FINNISH MINE WATER EXCELLENCE NETWORK

Current and New Water Management Solutions at Northern Mines

Teollisuustaito Oy

Programme for Sustainable Growth and Jobs

Teollisuustaito Oy

Leverage from the EU 2014–2020

European Union
European Regional Development Fund

Teollisuustaito Oy
Teknologiapuisto PL 102
87400 Kajaani
www.teollisuustaito.fi

Geological Survey of Finland

Current and New Water Management Solutions at Northern Mines

Date: Monday, 12 September 2016

Review produced for Finnish Mine Water Excellence Network, Geological Survey of Finland, by Teollisuustaito Oy

Programme for Sustainable Growth and Jobs

Teollisuustaito Oy

Leverage from
the EU
2014–2020

European Union
European Regional
Development Fund

Contents

Abstract

The first part of this report presents a review of the current water management practices, concentrating on Finnish mines. The focus is on base metal sulphide mines which also comprise a flotation based enrichment process. Water management practices are compared with other types of mineral processing technologies, and with other mines located in the Northern countries.

The second part of the report describes new, potential solutions for improving the water management practices at Finnish mines. New ideas originate from the literature and additional ideas were produced in a project workshop.

In Northern countries, mine water management is characterized by abundance of surface water and ground water. Mine water balance is typically positive, which normally leads to a need to release water to the environment, and to build water storage ponds. Mine water management comprises water and solid material feeds from the process itself, and naturally occurring water streams. Segregation of aqueous and solid streams, based on their composition, would be beneficial for water management. Segregation of the different water streams in Finland is currently not complete, whereas segregation of different solid waste streams is somewhat more common. The tailings pond is usually the main collection point for various water streams and solid material streams.

Despite the abundance of water, it is common to use additional fresh water as process water in certain consumption points of the flotation process at Finnish mines. Water is partly recycled from the tailings pond to the first stages of the enrichment process, i.e. grinding and flotation. The composition of the recycled water limits the use in certain processes.

Based on literature sources, water management has not been commonly integrated in the design of the enrichment process, or in the design of solid waste management. This means e.g. that different solid waste streams are not always being separated, and that the selection and optimization of process conditions, chemicals, and equipment does not always include analysis of the effects on water treatment and management. The tailings pond and waste rock storage solutions will affect mine water management especially in the case of sulphide containing ores, which are abundant in Finland.

Development of the mining operations and the beneficiation process is an important way to improve mine water management. Utilization of mineralogical data to optimize mining operations and pre-treatment processes would decrease the material stream to flotation process, which in turn would decrease consumption of water, chemicals, and production of waste water, and solid waste. Flotation process can be utilized to separate different waste streams, too. Selection of process chemicals based on their behaviour throughout the process and the water treatment system should be applied.

Development of the water management system includes segregation of water and solid waste streams. This requires new, although partly existing technology, for the measurement and modelling of these streams. Modelling is an important tool when water recycling rate is being increased.

One important improvement method for the management of natural waters is the minimization of drainage area. Technical solution for decreasing drainage area include: use of solid-liquid separation equipment for tailings, section-wise filling and coverage system of the tailings pond, separation of natural waters by an effective drainage system, and minimization of the waste rock material contact with air and water.

The increased water recycling rate, especially if it is based on short circuit from solid-liquid separation instead of the long circuit provided by a conventional tailings pond system, will influence the process water composition. More information is needed to define the effects of the recycled process water on different processes, and to define the need and the correct technology for separating potentially harmful compounds from the process water stream. Increased process water recycling may enable recycling of process chemicals, too.

1. Introduction

This report provides a review of current mine water management practices in Finland. Practices from other Northern countries with similar climate conditions and similar types of mineral deposits are presented as well. In the second part of the report, improvement possibilities and potential technical solutions for mine water management systems are described.

The focus of the report is on water management inside the mine area and concentration process. This includes e.g. the technical characteristics of the production process itself, water treatment processes, tailings facilities, and waste rock handling. The main focus is on base metal sulphide ore deposits, and concentration processes based on flotation. Bioheapleaching, gold cyanide leaching, and chromium oxide beneficiation processes are described as well, mainly from the perspective of water management.

The aim of this report is to identify development possibilities, and to define the potential need of new technologies for improving Finnish mine and concentrator water management practices. New concepts have been searched from other Northern countries, from the literature, and based on professional knowledge of project participants (working group with representatives from Geological Survey of Finland, University of Eastern Finland, Teollisuustaito Oy).

2. Part 1: Description of Current Water Management Solutions at Northern Mines

Part 1 of this report consists of a review on water management solutions at operating mine sites in the Northern countries. Main focus is on Finnish base metals mines, in which the ore is most commonly sulphide-containing, relatively low-grade ore. Production processes, especially flotation, are described with the focus on water treatment and water management solutions.

A number of examples from Swedish and Canadian base metals mines and concentrators are included, too. These mines have been selected based on similar ore composition and similar environmental (weather) conditions that are typical for Finnish mines.

Further processing of gold concentrate, nickel sulphide bioheapleaching, and gravity concentration chromium oxide ore are described as case studies of other mine and process technologies.

2.1. Mine Water Management

Mine water management is influenced by the ore composition, the chosen process concept, the side product management concept, and the local conditions at the mine site. Water is essential for the most production processes – starting from drilling, including flotation, as well as purification of the intermediate or the final products of the process. In Finland, and in many other Northern countries, water is naturally abundant at the mine areas. This means that mine water management includes a) management of the naturally occurring waters (e.g. rainwater) and b) input and output waters of the production processes.

Figure 1 gives one example of water storages of a mine and the origin of water. In addition to the shown water streams:

- ground water is commonly accumulated in open pits and underground mines
- process chemicals may also contain water
- a minor amount of water is in some cases removed from the mine in products (intermediate concentrates) and bound to solid waste residues (tailings, solid precipitates)

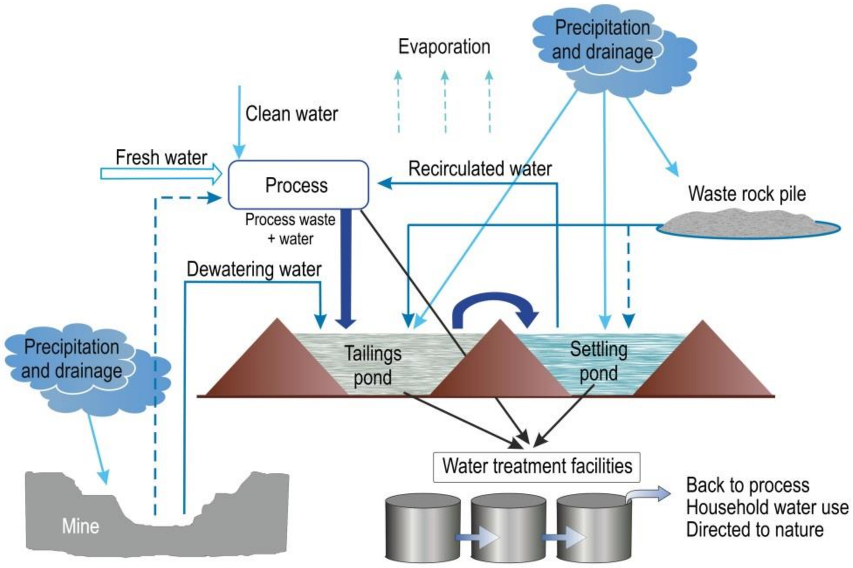

Figure 1 Example of different mine water sources and streams (Punkkinen et al., 2016)

2.2. Overview of Environmental Conditions at Northern Mines

Northern climate sets specific requirements for the mine water management. Common environmental conditions for all mines in Finland and Sweden, as well as certain parts of Canada, include:

- **Net positive rainfall.** On average, annual rainfall is larger than the natural evaporation. Evaporation mostly occurs during the summer months. There is periodic annual variation in the net positive rainfall. As a result, **there is a need to release water to the environment** (unless the production process is water consuming).

The most common mine operations such as quarrying, crushing, milling, and flotation, require process water of a certain quality, but these processes do not remove remarkable amounts of water from the mine water system. This is why practically all mines located in these Northern regions will need to release purified waters to the environment.

- **Cold winter and melting period.** Rainfall during winter time occurs usually in the form of snow. There is an annual snow melting season between March and June (often in April/May) that causes a sudden increase in the naturally occurring waters. This is why e.g. **buffer ponds are typically required.**

Environmental legislation and permits limit both composition and amount of released water, which has to be considered in the design of the process water management system. Flowrate may be restricted by the flowrate of receiving waters, or based on the statistical melting period. In addition, quality requirements of the process water are often set.

- In addition to the rainfall and the surface waters, such as rivers and lakes, **groundwater** is always present at Finnish mine sites. Groundwater accumulates in the mine and needs to be removed by pumping to allow normal mining operations. The effect of groundwater to mine water management varies based on the composition of sediments and bedrock on site.

In Finland, precipitation is on average 500-750 mm per year. Evaporation varies between 300-400 mm. Table 1 summarizes typical net rainfall conditions in Finland.

Table 1 Precipitation, overall runoff, and evaporation in Finland (Punkkinen et al., 2016).

	Amount, mm/a	**Comments**
Precipitation	500-750	August is the rainiest, March the driest month
Overall runoff	200-400	Proportion of spring runoff is around 30-50 %
Evaporation	300-400	In the Northern Finland the evaporation rate is only ~25-50 % of the average evaporation (i.e. it could vary between 75-200 mm)

In Sweden, precipitation varies between 600 mm and 1500 mm per year. Northern Inland Sweden and Southern Inland Sweden, where base metal mines are located, receive typically 600-700 mm annual rainfall. In the Southern parts of Sweden, the evaporation is 400-600 mm per year, in Inland 200-400 mm per year, and in the mountain areas below 200 mm per year. Conditions are thus similar to the Finnish weather conditions. (Brandt *et al.,* 1994). Similarly to Finland, Sweden is covered with snow during the winter months (SMHI, 2014).

In Canada, the variation of the precipitation and the evaporation is significant. There is a net positive precipitation in the regions of Ontario, Quebec, Nova Scotia, as well as Western coast of the country. In the region of Ontario, Quebec and Nova Scotia, annual precipitation is 800-1600 mm and evaporation varies between 400 and 600 mm per year. (Natural Resources Canada, 2015 and 2009).

2.3. Current Water Management Practices at Northern Mines

Although most of the mine sites in Finland and Northern regions have a net positive water balance, it is typical to use fresh water from rivers, lakes, or similar as process water in the mine operations. This is common when good quality process water is required and the recycled, untreated water could cause process disturbances. Fresh water is often used as such, or only as filtered. For the most sensitive processes, water from the river or lake is treated either in a chemical water treatment processes, in reverse osmosis, or in ion exchange processes. The two last ones are seldom used. Use of fresh water leads in increased amounts of water within the mine area, which needs to be purified and managed.

In Finland, mine water management and water treatment is largely focused on effluent treatment. This means that water treatment techniques are mainly designed to remove or separate compounds, which are harmful for the environment. Well known, environmentally harmful impurities in the mine effluents are described in Table 2.

Some of these compounds are relevant when considering the use of treated effluent as process water, too. E.g. solids may cause plugging of pipelines and equipment parts, such as filter nozzles. On the other hand, certain compounds, such as gypsum that are formed in the effluent treatment processes may limit the possibilities for increasing water recycling rate.

Certain production processes are more sensitive to e.g. sodium sulphate content, or residues of organic chemicals, which are not as harmful for the environment as some of the above mentioned compounds. This is why the water recycling may require additional and different water treatment techniques than the conventional effluent treatment plants.

Table 2 Common impurities in mine effluents, their origin, and typical purification processes.

Compound	Origin	Common purification processes
Heavy metals	Ore (oxidation and leaching of minerals)	Chemical precipitation processes (mainly hydroxide precipitation) Biological precipitation / adsorption processes (e.g. constructed wetlands)
Nitrogen compounds	Explosives Gold cyanide leaching process	Natural oxidation of ammonia in tailings management facilities
Sulphate	Ore (oxidation and leaching of sulphide containing minerals) Chemicals (sulphuric acid, sodium sulphate)	Gypsum precipitation, biological reduction at wetland areas and open pit mines
Chloride	Ore Chemicals (hydrochloric acid, water treatment chemicals)	Not commonly removed from effluent. Possible techniques include reverse osmosis, ion exchange, evaporation.
Solids	Mining and concentration processes (milling, solid-liquid separation)	Settling ponds, clarifiers, thickeners, filters Polymer / coagulant addition

There are, however, examples in which recycled water is purified especially for the use as process water. At Terrafame Oy nickel mine, unwanted metals are removed in a two-stage neutralization process. Clarified solution from the final neutralization step is partly recycled to process water pond, and partly led to further purification in a reverse osmosis process. Clean water from the reverse osmosis is used as a process water at the most critical consumption points. (Terrafame, accessed 24 May 2016)

2.4. Flotation of Sulphide Ores

Flotation based processes are widely used to separate valuable minerals from the ore. In Finland, flotation is currently used both in beneficiation processes of base metals and gold. Table 3 (base metal mines) and (gold mines) provide an overview of the flotation processes at Finnish mines.

Table 3 Application of flotation processes at Finnish base metals mines.

Mine	**Flotation used for**	**Source**
First Quantum Minerals Pyhäsalmi Mine	Production of 1. copper concentrate 2. zinc concentrate 3. pyrite concentrate	The Regional Environmental Permit Agency of Northern Finland, 2007 Sept
Boliden Kevitsa Mine	Production of 1. copper-gold concentrate 2. nickel-cobalt-PGM (platinum group metals) concentrate And separation of 3. pyrrhotite	Regional State Administrative Agency of Northern Finland, 2014
Boliden Luikonlahti Site (processing of Kylylahti ore)	Production of 1. copper-gold concentrate 2. zinc concentrate 3. cobalt-nickel concentrate 4. sulphur concentrate	Regional State Administrative Agency of Eastern Finland, 2014
Belvedere Mining Oy Hitura Mine	Production of 1. nickel sulphide concentrate Further purification 2. of nickel concentrate in two-stage process, including separation of magnesite.	Regional State Administrative Agency of Northern Finland, 2010 Aug

Table 4 Application of flotation processes at Finnish gold mines.

Mine	**Flotation used for**	**Source**
Agnico Eagle Kittilä Mine	1. Removal of carbon from the ore in pre-flotation circuit 2. Production of gold sulphide concentrate. The majority of gold occurs in arsenopyrite and pyrite. Subsequent process stages: pressure leaching, cyanide leaching, gold electrolysis.	Regional State Administrative Agency of Northern Finland, 2013 June
Endomines Pampalo Mine	Production of gold concentrate. 90% of sulphide minerals (mostly pyrite) are co-extraced with gold.	Regional State Administrative Agency of Eastern Finland, 2015
Nordic Mines Laivakangas Mine	Production of gold concentrate. Subsequent process stages: gravity separation, cyanide leaching.	The Regional Environmental Permit Agency of Northern Finland, 2009
Dragon Mining Vammala Site (processing of Orivesi, Jokisivu, and Kaapelinkulma ores)	Production of gold concentrate. Heavy minerals such as arsenopyrite are co-extracted with gold. Pretreatment includes gravity separation.	Regional State Administrative Agency of Western Finland, 2014

2.4.1. Process Description, Flotation Process

Flotation is a process, which tries to separate hydrophobic mineral particles from hydrophilic ones. The process is carried out in flotation cells, where hydrophobic particles are attached to air bubbles and transferred into the froth phase. The froth is then collected from the top of the cell. Hydrophilic particles remain in the slurry phase, and are collected from the bottom of the cell. This fraction is called tailings.

As the separation is based on differences between mineral surface chemistry, and the behaviour of the mineral in a slurry-air system, the technology is only suitable for ores where the valuable mineral/minerals behave differently from the unwanted waste (gangue) minerals. In the ideal case, surface chemistry of the valuable mineral is very different from gangue. In such case, the product will have high purity and high valuable metal content. (Niemistö and Neitola, 2015)

Because most valuable minerals are finely disseminated and intimately associated with the gangue minerals, they must be initially unlocked, or liberated before separation can be undertaken. This is achieved by comminution in which the particle size of the ore is progressively reduced. Comminution in the mineral processing plant takes place as a sequence of crushing and grinding processes. Crushing is usually a dry process and is performed in several stages. It reduces the particle size of run-of-mine ore to such a level that grinding can be carried out. Grinding is usually performed wet by adding water to the process. In addition, some chemicals such as neutralizing agents can be added to the grinding mills as well.

All ores have an economic optimum particle size, which depends on the ore and the subsequent separation process. Insufficient grinding results in low degree of liberation and, therefore, poor recovery and grade of the valuables in the concentration stage. On the other hand, overgrinding may produce slimes and reduce the particle size below the size required for the most efficient separation. In addition, energy is wasted in the process.

After flotation, the concentrate is thickened and / or filtered to reduce the moisture content. Thickening can be arranged in a counter-current-decantation (CCD) system. In addition to thickening, CCD circuit is applied to wash the concentrate by adding clean water to the last thickener. Similarly to CCD circuits, filtering often includes washing of the filter cake, too.

In some cases, gravity separation is applied after the flotation, e.g. Nordic Mines Laivakangas, gold recovery process. The purpose of the gravity separation is to further reduce the amount of unwanted minerals in the final concentrate, or in the intermediate product.

Flotation plants often consist of several flotation stages. In addition, within a flotation stage, there are typically several flotation cells installed in series. Flotation stages may include:

- pre-flotation (e.g. separation of carbon)
- rougher flotation (the rougher concentrate is sometimes ground and reported to cleaner flotation, and tailings are directed to scavenger flotation or to the tailings pond)
- cleaner flotation (further cleaning of the rougher concentrate)
- scavenger flotation (recovery of valuable minerals from rougher flotation tailings)

If the purpose of the process is to separate several valuable minerals from each other, there can be several similar flotation systems, for example roughers, cleaners and scavengers to produce separate zinc, nickel, and copper concentrates. In addition, tailings are sometimes separated into several fractions, e.g. to separate acid producing sulphide waste from other solid waste fractions (e.g. FQM Pyhäsalmi mine, Boliden Luikonlahti plant).

The performance of a flotation process is practically always enhanced by adding process chemicals. Ore particles are typically hydrophilic after milling, and need to be chemically modified prior to flotation. (Niemistö and Neitola, 2015) Flotation agents are typically added to the conditioning tanks, which are equipped with suitable agitation.

Examples of the typical flotation process chemicals, and their purpose, are presented in Table 5.

Optimal process chemistry (e.g., pH and redox potential of the pulp) is highly dependent on the mineral composition of the ore and the surface chemistry of the valuable mineral. pH and redox potential are often adjusted by adding specific chemicals to the process. These chemicals are included in Table 5.

Flotation is one of the major water consuming processes. Other water consumption points include e.g.:

- Milling
- Dilution of process chemicals
- Washing of filter cake, filter cloth, and washing of the concentrate in CCD circuits
- Pump sealing water

The main water consumption points are milling and flotation processes. Typically, the quality requirement of milling and flotation process is not very strict, whereas the quality of the water matters much more for the dilution of process chemicals, product washing, or pump sealing water. Anyhow, organic and inorganic compounds in the water can reduce the effectiveness of the flotation process.

Table 5 Flotation chemicals (Opasnet.fi, 2013, Niemistö and Neitola, 2015, Regional State Administrative Agency of Western Finland, 2014, Regional State Administrative Agency of Northern Finland, 2014)

Function	**Examples**
Collectors: cover the surface of an hydrophilic mineral, making it hydrophobic the chemical contains both hydrophobic and hydrophilic end	Xanthates, general formula R-O-CS2-Me, e.g. sodium ethyl xanthate, sodium isobutyl xanthate, potassium amyl xanthate Dithiophosphates, general formula (RO)2 = P = S2-M, e.g. Danafloat 245 Dithiophosphinates, general formula (C4H9)2-P-(S)-S-Na, e.g. Aerophine 3418A, sodium diisobutyl dithiophosphinate
Frothers: increases formation of froth by adsorbing to the liquid-gas-surface the chemical contains both hydrophobic and hydrophilic end	Long chained alcohols, e.g. Montanol, methyl isobutyl carbinol Ethers, e.g. Nasfroth, Dowfroth, polypropylene-glycol-methyl ethers
Depressants prevent the collector from adsorbing on unwanted mineral surface	E.g. zinc sulphate (to depress zinc from copper sulphide minerals) CMC (carboxymethyl cellulose; to depress silicates from sulphide minerals) Starch (to depress silicate from sulphide minerals) Sodium dichromate (to depress lead in copper-lead separation) Sodium cyanide (to depress zinc from copper minerals)
Activators increase adsorption of the collector on mineral surface	E.g. copper sulphate (to activate pyrites and sphalerite)
pH adjustment chemicals	Sulphuric acid; Burned or hydrated lime; Caustic soda and soda ash
Redox potential adjustment chemicals	Sulphuric acid (for oxidative conditions); Sodium sulphide (for reducing conditions)
Additives	Flocculants (to improve solid-liquid separation) Froth prevention agents (to remove froth from e.g. pumps) Filtering aids (e.g. aluminium sulphate)

2.4.2. Review on Current Side Product and Water Management Practices in Finland

Table 6 contains a review on the current side product (waste rock, tailings) and water management practices at the Finnish mines where flotation technique is used. Technical solutions and their characteristics are described in the following sections. Gold mines, which include further processing of the flotation concentrate, are described in section 2.5.

Table 6 Summary of the waste rock management, tailings management, and water management practices at Finnish mines comprising a flotation process (Environmental permits by: The Regional Environmental Permit Agency of Northern Finland, 2007; Regional State Administrative Agency of Northern Finland, 2010 Aug and 2014; Regional State Administrative Agency of Eastern Finland, 2014 and 2015; Regional State Administrative Agency of Western Finland, 2014)

Mine	**First Quantum Minerals Pyhäsalmi Mine**	**Boliden Kevitsa Mine**	**Boliden Luikonlahti Site (process-sing of Kylylahti ore)**	**Endomines Pampalo Mine**	**Belvedere Mining Hitura Mine**	**Dragon Mining Vammala Site (processing of Orivesi, Jokisivu, and Kaapelinkulma ores)**
Waste Rock Handling	Backfill of the underground mine Additional waste rock is required to cover the needs of underground mine; separate mining at an open pit mine.	Utilization in pond/dam structures. Waste rock area is constructed, filled, and covered step by step to prevent acid production. Collection of waste rock area drainage to a separate water pond. Further treatment at wetlands, or recycling to the water pond.	No waste rock to Luikonlahti concentrator.	Waste rock has been used in dam structures, and it is being utilized in underground mine backfill.	Waste rock has been utilized in the earthworks and backfill of the underground mine. No new waste rock would be produced if operation was continued. Waste rock area waters are collected to the mine. Waste rock storage areas are not intended to be covered. Cover is predicted to increase the dissolution of minerals.	No waste rock formed

Mine	**First Quantum Minerals Pyhäsalmi Mine**	**Boliden Kevitsa Mine**	**Boliden Luikonlahti Site (process-sing of Kylylahti ore)**	**Endomines Pampalo Mine**	**Belvedere Mining Hitura Mine**	**Dragon Mining Vammala Site (processing of Orivesi, Jokisivu, and Kaapelinkulma ores)**
Tailings Management	High grain size fraction (10-20%) is separated with cyclones and returned to the underground mine backfill. Tailings is also used to the construction of pond walls. The rest is neutralized to pH 10 using lime and pumped to the Tailings ponds. This fraction contains also the mine water. Pond B receives pyrite containing tailings; Pond D receives non-pyrite containing tailings	Tailings with lower acid production potential are pumped to the pond A. Sulphide containing tailings fraction is pumped to pond B. Basal structure is less permeable than for pond A. Tailings pond A receives dam infiltration waters (0.8 million m^3/a), drainage from the ore intermediate storage area, neutralization residues from the effluent treatment, and water from pond B.	The coarse flotation sand fraction is separated to dam edge areas and utilized in the dam structures. Cobalt-nickel product and sulphur product are being stored at a separate tailings pond area. Water is returned to the beneficiation process. Existing tailings ponds (main ponds) contain magnetite rich tailings residues, which have good neutralizing potential.	Tailings solids include 10 % of total sulphides (rest will stay in the gold concentrate). Water pH is close to neutral. Tailings pond receives: Tailings + process water (0.55 million m^3/a) + clarified mine water (0.18 million m^3/a) + purified sanitary water. Tailings pond waters are clarified in a clarification pond, from where water is returned to the beneficiation process or lead to the environment.	Tailings have a low acid producing potential. Tailings pond structure is permeable, and drainage waters are collected to the clarification section in tailings pond. Tailings ponds receive tailings, process water, and dam infiltration waters. Water flows to the clarification pond section, and then to the return water pond from where the majority of the water is returned to the beneficiation process.	Solid fraction of the tailings has been in tailings pond construction. Tailings pond receives both acid producing and non-acid producing tailings. Old tailings are partly stored at an open pit mine. Tailings area consist of three ponds, which all receive tailings material (A-C).

Mine	**First Quantum Minerals Pyhäsalmi Mine**	**Boliden Kevitsa Mine**	**Boliden Luikonlahti Site (process-sing of Kylylahti ore)**	**Endomines Pampalo Mine**	**Belvedere Mining Hitura Mine**	**Dragon Mining Vammala Site (processing of Orivesi, Jokisivu, and Kaapelinkulma ores)**
Tailings Management	Other water fractions to the tailings ponds: process water from the concentration plant, surface waters from the plant area, open pit mine water (mixed with tailings), dam infiltration water. Water is recycled from tailings pond C to the concentrator, and the rest is lead to the environment after pH-adjustment.	Extra water from both ponds (A and B) to the water storage pond.	The main tailings pond receives process waters, drainage, and infiltration waters.			Tailings pond is surrounded by an open channel, which receives: pond area drainage waters, dam infiltration water, plant area drainage water, and water fractions which are collected from nearby forest. Extra water from the pond area is led to clarification pond.

Mine	First Quantum Minerals Pyhäsalmi Mine	Boliden Kevitsa Mine	Boliden Luikonlahti Site (process-sing of Kylylahti ore)	Endomines Pampalo Mine	Belvedere Mining Hitura Mine	Dragon Mining Vammala Site (processing of Orivesi, Jokisivu, and Kaapelinkulma ores)
Water Management	Pond C is the water storage pond, located at the tailings pond area.	Total water need 22.7 million m^3/a.	Total process water need 2.5 million m^3/a.	Total water consumption ~0.55 million m^3/a (2011).	Recycling rate of the tailings pond water + mine water 96 % (about 3 million m^3/a).	Total water consumption 1.3 million m^3/a.
	Recycling of tailings pond C water (0.5 million m^3/a). Recycling within the flotation plant is about 10% (water from the zinc flotation is separated in a thickener and returned to the milling)	Fresh water intake 1.7-1.8 (target 1.35) million m^3/a. Fresh water to the flotation chemical preparation, filtration, and certain points in flotation.	50 % recycling rate from the clarification pond.	Water recycling rate from the clarification pond 96 % (0.52 million m^3/a 2011).	No fresh water used in the process.	Water is recycled from clarification pond to the beneficiation process. Extra water is lead to the closed open pit mine.
	Fresh water intake 5.5-6 million m^3/a	Water recycling rate is 90%. Recycled water is used in: milling, flotation, filtration, pump sealing water.	Fresh water intake 1.25 million m^3/a (at 50 % recycling rate).	Fresh water intake 0.022 million m^3/a.	During the winter period, all tailings pond water is recycled. During other periods, extra water infiltrates from the tailings pond and is released to the environment.	Open pit mine water is used as fresh water.

Mine	First Quantum Minerals Pyhäsalmi Mine	Boliden Kevitsa Mine	Boliden Luikonlahti Site (process-sing of Kylylahti ore)	Endomines Pampalo Mine	Belvedere Mining Hitura Mine	Dragon Mining Vammala Site (processing of Orivesi, Jokisivu, and Kaapelinkulma ores)
Water Management	Water treatment: gypsum and heavy metal precipitation with lime at the tailings pond area.	Water pond receives mine water (0.4 million m^3/a), and extra water from pond A (16 million m^3/a) and plant area waters from plant water settling pond (0.4 million m^3/a).	Effluent 1.65 million m^3/a (at 50 % recycling rate). No water treatment due to carbonate content of the tailings (talc production).	No chemical water treatment.	Water treatment 1: Infiltrated water from specific tailings pond area is neutralised with caustic soda at a water tank, after which it is settled in a pond. Solids are periodically removed and mixed with tailings. Water is pumped to the return water pond, from which it is pumped to the beneficiation process.	Effluents are discharged to the wetland area.
	Treated effluent 6-6.5 million m^3/a	Water treatment: With hydrated lime. Solid residues are settled in a pond and slurry is periodically transported to the pond A.		Effluent 0.23-0.28 million m^3/a (including infiltration water).	Water treatment 2: Mine waters (~1.5 million m^3/a) are clarified, and lead to the environment. Part of the water can be recycled to the return water pond.	Extra water from surrounding channel is discharged to the receiving waters (30 000-120 000 m^3/a).
		Effluent is further treated at a constructed wetland area. Amount of effluent 1.7 million m^3/a.			No effluent from Tailings pond during operating period 2001->	

2.4.3. Waste Rock Management

There are two main side products formed in a typical mine: 1. waste rock from the excavation and, 2. tailings from the flotation process.

The composition and the quantity of the waste rock is mostly defined by the ore composition and ore body properties. By definition, waste rock contains lower quantities of valuable metals, and higher amounts of undesired, invaluable compounds. If the ore is sulphide-type ore, the waste rock will also contain sulphides – in some cases more and in some cases lower amounts than the ore which is led to further processing. Sulphides, especially pyrite, have a high acid production potential. That greatly affects the requirements of the side product storage; utilization of the waste rocks; and the site water management. (Punkkinen *et. al*, 2015)

Certain minerals, such as carbonates, oxides, and silicates, have a neutralizing or buffering effect on acid mine drainage formation (Laine-Ylijoki *et al,* 2015). In such case, handling of the sulphide ore can be easier, from the point of view of the mine water treatment, which is the case for Belvedere Mining Hitura mine and Boliden Luikonlahti sites.

Usually the aim is to avoid the oxidation of sulphide ores, because that would lead to the acidic pH, and consequently to the dissolution of metals. Therefore the chosen storage structure should be designed to minimize contact with water and air. Waste rock storage can include e.g. the following technical solutions (Tornivaara, 2015):

- Impermeable or reactive basal structure
- Backfill in the underground mine or closed open pit mine
- Utilization in earthworks (limited by the properties and composition of the waste rock)

As soon as a waste rock area (apart from the underground backfill system) is full, the area should be covered to prevent oxidation effects caused by rain, snow, sunlight, and air. Technical solutions include (Kauppila *et al.,* 2015):

- Dry cover
- Water cover
- Partial water cover / wet cover
- Encapsulation with neutralising material
- Coating/passivation with chemical amendments (microencapsulation)

In addition to acids, heavy metals, and sulphides, waste rock area waters can contain nitrogen compounds, which are residues from explosives. There is typically no separate nitrogen removal process at the Northern mines. Nitrogen emissions can be reduced by using adequate explosion chemicals and correct explosion techniques.

2.4.4. Tailings Management

Tailings formed in the flotation process contains both solid and liquid residues The quality of tailings depends on the ore type, the details of the flotation process, chemicals used in the process as well as the recovery of valuable minerals to the concentrates. In addition, pH has usually a crucial role in tailings management. The lower the pH, the more soluble metals and sulphates will be found in the tailings water.

In most of the cases, tailings are pumped to a pond or a dam, in which the solid compounds are settled to the bottom of the pond. Spigots can be used to evenly distribute tailings slurry to the pond. As long as the tailings pond section is in use, there will be a (partial) water cover on the settled solids. This is also the prerequisite for the recycling of the tailings pond water: solids must be properly removed before water is returned to the milling / flotation process, or to the effluent treatment plant.

Other input streams of the pond typically include rain, snow, return pumping from dam surrounding drainage system, and often a number of other contaminated water streams. There are cases in which water or tailings ponds have been constructed to former lakes or natural ponds. In such cases it is important to note that there may be sources of ground water on the bottom of the pond. In addition, lake areas typically collect natural drainage from a large area. Also the tailings itself, independent of where it is built, may cause the rise in groundwater surface, and an input stream to the tailings area.

Only a part of the water is bound in a solid fraction of the tailings stream. Natural evaporation rate in the Northern conditions is lower than the precipitation. This is why there is always extra water that needs to be removed from the pond.

In most cases, sulphide containing tailings will slowly react with oxygen and water, even though the water cover partly prevents oxidation. Acidic properties are not a problem when process waters are recycled to the early stages of the beneficiation process, milling, and rougher flotation. Instead, acidity may need to be removed before other water use points, and before releasing it into the environment.

Acid production potential is the main reason for the current practice of using impermeable basal structures – with natural or synthetic lining (e.g. Boliden Luikonlahti) – or neutralizing basal structures in the tailings ponds. Many of the old dam structures are, however, permeable.

In certain cases, tailings are dewatered (Nordic Mines Laivakangas) or chemically treated (FQM Pyhäsalmi) before transportation of the fraction to the final storage area. If part of the process water is separated already at the concentration stage, size and cost of the transportation pipelines, pumps, and the pond itself may be reduced. That could also reduce the installation and construction costs accordingly. If tailings residue is neutralised, basal structures may have less strict requirements for water tightness.

2.4.5. Water Management

Based on the descriptions of the Finnish mine operations, a typical water management system of a mine with flotation based process includes:

- **Fresh water** intake from a nearby lake or river
- **Collection of drainage and ground water** from the mine (open pit or underground mine), waste rock area, plant area, and other contaminated areas, with the help of open channels, pipelines and pumps
- **Collection of dam infiltration water** with the help of open channels, pipelines and pumps to the tailings pond
- **Storage and clarification of tailings water at tailings pond(s)**
- **Clarification of extra water, often in one pond** which is located close to the tailings pond
- **Partial recycling of the clarified water to the concentrator**
- **Possible chemical or passive wetland treatment of extra water**, which is released to the receiving waters

This, very simplified system, is described in the block diagram in Figure 2. The following sections in this subsection describe general practices for design of a controllable and efficient water management system for these unit processes and processing areas.

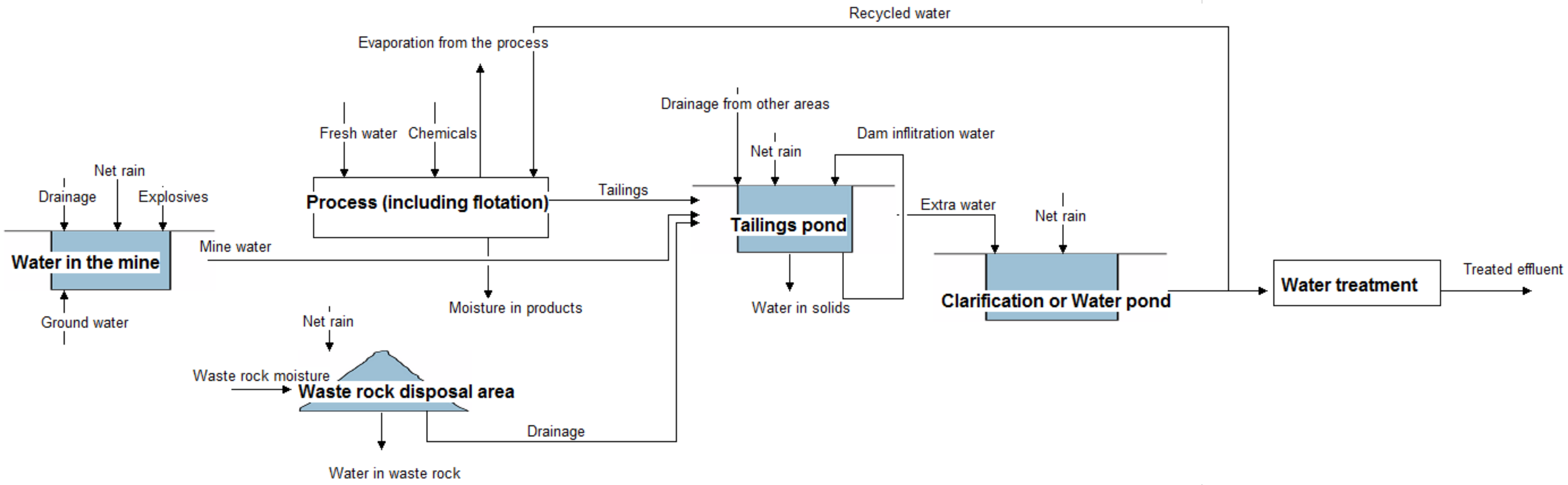

Figure 2 General flowchart of the water recycling system of a flotation process (figure based on flotation process descriptions in Environmental permits of Finnish mines).

Water Management in the Flotation Process

Ore composition has an important effect on the design and operation of the mine water management system. Many decisions made in the design of the production process e.g. flotation –will have an effect on the water management, too.

Processes operating at a neutral or high pH generally have less effects to the environment. This is due to the chemical properties of the heavy metals that tend to be in soluble form at low pH.

Separation of acid producing fractions – especially pyrite – from other tailings fractions is highly desirable. By separating the pyrite fraction and by storing the fraction at a separate tailings dam, dissolution of heavy metals can be avoided from the other tailings dam areas. Sulphate concentration of the process waters can be decreased by limiting the contact of the acid producing minerals with other materials and cleaner water streams.

From the perspective of the mine water management, it is wise to optimise the recovery of valuable metals. This is because many valuable base metals are also heavy metals, which are harmful to the environment, and thus are unwanted at the tailings ponds or other side product storage areas. On the other hand, if optimal separation requires a large amount of chemicals, which are challenging for water treatment processes, maximizing the yield is not necessarily the best solution from the perspective of overall water management. The costs of water treatment, caused by incomplete metal recovery, are usually not considered.

The selection of the process chemicals will have an influence on water management of the plant. For example:

- Sodium containing chemicals will complicate removal of sulphate as gypsum, as sodium sulphate will not be removed in the conventional gypsum precipitation process
- Calcium containing chemicals may cause solid gypsum formation in unwanted stages and places, such as equipment surfaces (plugging of pipelines), or concentrate products (lower product quality)
- Organic chemicals may act as complexing agents for heavy metals, complicating the precipitation based effluent treatment processes, and causing environmental effects to receiving waters
- Any flotation chemical in wrong flotation stage may cause process disturbances

Quality requirements of process water is not necessarily same in all consumption points. Quality should be based on process functionality: in case the process can tolerate a less clean process water, fresh water should not be used. It is however essential to identify compounds, which are harmful for the process. The origin of these harmful chemicals differ: they are a) from process chemicals (e.g. gypsum, residues of flocculants etc.); b) often from the ore (sulphates); and c) sometimes from the fresh water (natural organic compounds).

These themes are further discussed in Part 2 of the report, section 3.1.5.

Water Management at Waste Rock Areas

During the mine operation, it is seldom possible to completely avoid contact of the water and air with the minerals. This is why drainage from waste rock areas – also temporary, short-time storage areas – should be collected to a drainage system. Water quality can be monitored by sampling, or in the case of permanent drainage systems, by e.g. pH and conductivity online measurements. Water quality should be the basis for selection of correct water management solution:

- Clean drainage water should be used in the process instead of fresh water, or directed to the receiving waters
- Slightly contaminated water should be treated in the effluent treatment plant
- Strongly contaminated water can either be treated in the effluent treatment plant, or, if there is a collection pond for strongly contaminated water, it can be stored and treated with other water streams of similar quality

It is good to note that the water from waste rock area can be more suitable for the use as process water than the fresh water. This is due to the lack of the naturally occurring organic compounds (e.g. humic acids and humines), which may have adverse effects for certain production processes. In some cases, water from the waste rock area could replace the fresh water in these consumption points.

Waste rock area drainage water quality should be monitored around the year: quality varies depending on the weather conditions. Therefore the most suitable water management solution may also vary.

Monitoring and segregation of different water streams are further discussed in Part 2 of the report, sections 3.1.1 and 3.1.4.

Water Management of the Tailings Pond(s)

At Finnish mines, tailings pond is traditionally a pond where contaminated water streams are collected from various sources. It is common to pump acidic mine water, water from the waste rock areas, and water from the surrounding drainage channels to the same pond. This water collection system will have a number of effects on the tailings pond, and on the overall water management of the mine:

- Size of the pond has to be large enough (both as a surface area to ensure settling; and as a volumetric size to ensure sufficient capacity during spring floods)
    - Large surface area leads to large catchment area
- Water flowrate through tailings pond is large, and the flowrate is variable because of variation in precipitation (process originated flows are typically constant, whereas naturally occurring waters are not)
    - Large pipelines, pumps, and effluent treatment plants are needed
- All water fractions, independent of their composition, are mixed. Water quality is often not sufficient for all consumption points in the process.
    - Need of fresh water (and fresh water purification process)
    - Need of larger effluent treatment facility
    - Possible difficulties in effluent treatment

Important: Separation of cleaner water fractions to a different collection pond (or several ponds, based on the quality), will improve possibilities to increase the water recycling rate within the mine area. Water collection system will, on the other hand, be more complicated and the costs may be higher when compared to a one-pond-system. When considering the total costs, construction of several ponds may lead to a smaller effluent treatment plant and to less expensive base structures in ponds.

As described earlier in this section, details of the flotation process and recoveries of valuable minerals to the concentrates will influence tailings pond water management. In case the process produces more than one type of tailings, it is worth considering several ponds for tailings. This is to avoid contamination of the water, and dissolution of metals from the cleaner tailings residue. It is important not to mix the water qualities of the two ponds, too.

One purpose of the pond is to settle solids. Solids settling rate (m/h, or kg/h) is one design basis for the surface area of the pond. Solids settling properties and settling rate can be enhanced by flocculation / coagulation, adequate design of sludge distribution system, and special process equipment.

It is important to note that many of the organic flotation chemicals are reported to be encapsulated or slowly decomposed at the tailings ponds. Residues of decomposed chemicals have been found in e.g. Belvedere Mining Hitura tailings residue (solid phase, e.g. decomposition product of xanthate, i.e. carbon sulphide) and in the effluent e.g. Boliden Kevitsa pilot test runs (xanthate 1.6–2.7 mg/l) (Regional State Administrative Agency of Northern Finland, 2010 Aug and 2014). If the residence time of the pond is decreased and water is discharged to the environment, it is important to monitor levels of these chemicals, as they are harmful for the environment.

Development possibilities of the process, solid waste management, and the influence of chemicals are discussed in Part 2 of the report.

2.4.6. Canadian Mines

Trevali's Caribou Mine and Mill Complex

Trevali's Caribou Mine and Mill Complex consists of an underground mine, and a processing plant that includes milling, flotation and dewatering of the products, tailings ponds, and a water treatment system. The site is located approximately 50-km west of Bathurst, New Brunswick, Canada. The deposit is a multi-metal sulphide deposit, and products include lead, zinc, and copper sulphide concentrates. The operations at the mine started in 1970, and have been periodically closed and operated since then. The current production process has been recommissioned in 2015. (SRK Consulting, 2013 and Trevali Mining Corporation, 2016)

Process Description

Primary crushed ore is milled in a two stage milling process. Tailings pond water is used as process water in the milling. Soda ash and sodium cyanide are added to the milling circuit as pyrite and sphalerite depressants. (SRK Consulting, 2014)

The flotation circuit consists of lead flotation, zinc flotation, and copper flotation. (SRK Consulting, 2014)

Milled ore is led to pre-aeration for the depression of pyrite. The discharge is lead to rougher flotation circuit, which will separate lead and copper from zinc. MIBC (methyl isobutyl carbinol) is used as frother. The concentrate will pass re-milling and continue to cleaner flotation. In the first stage of the cleaning flotation circuit, copper flotation feed is separated as the overflow. The underflow will continue to two additional lead concentrate cleaning flotation circuits. After that the concentrate is dewatered in a thickener, filtered and stored for the transportation. Wash waters from the filtering and thickener overflow are returned to the process. (SRK Consulting, 2014)

Copper circuit consist of two stage flotation process and thickening of the concentrate product. Thickener overflow is returned to the copper circuit. (SRK Consulting, 2014)

Zinc circuit contains a rougher flotation circuit, concentrate reground and cleaning flotation cells, as well as thickening of the concentrate product. Thickener overflow is returned to the zinc circuit. The primary cleaner tailing will operate in open circuit with the tailing passing direct to final tailings pond. (SRK Consulting, 2014)

Sulphur dioxide is used as oxidant and lime is used as pH adjustment chemical in the process. (Stantec Consulting, 2015)

Water Management (SRK Consulting, 2014)

The water management system of Caribou Mine and Mill complex is relatively similar to the flotation based beneficiation processes in Finland. It contains a tailings area, from where the water is recycled to the concentration process (milling). Extra water from the process is discharged from the tailings pond. The site's water management system also contains a mine drainage system, and two lime neutralization stations.

The tailings pond receives process waters and tailings from the flotation process. Tailings are potentially acid producing due to their pyrite content. A water cover is kept over the solid residues in order to prevent oxidation of sulphide containing minerals. The surface area of the pond is 90 ha.

A hydrated lime dosage and mixing system is available for the neutralization of the water in the tailings pond.

Acidic mine water drainage is collected and clarified in sedimentation pond, which is lined with an HDPE liner. The pond receives underground and old open pit mine waters.

Neutralization process of the acidic mine water starts with pH adjustment. At the first stage, pH is adjusted to 8.5 with lime milk to precipitate metals and gypsum. The slurry is gravity fed to a tank, to which flocculant and additional lime milk is added (targeted pH 9.5). The slurry is then directed to a settling and storage pond. Overflow from the pond is pumped to the tailings area, to a polishing pond section (surface area 1.7 ha). The polishing pond also receives potential seepage of the main tailings pond.

The purification results of the above described neutralization process are likely to be good, when compared to direct addition of lime or lime milk to a pond or pipeline. This is due to well-controlled process conditions and agitated tanks, which provide sufficient mixing of the effluent and chemicals. Solids separation is more efficient too, as it is performed separately from the neutralization stage.

2.4.7. Swedish Mines

Boliden AITIK Mine and Processing Plant

Boliden AITIK site is a large open pit copper mine, located in the Northern Sweden. The ore contains low concentrations of chalcopyrite, and gold and silver as side metals. Copper concentrate is transported to Boliden Rönnskär smelter. (Boliden, A, Accessed 3 June 2016)

Process Description

After crushing, the ore is fed into two mills. Flotation reagents (potassium amyl xanthate, PAX) and water is added to the milling. The slurry is lead to the copper flotation circuit. The concentrate is then thickened and filtered in a press filter.

Tailings and extra process water are pumped to a tailings pond (Boliden, B, Accessed 3 June 2016 and Book, 2014).

Large quantities of waste rock are formed at the open pit mine. Waste rock is also a commercial product as it is used to reinforce roads and as ballast material in the cement (Boliden, B, Accessed 3 June 2016). Waste rock is currently stored at a surface area of 4 km^2 (Punkkinen, 2015).

Water Management

The water management system of the Boliden AITIK mine and processing complex is relatively similar to the flotation based beneficiation processes in Finland.

The area of the tailings pond is large, currently covering 13 km^2 (Punkkinen, 2015). The pond receives process water and solid tailings from the flotation process, as well as runoff from the catchment (Mueller, 2014). There is a clarification pond that receives water from the tailings pond, and acts as a water buffer pond for recycled water and discharge water. Tailings contain 0.5-1.5% of sulphides, but there are also carbonates and silicates, which reduce the acid producing potential of the solid material. (Punkkinen, 2015)

Xanthate, the flotation chemical, can be transported from the tailings to clarification ponds, and further to the environment. Xanthates and their decomposition products are relatively stable at low temperatures. (Book, 2014)

The waters in the waste rock area are acidic. Cut-off ditches have been built around the waste rock dumps. Basically all waters infiltrating through the waste rock dumps are collected in ditches at the toe and reused as process water in the mining operations (Punkkinen, 2015). Collected water is pumped to the Return Water Basin, from where it can be either recycled to the mill, or discharged (Mueller, 2014).

There are plans to use the water of the open pit mine in the process, when the mine and process are expanded (Mueller, 2014).

The site water balance model has been constructed to predict and to develop the water management system of the AITIK mine and processing site. A detailed water balance model can be utilized e.g. in the following: (Mueller, 2014)

- Reporting of raw water intake, water consumption rate, amount of released contaminats
- Prediction of the future water consumption figures; based on information from production, and from water quality and quantity measurements
- More efficient water and contaminant management

The water balance model is being developed further, by e.g. adding weather data as source data to the model (Mueller, 2014).

Boliden Garpenberg

Boliden Garpenberg Mine and Processing Plant is located in the Middle Sweden, Hedemora. The mine has been operating since 800-900’s. The plant includes an underground mine, flotation based concentration plant, and tailings areas. Products are zinc, lead, and copper sulphide concentrates. The ore processing plant as well as plant infrastructure were rebuilt and started up on 2014. (Boliden C, Accessed 6 June 2016 and Eriksson and Lindeström, 2011)

Process Description

The processing starts with two stage milling. Process water in the milling is recycled water from the tailings pond. (Eriksson and Lindeström, 2011)

Slurry from the milling is first treated in the copper-lead flotation circuit, in which zinc is separated from the copper-lead containing ore fraction. Copper-lead fraction goes further to the copper flotation. Precious metals, gold and silver, are co-extracted with the copper. The two concentrates, i.e. lead and copper concentrate, are then thickened and filtered. (Eriksson and Lindeström, 2011)

Tailings from the copper-lead flotation circuit continues to zinc flotation. Zinc product is thickened and filtered, whereas tailings from the zinc flotation circuit goes to the tailings pond, or to the paste-fill plant. (Eriksson and Lindeström, 2011)

Flotation chemicals include potassium amyl xanthate or isobutyl xanthate. Frothers include polypropyl glycol and other alcohols. Zinc sulphate is added as zinc depressant to the first flotation circuit. Copper sulphate is used as an activator in the zinc flotation. Sodium dichromate is used to separate copper and lead. Flocculants are used to improve the solid-liquid separation properties of the product concentrates. Hydrated lime / lime milk is used to adjust the pH. (Eriksson and Lindeström, 2011)

Tests have been carried out to separate tailings based on their sulphur content (rich and low) in an additional flotation step. According to the obtained results, the separation was not efficient enough to produce two separate tailings qualities. (Eriksson and Lindeström, 2011)

Waste rock is mixed with the tailings residue and used as a mine backfill. About 25-35% of tailings residues can be utilized there. Extra waste rock is planned to be used to fill the old open pit mine. (Eriksson and Lindeström, 2011)

Water Management

The water management system of the Boliden Garpenberg complex includes similar processing stages as Finnish mines utilizing flotation. Additionally, the Garpenberg water management system includes less common solutions for nitrogen removal, thiosulphate removal, and ground water management.

Tailings and process water are pumped to the tailings pond (surface area 98 ha). They are distributed with spigot system, or partially just led with a direct pipeline to the pond. The pond also receives dam infiltration waters, mine water, and drainage water from other mine areas. There is a clarification pond, which is separated from the tailings pond by an embankment. Water is recycled to the processing plant, and extra water is released to the environment from the clarification pond section. (Eriksson and Lindeström, 2011)

The recycling rate of the process water has reached 80% during the operation of the old beneficiation process. Below 0.6 million m^3/a of fresh water has been needed, and the total need of the process water has been 3 million m^3/a. The plan is to decrease the fresh water intake still even though a new, expanded process. Recycling rate is to be increased further. With the old production plant, annual effluent discharge has been 2.5 million m^3/a. (Eriksson and Lindeström, 2011)

The tailings pond area has been constructed to a former lake area. The coarse fraction of the tailings sand will be utilized to increase tailings pond dam height. (Eriksson and Lindeström, 2011)

According to the test results the current tailings material has a higher acid producing potential than the old tailings material that contained larger fraction of carbonates and talc. (Eriksson and Lindeström, 2011)

Process water treatment includes a Fenton process. In this process, hydrogen peroxide is added to the acidic process water to destruct thiosulphates. Iron sulphate acts as a catalyst. After the Fenton process, lime is added to adjust the pH and to precipitate metals to the desired level. (Källs, 2014 and Boliden C, Accessed 6 June 2016)

The water from the mine drainage is collected to the clarification ponds, where the clarified water is pumped to the tailings facility. When production is expanded, it may be necessary to lower the level of the ground water by pumping it with separate clean water pumping stations. As long as the ground water is not in contact with the ore, the quality remains good enough for discharging the water to the natural waters. (Eriksson and Lindeström, 2011)

Mine water is treated in a biological nitrogen removal process. Mine drainage is first pumped to the purification plant, from where it goes to the tailings pond. The technology is based on the MBBR process (Moving Bed Biofilm Reactor), which consist of pre-nitrification, 2-stage nitrification, post-nitrification, and re-oxidation for the removal of carbon. Methanol is used as carbon source. The requirement in the environmental permit is below 2 mg/l nitrogen. (Boliden C, Accessed 6 June 2016 and Veolia, Accessed 6 June 2016)

2.5. Gold Cyanide Leaching

Further processing of the gold concentrate can be located at the same production site as gold mining and flotation, or at another location to which the gold concentrate is transported. There are two examples of combination of gold mine, flotation, and further processing of the gold concentrate in Finland. These mine and processing plants are described in this section, focusing on their special water management requirements.

2.5.1. Process Description, Beneficiation

Agnico Eagle Kittilä

Agnico Eagle Kittilä mine’s flotation circuit includes pre-flotation of carbon and flotation to separate the gold-containing minerals. Gold is mainly associated with the sulphide minerals arsenopyrite and pyrite. The tailings – both from the carbon flotation and from the gold flotation - are lead to the so-called NP tailings pond. Flotation chemicals include common additives, such as potassium/sodium amyl xanthate, MIBC, lime, caustic soda, and copper sulphate.

Gold flotation concentrate is first leached in an oxidative pressure leaching process. Sulphides are oxidized to water soluble sulphates. That takes place in an autoclave, which is equipped with oxygen feed. The slurry is lead to a flash tank, in which pressure is lowered to the normal atmospheric pressure. At the same time, temperature of the slurry decreases, and the liberated heat energy is consumed in the evaporation of the water. The slurry is then washed in a counter current decantation circuit (CCD-circuit) prior to the cyanide leaching circuit.

Cyanide leaching circuit consist of:

- Conditioning of CCD slurry with lime milk at pH 11
- Carbon-in-leach circuit (CIL circuit): Cyanide leaching in a series of agitated tanks; cyanide, oxygen gas, and activated carbon is added to the leaching reactors
- Activated carbon that contains gold goes to nitric acid washing, where gypsum is removed. Caustic soda is used to neutralize the acid. The used washing solution is lead to the cyanide destruction.
- Gold is stripped from the activated carbon with a solution containing sodium cyanide and caustic soda. Gold is precipitated in the gold electrolysis and activated carbon is reused in the CIL circuit after regeneration.

- INCO-process: Process solution containing cyanide is lead to the cyanide destruction process; oxygen and sulphur dioxide is used for destructing the cyanide, and the reaction is catalysed by copper sulphate. pH is adjusted with lime. Resulting slurry is stored at a separate CIL-tailings pond.

Extra water from the CIL tailings pond is recycled to the gold leaching circuit. Water recycling rate is 60%. Chloride concentration of the process water limits the use of recycled process water due to its adverse effect on gold recovery process. (Regional State Administrative Agency of Northern Finland, 2013 June)

Nordic Mines Laivakangas

The flotation process in Nordic Mines Laivakangas starts with the rougher flotation of the ore. Flotation concentrate is reported to the thickening and regrinding. Tailings from the rougher flotation goes to the Knelson gravity separation. From there the gold-rich heavy fraction goes to the thickening (with rougher flotation concentrate). The lighter fraction is further treated in the cyclone separation process, from where the finer fraction is led to the further processing. Flotation chemicals include potassium amyl xanthate and copper sulphate.

At Laivakangas mine, there are two CIL circuits for processing of the two concentrates.

1. The underflow of the gravity separation process is mixed with rougher flotation concentrate, and led to a separate CIL circuit after thickening and milling.
2. The other concentrate consists of fine particles, i.e. overflow of the gravity separation process.

The CIL process is of the same type as at the Agnico Eagle Kittilä mine, described above. Process chemicals are slightly different (lead nitrate and hydrochloric acid are used in leaching). The cyanide destruction process is based on the same process, INCO cyanide destruction, as in Kittilä mine. (The Regional Environmental Permit Agency of Northern Finland, 2009)

2.5.2. Tailings and Waste Rock Management

Agnico Eagle Kittilä

Agnico Eagle Kittilä process produces two main types of tailings: a) flotation tailings and b) CIL process leach residue. The flotation tailings are neutralized with lime and stored in NP ponds (surface area 90 ha). Part of the tailings material is used in underground mine backfilling.

CIL leach residue is first treated in cyanide destruction process, neutralized, and then sent to a separate pond (13 ha). Surface area of the CIL residue pond will grow, as the company plans to use one NP pond for CIL leach residue storage in the future.

Extra water is pumped from the NP pond to the CIL pond. The remaining water from the NP pond is lead to the environment through a natural wetland area. CIL pond water is recycled to the beneficiation process.

NP tailings is potentially acid producing, whereas CIL tailings is neutral. The tailings from the NP pond together with the waste rock are also used as underground mine backfill.

Different qualities of waste rock is formed. Main fraction of the waste rock consists of non-acid producing, neutralizing material. The potentially acid producing fraction of the waste rock is partly used in mine backfill, and partly stacked to separated stockpiles to the waste rock area. These stockpiles will be covered with neutralizing waste rock layers in order to reduce acid mine drainage formation. (Regional State Administrative Agency of Northern Finland, 2013 June)

Nordic Mines Laivakangas

Tailings from the CIL circuit 1 contain higher amounts of arsenic and acid producing sulphides than tailings from the CIL circuit 2. Therefore they are stored at Tailings pond B. Tailings from CIL circuit 2 are stored at Tailings pond A. (The Regional Environmental Permit Agency of Northern Finland, 2009) Tailings in the pond A are not acid producing (Regional State Administrative Agency of Northern Finland, 2016 June).

Tailings treatment of CIL circuit 2 tailings includes thickening of the residue in a paste thickener. That is located next to the tailings storage area, at a 7.4 km distance from the mine area itself. Flocculant is added to improve the settling properties of the solid material. Thickener underflow is pumped to the tailings area whereas overflow is returned to the water storage ponds. (Regional State Administrative Agency of Northern Finland, 2016 June)

Tailings pond A (surface area currently 55 ha) has no artificial basal structures, but there is a naturally occurring peat layer. The area is surrounded by an open channel type drainage system. The intention is to prevent emissions (solids) to the environment, and to prevent accumulation of additional waters to the area. The original design of the tailings area does not include wall or dam structures. During the first years of the operation, wall structures have shown to be necessary in order to prevent the uncontrollable spreading of the paste. (Regional State Administrative Agency of Northern Finland, 2016 June)

Waste rock is not predicted to be acid producing. It is stored at natural peat containing areas (The Regional Environmental Permit Agency of Northern Finland, 2009).

2.5.3. Water Management

The processes of these two gold producing plants begin with a conventional flotation of the ore. As a consequence, water management consists of similar main unit processes as in base metal or gold concentrate producing mine site:

- Mine water collection and treatment
- Waste rock area drainage collection
- Waste rock management
- Tailings storage and utilization
- Tailings pond water management

These plants also experience similar challenges as other flotation based concentrators (not specifically caused by the further processing of the gold concentrate):

For example **Agnico Eagle Kittilä** site’s solid removal capacity of the mine water settling ponds has been insufficient. There has been releases from the constructed wetland area, higher than expected. (Regional State Administrative Agency of Northern Finland, 2013 June)

Nordic Mines Laivakangas has experienced problems with the quantity of the water accumulating at the mine area. Water storage ponds have been constructed to store extra water at the mine. In addition, a new pipeline to discharge waters to the sea instead of nearby smaller waters, have been constructed. (Regional State Administrative Agency of Northern Finland, 2016 Jan)

Special requirements of cyanide leaching processes include:

- need to destruct / separate all cyanide compounds, which are highly toxic
- need of high quality process water for certain consumption points
- consumption of e.g. chloride containing chemicals, which may be challenging for conventional mine water treatment processes
- gold cyanide leaching process water will contain higher amounts of nitrogen compounds, which originate from the process chemicals (instead of explosives, which are the main source of nitrogen at the flotation process based base metal plants)

Agnico Eagle Kittilä mine and processing plant uses about 1.1 million m^3/a fresh water from a nearby river (amount is expected to increase to 2.2 million m^3/a as the production capacity is increased). The recycling rate of the process waters is 60%. The amount released to the environment after treatment, is about 0.9 m^3/a (1.75 m^3/a as production is expanded). The main contaminant, which currently prevents the use of the recycled water at certain process stages, is chloride. (Regional State Administrative Agency of Northern Finland, 2013 June)

On the other hand, as a result of high leaching pressure and temperature, additional evaporation (removal of water from the process water circuit) occurs after the leaching autoclave. This mine also applies segregation of certain drainage waters from process waters.

Nordic Mines Laivakangas beneficiation process uses recycled water from the tailings pond B and fresh water from the drinking water network. In addition, water from a water storage pond is partially recycled to the process. The water storage pond collects mine drainage water, waste rock and concentrator plant area drainage waters, as well as extra water from the tailings pond area A. (Regional State Administrative Agency of Northern Finland, 2016 Jan)

2.6. Bioheapleaching of Low-Grade Sulphide Ore

There are minerals and ores that cannot be concentrated and purified cost-effectively by a flotation process. Alternative processes include e.g. gravity separation and leaching in reactors, in-heap leaching system, or in-situ system.

This section describes the process of Terrafame mine (former Talvivaara). The process is designed for the low-grade base metal ore, and is based on bioheapleaching and selective precipitation of metals. Characteristics of the water treatment associated with the heapleaching and precipitation process are included.

2.6.1. Process Description, Bioheapleaching and Metals Recovery

Bioheapleaching

The quarried ore is crushed in a three stage crushing circuit, and agglomerated with PLS solution (pregnant leach solution). Then the ore is stacked to the primary bioleaching stack, which is about 8 m high. The stack is aerated through ventilation channels, which are installed in the lower parts of the stack, and irrigated through a pipeline-hose-system from the top of the heap. Leaching solution is collected to the PLS ponds, from where it is partially recycled back to the heap irrigation, and partially lead to the metal precipitation plant. Sulphuric acid is added to the irrigation solution, if needed. (The Regional Environmental Permit Agency of Northern Finland, 2007 March)

After the primary leaching (1.5 years), the ore is transported to the secondary heaps. Leaching continues at the secondary leaching area, which is also the final repository of the leached ore. Aeration and irrigation systems are similar to the primary leaching stacks. The irrigation solution of the secondary heaps consists of the raffinate (barren leach solution from the metals recovery plant) and recycled SLS solution. SLS solution (secondary leach solution) is pumped to the primary heaps. (The Regional Environmental Permit Agency of Northern Finland, 2007 March)

Leaching is based on oxidation of the iron sulphides at a low pH. This reaction is catalysed by naturally occurring microbes. Dissolution of iron facilitates further the leaching of valuable metals such as nickel, cobalt, copper, and zinc. Side metals, such as manganese, magnesium, and aluminium, are leached as well. (The Regional Environmental Permit Agency of Northern Finland, 2007 March) Process water is needed for pump sealing water. Fresh water is not added to the bioleaching process.

Metal Precipitation

PLS solution from the primary heap leaching is pumped to the metals recovery plant. The plant is based on a selective sulphide precipitation of valuable metals, and includes the following process stages:

- Copper sulphide precipitation (and reduction of iron); hydrogen sulphide gas + pH adjustment with caustic soda or recycled gas scrubbing solution
- Zinc sulphide precipitation; hydrogen sulphide gas + pH adjustment with caustic soda or used gas scrubbing solution. Hydrogen peroxide is added to the sulphide thickener overflow, in order to oxidize extra hydrogen sulphide to elemental sulphur.
- Pre-neutralization with limestone
- Nickel and cobalt sulphide precipitation; hydrogen sulphide gas + pH adjustment with caustic soda or used gas scrubbing solution. (The Regional Environmental Permit Agency of Northern Finland, 2007 March). Hydrogen peroxide is added to the thickener overflow to oxidize extra hydrogen sulphide to elemental sulphur.
- Precipitation of aluminium, oxidation of iron with oxygen gas, and precipitation of iron with limestone (Regional State Administrative Agency of Northern Finland, 2013 May)
- Precipitation of remaining metals with lime milk (The Regional Environmental Permit Agency of Northern Finland, 2007 March)

Metals are precipitated in a series of agitated tanks. Solids are settled in the thickeners. Flocculants are used to improve the thickening process. Metal suphide products are further dewatered and washed on filters. The wash waters from the filter are directed to the raffinate tank. From the raffinate tank, the solution is pumped to the secondary leaching process. (The Regional Environmental Permit Agency of Northern Finland, 2007 March)

Vent gases from sulphide precipitation reactors, thickeners, and filters are collected to an absorption reactor. Hydrogen sulphide gas is absorbed to caustic soda solution. Final traces of hydrogen sulphide gas are scrubbed in a wet scrubber, which uses caustic soda as well. The waste solution from the scrubbing contains caustic soda and sodium sulphide that are exploited in the metal precipitation. (The Regional Environmental Permit Agency of Northern Finland, 2007 March)

Vent gases from the pre-neutralization and iron precipitation contain mostly carbon dioxide. Traces of hydrogen sulphide are found, too. Therefore, the gases are collected for the separate scrubbing system. Hydrogen sulphide, and part of carbon dioxide, are absorbed in the caustic soda to form a solution containing sodium sulphide, sodium carbonate, and caustic soda. (TUKES, 2012) This solution is mixed with the neutralization residues to prevent the reliberation of hydrogen sulphide gas (which would occur in acidic conditions); and to exploit the neutralization potential of the solution, which contains caustic soda and sodium carbonate.

The effluent treatment system and water recycling system are described in section 2.6.3. The process utilizes two water fractions with different qualities: recycled process water, and clean process water.

Recycled process water is used in (Talvivaara Mining Company, 2013)

- Limestone slurry preparation
- Pump and agitator sealing waters
- Filter cake and cloth wash water

Clean process water is used in e.g. (Talvivaara Mining Company, 2013)

- Lime milk preparation
- Make-up water for the cooling water system
- Make-up water for the power plant

2.6.2. Solid Waste Management

There are five main solid waste types at the Terrafame mine:

- Leached ore, which is stored at the secondary heap (The Regional Environmental Permit Agency of Northern Finland, 2007 March)
- Pre-neutralization residue, which is utilized as a construction material for basal structures of the secondary leaching area
- Iron precipitation residue, which is pumped to the gypsum pond
- Final neutralization residue, which is pumped to the gypsum pond (The Regional Environmental Permit Agency of Northern Finland, 2007 March)

- Waste rock, which is utilized as a construction material for the leaching heaps. Waste rock is potentially acid producing. (The Regional Environmental Permit Agency of Northern Finland, 2007 March)

The underflows of the neutralization thickener from the iron precipitation and final neutralization are pumped to the gypsum ponds (Regional State Administrative Agency of Northern Finland, 2013 May). Gypsum ponds have a surface area of 116 ha (Regional State Administrative Agency of Northern Finland, 2015). Extra water from the gypsum pond is pumped to bioheapleaching, to final neutralization, or to other neutralization stations located at the mine site. The structure of the gypsum pond includes polyethylene lining, meaning that the ponds are designed to be impermeable. (The Regional Environmental Permit Agency of Northern Finland, 2007 March)

Pre-neutralization precipitate contains mostly gypsum. The precipitate is filtered after thickening. (The Regional Environmental Permit Agency of Northern Finland, 2007 March) Then it is transported to the secondary heaps, where it is used in the construction of new leaching areas.

Also, due to the leaks from the gypsum pond, a mixed metal hydroxide and gypsum precipitate is formed at other neutralization stations at the mine site. This residue has partially been stored to the geotubes, and partially transported to the gypsum pond while part of the precipitate is temporarily stored at the contaminated water ponds. The structure of these ponds is based on former wetlands and lakes, i.e. there is no artificial basal structure. (Regional State Administrative Agency of Northern Finland, 2013 May)

2.6.3. Water Management

Water Treatment, Recycling, and Storage

Management of Terrafame mine waters is challenging due to the large production areas, large contaminated land areas, and large amounts of metal sulphate containing waters. There is a need to release large amount of treated effluent (estimated to 7.5 million m^3/a (Regional State Administrative Agency of Northern Finland, 2015)) to the environment. This is even though the water recycling has been improved, and fresh water intake can be decreased close to zero during the normal operations.

Water treatment and management at Terrafame mine can be considered as two entities (Regional State Administrative Agency of Northern Finland, 2015):

1. **Management of the process water**: Treatment of extra water from the metals recovery plant – bioheapleaching circuit, which also receives rain waters from a surface area of 5.38 km^2.
2. **Management of water originating from the gypsum pond leakages**: Treatment of the contaminated natural waters, which are stored at several ponds in the mine area. This area receives rain waters from a surface area of 8.68 km^2.

Current process water management system consists of

- The metal recovery plant, which precipitates heavy metals, other side metals, and gypsum from the solution
  - The overflow solution from the final neutralization thickener is further clarified in a clarifier
  - The clarified solution is pumped to the recycled water pond, from where it is distributed to the process water network of the metals recovery plant. A small amount of fresh water from the fresh water source (lake or clean water pond) is added to the recycled water pond in order to prevent scaling.
  - Part of the solution is pumped to the reverse osmosis plant.
- The reverse osmosis (RO) plant – that consists of pre-treatment and membrane units - separates calcium, sodium, and magnesium sulphate from the feed solution
  - Permeate, i.e. clean water is pumped to the clean water pond from where it is distributed to the process water network of the metals recovery plant.
  - Retentate, i.e. the concentrated water stream is pumped to the gypsum pond or to the bioheapleaching. The intention is to lead the concentrated solution to place in which sodium sulphate is precipitated, and in which the gypsum oversaturation will not cause problems.
- Water storage, which is located at the open pit mine due to the highly positive water balance. Open pit water contains acid mine drainage, as well as raffinate solution from the metals precipitation plant. (Regional State Administrative Agency of Northern Finland, 2013 May)

The system comprising lime milk neutralization, RO and recycling of different qualities of the treated effluent to the process water system, is an example of a more developed water circulation process. Lower quality process water is used at certain points, and intake of fresh water to the circuit is minimized by an additional water treatment process, the RO plant (Regional State Administrative Agency of Northern Finland, 2013 May).

Treatment of the solution from leaks of the gypsum pond is arranged to several treatment stations. The process is solely based on the lime milk neutralization. Lime milk is transported to small storage tanks around the mine area. Lime milk is mixed with the solution of the pond in simple agitated containers. From there the slurry flows back to the pond, or at some treatment stations, to a separate settling pond. Precipitates are stored at the ponds, or periodically emptied by dredging. (Regional State Administrative Agency of Northern Finland, 2013 May)

Large quantities of water are stored at the mine area. Water streams have been separated based on their quality – specific ponds are solely used for storage of the treated effluent, whereas certain ponds contain contaminated water. (Regional State Administrative Agency of Northern Finland, 2013 May)

The company is planning to build a centralized neutralization treatment plant for the leakage solutions (Regional State Administrative Agency of Northern Finland, 2016 March 7). This development improves the process control and allows the use of more efficient process equipment than the current system. The centralized treatment plant could improve also the handling of the solid waste (see section 2.6.2).

Due to the very large water inventories, and in order to prevent emissions to nearby small lakes, a discharge pipeline has been constructed for releasing the treated waste water to a larger lake. (Regional State Administrative Agency of Northern Finland, 2015)

Water Management of the Bioheapleaching Process

Due to the low grade of the ore and the long residence time in the leaching, primary and secondary leaching areas are large: the surface area of the primary heaps is 320 ha (The Regional Environmental Permit Agency of Northern Finland, 2007 March), and secondary heap 196 ha (Regional State Administrative Agency of Northern Finland, 2015). The surface area of the secondary leaching stacks grows section by section as ore is transported from primary heaps to the second stage leaching.

Rain water as well as melting waters from this surface area are mixed with the process solution, causing accumulation of water in the ‘bioheapleaching–metal precipitation’ -circuit during the rainy seasons. On the other hand, sulphide leaching reactions are exothermic, meaning that additional evaporation will occur on the leaching stacks, which are in operation. In addition, process water from the metal precipitation plant is mixed with raffinate and directed to the secondary leaching process. Water is also returned to bioheapleaching from the gypsum pond.

Based on historical data, additional evaporation of the bioheapleaching process has not been sufficient for balancing the overall water balance of the process. In the early years of operation, the annual limit for discharging the water was not sufficient to balance the water situation either – instead, water was accumulated at the gypsum ponds.

In addition to the leaching reactions, precipitation of certain compounds occurs during the process. Sodium jarosite, a sodium, iron, hydroxide and sulphate containing precipitate is formed. Sodium balance of the ‘heap leaching – metals recovery process’ -circuit is largely managed thanks to precipitation of jarosite.

Water Management of the Metal Precipitation process

Metal precipitation plant is the main consumer of the process water. It is the main consumer of clean process water as well. The plant’s water recycling system has been constructed several years after the plant start-up. During normal plant operation, only a small amount of fresh water from the nearby lake is needed.

Use of sodium based chemical, caustic soda, results in a relatively high sodium sulphate concentrations in the raffinate solution. This compound is highly soluble in water and thus will not be removed in the original water treatment process, which is based on the gypsum and metal hydroxide precipitation. It is important to note that all streams originating from the metals recovery plant will contain sodium sulphate. This has led to the need of more expensive effluent treatment techniques.

Waste Area Water Management

Different qualities of neutralization waste from the metals recovery plant are stored at the same gypsum pond. Gypsum ponds correspond to some extent the tailings ponds of the flotation processes. Accordingly, the same type of principles should be applied at the gypsum pond:

- Separation of the waste streams based on their properties: i.e. separation of acidic iron precipitate from final neutralization residue to own pond areas

- Step-by-step fill of the gypsum ponds, removal of water and covering of the ponds as soon as possible
- More efficient dewatering of the waste precipitates prior to pumping the slurry to the storage area

The becoming leach residue areas, i.e. secondary leaching areas, will have to be covered according to similar principles as waste rock areas of other mines.

2.7. Concentration of Chromium Oxide Ore

Outokumpu Chrome Ltd Kemi mine and beneficiation process produces chromium oxide concentrate for Outokumpu stainless steel plant. The beneficiation process is based on gravity separation of the ore. Water management of Kemi chromium mine and the associated process is clearly different from most of the Finnish mines. The process and the requirements for its water management are briefly described in this section.

2.7.1. Process Description, Gravity Separation

The beneficiation process consists of crushing and processing of the coarse and fine fractions of the crushed ore by gravity separation techniques.

The coarse fraction is reported to dense medium separation, also known as sink-float separation.

There the heavier ore particles with higher grade of chromium are separated from lighter particles using drum separators. The idea is that particles which are denser than the medium will sink and particles less dense than the medium will float. Ferrosilicon slurry is used as the medium and it is separated, washed, and recycled back to the process. A third stream, an intermediate product is formed as well, and it is transported to the production of the high-grade concentrate.

The fine ore fraction from the crushing circuit is mixed with the intermediate product (from ferrosilicon aided gravity separation process), milled and processed in a wet gravity circuit (Regional State Administrative Agency of Northern Finland, 2010 Dec).

The concentrate is dried in drum filters. Tailings and process water are pumped to the tailings pond.

Flocculant is the only chemical, which is used in the beneficiation process.

Process water is consumed in e.g.

- Ore washing
- Ferrosilicon slurry aided gravity separation
- Milling and wet gravity separation

2.7.2. Tailings and Waste Rock Management

Solid material of the tailings contains up to 12 % of chromium oxide. Solubility of the metals from the solid fraction is on a low level, corresponding to natural rocks. The solid residue contains very low amounts of sulphides, sulphur content being as low as 0.04%.

Tailings go to the tailings pond. Overflow from the tailings pond is directed to the settling pond 4 and 5, from where it is recycled back to the process. Extra water (up to 1 million m^3/a) is led to the environment. The structure of the pond is permeable, meaning that part of the extra water is infiltrated through the dam structures.

Tailings ponds also receive water from the open pit and underground mines. The amount of the mine water is 0.5-2.5 million m^3/a. Tailings pond surface area is 187 ha, which is also the area where the rain water accumulates.

(Regional State Administrative Agency of Northern Finland, 2010 Dec)

Tailings ponds act as solid settling and storage ponds, but they also play a role in removal of nitrogen. Unreacted explosives contain nitrogen compounds, which are partly (82%) decomposed in bacteria catalyzed nitrification-denitrification processes. There is annual variation in the removal efficiency due to variation in oxygen availability and temperature. (Regional State Administrative Agency of Northern Finland, 2016 March 17)

Old waste rock is utilized in the underground mine backfill, and it is being stored at a waste rock area of 156 ha. In addition, large size ore particles from concentration of the coarse ore fraction are used as a mine backfill. (Regional State Administrative Agency of Northern Finland, 2010 Dec)

2.7.3. Water Management

Process water collection and recycling system of the Kemi chromium oxide mine and beneficiation process is relatively traditional. Practically all drainage water from the mine area (open pit, underground mine) as well as process water mixed with solid residues, are directed to the tailings pond. Water from the clarification pond and from the open pit mine are used as a process water.

Total process water consumption rate is 2.5 million m^3/a. In addition, water is needed for mining operations, such as drilling, irrigation, and pump sealing water. There the annual consumption rate is about 0.1 million m^3. Open pit water is used in drilling, whereas the majority of the beneficiation process water consists of recycled tailings pond water. Recycling rate is very high, as the amount of the fresh water has been less than 1% of the annual consumption (in 2008).

Despite the low fresh water intake, amount of extra water is 0.4-1 million m^3/a (excluding infiltration water). The mine is described as a dry mine, meaning that most of the water is originating from rain and snow. Those are collected from relatively large surface areas, tailings pond, open pit mine area, etc. Exact amount of infiltrated water has not been defined.

There is development ongoing to decrease the surface area. Old, filled tailings ponds have been stage wise closed. Transportation of the waste rock from the old storage areas is ongoing. (Regional State Administrative Agency of Northern Finland, 2010 Dec)

The composition and low acid producing potential of the ore and side products resulting from the concentration process significantly facilitates water management of the mine. It is, however, good to note that e.g. nitrogen emissions can be limited by limiting the amount of effluent, and by separating emptied or full waste areas from the process water cycle.

3. Part 2: Development of Water Management Concepts

This part of the report describes potential, new ways to manage water streams and storages at Finnish mines. Main focus is on the mines and concentrators that comprise flotation of sulphide ore containing base metals. Suggestions for development of beneficiation processes of gold and Terrafame bioleaching are briefly described.

3.1. Flotation of Sulphide Ores

This section presents potential ways to develop water management of Finnish mines and concentrators. Findings of the literature review in Part 1, as well as new ideas presented in the project workshop on the 14th of June, 2016, are presented.

3.1.1. Development of the Water Management Concept

Most of the Finnish mines already apply quite efficient water management practices, but based on the review in Part 1, there is clearly a significant development potential at practically all mines.

One important objective for water management is to develop the system so that it is less prone to the environmental conditions and their variations. Currently, the variation in precipitation and temperature causes unwanted variation in water flows and inventories. This causes variation in process water quality, as well as variation in the water discharge rate to the environment. The most important method for reducing the effect of environmental conditions is the reduction of the drainage area. Drainage area consists of the whole catchment area from which water is collected to process water circuit. The drainage area can be reduced by

- Separation of clean water (surface water) from mine operation areas by drainage collection system, open channels, pipelines, pumps, and quality control instruments
- Minimization of waste rock and tailings pond surface area (see section 3.1.3 for more information)
- Minimization of such waste material formation which causes contamination of the natural waters (section 3.1.2)

Another objective, mainly related to the environmental effects of mine water management, is to decrease the amount of discharged water to the environment. This can be achieved by reducing fresh water intake, in addition to decreasing the drainage areas. In practice, reduction of fresh water intake can be achieved by

- Reducing water consumption (section 3.1.2)
- Increasing process water recirculation

Increased process water recirculation requires knowledge of the quality of the recycled water streams, and of the quality requirements of each process water consumption point. It is clear that use of contaminated water will modify the process chemistry of the beneficiation process too. The potential effects, and ways to control the effects, are described in sections 3.1.4 and 3.1.5. It is good to note that recycled water can sometimes be cleaner or better suitable for the beneficiation process than natural waters.

Separation of slightly contaminated water from the strongly contaminated water is advisable, similarly to separation of different solid waste streams. It may be possible to utilize the less contaminated water streams in more demanding unit processes. If there is no need for cleaner process water, the separation of these streams can allow design of simpler and less expensive water treatment plant. In practice, separation of different water streams requires separate collection systems (pipes, pumps, open channels, ponds) and continuous or frequent measurement of water quality.

Development of the operation principles of the tailings ponds is clearly one potential way to improve water management of the flotation process. It is also one prerequisite for the separation of different solid and aqueous waste streams. Currently the practice is to use tailings ponds as clarification, storage, and water collection ponds for a wide range of more or less contaminated water streams. Potential development methods are described in section 3.1.3.

Use of more advanced process equipment and process control system for water treatment plants is one way to reduce the environmental effects of mining operations. Currently only a part of the existing water treatment plants are using process equipment which is specifically designed for the purpose. One example is addition of neutralizing chemical in the process water: instead of pH controlled dosage to agitated tanks and separation of solid residue in thickeners equipped with flocculant feed, it is common to simply add the neutralization agent to a pipeline or channel. The slurry then flows to a pond. It is clear that the chemical efficiency and the purification result is higher when using the more advanced system. The use of advanced process equipment and process control for the recycled process water purification is equally recommendable.

Similarly, use of more advanced process equipment, and selection of less water consuming process equipment, is a part of good water management (see section 3.1.2).

3.1.2. Process Development Potential

Ore composition and local conditions of the mine have a large effect on the mine water management. The details of the concentration process are at least equally important. This is why the water management should be a part of process design already at early stages of a feasibility study. In subsequent engineering phases (basic engineering and detail engineering), additional choices can be made to reduce impacts of the process on water management, e.g. by choosing process equipment which consumes less process water.

Development of the Process Concept

Completely new mineral processing techniques are not widely known (Working Group, 2016). Flotation is likely to be selected as the key technology in the future as well. As a result, focus of the future developments in mineral processing will be in developing the flotation process itself, as well as the pre-treatment processes and tailings management.

The purpose of the pre-treatment processes is to reduce the material flow to flotation by separating valuable minerals from waste minerals. The smaller the material flow to flotation, the lower will be the need of process water and process chemicals. A prerequisite for efficient pre-treatment process (and for selective and efficient mine operations) is a good knowledge of the mineral composition of the feed material (Working Group, 2016). Proper mineralogical characterization should be the first step for designing the concentration process, as well as the basis of process operation, such as chemical dosage.

Pre-treatment processes include e.g. crushing, grinding, gravity separation and pre-flotation, as well as dewatering of the intermediate concentrate.

The beneficiation process should be designed to enable separation of different waste streams. This means that waste rock, pre-treatment process waste fractions, and tailings from each flotation stage should be separable, if their composition is unequal. In practice, separation of different waste fractions can consist of separate conveying and pumping systems, and in some cases the separation requires a new flotation circuit to the process (e.g. separation of acid-producing pyrite).

The selection of process chemicals is mainly based on their availability on the market, the price, and the efficiency in the process. Usually there exist several alternative chemicals with similar effects on the process. At the same time, the composition of the chemical and its behaviour in the beneficiation process as well as in the water treatment process can be very different. For example,

- Commonly used pH adjustment alkali include calcium carbonate (limestone), calcium oxide (burned lime), calcium hydroxide (hydrated or slaked lime), sodium hydroxide (caustic soda), and sodium carbonate (soda ash).
- In sulphate containing solutions, calcium based chemicals form scarcely soluble calcium sulphate, which is precipitated as gypsum. Gypsum precipitation must be carefully designed and operated to prevent plugging of process equipment.
- Sodium containing chemicals form a highly soluble sodium sulphate salt, which is not precipitated under normal process conditions. Sodium sulphate tends to accumulate in the process water circuits with high process water recycling rate. Removal of sodium sulphate requires advanced and costly process techniques, such as reverse osmosis, evaporation, or ion exchange.

Selection of process chemicals should thus – at least partly – be based on knowledge on their behaviour in the whole beneficiation process and in the water management system.

Process conditions, especially pH and reduction-oxidation potential, have an important effect on the solubility of most metals. This is why aqueous solution composition is affected by process conditions during flotation. Typically, the lower the pH, the higher will be the concentration levels of metals and associated sulphate. Thus, for water treatment, it would be better to develop processes which are operated at neutral pH, and chemicals which are effective in these conditions.

Optimization of the Process

Optimization of the beneficiation process itself is often beneficial for the water management system as well. As previously described, the high recovery of valuable (heavy) metals is important for improving the quality of the waste streams.

In addition to recovery, the chemical efficiency, solid-liquid separation efficiency, as well as e.g. precipitation yield can be optimized (see section 3.1.3 for more details on solids removal). The efficiency of process chemicals can be improved e.g. by adjusting the dosage point in the process, by providing correct mixing of the chemicals in process solution, by ensuring the correct quality of the chemical, and by dosing the correct amount of the chemical, based on process control system.

Optimization of chemical efficiency may include recycling of process chemicals. The positive effect of recycled process chemicals has already been reported as a part of water recycling studies (Muzenda, 2010).

Optimization of the process equally applies to precedent process stages, such as grinding and mine operations. Process plant feed should be optimized to decrease amount of side rock in flotation, and the grinding result should be measured and adjusted according to the needs of flotation.

Equipment Selection

One important factor in equipment selection should be the specific water consumption rate. This applies to many equipment groups, such as

- Filters (counter-current washing is usually less water consuming than co-current washing)
- Milling (high pressure grinding rolls (HPGR) use less water than other fine grinding equipment) (Kessler and Burchardt, 2015)
- Pumps (consumption of sealing water)

3.1.3. Solid Waste Development Potential

Development of Storage Methodology

Solid waste management system has an important effect on the mine water quality and quantity. Main principles in the solid waste management are:

1. to prevent formation of such waste
2. to utilize the waste in e.g. construction of dams or backfill of underground mills

It is common to use waste rock as construction material for the mine area dams. It is also common to mix tailings with the waste rock and use the mixture as underground mine back fill. Due to the quantity and quality of the tailings materials, it is seldom possible to utilize all fractions of tailings in construction work.

For the solid mine waste, which is not reused, it is important:

3. to separate potentially acid producing and soluble materials from the inert materials

Separation of acid producing and non-acid producing residues in the flotation process is already applied at a number of mines (e.g. Boliden Kevitsa, nowadays also FQM Pyhäsalmi). Flotation processes could be further developed to separate waste minerals more efficiently, as described in the previous section. This is likely to cause additional investment and operating costs for the beneficiation process, but on the other hand, it may be possible to reduce investment and operating costs of the water treatment plant and pond construction, as the fraction of the harmful waste gets smaller.

In addition to the changes in the flotation process, separate storage areas are necessary to completely avoid mixing of different waste qualities. In addition, water systems of these area should be designed in a way that the acidic water is not collected to the inert waste pond.

All storage areas for the reactive waste stream should be designed:

- to prevent contact of reactive solid materials with water and air
- to minimize the surface area of the solid waste storage

During mining and beneficiation operations, tailings ponds are usually covered with a layer of water, which decreases the availability of air and oxygen. After mine closure, or after the closure of a tailings pond section, it is typical to cover the waste area with a dry cover. Dry covers are described in section 2.4.3: there are several alternatives for the partial or complete encapsulation of waste rock and tailings pond areas.

One potential, relatively new method is the formation of a so-called hardpan layer, which is naturally or by design formed on the surface of sulphide containing tailings residues. Formation of such layer has been studied by several authors (Graupner *et al.,* 2007; Lottermoser and Ashley, 2006; McGregor and Blowes, 2002). The formation of a hardpan layer is reported to include oxidation and precipitation of iron compounds, further crystallization and weathering reactions of the secondary iron compounds, and formation of gel type layers, which contain silicates. This hardpan layer is reported to collect heavy metals by adsorption, and potentially by chemical reactions between the heavy metal and the cemented layer.

It is also possible to artificially form a hardpan layer – a so-called engineered hardpan. E.g. hydrated lime and waterglass, which form a layer of calcium silicate, have been studied as the constituents of the hardpan layer. It is worth noting that most of the research has been carried out in arid or semi-arid conditions, which are not valid in the Northern countries. (Ahn *et al.,* 2011)

Development of the Operation of Tailings Ponds

In addition to the function as final storage of tailings solids, tailings ponds act as settling and water collection ponds. Settling rate of the solid material, in combination with the flowrate, will define the minimum surface area of the pond. Settling could alternatively be operated in specific process equipment such as thickeners and/or filters (Outotec, 2016, Accessed 20 June 2016). When performing solid-liquid separation in thickeners, only the underflow, which contains higher amount of solids, would be stored at the pond, and the clear overflow could be recycled back to the process. This solution is already applied to some extent at certain mines, such as Nordic Mines Laivakangas and FQM Pyhäsalmi mine. It is important to note that the pumping properties of the thickener underflow may demand special equipment design, and that the so-called short circuit of process water recycling may cause changes to process water quality.

Tailings ponds also act as clarifying ponds. Instead of large ponds, settlers could be used for separating the fine solid residues prior to the recycling, or prior to releasing extra water from the mine site.

Instead of building large, uniform tailings ponds, which will be filled during a long time period, a section-wise filling system could be considered. When the pond is divided into several sections, the full and dry sections can be covered earlier. That minimizes the contact with air and water and also limits the drainage area.

If the solid material is stable enough, drying of the material with filters and storage as stockpiles could be considered. This requires reliable information of the properties of the solid material. In addition, to prevent the contact with air and water, the stockpile should be covered relatively soon after stockpiling. (Working Group, 2016)

The use of tailings ponds as water collection ponds has a number of disadvantages, which have been discussed in the report (section 2.4.5). Section 3.1.5 describes potential disadvantages and advantages of the short circuit system, in which water is recycled from settler / thickener or filter to the process, without the long residence time at the tailings pond.

3.1.4. Need of Water Balance Modelling and Online Measurements

In order to achieve higher recycling rate of process water, and to be able to separate different water and solid waste fractions, reliable information on the flowrates and solution compositions are needed. Accurate and sufficient information is necessary both in the design phase and in the operating phase of the plant. Modelling is almost inevitable due to the annual variation in water flows and chemistry, caused by weather conditions.

At operating mines, collection and utilization of this information often requires

- Process control system
- On-line quality measurements
- On-line flowmeters and level measurements
- Up-to-date water (or material) balance model comprising the whole mine area, both process water and mine area water balance
- Combination of the water balance model with weather condition data – prediction of the development of the water inventories

The final report of the WaterSmart project describes monitoring and measurement solutions, which are required for mine water management (Punkkinen *et al.,* 2016)

- Monitoring of ground waters and surface waters
- Monitoring of tailings ponds, seepage waters and dams
- Monitoring sensors and analyses
- Water quality and quantity data for water management

Modelling software is available on commercial market. There are different technical solutions which can be utilized for mine water balance modelling. In many cases, however, the most important factors for obtaining reliable and useful water balance model are the quality of source data and the skills of the modeller.

Measurement systems are important for the investigation of process chemical behaviour throughout the process. Online measurements can provide valuable data of accumulation of chemicals, and combined with the information of the process performance, they can provide information on the effects of process water composition on the process. Based on this information, mine water management system can be developed further.

3.1.5. Effect of the Recycled Water on Process Performance - Need of New Techniques for Increasing Water Recycling Rate

Tailings pond water is commonly recycled at current mine operations in Finland and in other Northern countries. As water recycling rate is increased further, the effects of different water constituents can become more significant. It is important to identify the behaviour of these compounds on the process, and to find a solution to prevent adverse effects on the process. The technical solutions may include segregation of water streams, use of additional purification techniques, or use of alternative chemicals.

Water quality is known to have an effect on flotation processes (Muzenda, 2010; Levay *et al.*, 2001; Liu *et al.*, 2013). The influences of increased use of several, recycled water sources can be grouped e.g. in the following way:

- Variable and unpredictable composition of process water
- Combined effect of high ion strength water on process performance
- Effect of individual compounds / parameters on process performance

1. **Variable and unpredictable composition of process water**

The use of recycled water from several sources, such as open pit mine, tailings pond, or side rock area, can cause unpredictable changes in grinding and flotation process conditions (Levay *et al.*, 2001; Liu *et al.*, 2013). Process water composition of these sources may also vary depending on the season – e.g. oxygen concentration of water is influenced by winter conditions, such as ice covers on tailings ponds.

The effect of variable process water composition can be managed by frequent analysis of process water composition, by online measurements, and by careful dosage of process chemicals. For the most sensitive processes, it is recommendable to always ensure the stability of process water quality by treating it in an adequate purification process.

2. Combined effect of high ion strength water on process performance

Increased amount of dissolved compounds will increase the specific gravity of the process solution. Separation of minerals by flotation is based on the difference in surface properties but also partly on the difference in densities. As the specific gravity of the process solution is increased, the separation properties of minerals may also change. (Muzenda, 2010)

Testwork on the influence of water quality on flotation performance has been carried out with original solutions from a mine site, and compared to the results achieved with potable water. According to the bulk flotation results of the study, flotation yield was decreased when using recycled water, which had a higher conductivity and total dissolved solids value than clean water. On the other hand, concentrate grade was shown to be higher when using recycled water, which may have been caused by residual flotation chemicals of the recycled water. (Muzenda, 2010)

3. Effect of individual compounds / parameters on process performance

In some cases process water circulation is limited by the water quality. Such cases include at least:

- Gypsum
- Chlorides
- Solids

In addition, some water soluble compounds may accumulate in the process water circuit. For the accumulation to occur, the fresh water intake (including also rain water to the drainage area) must be very small, and discharged water flow very low. These compounds include at least:

- Halides, such as chlorides and fluorides
- Sodium and potassium sulphate

- Organic process chemicals, such as xanthates
- Other soluble chemicals, such as nitrogen compounds

In some cases, increased use of the recycled process water can improve the process water quality. Surface waters in Finland often contain humic compounds and other organic compounds, which may have an adverse effect on e.g. metal precipitation. Natural organic compounds can act as complexing agents, disturbing the process. Usually there are no natural organic compounds in the mine water or drainage water from the mine area. In addition, the quality of the natural waters is not stable, but varies depending on the season.

Gypsum

At FQM Pyhäsalmi mine, **gypsum scaling** has caused problems when water has been recycled from the tailings pond to the flotation process (The Regional Environmental Permit Agency of Northern Finland, 2007 Sept). Water in the tailings pond is gypsum saturated. That is because the lime milk is used for adjusting the pH of the tailings (and mine water), as well as to adjust the pH of the water, which is released to the environment.

Gypsum scaling is a common phenomenon in the hydrometallurgical industry. All gypsum saturated solutions cause a potential risk for scaling of process equipment and pipelines. It can also affect the quality of the solid materials in the process, by precipitating on the surfaces of these solid material particles. In flotation processes, calcium sulphate may also precipitate on mineral surfaces, changing their separation properties (Levay *et al.*, 2001).

At Terrafame nickel mine, gypsum scaling is managed by adding a small amount of clean water to the recycled water pond, which would otherwise contain gypsum saturated water. With the addition of clean water, the recycled water is no longer gypsum saturated, and thus it will not cause scaling problems in the process. Additionally, reverse osmosis is used to produce clean water which contains no gypsum at all, and only very low amounts of other sulphates. E.g. lime milk preparation requires process water, which is free from sulphates. Sulphates inhibit the reaction of burned lime to hydrated lime. (Regional State Administrative Agency of Northern Finland, 2013 May)

There are also antiscaling chemicals, which can be used to prevent gypsum precipitation. It is important to remember that some antiscaling chemicals can act as complexing agents, and their potential negative effects on the production process should be investigated beforehand.

There are several advanced processes for removing gypsum from aqueous solutions: gypsum removal cooling towers, water softening, ion exchange, reverse osmosis, and solvent extraction processes. These processes are nowadays used at metal refining plants, but very seldom at mines, due to their investment and operating costs.

Chlorides

At Kittilä mine, chloride content of the water in the tailings pond limits the use of the recycled water in the process. Chlorides have an adverse effect on the gold leaching process. (Regional State Administrative Agency of Northern Finland, 2013 June)

Chlorides also have a corroding effect: even small concentrations of chlorides combined with slightly acidic process solution can cause pitting corrosion of lean stainless steel grades.

Based on laboratory test work, metal chlorides influence also flotation processes. Aluminium, calcium, and sodium chloride containing water was used in zinc sulphide flotation. MIBC was used as the frother. Froth stability, viscosity, and zeta potentials increased by increasing metal chloride concentration. The proposed mechanism is more related to metal ions than to chloride ions. (Farrokhpay and Zanin, 2011) It is important to note that chlorides are easily built up in a process water circle, and that the most common cations include metal cations, which corresponds to the conditions of this study.

Chlorides are highly soluble compounds, and their removal requires special separation processes. Examples of such processes include membrane separation (reverse osmosis), ion exchange, and evaporation. All of these solutions have a relatively high operating and investment cost. Thus, it is worth considering to use alternative, non-chloride-containing chemicals in the process.

Solids

Solids are found in natural waters as well as mine drainage waters and concentrator process waters. Their composition varies and depends on the origin.

All solids can cause plugging of small pipelines and nozzles. Solids can e.g. plug nozzles of a filter’s washing system. In large pipelines with low flow velocity, solids can accumulate on the bottom of the pipeline. Solids need to be very carefully removed prior to certain processes, such as membrane separation processes or solvent extraction.

The composition of solid material may also be the reason for not being able to use the water stream in certain applications. One example is the concentrate product quality: if the residual solids in the process water worsen the quality of the final concentrate, such process water should not be used in the beneficiation stage.

Efficient solids removal often requires adequate process equipment and addition of flocculation or coagulation chemicals. The correct equipment solution depends on the initial solid concentration, the size and shape of the particles, and the targeted final solids concentration.

If the feed solid concentration is low (under 1 mass percent), clarifiers and clarification ponds are often the choice. Both solutions are based on gravity separation. Clarifiers have the advantage of continuous solid removal, whereas clarification ponds will need to be periodically emptied. In addition, clarification ponds will receive natural waters, such as rain, and the clarification result is thus not as reliable as that of a clarifier. Accurate dosage of flocculation/coagulation chemicals is easier to arrange in clarifiers, too.

If the feed solid concentration is high, a thickener can be used to separate majority of the solid material to the thickener underflow. Thickening is based on gravity separation, too. Thickener overflow often contains residual solids (about 100 mg/l), which can be further separated in a clarifier or in a clarification pond.

If gravity separation is not sufficiently efficient, filtering equipment can be considered. Filter types include sand filters and cartridge filters (for low feed solid concentration), as well as belt and pressure filters (for high feed solid concentration).

Potential, new equipment solutions for removal of residual fine solids fraction include dissolved air flotation (DAF). In this technique, air is fed under pressure to the water stream, and released to form bubbles on the surface of the flotation cell. This process has been applied in e.g. drinking water purification, especially for the removal of organic compounds. (Rodriguez and Rubiro, 2007).

The investment cost of a clarification pond is normally the cheapest, whereas filters are the most expensive equipment types. Overall costs, which comprise operating costs as well as costs caused by insufficient solids removal, however, can be surprisingly high for the simple pond solutions.

Sulphates

Most metal sulphates are highly soluble in acidic process solutions. Certain sulphates, such as sodium and potassium sulphate are highly soluble in alkaline process water as well. In practice, calcium sulphate precipitation is applied to remove sulphates from mine water.

Sulphate containing water will have higher specific gravity and conductivity than clean water. The effects of these parameters have been described earlier in this section. In addition, sulphate containing water is not usable in all applications: e.g. lime milk preparation from burned lime requires sulphate-free water. Sulphates may act as colloidal species, which may remain dispersed in solution or attached to mineral particle surfaces as hydrophilic surface layers (Levay *et al.*, 2001).

Sulphates are commonly found in mine area process and drainage waters at metal sulphide deposits. Sulphate concentrations in process water can be controlled by solid material management and process design:

- Limiting the contact of water and air with minerals
- Selection of process conditions, e.g. prevention of acidic conditions, which increase dissolution of heavy metals
- Selection of process chemicals, e.g. prevention of use of sodium and potassium containing chemicals, which can lead to sulphate build-up also in neutral and alkaline solutions

Gypsum precipitation (precipitation of calcium sulphate with lime based chemicals) is clearly the most common sulphate removal process. Gypsum precipitation, when performed at high pH, will remove sulphate which is associated with divalent and trivalent metal ions (heavy metal ions, aluminium, manganese, etc.). Gypsum precipitation will not remove sodium or potassium sulphates. The minimum final concentration of sulphate is defined by the solubility product of gypsum – corresponding sulphate concentration is about 1200-1500 mg/l, and the additional sulphate which is associated with sodium and potassium ions.

Other sulphate removal processes are seldom used. Potential techniques include:

- Separation processes: produce a sulphate free and a sulphate concentrated stream
    - Membrane separation (nano and reverse osmosis)
    - Ion exchange (and absorption)
    - Evaporation

- Precipitation processes
    - Gypsum
    - Ettringite
    - Barium sulphate
    - Jarosite
    - Adsorption
- Reduction of sulphate
    - Biological sulphate reduction process
- Other processes
    - Electrocoagulation

Organic Process Chemicals; Example: Xanthates

Properties of Xanthates

According to a xanthate chemical manufacturer (Flomin, 2013), solid xanthates are hygroscopic and decompose in the presence of water to form carbon disulphide, hydrosulphide, carbonyl sulfide, pseudo-xanthate, alcohols, hydroxides, and mono-, di-, and trithiocarbonates. Further, xanthates hydrolyze very rapidly under acidic conditions but are stabilized at high pH (>12). They dissociate totally under pH 9 and very rapidly under pH 7. It is also emphasized that the higher the temperature, the faster will be the decomposition rate. (Flomin, 2013)

Occurrence of Xanthates in Flotation Process Waters and Tailings

Xanthates and their decomposition products have been reported at Finnish mine tailings (Regional State Administrative Agency of Northern Finland, 2010 Aug and 2014). Based on environmental permits, behaviour of xanthates at Finnish mines has not been studied in much detail. Based on one risk assessment report regarding Boliden AITIK mine in Sweden, the xanthates or intermediate decomposition products of xanthates could be found in tailings ponds, clarification ponds, and also discharge water streams of these ponds (Book, 2014). The risk assessment emphasizes the effect of cold climate on decomposition rate of the chemical.

Behaviour of Xanthates in Flotation Processes and Tailings

In mining, xanthates are used in liquid form, i.e. dissolved in water. Process conditions are in most cases neutral or alkaline.

There are three decomposition pathways of xanthates in aqueous solution. In acidic solutions, reactions A and B take place, whereas reaction pathway C is predominant in alkaline conditions. (Australian Government Publishing Service, 1995)

A. Xanthates dissociate forming alkali metal cations and xanthate anions. The solution undergoes further hydrolysis to xanthic acid which decomposes into carbon disulphide and alcohol.

$ROCS_2Na + H_2O \rightarrow ROCS_2H + NaOH$

$ROCS_2H \rightarrow CS_2 + ROH$

B. Xanthate is oxidised to dixanthogen. The extent of this reaction is very small and dependent on the pH. Equilibrium is reached after about 5–10% of the xanthate is oxidised, and the reaction increases with a fall in the pH.

$2ROCS_2^- + H_2O + ½O_2 \rightarrow (ROCS_2)_2 + 2OH^-$

C. In neutral and alkaline media, xanthates decompose by hydrolytic decomposition.

$6\ ROCS_2^- + 3H_2O \rightarrow 6ROH + CO_3^{2-} + 3CS_2 + 2CS_2^{2-}$

Further hydrolysis of sodium trithiocarbonate to sodium carbonate and hydrogen sulphide and carbon disulphide to carbon dioxide and hydrogen sulphide may occur. The reaction is catalysed by the alcohol formed from the xanthic acid and is self-accelerating.

Part of the carbon disulphide formed may decompose further to carbonate and thiocarbonate salts, some of it may evaporate and some may build up in the xanthate solution.

In flotation processes, xanthates form soluble and insoluble metal complexes (Sihvonen, 2012).

Impact of Xanthates on Beneficiation Processes

In the case of short circuit water recycling, the possibility of finding residues of xanthates and their decomposition products increases. It has been observed that flotation selectivity of copper–lead–zinc ore is compromised by the accumulation of the decomposition products of a xanthate copper collector Z-200 due to water reuse and its subsequent non-selective adsorption (Liu *et al.*, 2013).

The chelating effect of xanthates is well known from sphalerite flotation, too. If copper sulphate is not added to modify the mineral surface, xanthate will form a complex with zinc ions, which results in less efficient flotation separation result.

Xanthates may affect the performance of other than flotation processes, too:

Isobutyl and isopropyl xanthates have been found to have an inhibiting effect on bioleaching processes, due to their toxic nature to bacteria (Loon and Madgwick, 1995).

On the other hand, ethyl and amyl xanthates have been reported to stimulate, to a limited extent, the metabolic activity of the sulfur-oxidizing bacteria Acidithiobacillus thiooxidans (Pacholewska *et al*., 2008).

In addition to their use as flotation agents, use of xanthates as heavy metal chelating agents in waste water treatment has been studied as well. According to a review article, copper ions have been successfully removed from waste water with ethyl xanthate. (Fu and Wang, 2011).

Analytics of Xanthates

In order to define the behaviour and occurrence of xanthates in flotation processes, xanthates and also the numerous decomposition products should be analysed.

At Boliden Kevitsa mine, xanthates are monitored by measuring sodium concentration. Monitoring results show increase in sodium level. It is worth noting that sodium can originate from other chemicals and the ore, too.

COD (chemical oxygen demand) measurement has been used to define xanthate concentrations in test conditions. (Dong *et al.*, 2014) Also other oxygen consuming compounds will affect this analytical result.

Capillary electrophoresis analysis has been developed for xanthates and their decomposition products (Sihvonen, 2012).

Xanthate Removal / Recycling from Mine Water

Based on the data provided by chemical manufacturer (Flomin, 2013), xanthates are relatively easily decomposed. According to an Australian report, they are not expected to accumulate in natural waters (Australian Government Publishing Service, 1995). But, decomposition data in real, on-site conditions in cold climate is limited.

Potential process technologies for removing xanthate residues from water streams include:

- Heating
- Biological degradation
- Oxidation
- Biological, activated carbon filtration (Dong *et al.*, 2014)

The current decomposition pathways most likely include oxidation in flotation and in tailings ponds, and biological degradation at wetland areas.

Potential process technologies for separating and recycling of xanthates from mine water streams could include:

- Biological, activated carbon filtration
- Membrane separation processes

3.2. Gold Beneficiation Processes

The main technique for the production of metallic gold is cyanide leaching. The cyanide leaching process uses a number of harmful and somewhat troublesome chemicals such as cyanide and hydrochloric acid or other source of chloride.

Significant number of research projects have been and are being carried out to develop an alternative for cyanide leaching. The research includes e.g. thiosulphate in the presence of ammonia or copper, chloride and hypochlorite, and thiourea, among many other alternatives. Bio-oxidation as a pretreatment method for thiosulphate leaching is under growing research. (Hilson and Monhemius, 2006) The changes in the key process concept will cause changes to the processes of gold recovery from the leach solution as well (Grosse *et al.,* 2003). These techniques are under research as well.

None of the new technologies have yet been able to achieve the overall efficiency of gold cyanide leaching process. More information and understanding of the process chemistry is required to optimize the new processes.

In addition to research on alternative process chemicals, there is research to further develop the cyanide leaching process, too. One development is the recycling of cyanide using membrane technology. This process could allow lower consumption of cyanide in the beneficiation of copper containing ores. The technique is a combination of membrane and electrowinning technologies, and allows the recovery of metallic copper and the simultaneous liberation of free cyanide from the copper cyanide complexes. The free cyanide may then be recovered and returned to the gold beneficiation process. (European Commission, 2007).

3.3. Bioheapleaching of Low-Grade Sulphide Ore

Terrafame mine comprises mining, bioheapleaching, metal precipitation, and water treatment processes. The mine has experienced difficulties in both process performance and water management. The company is currently investigating a new process concept which is aiming at process improvements and decreased environmental effects on the aquatic environment (Terrafame, 2016, A).

The new process concept will still be based on bioheapleaching of nickel sulphide ore. In order to enhance the efficiency of the bioheapleaching process, the company is planning to purify the return solution from metals recovery plant, i.e. raffinate, before returning it back to bioheapleaching process. (Terrafame, 2016, A)

The metals recovery plant will still be based on sulphide precipitation of valuable metals. Instead of caustic soda, the company plans to use potassium hydroxide as pH adjustment and gas treatment alkali. This allows production of valuable side products, such as potassium carbonate and potassium sulphate. (Terrafame, 2016, A) Other potential, new side products include aluminium oxide. Aluminium oxide is currently stored at the gypsum pond. (Terrafame, 2016, B)

In addition to the new chemical and the new side products, the company is planning to investigate the use of forward osmosis technique to separate water molecules from reverse osmosis reject, and bioreactors to recycle hydrogen sulphide gas to the metals recovery processes. These technologies are currently not available on the market at this scale of operation. Significant modifications, e.g. increased iron precipitation capacity and increased reverse osmosis capacity, are required to the current metals recovery plant, too. (Terrafame, 2016, A)

From the perspective of water management, this development project is an example of incorporating water management as part of the production process design. In addition, the intention is to increase chemical recycling rate and recover additional metals from the process. On the other hand, this project is based on new, unestablished techniques, which will require extensive research and piloting before designing the full scale plant. It is also notable that the project does not aim at solving the problem of the current large water storages, or at developing of the gypsum pond storage system.

4. Conclusions and Further Actions

More attention is being paid to mine water management by the public, and the authorities, as well as by the mine companies now than in the earlier times. Mine water management is being studied by numerous research organizations, and guidelines are being published for the best practices.

The application of the newly developed guidelines and technologies at Finnish mines seems to be time consuming and relatively slow, although not all of the practices would require significant additional investments. In order to more efficiently apply the good practices, information sharing between different organizations of the mining sector would be important. Educational organizations could be utilized to share information to the new professionals, as well as to professionals with longer experience in the industry. It is also clear that additional research will be required to ensure the functionality of the production process while water management is being developed.

Good mine water management practices, which are in more detail described in the report text, include

- **consideration of water management design as a part of the mine and beneficiation process design.** Process concept, process chemicals, process conditions, and process equipment will influence the mine's water management.
- **continuous target to decrease water consumption rate** by e.g. equipment selection, and by decreasing the material flow to water / slurry phase processes by more optimized pre-treatment solutions and mineralogical knowledge.

  use of up-to-date online measurements, modelling, and adequate process equipment in water management operations.

Water balance of the Nordic mine sites is practically always positive. This is why it is important to

- **reduce the amount of water which is being contaminated due to mining operations**. By segregation of different water streams, minimization of drainage area, and by increasing the water recycling rate the water balance can be developed to less positive direction.

reduce the use of fresh water. This means utilization of recycled water instead of fresh water from an external water source. Solid waste stream management is equally important for water management. At Finnish mines,

- **separation of different solid wastes** is becoming more common, but there is still space for development.
- **the operation principle of tailings ponds should be developed** so that the pond is not the collection pond of any type of water streams and solid wastes, but rather a storage area for the dewatered (and stabilized) solid waste fraction.

New information and technology will be required at many areas:

- effect of the recycled water quality on different processes
- understanding of the mechanisms between process chemicals and minerals
- development of new chemicals based on the needs of the beneficiation and the water treatment process
- development of new production processes, which are less water consuming and can be operated in leaner conditions and with less harmful chemicals
- definition of the need for new water purification processes, and the development of these processes in order to increase water treatment recycling rate
- development of solid waste stabilization and isolation processes

5. References

Ahn, J., S., Song, H., Yim, G.J., Ji, S.,W., Kim, J.G. 2011 [Abstract] **An engineered cover system for mine tailings using a hardpan layer: a solidification/stabilization method for layer and field performance evaluation**. Journal of Hazardous Materials 197 (2011) 2011 153-60. Available online: http://www.ncbi.nlm.nih.gov/pubmed/21974852 [Accessed 21 June 2016]

Australian Government Publishing Service, 1995. **Sodium Ethyl Xanthate: PRIORITY EXISTING CHEMICAL NO. 5**, Commonwealth of Australia 1995, ISBN 0 644 35283 3.

Boliden A [Website] No date. **Boliden Aitik.** Available online: http://www.boliden.com/Operations/Mines/Aitik/ [Accessed 3 June 2016]

Boliden B [Brochure] No date. **Boliden Aitik.** Available online: http://www.boliden.com/Press/Publications/ [Accessed 3 June 2016]

Boliden C [Brochure]. No date. **Boliden Garpenberg**. Avaible online: http://www.boliden.com/sv/Verksamheter/Gruvor/Garpenberg/ [Accessed 6 June 2016]

Book, F., 2014. **Risk assessment of mining effluent sin surface water downstream the sulphide ore mine Aitik, northern Sweden**. Degree project for Master of Science, Department of Biological and Environmental Sciences, University of Gothenburg.

Brandt, M., Jutaman, T., Alexandersson, H., 1994. **Sveriges vattenbalans. Årsmedelvärden 1961-1990 av nederbörd, avdunstning och avrinning.** Report in series Hydrologi 49. Swedish Meteorological and Hydrological Institute. Available online: http://www.smhi.se/publikationer/sveriges-vattenbalans-arsmedelvarden-1961-1990-av-nederbord-avdunstning-och-avrinning-1.2564 [Accessed 23 May 2016]

Dong, Y., Lin, H., Liu, H., Huo, H. 2014. **Treatment of flotation wastewater using biological activated carbon**. Journal of Central South University of Technology 21 (2014) 3580−3587.

Eriksson, N., and Lindeström, L. 29 January 2011. Environmental Impact Assesment: **Miljökonsekvensbeskrivning gällande produktionsökning till 3 Mton vid Garpenbergsgruvan, Hedemora**.

European Commission, 2007. [Reference Document on Best Available Techniques]. Management of Tailings and Waste-Rock in Mining Activities. Available online: http://eippcb.jrc.ec.europa.eu/reference/ [Accessed 21 June 2016].

Farrokhpay, S. and Zanin, M. 2011. **Effect of Water Quality on Froth Stability in Flotation.** Chemeca 2011, Engineering a Better World Sydney, New South Wales, Australia, 18–21 September 2011.

FloMin, 2013. [Brochure]. **FloMin Xanthates: Safe Design, Operating and Maintenance Manual.** Available online: http://www.xanthate.com/ [Accessed 8 June 2016]

Fu, F., Wang, G., 2011. **Removal of heavy metal ions from wastewaters: A review.** Journal of Environmental Management 92 (2011) 407-418.

Graupner, G., Kassahun, A., Rammlmair, D., Meima, J., A., Kock, D., Furche, M., Fiege A., Schippers, A., Melcher, F. 2007. **Formation of sequences of cemented layers and hardpans within sulfide-bearing mine tailings (mine district Freiberg, Germany).** Applied Geochemistry 22 (2007) 2486–2508.

Grosse, A., C., Dicinoski, G., W., Shaw, M., J., Haddad, P., R., 2003. **Leaching and recovery of gold using ammoniacal thiosulfate leach liquors (a review).** Hydrometallurgy 69 (2003) 1 –21.

Hilson, G., Monhemius, A., J. 2006. **Alternatives to Cyanide in the Gold Mining Industry: What Prospects for the Future?** Journal of Cleaner Production 14 (2006) 1158–1167.

Kauppila, P., Räisänen, M.L. & Myllyoja, S. 2011. **Best Environmental Practices in Metal Ore Mining.** Finnish Environment 29 en/2011.

Kauppila, P., Tornivaara, Al, Karlsson, T., Larkins, C., Punkkinen, H, Wahlström, M. [Online source]. Updated 24 September 2015. **Closure technologies / Wastes and waste facilities.** Available online: http://wiki.gtk.fi/web/mine-closedure/wiki/-/wiki/Wiki/Closure+technologies+%252F+Wastes+and+waste+facilities [Accessed 23 May 2016]

Kessler, M., Burchardt, E. 2015. **High Pressure Grinding Rolls – A Promising and Cost-Effective Technology of Ore Pretreatment in Mineral Processing**. Eurasian mining 1 (2015) 13-16.

Källs, J. [News article] 10 juni 2014. **Här renas gruvans vatten**. Available online: http://www.dt.se/dalarna/hedemora/har-renas-gruvans-vatten [Accessed 6 June 2016]

Laine-Ylijoki, J., Juvankoski, M., Kaartinen, T., Merta, E., Mroueh, U-M., Mäkinen, J., Niemeläinen, E., Punkkinen, H., Wahlström, M. [Online source] Updated 24 September 2015. **Determination of the acid neutralization capacity (ANC).** Available online: http://wiki.gtk.fi/web/mine-closedure/wiki/-/wiki/Wiki/Determination+of+the+acid+neutralization+capacity+%28ANC%29 [Accessed 23 May 2016]

Levay, G., Smart, R., Skinner, W., 2001. **The impact of water quality on flotation performance**. The Journal of The South African Institute of Mining and Metallurgy.

Liu, W., Moran, C., J., Vink, S. 2013 **A review of the effect of water quality on flotation**. Minerals Engineering 53 (2013) 91–100.

Loon, H., L., Madgwick, J. 1995. [Abstract] **The effect of xanthate floatation reagents on bacterial leaching of chalcopyrite by *Thiobacillus ferrooxidans***. Biotechnology Letters 17 (1995) 997-1000. Available online: http://link.springer.com/article/10.1007%2FBF00127442

Lottermoser, B., G., Ashley, P., M., 2006. **Mobility and retention of trace elements in hardpan-cemented cassiterite tailings, north Queensland, Australia.** Environmental Geology 50 (2006) 835–846.

McGregor, R., G., Blowes, D., W. 2002. **The physical, chemical and mineralogical properties of three cemented layers within sulfide-bearing mine tailings**. Journal of Geochemical Exploration 76 (2002) 195–207.

Mueller, S., [Presentation] 2014. **Strategi för hållbar vattenhantering inom gruvverksamhet -exempel Aitik**, SveMins Miljökonferens 2014. Available online: http://www.svemin.se/material/presentationer-pa-konferenser/svemins_miljokonferens_2014 [Accessed 3 June 2016]

Muzenda, E., 2010. **An Investigation into the Effect of Water Quality on Flotation Performance**. World Academy of Science, Engineering and Technology 69 (2010).

Natural Resources Canada [Online source]. Updated 20 November 2015. **Thematic maps: Average Annual Potential Evapotranspiration.** Available online: http://ftp2.cits.rncan.gc.ca/pub/geott/atlas/archives/english/4thedition/environment/climate/049_50.jpg [Accessed 23 May 2016]

Natural Resources Canada [Online source]. 2009. **Thematic maps: Annual Mean Total Precipitation.** Available online: http://www.nrcan.gc.ca/earth-sciences/geography/atlas-canada/selected-thematic-maps/16888 [Accessed 23 May 2016]

Niemistö, M., Neitola, R., 2015. **6 KAIVOSTEN PROSESSITEKNOLOGIAN KEHITYS**, In publication: Kivinen, M., Aumo, R., Report of Investigation 221, Kaivostoiminta ja malminetsintä Suomessa: Teollisuuden tukijalasta verkostoyhteiskunnan osaksi 2015, Geological Survey of Finland, Espoo.

Opasnet.fi [Online source]. Updated 22 March 2013. **Rikastusprosessit.** Available online: http://fi.opasnet.org/fi/Rikastusprosessit [Accessed 27 May 2016]

Outotec [Online source]. 2016. **Outotec® Paste Solutions.** Available online: http://www.outotec.com/en/Products--services/Tailings-treatment/Paste-solutions/#tabid-5 [Accessed 20 June 2016]

Pacholewska, M., Cwalina, B., Steindor, K. 2008. **The Influence of Flotation Reagents on Sulfur-oxidixing Bacteria Acidithiobacillus Thiooxidans.** Physicochemical Problems of Mineral Processing 42 (2008) 37-46.

Punkkinen, H., [Online source] 23 September 2015. **Waste management for mine closure – Aitik Cu mine, Sweden**. Available at: http://wiki.gtk.fi/web/mine-closedure/wiki/-/wiki/Wiki/Aitik+mine%2C%20Sweden [Accessed 3 June 2016]

Punkkinen, H., Räsänen, L., Mroueh, U-M., Korkealaakso, J., Luoma, S., Kaipainen, T., Backnäs, S., Turunen, K., Hentinen, K., Pasanen, A., Kauppi, S., Vehviläinen, B., Krogerus, K. 2016. **Guidelines for Mine Water Management,** VTT Technology 266, ISBN 978-951-38-8443-7.

Punkkinen, H., Karlsson, T., Juvankoski, M., Kaartinen, T., Laine-Ylijoki, J., Merta, E., Mroueh, U-M., Mäkinen, J., Nieméläinen, Em., Wahlström, M. [Online source] Updated 24 September 2015. **Acid generation potential.** Available online: http://wiki.gtk.fi/web/mine-closedure/wiki/-/wiki/Wiki/Acid+generation+potential [Accessed 23 May 2016].

Regional State Administrative Agency of Eastern Finland [Decision for Environmental Permit]. 3 July 2014. **Luikonlahden kaivoksen ja rikastamon ympäristöluvan muutos ja toiminnan aloittamislupa, Kaavi,** permit number 52/2014/1. Decision reference number ISAVI/86/04.08/2012.

Regional State Administrative Agency of Eastern Finland [Decision for Environmental Permit]. 27 April 2015. **Pampalon kaivoksen ja rikastamon ympäristölupa ja toiminnan**

aloituslupa, Ilomantsi, permit number 22/2015/1. Decision reference number ISAVI/18/04.08/2012.

Regional State Administrative Agency of Northern Finland [Decision for Environmental Permit]. 27 December 2010. **Kemin kromiittikaivoksen ja rikastamon ympäristö- ja vesitalouslupa sekä toiminnan aloittamislupa, Keminmaa**, permit number 125/10/1. Decision reference number PSAVI/121/04.08/2010.

Regional State Administrative Agency of Northern Finland [Decision for Environmental Permit]. 13 August 2010. **Hituran kaivoksen ympäristö- ja vesitalouslupa sekä toiminnanaloittamislupa, Nivala,** permit number 66/2010/1. Decision reference number PSAVI/3/04.08/2010.

Regional State Administrative Agency of Northern Finland [Decision for Environmental Permit]. 26 June 2013. **Kittilän kaivoksen toiminnan laajentaminen ja ympäristö- ja vesitalousluvan tarkistaminen, Kittilä,** permit number 72/2013/1. Decision reference number PSAVI/100/04.08/2011.

Regional State Administrative Agency of Northern Finland [Decision for Environmental Permit]. 31 May 2013. **Talvivaaran kaivoksen ympäristöluvan muuttaminen koskien jätevesien varastointia, puhdistamista ja johtamista Oulujoen ja Vuoksen vesistöihin, Kajaani ja Sotkamo,** permit number 52/2013/1. Decision reference number PSAVI/12/04.08/2013.

Regional State Administrative Agency of Northern Finland [Decision for Environmental Permit]. 11 July 2014. **Kevitsan kaivoksen tuotannon laajentamisen ympäristö- ja vesitalouslupa sekä töiden ja toiminnan aloittamislupa, Sodankylä,** permit number 79/2014/1. Decision reference number PSAVI/144/04.08/2011.

Regional State Administrative Agency of Northern Finland [Decision for Environmental Permit]. 24 April 2015. **Purkuputken rakentaminen ja puhdistettujen jätevesien johtaminen Talvi-vaaran kaivosalueelta Nuasjärveen sekä nykyisien purkupisteiden kautta Kalliojokeen johdettavan puhdistetun veden määrän tilapäinen lisääminen vuoden 2015 aikana, Sotkamo,** permit number 43/2015/1. Decision reference number PSAVI/2960/2014.

Regional State Administrative Agency of Northern Finland [Decision for Environmental Permit]. 7 January 2016. **Laiva-kaivoksen ympäristölupien nro 84/09/2 ja nro 54/12/1 muuttaminen Perämereen johdettavien vesien määrän ja laadun osalta sekä**

toiminnanaloittamislupa, Raahe, permit number 4/2016/1. Decision reference number PSAVI/34/04.08/2013

Regional State Administrative Agency of Northern Finland [Announcement of an Environmental Permit Application]. 7 March 2016. **Talvivaaran kaivoksen keskitetyn vedenpuhdistamon ympäristölupa ja toiminnanaloittamislupa, Sotkamo**. Announcement reference number PSAVI/702/2016.

Regional State Administrative Agency of Northern Finland [Environmental Permit Decision]. 17 March 2016. **Kemin kaivoksen rikastushiekka- ja selkeytysaltaiden typpiselvitys, Keminmaa**, permit number 39/2016/1. Decision reference number PSAVI/3880/2014.

Regional State Administrative Agency of Northern Finland [Decision for Environmental Permit]. 17 June 2016. **Laivakankaan kaivoksen ympäristöluvan muuttaminen koskien rikastus-hiekan A varastoaluetta ja toiminnan aloittamislupa, Raahe**, permit number 76/2016/1. Decision reference number PSAVI/126/04.08/2013.

Regional State Administrative Agency of Western Finland [Decision by the Environmental Permit Authority]. 24 June 2014. **Dragon Mining Oy Vammalan rikastamon ympäristölupa, olennainen muutos ja lupamääräysten tarkistaminen, Sastamala (Asia 1). Ympäristölupapäätöksen nro 15/2008/2 lupamääräyksen 3 mukainen selvitys rikastushiekka-altaan aiheuttamasta sulfaatti- ja nikkelikuormituksesta Kovero-ojaan (Asia 2).** Number 124/2014. Decision reference numbers LSSAVI/96/04.08/2011; LSSAVI/373/04.08/2010.

The Regional Environmental Permit Agency of Northern Finland [Decision for Environmental Permit]. 29 March 2007. **Talvivaaran kaivoksen ympäristö- ja vesitalouslupa, Sotkamo ja Kajaani**, permit number 33/07/01. Decision reference number PSY-2006-Y-47.

The Regional Environmental Permit Agency of Northern Finland [Decision for Environmental Permit]. 18 September 2007. **Pyhäsalmen kaivoksen ympäristö- ja vesitalouslupa, Pyhäjärvi**, permit number 85/07/02. Decision reference number Psy-2004-y-199.

The Regional Environmental Permit Agency of Northern Finland [Decision for Environmental Permit]. 24 November 2009. **Laivakankaan kaivoksen ympäristö- ja vesitalouslupa sekä töiden- ja toiminnanaloittamislupa, Raahe,** permit number 84/09/2. Decision reference number Psy-2007-y-160.

Rodriquez, R., T., Rubio, J. 2007. [Abstract] **DAF-Dissolved Air Flotation: Potential Applications in the Mining and Mineral Processing Industry**. International Journal of Mineral Processing 82 (2007) 1-13.

Sihvonen, T., 2012. **Determination of collector chemicals from flotation process waters using capillary electrophoresis**. Master's Thesis, LAPPEENRANNAN TEKNILLINEN YLIOPISTO, Faculty of Technology, LUT Kemia.

SMHI - Swedish Meteorological and Hydrological Institute [Online source]. Updated 23 April 2014. **Normalt största snödjup under vintern, medelvärde**. Available online: http://www.smhi.se/klimatdata/meteorologi/sno/normalt-storsta-snodjup-under-vintern-medelvarde-1.7931 [Accessed 23 May 2016]

SRK Consulting, 25 February 2013. **Independent Technical Report for the Caribou Massive Sulphide Project, Bathurst New Brunswick, Canada.** Report Prepared for Trevali Mining Corporation. Available online: http://www.trevali.com/s/Caribou.asp [Accessed 3 June 2016]

SRK Consulting, 25 June 2014. **Technical Report on Preliminary Economic Assessment for the Caribou Massive Sulphide Zinc-Lead-Silver Project, Bathurst, New Brunswick, Canada.** Report Prepared for Trevali Mining Corporation. Available online: http://www.trevali.com/s/Caribou.asp [Accessed 3 June 2016]

Stantec Consulting, 13 February 2015. **Environmental Impact Assessment (EIA) Registration: Caribou Mine Copper Circuit**.

Talvivaara Mining Company, 3 July 2016. **Vesienhallintasuunnitelma**. Available online: https://www.avi.fi/web/avi/ymparistoluvat-vireilla-pohjois-suomi-talvivaara-sotkamo?p_p_id=122_INSTANCE_aluevalinta&p_p_lifecycle=0&p_p_state=normal&p_p_mode=view&p_r_p_564233524_resetCur=true&p_r_p_564233524_categoryId=14251#.V0_a7uSlMyM [Accessed 2 June 2016]

Terrafame [Online source]. No date. **Water Purification.** Available online: http://www.terrafame.fi/en/environment/environment-water-management/water-purification.html [Accessed 24 May 2016]

Terrafame, 2016, A. [Press release]. **Terrafamen kaivokselle uusi vesienhallinnan suunnitelma – mahdollisuus merkittäviin hyötyihin**. 16 June 2016. Available online: http://www.terrafame.fi/kaivoksella-tapahtuu/uutiset/2016/06/terrafamen-kaivokselle-uusi-vesienhallinnan-suunnitelma-mahdollisuus-merkittaviin-hyotyihin.html [Accessed 22 June 2016]

Terrafame, 2016, B. [Presentation snapshot]. Presentation 16 June 2016.

Tornivaara, A. [Online source]. Updated 24 September 2015. Basal structures of waste facilities. Available online: http://wiki.gtk.fi/web/mine-closedure/wiki/-/wiki/Wiki/Basal+structures+of+waste+facilities [Accessed 23 May 2016]

Trevali Mining Corporation [Website]. No date. **Caribou Mine & Mill.** Available online: http://www.trevali.com/s/Caribou.asp [Accessed 3 June 2016]

TUKES, Penttinen, H., Ijäs, A. [Report by the Finnish Safety and Chemicals Agency] 19 June 2012. **Talvivaara Sotkamo Oy:n tehdasalueella 15.3.2012 sattunut kuolemantapaus.** Document reference number 2007/06/2012.

Veolia [Brochure] No date. **Garpenberg, mining treatment plant, Sweden**. [Accessed 6 June 2016]

Working group: Geological Survey of Finland: Raisa Neitola, Antti Pasanen, Antti Taskinen, Krista Pussinen, Kaisa Turunen; University of Eastern Finland: Mika Raatikainen; Teollisuustaito Oy: Annika Hämäläinen. 2016.