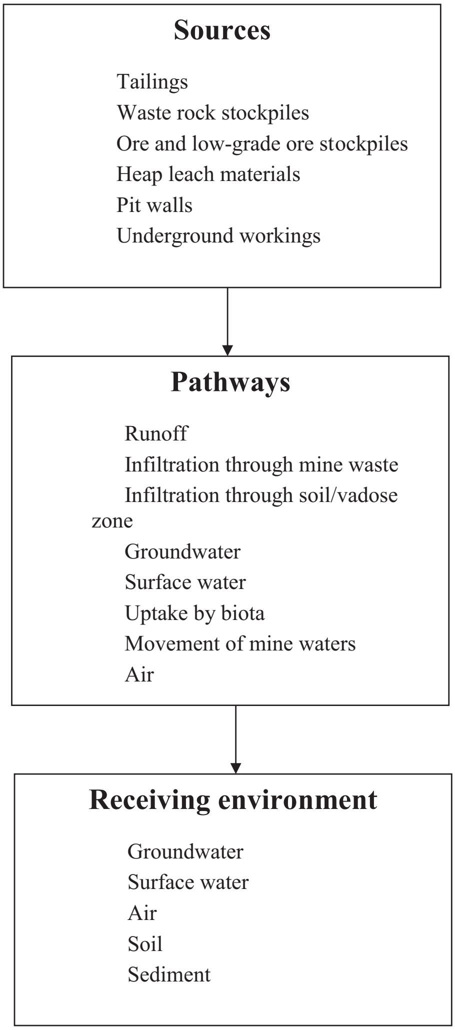
6.3.1.2 Acid Rock Drainage Formation

The formation of acid rock drainage (ARD), neutral mine drainage (NMD) or saline drainage (SD) results from the oxidation of sulphide minerals. When sulphide minerals are exposed to oxygen from atmosphere or oxygenated water due to mining or

Table 6.6 Classification of drainage from waste rock (INAP 2009)

Acid rock drainage	Neutral mine drainage	Saline drainage
Acidic pH	Near neutral to alkaline pH	Neutral to alkaline pH
Moderate to elevated metals	Low to moderate metals. May have elevated zinc, cadmium, manganese, antimony, arsenic or selenium	Low metals. May have moderate iron
Elevated sulphate	Low to moderate sulphate	Moderate sulphate, magnesium and calcium
Treat for acid neutralization and metal and sulphate removal	Treat for metal and sometimes sulphate removal	Treat for sulphate and sometimes metal removal

Fig. 6.5 Sources, pathways and receiving environment for acid rock drainage (adapted from INAP 2009)



mineral processing, sulphides become unstable. The reactions taking place under these conditions can be illustrated using the mineral pyrite (FeS_2), which is the most common sulphide mineral.

$$\text{Reaction}\,(1): 2FeS_2 + 7O_2 + 2H_2O = 2Fe^{2+} + 4SO_4^{\;2-} + 4H^+$$

$$\text{Reaction}\,(2): 4Fe^{2+} + O_2 + 4H^+ = 4Fe^{3+} + 2H_2O$$

$$\text{Reaction}\,(3): 4Fe^{3+} + 12H_2O = 4Fe(OH)_3 + 12H^+$$

$$\text{Reaction}\,(4): FeS_2 + 14Fe^{3+} + 8H_2O = 15Fe^{2+} + 2SO_4^{\;2-} + 16H^+$$

$$\text{Overall reaction}: 4FeS_2 + 15O_2 + 14H_2O = 4Fe\left(OH\right)_3 + 8H_2SO_4$$

Reaction (1) is the oxidation of pyrite by oxygen in the presence of water. During this reaction, sulphur is oxidized to sulphate with the release of ferrous iron. Two H^+ ions are generated for each mole of pyrite.

Reaction (2) is the oxidation of ferrous iron to ferric iron. One H^+ ion is consumed to convert one ferrous iron to ferric iron. The rate of conversion from ferrous to ferric iron can be increased by certain bacteria. The reaction proceeds slowly under stronger acidic conditions (pH 2–3) when no bacteria are present. The rate of reaction is several orders of magnitude faster under mildly acidic conditions (pH~5). This reaction is considered as a rate-limiting step.

Reaction (3) is the hydrolysis of iron, which results in the generation of three H^+ ions for each ferric ion. Ferric hydroxide precipitate is formed due to hydrolysis.

Reaction (4) is the oxidation of additional pyrite molecules by ferric iron. The reaction takes place very rapidly and continues until either ferric iron or pyrite is consumed. Overall reaction shows that two moles of sulphuric acid are produced for each mole of pyrite.

Above reactions show the formation of acid by the oxidation of pyrite. Although pyrites are dominant sulphide species in the minerals, there are other sulphide minerals present in the ore and waste rock. The oxidation of these sulphide minerals may or may not generate acid. Iron sulphides (pyrite, marcasite, pyrrhotite), sulphides with molar metal/sulphur ratios <1 and sulfosalts (e.g. enargite) generate acid by reacting with oxygen and water. Sulphides with molar metal/sulphur ratios = 1 (e.g. sphalerite, galena, chalcopyrite) do not generate acid by reacting with oxygen and water. However, all sulphides can generate acid in the presence of ferric ion. Therefore, the presence of iron sulphide is the determining factor in the potential for generating acid. The presence of carbonate minerals may result in neutralizing the acid generated by oxidation of sulphide minerals.

6.3.1.3 Acid Rock Drainage Prediction

The tests for prediction of acid rock drainage are classified in two groups: static tests and kinetic tests. The static tests are based on chemical balance and do not take rate of reactions into account. These tests assume that all the sulphur in the rocks is acid-forming pyritic sulphide and all acid-consuming components are available to neutralize acid. These tests are performed by calculating acid production potential (APP) and neutralization potential (NP). The difference between neutralization potential and acid production potential is termed Net Neutralization Potential (NPP).

The kinetic tests are conducted for the following reasons (Ritcey 2005):

(a) Confirmation of the static tests
(b) Assessment of rates of AMD potential
(c) Determination of the effect of bacterial action

(d) Assessment of the rate of depletion of neutralization capacity
(e) Estimation of metals concentration in leachate from the waste
(f) Determination of the overall biogeochemical changes
(g) Evaluation of different waste management and control strategies for the particular waste

Kinetic tests are first conducted at bench scale and are followed by large-scale testing on site. While static tests can be useful as a guide, kinetic tests are needed for better prediction of acid rock drainage potential. Kinetic tests include soxhlet, columns, humidity cell and lysimeter tests.

6.3.1.4 Acid Rock Drainage Treatment Technologies

Table 6.7 lists the various technologies that can be utilized for the treatment of acid rock drainage, which can be grouped under four categories: neutralization, metals removal, desalination and specific target pollutant treatment.

6.3.1.5 Acid Rock Drainage Management

To avoid the contamination of soil and water in the affected area, proper management plan has been developed by the International Network for Acid Prevention (INAP). The INAP is an international organization that is dedicated to understanding and

Table 6.7 Acid rock drainage treatment technologies (adapted from INAP 2009)

Neutralization	Lime/limestone process Sodium based alkali's (NaOH, Na_2CO_3) Ammonia Biological sulphate reduction Wetlands, anoxic drains Other technologies
Metals removal	Precipitation/hydroxide Precipitation/carbonates Precipitation/sulphides Wetlands, oxidation ponds Other technologies
Desalination	Biological sulphate removal Precipitation processes such as ettringite Membrane-based processes Ion-exchange processes Wetlands, passive treatment processes
Specific target pollutant treatment	Cyanide removal: chemical oxidation, biological oxidation, complexation Radioactive nuclides: precipitation, ion exchange Arsenic removal: oxidation/reduction, precipitation, adsorption Molybdenum removal: iron adsorption Other technologies

meeting the challenge of acid drainage. The INAP was founded in 1998 and is a proactive, global leader in this field. Its members include Anglo American, Antofagasta Minerals, Barrick, Freeport-McMoRan, Kinross Gold Corporation, Newcrest, Newmont, Rio Tinto, Vale and Xstrata. Based on the interactions with the global gold mining companies, the INAP has developed the Global Acid Rock Drainage (GARD) Guide (INAP 2009), which is a worldwide reference for the prevention and mitigation of acid rock drainage. The GARD Guide is periodically updated to reflect the current understanding of acid rock drainage.

Acid rock drainage management plan shown in Table 6.8 details the different activities that need to be performed at each stage of mine operation. For the management of acid rock drainage, it is important to be able to predict acid rock drainage. The approach to the prediction of acid rock drainage is shown in Fig. 6.6.

6.3.2 *Tailings Management*

The tailings management system has many components and may include many steps such as tailings treatment in the mill, slurry thickening, slurry transport, tailings impoundment, water recovery and recycle, tailings and effluent treatment and

Table 6.8 Acid rock drainage management plan (adapted from INAP 2009)

Exploration	Characterization
Assessment	Prediction
Design	Planning for avoidance
Construction	Surface water control works Groundwater control
Operation	Waste rock: special handling, segregation, encapsulation, layering, blending, re-mining, backfilling, passivation, selective mining and avoidance, hydrodynamic controls, appropriate siting of facilities, co-disposal, in-pit disposal, permafrost and freezing, bactericides, alkaline materials, organics Tailings: desulphurization, compaction, amendment, dewatering, re-mining, backfilling, passivation, selective mining and avoidance, hydrodynamic controls, appropriate siting of facilities, co-disposal, in-pit disposal, permafrost and freezing, bactericides, alkaline materials, organics Open pit: re-mining, backfilling, passivation, selective mining and avoidance, hydrodynamic controls Underground workings: re-mining, backfilling, passivation, selective mining and avoidance, hydrodynamic controls
Decommission	Dry cover for waste rock and tailings Seals for underground workings Water cover for tailings and open pit Flooding for waste rock, tailings, open pit and underground workings
Post-closure	Monitoring Maintenance Inspection Long-term collection and treatment were required

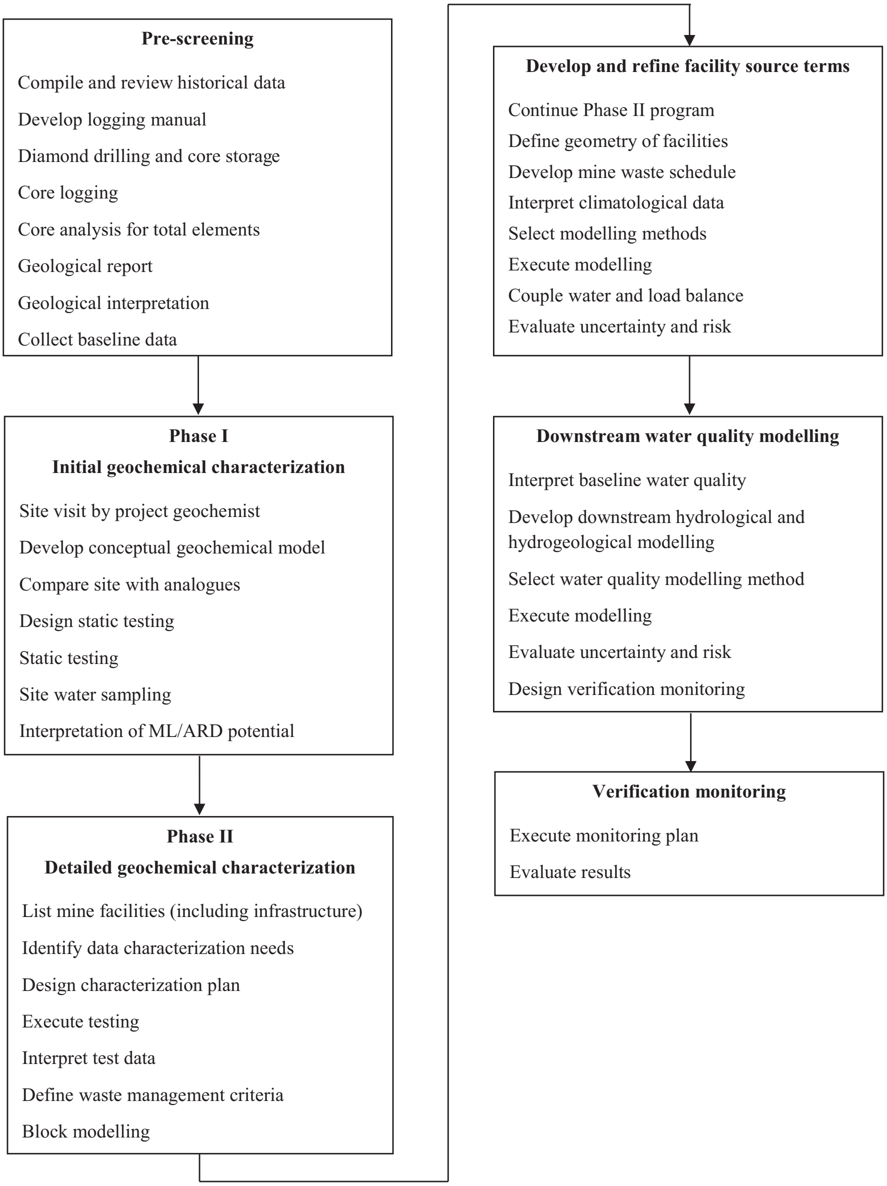


Fig. 6.6 Acid rock drainage prediction approach (adapted from INAP 2009)

evaporation and restoration of the site (Ritcey 2005). The amount of tailings produced by the mining industry in 2010 was 14 billion tons (Jones and Boger 2012). The generation of such a huge amount of tailings leaves a large environmental footprint. In terms of space, it occupies a large area for storage, which needs to

Table 6.9 Potential risks associated with mine tailings (Adiansyah et al. 2015)

Phase	Potential risks
Operation	Leaking of tailings slurry pipeline Geotechnical failure TSF overflow Seepage through containment wall Seepage infiltration to groundwater Particulate matter (PM): dust or gas emissions Interaction of wildlife or livestock with tailings Mine acid pollution into the water: groundwater and surface water
Closure	Erosion of containment wall Spillway failure Overtopping by rainfall runoff Failure of land cover system on tailings surface

be managed for environmental degradation. The management of tailings is a crucial issue in mining operations because of the potential for accidents.

6.3.2.1 Incidences of Tailings Dam Failures

Potential risks associated with mine tailings are shown in Table 6.9. A proper tailings management plan will take into account all the potential risks during the operation and closure of the tailings facility. The failure to properly manage tailings can have catastrophic consequences which can be very costly to remedy.

The failure of Santarém and Fundão tailings dams in Brazil to contain the water and sediment from iron ore extraction resulted in one of the worst environmental disasters of recent history. The two dams are owned and operated by Samarco, a privately held Brazilian mining company, which is controlled in equal parts by two shareholders: the Brazilian Vale S.A. and the Anglo-Australian BHP Billiton. The tailings dams located in the Mariana region, state of Minas Gerais, Brazil, burst on November 5, 2015, releasing about 60 million cubic meters of tailings (da Costa 2017). The tailings entered the River Doce, one of Brazil's most important rivers, and reached about 20 municipalities downstream from the mine site in the next 17 days. This had a devastating impact on water supply, fisheries activities, agriculture and tourism in the affected area. The failure of Santarém and Fundão tailings dams resulted in 19 persons losing their lives and more than 600 people losing their homes.

On January 25, 2019, another tailings dam failure took place at the Córrego do Feijão iron ore mine in Brazil operated by Vale. This dam collapse resulted in at least 58 people dead and hundreds missing. This is widely considered as a sad consequence of the lessons not learned.

Another catastrophic failure of a tailings storage facility was a leak of cyanide near Baia Mare, Romania, into the Someș River in 2000. This facility was operated by the gold mining company Aurul, which was a joint venture between the Australian company Esmeralda Exploration and the Romanian government. This spill has been called the worst environmental disaster in Europe since the Chernobyl disaster which resulted in killing large numbers of fish in Hungary and Romania as the polluted waters reached the Tisza River and then the Danube River. This toxic spill contaminated the water supplies of more than two million people (Lottermoser 2010).

The catastrophic failure of the Los Frailes tailings dam near Seville, Spain, in April 1998 released approximately 528 million gallons of pyrite sludge and another 1 billion gallons of acid water containing high concentrations of heavy metals (zinc, lead, arsenic, copper, antimony, thallium and cadmium) into the Guadiamar River affecting a 62 kilometre long section of the river, ranging from 500 to 1000 meters in width (Arenas and Méndez 2002). The area affected by the accident included 6560 acres within Doñana Nature Park and 242 acres within Doñana National Park. The cost of cleanup exceeded $225 million. It resulted in a loss of 5000 jobs in various sectors and contamination of water stream with acid, metals and metalloids. Such accidents can be avoided by proper tailings management.

Between 1910 and 2009, 218 cases of tailings accidents have taken place worldwide (Azam and Li 2010). Figure 6.7 shows the number of accidents per decade starting from 1910.

6.3.2.2 Causes of Tailings Dam Failures

Figure 6.7 shows that most accidents took place during the 1960–1980s. Out of the 218 accident, 167 accidents were analysed for causes of failure as information from the rest of the accidents were not available to make an informed conclusion. Figure 6.8 shows the number of accidents as a function of causes of tailings dam failures. These causes include unusual weather, management, foundation subsidence,

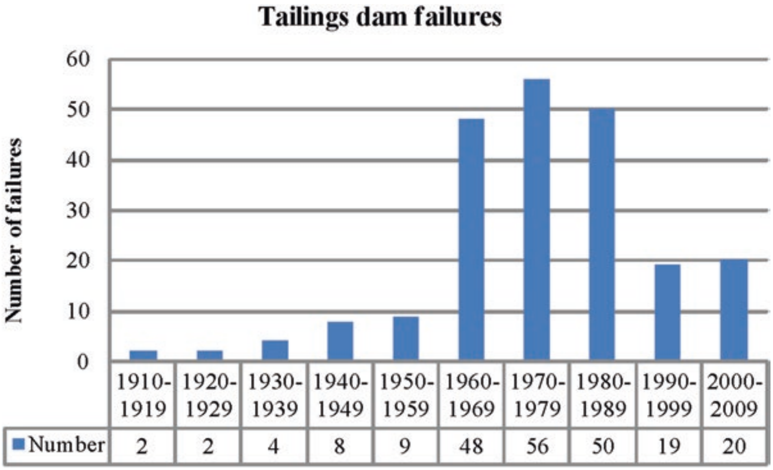


Fig. 6.7 Tailings dam failures around the world (adapted from Azam and Li 2010)

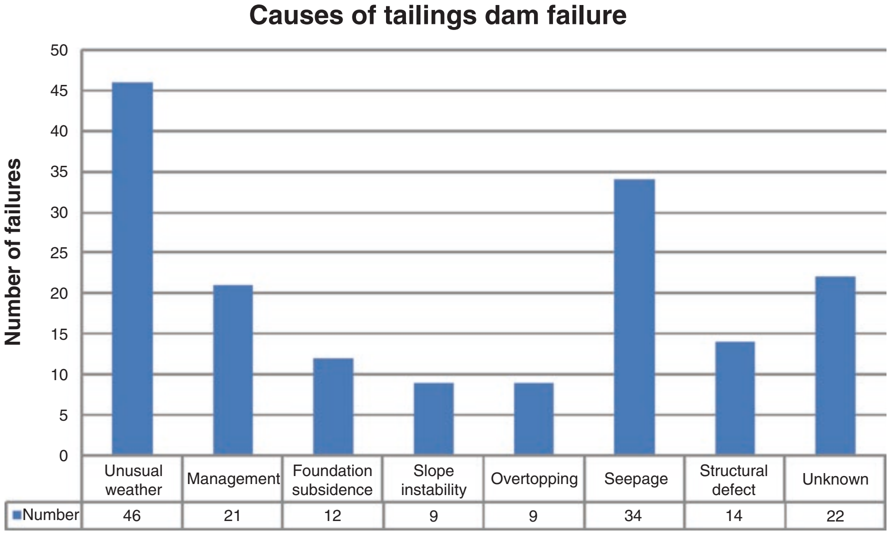


Fig. 6.8 Causes of tailings dam failures (adapted from Azam and Li 2010)

slope instability, overtopping, seepage and structural defect. For some accidents, the cause of failure could not be determined. Most accidents have taken place due to unusual weather, followed by seepage.

Tailings dams are supposed to last for a long time, but a number of factors make tailings dams more vulnerable than water retention dams. These factors are as follows (Rico et al. 2008):

1. Embankments are made from soil, coarse waste, overburden from mining operations and tailings.
2. Dams are raised as flow of solid material and effluent from mine including runoff from precipitation increases.
3. There is lack of regulations on specific design criteria.
4. There is lack of dam stability requirements regarding continuous monitoring and control during emplacement, construction and operation.
5. The cost of maintenance works for tailings dams after closure of mining activities is high.

6.3.2.3 Tailings Disposal Methods

The methods of tailings disposal can be classified in two different groups: direct disposal methods and indirect disposal methods.

Direct Disposal

Direct disposal involves discharging tailings directly into rivers and oceans, which raises environmental concerns. Direct disposal methods can be subdivided in two groups: riverine tailings disposal (RTD) and submarine tailings disposal (STD). These methods are currently being practiced at 16 mine sites located in Europe and Asia as shown in Table 6.10 (IMO 2012).

RTD is the simplest tailings disposal method in which tailings are transported to the river by a pipe and discharged in the river. There are only four mines in the world carrying out tailings disposal by direct discharge in the rivers. One of these sites is located in Indonesia and three sites are located in Papua New Guinea (IMO 2012). Nearly 295 million tons of tailings are disposed in the rivers and oceans per year, out of which Indonesia and Papua New Guinea account for over 93% of tailings disposal by RTD and STD. Out of the 295 million tpy of total tailings, around 62% (~183 million tpy) is directly discharged in the rivers. There are 12 mines in the world that use STD for disposal of tailings. STD is also known as Deep Sea Tailings Disposal (DSTD). In this method, tailings are discharged into the ocean using a pipeline and settle to the bottom of the ocean floor. The density and temperature of the tailings product need to be controlled to prevent the tailings from flowing away from the location of tailings deposition. Earlier tailings were discharged on the ocean surface, which created close interactions between tailings and environments, both biotic and abiotic. Deep sea tailings disposal was introduced to reduce the impact of mine tailings on the biotic and abiotic environment of the ocean.

Indirect Disposal

In this method, tailings are disposed in a confined area such as an impoundment, cell or dam. Depending on the solids content of the slurry, various options for indirect disposal are exercised such as conventional tailings, tailings paste, thickened tailings and tailings cake. Out of these, the most common method of indirect disposal is conventional tailings. When the solids content of the slurry is approximately 25–30% solids, it is termed conventional tailings, which can be transported in slurry form

Table 6.10 Tailings disposal by RTD and STD (IMO 2012)

	Number of riverine tailings disposal sites	Number of submarine tailings disposal sites	Mine tailings volume million tons/year
Turkey	0	1	11
England	0	1	2
Norway	0	5	7
Indonesia	1	1	127
Papua New Guinea	3	4	148
Total	4	12	295

through pipes. One of the main causes of tailings dam failures is the high water content of the slurry. The risk of tailings dam failure can be reduced by decreasing the water content of the tailings to convert conventional tailings to tailings paste, thickened tailings or tailings cake. Tailings are dewatered using vacuums and filters, which helps in water balance and also reduces the environmental impact. Tailings cake cannot be transported by pipeline. It is normally transported by conveyor or truck to tailings disposal area, where it is deposited and spread. It is then compacted to form an unsaturated tailings deposit, which is referred 'dry stack' (Davies and Rice 2001). Dry stacking has many advantages such as water conservation and no risk of tailings dam failure. However, it involves higher capital needing investment in modern filtration equipment and maintenance and operation of these equipment.

Phytostabilization can be used for long-term stabilization and containment of tailings. It works by sequestering pollutants near the roots of the plants in the soil. The growth of plants reduces erosion by wind or water. Plants can immobilize metals by adsorption around the roots, which reduces the exposure of pollutants to livestock, wildlife and humans. Trees such as *Dalbergia sissoo*, *Eucalyptus*, *Cassia siamea*, *Acacia mangium* and *Peltophorum* can be planted over overburden dumps for best results (Das and Choudhury 2013).

6.3.2.4 Life Cycle of a Tailings Facility

A proper tailings management plan begins from the project conception and planning stage and incorporates complete life cycle of the tailings facility including post-closure stage. The life cycle of a tailings facility consists of the following stages (MAC 2017):

1. Project conception and planning: This phase begins with the planning of a proposed mine. It is integrated with conception and planning for the overall site, including the mine plan and plans for ore processing.
2. Design: This phase begins once the location and best available technology for the tailings facility have been selected. During this phase, detailed engineering designs are prepared for all aspects of the tailings facility and associated infrastructure.
3. Initial construction: This phase involves the construction of structures and infrastructure that need to be in place before the deposition of tailings commences. Examples of activities during this phase include the removal of vegetation and overburden and construction of starter dams, tailings pipelines, access roads and associated water management infrastructure.
4. Operations and ongoing construction: During this phase, tailings are transported to the tailings facility. The design of tailing facility includes the provisions for raising the height of tailings dams or construction of new tailings cells as needed during the operation of the mine. The period of commercial operations of the mine may or may not coincide with the operations and ongoing construction phase of a tailings facility.

5. Standby care and maintenance: This phase begins when the mine has ceased commercial operations and the deposition of tailings into the facility is no longer taking place. The surveillance and monitoring of the tailings facility continue during this phase. As the resumption of commercial operations is expected at some point in the future, the facility and associated infrastructure are not decommissioned and the closure plan is not implemented.
6. Closure: This phase begins when the deposition of tailings into the facility has stopped permanently. Now the tailings facility and associated infrastructure are decommissioned. The key aspects of the closure plan are:
    - Transitioning for operations to permanent closure
    - Removal of key infrastructure such as pipelines
    - Changes to water management or treatment
    - Recontouring or revegetation of tailings and any containment structures or other structural elements
7. Post-closure: This phase begins when the decommissioning work has been completed, key aspects of the closure plan have been implemented and the tailings facility has transitioned to long-term maintenance and surveillance. During this phase, the responsibility for the tailings facility could transfer from the owner of the facility to jurisdictional control.

6.4 Value Generation from Waste

To make the mining industry more sustainable, there is need for value generation from the mining waste while making the mining waste environmentally inert. Yesterday's tailings is today's resource and today's waste is tomorrow's resource. Tailings need to be stored in such a way that it facilitates the recovery of value at a future date. Tailings also need to be secured properly for future processing. The development of zero discharge technology has made it easier to store tailings safely till it is processed at a future date.

6.4.1 Recovery of Gold

Now it is possible to economically recover gold from tailings having 0.3 g/ton gold by heap leaching. A number of companies are currently involved in processing tailings from previously abandoned mines as technology has advanced and gold price has risen. These companies include DRDGold, Mintails Ltd., Gold Fields, Gold One Group, Carbine resources in Australia and PanTerra Gold (Ndlov et al. 2017). Gold Fields is running a tailings treatment project (TTP) in South Africa to recover gold and uranium. Enviro Gold, a subsidiary of PanTerra Gold, is running the Las Lagunas Gold Tailings project in Dominican Republic to recover gold from Pueblo

Viejo mine tailings. The project involves ultrafine grinding, flotation, sulphide oxidation using the Albion process and extraction of gold and silver using standard carbon-in-leach cyanidation.

6.4.2 Recovery of Sulphuric Acid

The Council for Scientific and Industrial Research (CSIR) based in South Africa has developed a chemical desalination process to neutralize acid mine drainage (AMD) and recover metals and sulphate (Motaung et al. 2008; Wilsenach et al. 2008). The process consists of the following steps:

Step 1: *Pretreatment*

The first step is pretreatment using $CaCO_3$, which neutralizes the free acid and precipitates iron(III) and aluminium(III), as hydroxides.

$$H_2SO_4 + CaCO_3 = CaSO_4 + CO_2 + H_2O$$

$$2M^{3+} + 3CaCO_3 + 3H_2O = 2M(OH)_3 + 3CO_2 + 3Ca^{2+} \left(M = Fe, Al\right)$$

Step 2: *Lime treatment*

The second step is treatment with hydrated lime for removal of magnesium and partial removal of sulphate as crystals of gypsum.

$$Mg^{2+} + Ca(OH)_2 = Mg(OH)_2 + Ca^{2+}$$

$$Ca^{2+} + SO_4{}^{2-} + 2H_2O = CaSO_4 \cdot 2H_2O$$

Step 3: *pH adjustment*

The third step is pH adjustment using carbon dioxide.

$$Ca(OH)_2 + CO_2 = CaCO_3 + H_2O$$

Step 4: *Removal of sulphate*

The fourth step is the removal of sulphate as barium sulphate.

$$Ca^{2+} + SO_4{}^{2-} + BaCO_3 = BaSO_4(s) + CaCO_3(s)$$

Step 5: *Recovery of CaS and CO_2*

The fifth step is the processing of the $CaSO_4 \cdot 2H_2O/Mg(OH)_2$ sludge to recover CaS and CO_2.

$$CaSO_4 + 2C = CaS + CO_2$$

Step 6: *Processing of CaS*

The sixth step is the processing of CaS to produce $Ca(HS)_2$, $CaCO_3$ and H_2S.

$$2CaS + CO_2 + H_2O = Ca\left(HS\right)_2 + CaCO_3$$

$$Ca\left(HS\right)_2 + CO_2 + H_2O = CaCO_3 + 2H_2S$$

Step 7: *Recovery of BaS and CaO*

The seventh step is the processing of the $BaSO_4/CaCO_3$ sludge to recover BaS and CaO.

$$BaSO_4 + 2C = BaS + CO_2$$

$$CaCO_3 = CaO + CO_2$$

Step 8: *Processing of BaS to $BaCO_3$*

The eighth step is the processing of BaS to produce $BaCO_3$.

$$BaS + CO_2 + H_2O = BaCO_3 + H_2S$$

Step 9: *Processing of H_2S to sulphur*

The final step is the processing of H_2S to produce sulphur, which can be used to make sulphuric acid.

$$2H_2S + SO_2 = 2S + 2H_2O$$

6.4.3 Recovery of Mercury

Mercury is released to the environment during extraction of gold or silver due to its presence in many gold ores. It can be produced as a by-product, which is preferable to its release in the atmosphere or tailings. The production of mercury at a Nevada gold mine has been studied by Miller (2007). Concentration of mercury in gold ores varies from less than 0.1 mg/kg to over 100 mg/kg. Generally, 80–90% of mercury in the ore is volatilized during roasting. If one million ton of ore containing 20 mg/kg mercury is roasted, 16–18 tons of mercury becomes available for recovery. Scrubbing systems such as the calomel and hypochlorite systems can be used for the capture of mercury.

$$\text{Calomel system}: HgCl_2 + Hg = Hg_2Cl_2$$

$$\text{Hypochlorite system}: NaOCl + 2Hg + HCl = Hg_2Cl_2 + NaOH$$

Mercury remaining in the ore is recovered during further processing steps. During cyanidation, both gold and mercury form water-soluble cyanide complexes according to the following reactions:

$$4\mathrm{Au} + 8\mathrm{NaCN} + \mathrm{O}_2 + 2\mathrm{H}_2\mathrm{O} = 4\mathrm{Na}\left[\mathrm{Au}\left(\mathrm{CN}\right)_2\right] + 4\mathrm{NaOH}$$

$$2\mathrm{Hg} + 8\mathrm{NaCN} + \mathrm{O}_2 + 2\mathrm{H}_2\mathrm{O} = 2\mathrm{Na}_2\left[\mathrm{Hg}\left(\mathrm{CN}\right)_4\right] + 4\mathrm{NaOH}$$

These complexes are adsorbed on carbon and stripped from the carbon and electrowon to recover gold. Mercury is separated from the gold by distillation and collected as liquid mercury.

6.5 Energy and Water Management

The International Council of Mining and Metals (ICMM) has developed ten principles of sustainable development as described below (ICMM 2015):

1. Apply ethical business practices and sound systems of corporate governance and transparency to support sustainable development.
2. Integrate sustainable development in corporate strategy and decision-making processes.
3. Respect human rights and the interests, cultures, customs and values of employees and communities affected by our activities.
4. Implement effective risk management strategies and systems based on sound science and which account for stakeholder perceptions of risks.
5. Pursue continual improvement in health and safety performance with the ultimate goal of zero harm.
6. Pursue continual improvement in environmental performance issues, such as water stewardship, energy use and climate change.
7. Contribute to the conservation of biodiversity and integrated approaches to land-use planning.
8. Facilitate and support the knowledge base and systems for responsible design, use, reuse, recycling and disposal of products containing metals and minerals.
9. Pursue continual improvement in social performance and contribute to the social, economic and institutional development of host countries and communities.
10. Proactively engage key stakeholders on sustainable development challenges and opportunities in an open and transparent manner. Effectively report and independently verify progress and performance.

Continual improvement in environmental performance issues, such as energy use and water stewardship has been described as a guiding principle for sustainable development. With the increasing demand for water and energy, the feasibility of many mining projects depends on the adequate supply of water and energy throughout the life of the mine. As a good strategy for water and energy management is crucial for the success of mining projects, mining companies are taking steps to minimize energy consumption and water usage. However, both of these targets may not be satisfied simultaneously. It is often the case that water management initiatives lead to higher energy consumption (Nguyen et al. 2014). Thus, energy and water management have to be undertaken in a coupled manner.

Recently two different approaches have been developed to optimize the energy and water requirements for mining activities such as optimal mine water network design using water pinch analysis and hierarchical systems modelling.

Optimal mine water network design using water pinch analysis was developed by Gunson et al. (2010) by combining the mine water network design (MWND) approach with the water pinch analysis (WPA) approach. The WPA approach maximizes water reuse and minimizes wastewater discharge for allocation of water within a water network (Hallale 2002). The MWND approach constructs energy requirement matrices of the water system by identifying quantity and quality of potential water providers (sources) and water receivers (users) and energy demand for water processes such as pumping, treatment, cooling and heating. It then uses linear programming to minimize energy usage and select the optimal water network. This approach is suitable for greenfield water projects, but not for existing mine water system where making extensive changes to the existing mine water system may not be feasible.

The hierarchical systems model (HSM) analyses water, energy and emissions interactions in mining at different scales: subsite, site and regional levels. Water input, water output, energy input and energy output are listed for each system component at each scale, and this approach allows water use and energy use to be displayed in parallel. Based on this data, energy and water consumptions can be optimized.

6.5.1 Energy Management

Mining is an energy intensive industry considered to be one of the five largest consumers of global energy (Adiansyah et al. 2016). Energy is used not only in mining and processing activities but also in water and wastewater treatment and for residential needs. There are many opportunities in the mining industry to either minimize energy consumption or reduce pollution from energy generation by using renewable energy sources.

6.5.1.1 Tailings Water Recycling

Tailings are transported to the tailings storage facility as slurry by a pipeline, which requires energy. Water from this slurry can be recovered and pumped back to the processing plant to be used as process water. Energy is also required for the

Table 6.11 Synergy and trade-off scenario matrix (Nguyen et al. 2014)

	$\Delta V > 0$	$\Delta V = 0$	$\Delta V < 0$
$\Delta E > 0$	Trade-off	Trade-off	Not applicable
$\Delta E = 0$	Synergy	Neutral	Not applicable
$\Delta E < 0$	Synergy	Synergy	Trade-off

recycling of water from tailings slurry. Thus, the water and energy consumptions are related. The efforts to conserve energy and improve water availability can result in different scenarios as shown in Table 6.11.

1. Scenario 1: $\Delta E > 0$ and $\Delta V > 0$; there is a trade-off between higher water availability and higher energy demand.
2. Scenario 2: $\Delta E > 0$ and $\Delta V = 0$; there is a trade-off between no change in water availability and higher energy demand.
3. Scenario 3: $\Delta E > 0$ and $\Delta V < 0$; this is not an acceptable scenario as water availability decreases and energy demand increases.
4. Scenario 4: $\Delta E = 0$ and $\Delta V > 0$; there is synergy as the water availability increases and energy demand remains same.
5. Scenario 5: $\Delta E = 0$ and $\Delta V = 0$; this is a neutral scenario as there is no change in water availability and no change in energy demand.
6. Scenario 6: $\Delta E = 0$ and $\Delta V < 0$; this is not an acceptable scenario as water availability decreases and energy demand remains same.
7. Scenario 7: $\Delta E < 0$ and $\Delta V > 0$; there is synergy as the water availability increases and energy demand decreases.
8. Scenario 8: $\Delta E < 0$ and $\Delta V = 0$; there is synergy as the water availability remains same and energy demand decreases.
9. Scenario 9: $\Delta E < 0$ and $\Delta V < 0$; there is a trade-off between lower water availability and lower energy demand.

Scenarios 3 and 6 can be rejected right away as energy demand increases while water availability decreases. Scenarios 4, 7 and 8 are acceptable as either water availability increases without an increase in energy demand or energy demand decreases without a reduction in water availability. Scenarios 1, 2 and 9 require a trade-off between increased water availability and reduced energy demand. Scenario 5 is a neutral situation where neither water availability increases nor energy demand decreases.

6.5.1.2 Use of Renewable Energy

Most of remote off-grid mines use diesel for power generation, which is expensive and generates greenhouse gases. Diesel generated electricity costs over 30¢/kWh in a typical Canadian mine located in the remote regions in Canadian North (Paraszczak and Fytas 2012). Recent technological advances have reduced the cost of installing and operating power generation systems based on renewable energy sources. Generation of power from solar energy, wind energy and geothermal energy can reduce the amount of diesel used by mining companies in remote locations, thereby making mining activities more cost-effective and have lesser carbon footprint. Mining companies have started incorporating the renewable power sources as part of the energy management plans.

There are thousands of inactive or abandoned mine tailings areas around the globe that are spread over hundreds of hectares and can be converted into renewable energy generation sites to produce carbon-free clean electricity (Loftis 2010). Chevron Mining has installed a solar power generating facility in a mine tailings area that can generate 1 MW of electricity at peak output at its molybdenum mine in Questa, New Mexico, USA (Woody 2011). Barrick Gold has spent $50 million in installing a wind power generation facility in the town of La Higuera in the Coquimbo Region of Northern Chile (Barrick 2011). This facility was inaugurated in 2011 and consists of 10 wind turbines that can generate 20 megawatts of power, which is enough to supply the energy needs of 10,000 families. The wind farm can be expanded to 18 turbines, which will generate 36 megawatts of power at an additional cost of $20 million. The Lihir gold mine has installed a geothermal power plant, which is rated at 57 MW and generates 75% of the mine's power requirements (Melaku 2005). This mine, now owned by Newcrest, is located in a remote region in Papua New Guinea. Before the installation of the geothermal plant, diesel-generated power was the only source of electricity, and now there is plan to run the entire mine on geothermal power alone.

6.5.1.3 Use of Energy Storage Technology

The use of renewable energy sources and energy storage technologies can help in reducing energy costs and greenhouse gas emissions. The backup systems can also help in keeping the power supply uninterrupted in case of emergencies. Energy shortage can affect production rate and cause substantial losses. This has led to installation of energy storage technologies in combination with power generation systems. An example of this emerging trend is the installation of a lithium-ion energy storage system at Glencore Raglan Mine by Electrovaya Inc. in 2015 (Electrovaya 2015). The energy storage system was worth $0.7 million. Electrovaya designs, develops and manufactures lithium-ion batteries, battery systems and battery-related products for energy storage, clean electric transportation and other specialized applications. Electrovaya worked closely with Tuqliq Energy Corp., a specialist independent power producer, and Hatch Ltd., a global multidisciplinary management, engineering and development consultancy, for this installation. Glencore Raglan mine located at the extreme limit of Northern Quebec is one of the richest base-metal mines in the world and consumes 50 million litres of diesel annually. Delivery of diesel to remote sites is expensive, and burning of diesel as fuel generates greenhouse gases. A reduction in the amount of diesel used for energy generation can not only reduce fuel cost but also reduce the carbon footprint. The use of lithium-ion batteries for energy storage by pairing them to diesel generators can lead to reduction of diesel usage above 30% as this allows the generators to operate at maximum efficiency, which reduces diesel consumption substantially and lowers maintenance costs.

6.5.2 *Water Management*

Management of water is very important for mining activities. On the one hand, water is needed for mining and mineral processing, and, on the other hand, these activities can have adverse environmental impact on the water sources. Water is required for a range of mining and mineral processing process steps such as grinding, flotation, gravity concentration, dense medium separation and hydrometallurgical processes. Leaching of gold ores requires large quantity of water due to the lower grades of ores. Water is also required for making ore and waste slurries for transportation, cooling systems around power generation and washing equipment used in mining and mineral processing. In addition, water is required for residential usage by people working in the mines and their families. All of these activities can add up to a large amount of water needed for mining. Table 6.12 shows the amount of freshwater and saline water withdrawn by the mining industry in the USA in 2010.

As the availability of water in many mining areas may not be abundant, many countries are adopting the concept of integrated water resources management (IWRM). Such an approach is needed to ensure that mine water needs are optimized and process water is treated to impact on water resources so that clean water is available for future generations.

6.5.2.1 Impact of Mining on Water Sources

Mining activities have the potential to adversely impact groundwater and river water in the area. This can take place due to discharge of mine effluents and seepage from tailings and waste rock. Higher metal concentrations and acidity has been observed in water from many mining areas. The oxidation of sulphide minerals can increase the amount of dissolved metals in surface waters downstream from the mine. Potential impact of mining operation on water sources is shown in Table 6.13.

Table 6.12 Water withdrawal for mining in the USA in 2010 (USGS 2017)

Source	Freshwater (million gallons/day)	Saline water (million gallons/day)	Total (million gallons/day)
Surface water	1130	280	1410
Groundwater	1120	2790	3900
Total	2250	3070	5310

Table 6.13 Potential impact of mining on water contamination (adapted from (Mohapatra and Kirpalani 2017)

Mining method	Potential impact
Opencast mining: excavation not intersecting water table	1. Affecting natural surface water regime 2. Affecting groundwater recharge regime
Opencast mining: excavation intersecting water table	1. Declining of water table 2. Affecting natural springs 3. Affecting natural surface water regime 4. Affecting groundwater recharge regime
Underground mining	1. Shallow aquifers 2. Deep aquifers 3. Affecting natural surface water regime 4. Affecting groundwater recharge regime 5. Affecting groundwater flow direction 6. Drying of upper aquifers

6.5.2.2 Treatment of Arsenic

Potential sources of water contamination from mining activities are acid mine drainage and accidental release of tailings from tailings storage facilities. This can adversely affect the quality of drinking water and the life cycle of plants and animals in the affected area. The corrosion rate of metals present in bridges, railways and ships in the area can also increase due to acid mine drainage. The presence of acid can also increase the concentrations of metals and metalloids in affected water. Among the metalloids, the presence of arsenic is of greatest concern.

Arsenic is found in the form of both inorganic and organic compounds. Organic arsenic compounds are found in seafood and are considered safe as these compounds pass through the body quickly. Inorganic arsenic compounds are considered a health risk. These compounds are found in soils and groundwater. Arsenic has different valencies in these compounds, As(III) being the dominant form under reducing conditions and As(V) being the stable form under oxidizing conditions. These compounds could be naturally occurring or a result of human activities such as mining, smelting and arsenic compounds manufactured for industrial use. Inorganic arsenic compounds have been used in pesticides, paint pigments, wood preservatives and medicines in the past, but are now restricted. Arsenic from these sources can contaminate the water sources and pose a health risk to humans. Arsenic level over 10 parts per billion in water is considered toxic.

The conversion of potentially hazardous arsenic compounds into stable non-toxic phases is the most effective method to reduce the leaching of arsenic in water sources. The chemical fixation of arsenic by iron and iron compounds has been investigated by many researchers. Moore et al. investigated the use of $FeSO_4{\cdot}7H_2O$ for fixation of arsenic in the soil (Moore et al. 2000). When the molar ratio of iron to arsenic was increased from zero to two, the concentration of arsenic in the non-saturated and saturated soil solutions decreased from 554 to 15.4 μL^{-1} and 3802 to 0.64 μL^{-1}, respectively. Garcia-Sanchez et al. investigated the adsorption of arsenic by iron oxyhydroxide and aluminium hydroxide (Garcia-Sanchez et al. 2002). At pH 5, iron oxyhydroxide and aluminium hydroxide had the arsenic adsorption capacity of 76 mg/g and 122 mg/g, respectively. Bang et al. investigated the effect of dissolved oxygen on arsenic removal with elemental iron (Bang et al. 2005). The dissolved oxygen had a significant impact on arsenic removal. In the presence of oxygen, greater than 99.8% of the As(V) and 82.6% of the As(III) was removed at pH 6 after 9 h of mixing. When the dissolved oxygen was removed from the solution by purging with nitrogen gas, less than 10% of the As(III) and As(V) was removed.

The use of nanoparticles for the treatment of acid mine drainage and tailings water has been investigated by mining researchers. Kim et al. synthesized nanosized iron and nanosized magnetite coated with sodium dodecyl sulphate and used them to study the stabilization of arsenic in mine tailings. (Kim et al. 2012). Concentration of arsenic in leaching solution was determined by toxicity characteristic leaching procedure (TCLP). Nanosized magnetite was found to be more effective in arsenic immobilization. This was attributed to the enhanced mobility of magnetite due to the surface coating, which changed the surface charge of the particles and prevented the aggregation of the magnetite particles. This allowed the nano-magnetite particles to move further into soil and enhance arsenic immobilization.

Donget al. conducted experiments to investigate the mechanism of microbial-mediated arsenic mobilization from tailings sediments containing with the addition of nanoparticles (Dong et al. 2014). Additions of three different nanomaterials were investigated: SiO_2, Fe_2O_3 and Fe_3O_4. While the addition of SiO_2 increased arsenic mobilization, the addition of Fe_2O_3 and Fe_3O_4 decreased arsenic mobilization.

6.5.2.3 Cyanide Detoxification

The liquid effluents from the cyanide leach process contain cyanide compounds such as sodium cyanide, metal cyanides and thiocyanate and may also contain sulphur compounds such as sulphides, polysulphide, sulphite and thiosulphate. Relative stability of metal-cyanide compounds and complexes in water is shown in Table 6.14 in the approximate order of increasing stability. There are many different methods for the removal of cyanide from liquid effluents. The most common methods for the removal of cyanide are described below.

1. Natural degradation

   The concentration of cyanide in process effluents can decrease by natural degradation, which can be used to decrease the amount of chemicals needed for cyanide detoxification. In one study in Canada, the concentration of cyanide decreased from 68.7 to 0.08 mg/L by natural degradation during the 6-month period starting from April and ending in September (Schmidt et al. 1981). The degradation of cyanide did not take place during the cold winter months. Natural degradation of cyanide depends on many variables such as the cyanide species in solution, relative concentrations of the cyanide species, temperature, pH, aeration, amount of sunlight, presence of bacteria, pond size, depth and turbulence (Ritcey 2005).

Table 6.14 Relative stability of metal-cyanide compounds and complexes in water (Ritcey 2005)

	Types	Compounds
1.	Free cyanide	CN^-, HCN
2.	Simple cyanide compounds	
	(a) Readily soluble	NaCN, KCN, $Ca(CN)_2$, $Hg(CN)_2$
	(b) Relatively insoluble	$Zn(CN)_2$, CuCN, $Ni(CN)_2$, AgCN, $Cd(CN)_2$
3.	Weak metal-cyanide complexes	$Zn(CN)_4^{2-}$, $Cd(CN)_2$, $Cd(CN)_4^{2-}$
4.	Moderately strong metal-cyanide complexes	$Cu(CN)_2^-$, $Cu(CN)_3^{2-}$, $Ni(CN)_4^{2-}$, $Ag(CN)_2^-$
5.	Strong metal-cyanide complexes	$Fe(CN)_6^{4-}$,$Fe(CN)_6^{3-}$,$Co(CN)_6^{3-}$,$Au(CN)_2^-$,$Hg(CN)_2^-$

2. Ozonation

   Cyanide is oxidized rapidly by ozone. Depending on the stability of the metal complex, the rate of decomposition of complex cyanides varies. Cyanide complexes of nickel, zinc and copper oxidize readily, while iron cyanides do not decompose easily. The rate of decomposition of iron cyanide increases as temperature is increased. The rate of decomposition also depends on the pH of the solution and concentration of metal ions.
3. Bacterial oxidation

   Detoxification of cyanide can also be done by bacterial oxidation. At a temperature where bacteria can thrive, bacterial oxidation can reduce the concentrations of cyanides and other complexes except ferrocyanide to nearly zero. Bacterial oxidation has been used successfully by the Homestake Mining Company in South Dakota (Scott 1984). The temperature was maintained at 50–65 °F. The process uses soda ash as a source of carbon to assist nitrification and phosphorus as a trace nutrient.
4. SO_2 process

   The SO_2 process for destruction of cyanide to cyanate was developed by Inco (Devuyst et al. 1982). Oxidation of cyanide takes place according to the following reaction:

   $$CN^- + O_2 + SO_2 + H_2O = CNO^- + H_2SO_4$$

   The solution containing over 50 mg/L Cu is sparged with 2–5% SO_2 in air. Copper is precipitated as the hydroxide at the end of the process. The oxidation of CN is dependent on the pH and temperature of the solution. The oxidation is very slow at pH 5–6, fast at pH 9–10 and nearly zero at pH 11. The oxidation rate increases as the temperature is increased. Instead of sulphur dioxide, soluble sulphite or metabisulphite can also be used for oxidation.
5. Acidification

   The acidification process was originally known as the Mills-Crows process, which was modified in to the AVR process (acidification-volatilization by aeration and reneutralization). The process consists of acidification of the solution containing cyanide using H_2SO_4. The HCN gas is swept by air to an absorber tower where it is contacted with lime slurry. The recovered cyanide reagent is returned to the process, which represents substantial saving in reagent costs. The following reactions take place during acidification and aeration:

$$\text{Acidification}: \mathrm{Na_2Ni\left(CN\right)_4 + H_2SO_{4+}xH_2O = Ni\left(CN\right)_2 .xH_2O + 2HCN + Na_2SO_4}$$

$$\text{Aeration}: \mathrm{Na_2Ni\left(CN\right)_4 + 2H_2SO_4 = NiSO_4 + 4HCN\left(g\right) + Na_2SO_4}$$

6. Ion exchange

   Ion exchange resins can be used to recover cyanide from process solutions, which can then be reused. Extensive test work including pilot testing has been conducted at CANMET for cyanide recovery using ion exchange. The cyanides and metal-cyanide complexes were removed using two columns in series containing Amberlite IRA-400 anion exchange resin in the sulphate form in the primary column for the metal-cyanide complex and in the Cu(CN)2 form in the secondary column for the free cyanide.

The main advantages of the ion exchange process are as follows (Gilmore 1976):

1. Total cyanide can be reduced to 0.1 mg/L.
2. Cyanide can be recovered and reused.
3. Thiocyanate (SCN) can be reduced to less than 1 mg/ L.
4. H_2SO_4 used for desorption of cyanide is economical to use and readily available.
5. The bisulphate form of the resin is converted to the sulphate form by water for the adsorption of cyanide and heavy-metal complexes.

The disadvantages of the ion exchange process are as follows (Gilmore 1976):

1. Metals may precipitate within the resin bed and foul the resin.
2. H_2SO_4 requirement is high.
3. Capital and labour costs are high compared to chlorination or ozonation.
4. Technology is sophisticated.
5. As the hydrocyanic acid vapour is hazardous, ion exchange system should be tightly sealed. The plant area should be well ventilated and safety procedures must be followed.

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