Literature review, PuMi task 1: Water Recycling in the Mining Industry

Päivi Kinnunen 9.9.2013

Table of Contents

1. Introduction

Water has always been a critical element for any mining project. Significant amounts of water are needed in mining, especially in the extraction and processing stages (Miranda and Sauer 2010). Water is also used in grinding, screening, dust scrubbing, washing, dust suppression, pump gland seal and reagent mixing (Gunson et al. 2012). On a global basis, the water usage of mining industry is relatively insignificant. However, on the local basis mining operations generally are the highest consumers of water in the immediate area. Many processes have been designed at a time, when water has been readily available and environmental regulations more relaxed. However, the current interest of mining industry is to take care of the water issues in a sustainable way, so that the issues don't jeopardise gaining the social licence to operate. (Mining, People and the Environment, 2013) Reuse, reduced consumption and desalination of mine water has the potential to increase the public acceptance of mining (Rubio 2012) and often at least some water is reused and recycled (Gunson et al. 2012). If water resources become unavailable, it can lead to work stoppages or even mine shut downs. Environmentally beneficial water recycling and reuse projects can also return a significant economic benefit. For example, Queensland Nickel's nickel refinery at Yabulu has saved considerable amounts of water by water reuse with simultaneous increase in nickel recoveries. (Minerals Council of Australia 2006)

The requirements of process water are highly dependent on specific industry applications. Every mine site is specific in terms of ore type, gangue material, plant situation, water quality etc. Water quality may have significant impact on the performance of separate unit processes and the whole process chain. Therefore, water recycling and reuse needs to be assessed individually case-by-case. Water of lower quality has also a value. It is often possible to replace fresh water with poorer quality water in the minerals industry and to recycle more water. The effluent of one unit operation can be considered as feed or makeup solution for another unit operation. Fit for purpose water concept means that the quality of water is matched to the requirements for the end use. Different end uses require different levels of treatment for recycled water. (Victoria University and CSIRO 2008) New cost-efficient water treatment technologies can be developed to obtain appropriate water quality for recycling. In addition, processes can be further developed to enable the use of lower quality water.

In this study, water usage in the metal mines and current effluent discharge regulations were assessed. Acceptable water qualities to individual operations were identified. The aim of the project was to define sufficient water qualities in the mining industry rather than determine the highest water quality possible. This information can be used in the selection of most cost-efficient water treatment methods for water recycling in the mining industry.

2. Water in the mining industry

Water has always been a critical element for any mining project. Approximately 1 % of total water consumption in USA and Canada and approximately 2 % in Australia was due to the mining industry (USGS 2013; Environment Canada 2013; Norgate and Lovel 2004). On the local basis mining operations generally are the highest consumers of water in the immediate area. For example, in Australia 95% of the water was sourced locally from surface and groundwater having significant local effects. (Norgate and Lovel 2004)

Grinding, flotation, gravity concentration, dense medium separation and hydrometallurgical processes consume substantial amounts of water (Norgate and Lovel 2004). Typical average water consumption values are shown in Tables 1-3. Mine and concentrator consume typically 0.4-

0.9 m^3 water/t ore. In addition, smelting with refining and leaching with SX/EW consume 5-13 and 3-30 m^3 water/t target metal, respectively. Flotation is used for concentrating the ore and it is one of the biggest water consuming unit processes (Table 2). Gold, platinum, diamonds, nickel and copper are associated with the highest water consumption due to their presence in low concentration in the ores. Mining operations often take place in countries with water scarce regions. Ore grades are declining globally resulting in higher water consumption per each unit of production. (Miranda and Sauer 2010) However, in Finland the recent challenge in many of the mines has been the excess of water in operations after heavy rains and melting of snow.

Table 1. Water consumption data derived from publicly-available literature representing typical average values (adapted from Norgate and Lovel 2004).

Metal	**Process**	**Stage**	**Water consumption**	
Copper	Smelting/converting & electrorefining	Mine & concentrator	0.37	m^3/t ore
		Smelting	7.8	m^3/t Cu
		Refining	0.6	m^3/t Cu
	Heap acid leaching & SX/EW	Mining & heap leaching	23.0	m^3/t Cu
		SX/EW	6.4	m^3/t Cu
Nickel	Flash furnace smelting & Sherritt-Gordon refining	Mine & concentrator	0.93	m^3/t ore
		Smelting	0.81	m^3/t conc
		Refining	7.16	m^3/t matte
	Pressure acid leaching & SX/EW	Total all stages	3.4	m^3/t ore
Lead	Blast furnace	Mine & concentrator	0.64	m^3/t ore
		Smelting	4.85	m^3/t Pb
		Refining	0.47	m^3/t Pb
	Imperial smelting process	Mine & concentrator	0.64	m^3/t ore
		Smelting	12.73	m^3/t Pb
		Refining	0.47	m^3/t Pb
Zinc	Imperial smelting process	Mine & concentrator	0.64	m^3/t ore
		Smelting	12.73	m^3/t Zn
		Refining	0.54	m^3/t Zn
	Electrolytic process	Mine & concentrator	0.64	m^3/t ore
		Electrolytic refining	12.33	m^3/t Zn

Table 2. Major water uses in a 50 000 tonne per day low grade copper deposit mine model (adapted from Gunson et al. 2012).

Major water users	**Flow (m^3/d)**	**Flow (% of total)**
Flotation process water (30% solids by mass)	115646	84.4
SAG mill cooling water	4100	3.0
Ball mill cooling water	4100	3.0
Compressor cooling water	4100	3.0
Road-dust suppression	3520	2.6
Froth wash water	2880	2.1
Pump GSW	1440	1.1
Reagent dilution water	720	0.5
Primary crusher dump pocket-dust suppression	358	0.3
Coarse ore stockpile-dust suppression	121	0.1
Mine/mill/office staff-domestic water	58.1	0

Table 3. Major ore flows in in a 50 000 tonne per day low grade copper deposit mine model (adapted from Gunson et al. 2012).

Process slurry flows	**Solids contents (tpd)**	**Solids content (%)**	**Water content (m^3/day)**
ROM → Comminution	50000	98	1020
Comminution → Flotation	50000	30	116667
Flotation concentrate → Concentrate dewatering	804	30	1875
Concentrate dewatering → Final concentrate	804	90	89
Flotation tailings → Tailings storage facility	49196	30	114792

Many water uses in the mines are insensitive to water quality and only a nominal water volume is crucial. However, water quality is a crucial operational issue in mineral processing operations such as flotation and agglomeration. Still, research efforts have been rather limited in understanding and controlling the influence of water quality on mineral processing. (Norgate and Lovel 2004) Recycled water can contain elements that are deleterious to the process performance. Technologies that are able to generate sufficient quality water at a reasonable cost are required. Traditionally, precipitation with lime and limestone has been most widely used water treatment process in the mining industry. Discharge regulations and the attempt to reduce the use of fresh water have resulted in the use of more expensive technologies such as reverse osmosis and ion-exchange based technologies. (Mining, People and the Environment 2013) Water savings can also be created by decreasing water losses and by utilizing dry ore upgrading technologies (Slatter et al. 2009).

3. Effluent discharge regulations

International effluent discharge standards applicable to metal mining operations are shown in Table 4. The limits for the Finnish metal mines were collected from their environmental permits into a separate excel-sheet, since the limits vary for each mine. In addition, water quality information from specific sources was collected into the same data sheet. Most stringent international limits are found in South Africa for copper, zinc, iron and total ammonia, in Chile for lead and selenium, in the U.S. for nickel, and in Canada for TSS. New stricter limits have been proposed for several elements in Canada.

High sulphate concentrations in the effluents have lately raised public concerns in Finland. International effluent discharge regulations related to sulphate are shown in Table 5. It is noteworthy, that the real concentrations of substances in the effluents are generally much lower than the limits in the environmental permits. For example, table 6 summarizes the measured effluent concentrations in the mines in Canada 2010, and the environmental discharge standards. These two values may differ significantly. Table 6 shows also the monthly variation of the effluent flow. Flows can vary significantly during the seasons affected by the amount of rain, melting of snow, evaporation etc.

Table 4. Effluent discharge standards applicable to metal mining operations. 1) Range of limits from environmental permits of metal mines in Finland (separate excel-sheet), the limits vary for each mine, 2) World Bank 1998, 3) Environment Canada 2012, 4) U.S. Code of Federal Regulations Title 40 part 440, discharge limits vary according to type of ore mined, mining technique and applicable treatment technology. MMER=Metal Mining Effluent Regulations, tbd=to be determined.

Parameter	**Unit**	**Finland[1] (single measurement in parenthesis)**	**World[2]**	**Canada MMER[3] (proposed new limit in parenthesis)**	**U.S.[4] (max for 1 day)**	**U.S.[4] (30 days average)**	**Most stringent international limit[3]**
Arsenic	mg/L	<0.5 - <1.0 (1.7) or no limit	0.1	0.5 (0.1)	1.0	0.5	0.1 (multiple)
Cadmium	mg/L		0.1		0.1	0.05	
Chromium (hexavalent)	mg/L	-	0.1				
Copper	mg/L	<0.2 - <0.5 (1.0) or no limit	0.5	0.3 (0.05)	0.30	0.15	0.02 (South Africa)
Cyanide	mg/L	0.4	1.0 0.1 free 0.5 WAD	1.0 (0.5)			0.5 (multiple)
Lead	mg/L	-	0.2	0.2 (0.05)	0.6	0.3	0.05 (Chile)
Mercury	mg/L	-	0.01		0.002	0.001	
Nickel	mg/L	<0.5 - <2.5 or no limit	0.5	0.5 (0.25)	0.2	0.1	0.1 (U.S)
Zinc	mg/L	<1.0 - <3.0 or no limit	2	0.5 (0.25)	1.0-1.5	0.5-0.75	0.3 (South Africa)
TSS	mg/L	<10 - <25	50	15.0 (15.00)	30-50	20-30	15.00 (Canada)
Oil and grease	mg/L		10				
Aluminium	mg/L	<3.0 or no limit		none (tbd)			1.0 (multiple)
Iron	mg/L	-	3.5	none (tbd)	2.0	1.0	0.3 (South Africa)
Selenium	mg/L			none (tbd)			0.01 (Chile)
Total metals	mg/L		10				
Total ammonia as Nitrogen	mg/L	-		none (tbd)		100 NH_3	1.0 (South Africa)
COD	mg/L		150		200	100-500	
Phosphorus	mg/L	-		no limit (no limit)			
Chloride	mg/L	-		no limit (no limit)			
pH		5.5-10	6-9	6.0-9.5 (no change)	6-9.1	6-9.1	

Table 5. Effluent discharge regulations in the world related to sulphates (Fleming and Radakovich 2011).

Country	Legal instrument	SO_4^{2-} (mg/L)	TDS (mg/L)	Conductivity (mS/m)
Chile	DS90	1000-2000		
	DS46			
	NCh1333	250-500		
Peru	DS-002-2008-MIN	300 (Cat 3)	500 (Cat 4)	
Ecuador	NCADE Lib VI, 1	1000	3000	
Brazil	Resolution 357	250 (Class 1)	500	
South Africa	Water Act 1998	-	-	70-150
Australia	ANZECC 2000/	1000	2400	

Table 6. Effluent concentrations in Canadian mines in 2010 (Environment Canada 2012). All units are mg/L except for flow in m^3/month, year 2010. 1)effluent treatment plant discharge, 2)phase 1 and 2 seepage collection ditch, 3)phase 3 seepage collection ditch, 4)Pike river discharge point, 5)Culvert, 6)Settling pond, 7)tailings pond 1. Grey background = over the regulatory limits.

Mine	Product	Parameters								
		As	Cu	CN	Pb	Ni	Zn	TSS	pH	Flow
MMER limit		**0.5**	**0.3**	**1.0**	**0.2**	**0.5**	**0.5**	**15**	**6-9.5**	**-**
Aurbel	Au	0.0462	0.0447	0.0270	0.0002	0.0060	0.0160	8.00	7.4	27.8
Barry	Au	0.0003-0.0011	0.0021-0.0126	0.0025-0.0330	0.0002-0.0020	0.0023-0.0093	0.0070-0.0350	0.50-2.80	7.0-8.2	582-13879
Beaufor	Au	0.0003-0.0016	0.0053-0.0128	NMR	0.0002-0.0038	0.0054-0.0127	0.0005-0.0220	1.88-5.50	6.9-9.0	14830-23715
Bell Creek1)	Au	0.0218	0.0141	0.0050	0.0003	0.0443	0.0010	3.00	7.3	8219
Bell Creek2)	Au	0.0229-0.1323	0.0054-0.0119	0.0105-0.0800	0.0002-0.0011	0.0093-0.0202	0.0047-0.0269	1.50-6.42	7.4-8.1	3902-17469
Bell Creek3)	Au	0.0289-0.0658	0.0067-0.0130	0.0070-0.0458	0.0003-0.0016	0.0124-0.0223	0.0080-0.5600	1.05-58.00	7.5-8.2	154-2936
Bellekeno	Ag-Pb-Zn	0.0043-0.0092	0.0008-0.0098	NMR	0.0297-0.1102	0.0056-0.0138	0.0268-0.1453	4.50-22.25	7.8-9.6	10695-13855
Birchtree	Ni-Cu	0.0164-0.0525	0.0050-0.0946	0.0025-0.0170	0.0150-0.0213	0.0208-0.0900	0.0050-0.0845	1.20-2.90	6.5-7.5	22967-53824
Black Fox4)	Au	0.0531-0.2022	0.0019-0.0100	NMR	0.0005-0.0007	0.0097-0.0896	0.0099-0.0513	0.40-4.38	7.2-8.3	6454-38096
Brunswick No. 12	Pb-Zn-Cu-Ag	0.0108-0.0350	0.0053-0.0191	NMR	0.0053-0.0225	0.0033-0.0125	0.0535-0.5325	2.10-5.40	8.7-9.5	359090-2248624
Bucko Lake	Ni	0.0003-0.0017	0.0005-0.0029	NMR	0.0001-0.0019	0.0206-0.2983	0.0023-0.0161	1.50-12.75	6.4-9.6	9167-33125
Campbell	Au	0.0255-0.0698	0.0063-0.0103	0.0455-0.1037	0.0001-0.0002	0.0557-0.1515	0.0064-0.0098	1.18-2.29	6.1-7.7	129101-508149
Cantung5)	W	0.0003-0.0009	0.0005-0.0011	NMR	0.0001	0.0005-0.0009	0.0009-0.0030	3.00-3.88	7.7-8.3	18994-95632
Cantung6)	W	0.0004-0.0009	0.0006-0.0026	NMR	0.0001-0.0002	0.0003-0.0008	0.0057-0.0183	3.00-3.47	7.9-8.4	3812-20236
Casa Berardi	Au	0.1800-0.2273	0.0220-00.241	0.0073-0.0173	0.0002-0.0009	0.0182-0.0457	0.0044-0.0123	2.14-2.88	6.8-7.6	273484-421896
Chisel North	Zn	0.0003-0.0006	0.0029-0.0062	NMR	0.0040-0.0053	0.0036-0.0570	0.1038-0.3463	1.03-7.44	6.4-9.4	49301-186801
Cigar Lake	U	0.0003-0.0009	0.0011-0.0032	NMR	0.0001-0.0003	0.0026-0.0059	0.0095-0.0330	0.69-3.33	6.6-8.1	22367-49418
Sorel-Tracy	Fe-Ti	0.0005-0.0025	0.0052-0.0520	NMR	0.0020-0.0693	0.0104-0.0430	0.0355-0.4350	4.85-106.25	7.0-9.3	3319230-4684759
Con Mine	Au	0.1949-0.3260	0.0028-0.0039	0.0224-0.0273	0.0003	0.0063-0.0255	0.0020	2.20-3.88	6.9-7.6	17302-202108

Copper Cliff Complex	Ni-Cu-Co-Pt	0.0010-0.0090	0.0050-0.1214	0.0010-0.0015	0.0150-0.0310	0.0575-0.4065	0.0050-0.0185	1.00-3.00	6.3-8.7	655718-4145351
Copper Rand	Cu-Au-Ag	0.0003-0.0062	0.0029-0.0153	0.0025-0.0130	0.0002-0.0018	0.0049-0.0117	0.0005-0.0030	0.50-3.88	7.0-8.1	1913-49245
Crean Hill	Ni-Cu-Co-Pt	0.0010-0.0330	0.0010-0.0265	NMR	0.0150	0.9855-0.3114	0.0050-0.0193	1.00-2.40	6.9-8.8	11186-120630
David Bell	Au	0.0014-0.0022	0.0024-0.0036	0.0021-0.0080	0.0005-0.0008	0.0028-0.0085	0.0195-0.0594	1.00-7.85	7.6-8.2	766-3415
Doyon	Au	0.0003-0.0130	0.0089-0.0942	0.0075-0.0805	0.0002-0.0003	0.0160-0.0576	0.0005-0.0120	1.38-6.50	6.3-9.2	20754-647461
Eagle River	Au	0.0002-0.0005	0.0007-0.0019	NMR	0.0001-0.0003	0.0008-0.0195	0.0013-0.0121	0.95-3.40	6.8-8.0	7053-30040
Endako Mines[7]	Mo	0.0003	0.0010-0.0045	0.0025-0.0198	0.0001	0.0013-0.0034	0.0025	2.00-3.82	7.7-8.3	120-75603
Garson Mine	Ni-Cu-Co-Pt	0.0010-0.0170	0.0010-0.0066	NMR	0.0150-0.0230	0.0382-0.1464	0.0050-0.0228	1.00-1.35	6.7-8.9	52140-101463
Géant Dormant	Au	0.0003	0.0003-0.0154	0.0110-0.0260	0.0002-0.0056	0.0003-0.0067	0.0655-0.1480	0.63-4.00	7.5-8.3	94203-132057
Giant Mine	Au	0.2467-0.3353	0.0130-0.0156	0.0040-0.0062	0.0001	0.0492-0.0515	0.0031-0.0071	0.70-0.93	7.5-8.0	114476-167297
Gibraltar Mine	Cu-Mo	0.0003-0.0004	0.0022-0.0036	NMR	0.0001	0.0006-0.0009	0.0035-0.0151	1.45-7.00	7.2-8.4	1831-406748
Golden Giant Mine	Au	0.0010-0.0021	0.0008-0.0048	0.0060-0.0790	0.0001-0.0002	0.0001-0.0144	0.0003-0.0104	1.00-8.98	6.7-7.6	1204-44557
Goldex	Au	0.0009-0.0032	0.0009-0.0019	NMR	0.0002-0.0022	0.0031-0.0035	0.0060-0.0104	2.00-8.50	7.1-7.5	78329-312288
Hislop Mine	Au	0.0005	0.0017-0.0022	0-0.0079	0.0005	0.0027-0.0039	0.0061-0.0118	3.19-4.71	7.0-7.8	5494-15080
Holloway Mine	Au	0.0030	0.0080-0.0085	0.0063-0.0080	0.0005	0.0275-0.0300	0.0011-0.0038	0.86-1.40	7.0-7.6	361860-903840
Kiena Mine	Au	0.0003-0.2437	0.0090-0.0420	0.0024-0.0220	0.0002-0.0039	0.0398-0.1000	0.0061-0.0160	2.00-7.50	7.5-8.1	931-106271
Lac des Iles Mine	Pd-Pt-Au-Cu-Ni-Co	0.0001-0.0009	0.0001-0.0017	NMR	0.0001	0.0065-0.0143	0.0003-0.0014	3.60-10.37	7.7-8.1	37594-124982
Lac Herbin Mine	Au	0.0003-0.0045	0.0019-0.0057	NMR	0.0002-0.0003	0.0016-0.0051	0.0010-0.0500	2.00-7.00	6.9-8.2	19655-28925
Langlois Mine	Zn-Cu-Au-Ag	0.0003-0.0031	0.0017-0.0113	NMR	0.0002-0.0034	0.0014-0.0059	0.1380-0.5040	0.88-2.63	6.9-7.9	41292-175530
Laronde Mine	Au-Ag-Cu-Zn	0.0003-0.0052	0.0256-0.0455	0.0159-0.3323	0.0002-0.0025	0.0219-0.0752	0.0039-0.0414	5.20-10.00	6.8-7.8	54125-276810
Lockerby Mine	Cu-Ni-Co	0.0015-0.0042	0.0044-0.0087	NMR	0.0005-0.0023	0.0317-0.0740	0.0007-0.0074	0.58-3.62	6.8-7.9	20338-37864
Macassa Mine	Au	0.0006-0.0015	0.0053-0.0282	0.0020-0.1781	0.0005	0.0042-0.0085	0.0020-0.0100	0.50-4.75	7.8-8.4	56825-343826
Matagami Mine	Zn-Cu	0.0003-0.0087	0.0004-0.0060	NMR	0.0002-0.0126	0.0029-0.0118	0.0010-0.2108	1.00-21.60	7.2-9.5	386511-1990246
McWatters Mine	Ni	0.0005-0.0025	0.0009-0.0054	NMR	0.0005-0.0008	0.0071-0.1430	0.0008-0.2604	0.96-17.61	7.9-8.8	4498-16321
Meadowbank Mine	Au	0.0003-0.0107	0.0009-0.0031	0.0025-0.0179	0.0002-0.0057	0.0015-0.0096	0.0012-0.0117	2.50-22.00	5.9-7.8	147029-1104674
Mouska Mine	Au	0.0003-0.0098	0.0080-0.0285	NMR	0.0002-0.0074	0.0050-0.0107	0.0030-0.0110	1.13-4.28	7.6-8.3	77473-98398
Musselwhite Mine	Au	0.0020-0.0049	0.0019-0.0041	0.0038-0.0094	0.0001	0.0030-0.0050	0.0014-0.0092	1.08-3.75	6.5-7.3	317930-511076
Niobec Mine	Nb	0.0005-0.0220	0.0020-0.0100	NMR	0.0005-0.0030	0.0005-0.0240	0.0070-0.0290	7.00-36.00	7.2-8.3	120-519211
Podolsky Mine	Cu-Ni-Pd-Pt-Au	0.0008-0.0025	0.0048-0.0109	NMR	0.0005-0.0008	0.0832-0.4644	0.0059-0.0391	0.01-2.28	6.2-7.8	1659-21464
Restone Mine	Ni	0.0011-0.0032	0.0018-0.0041	NMR	0.0005-0.0008	0.1353-0.4275	0.0011-0.0047	1.06-4.36	7.6-8.7	3734-18839
Rice Lake Gold Mine	Au	0.0013-0.0015	0.0644-0.3730	0.0093-0.0696	0.0002-0.0006	0.0033-0.0136	0.0025	8.00-13.00	8.2-8.4	21531-272909

4. Water quality and recycling

Recirculation of process water and changes in production can have considerable effects on the water quality. The increase of production as well as recirculation of process water has increased elemental concentrations in the process water at mine sites. All additives and chemicals in contact with process water affect the process water quality over the entire process chain, when a significant part of the process water is recirculated. (Westerstrand and Öhlander 2011) The appropriate points to recycle water should be properly identified. For example, introduction of high alkalinity water into an acid circuit is inefficient. (Slatter et al. 2009)

There are several challenges associated with water recycling in the mineral processing unit operations. The concentrations of dissolved and colloidal species in recycled water can change when different dams or sections of the dam are used. In addition water evaporation has effect on seasonal water balances. (Levay et al. 2001) Since metallurgical processes are sensitive to variations in water quality, the quality fluctuations should be minimized (Slatter et al. 2009).

Water quality has also influence on waste residues, which is considered as an important factor in the industry. In the studies of Whittington et al. (2003) the use of saline process water in the pressure acid leaching of nickel-laterite ore resulted in the increased formation of jarosite precipitates. Formation of alunite/jarosite generates more residue than the formation of hematite (Whittington et al. 2003).

Material selection for the processing equipment has a significant impact on capital costs of the plant. Material selection is important especially, when sea water or recycled process water is used in the plant. Table 7 shows the limits for sulphate and chloride on particular metals to control corrosion.

Table 7. Limits for sulphate and chloride on particular metals to control corrosion (Victoria University and CSIRO 2008).

Parameter	Metal	Limit (mg/L)
Cl^-	General	1500
	Copper	750
	316 Stainless Steel	1000
	304 Stainless Steel	200
SO_4^{2-}	General	2500
	Copper	1200

In this chapter, the water quality requirements in specific uses in mineral processing have been studied.

4.1 Cooling

Most mines use water as their primary cooling medium. Cooling water consumption can be approximately 10% of the total water consumption in the mine (Table 2), but the amount is site specific. Cooled water is used in a number of locations in the mines. All operational machinery needs to be sufficiently cooled. Especially in the deep underground mining the temperature can rise due to underground ambient conditions or heat produced by operational machinery. Cooling towers are used in processing applications that require efficient direct cooling. These processes include for example gypsum removal and copper solvent extraction. Manufacturer recommendations for water quality in cooling towers are shown in Table 8.

Table 8. Cooling tower manufacturer recommendations for water quality (adapted from Victoria University and CSIRO 2008).

Parameter	**Unit**	**Superchill**	**Marley**	**BAC**	**EVAPCO**
pH		7-8.3	6.5-9	7-9	6.5-8.0
Chloride	mg/L	300 50 (austenitic)	455 (galvanised) 910 (stainless)	125	200 (galvanised) 400 (stainless)
Sulphates	mg/L	500	800	125	-
Iron	mg/L	0.3	-	-	-
TDS	mg/L	2000	5000	1000	10000
TSS	mg/L	50	-	-	-
Conductivity	µS/cm	1200	-	-	-
Alkalinity	mg/L $CaCO_3$	80-400	100-500	500	50-300
Nitrites	mg/L	200-700	-	-	-
Silica	mg/L	-	150	-	-
Ammonia	mg/L	-	10-25	-	-
Chlorine	mg/L	-	0.4 continuous 1 shock	-	-
Nitrates	mg/L	-	300	-	-

4.2 Boilers

Recycled water treated to an MF/RO quality has been successfully used for boiler feed in a number of operations worldwide (Victoria University and CSIRO 2008). The consensus view is that oxygen, iron and copper concentrations should be very low and pH maintained between 8.5 and 9.5 for system corrosion protection. For example, for a 900 psig boiler, the feed water should contain less than 9 ppb oxygen, 20 ppb iron and 15 ppb copper. Calcium, magnesium, iron, copper, aluminium, silica and silt and oil can form deposits in the boilers. Generally MF/RO treatment for the feed water is a minimum. (GE Water 2013) The potential for foaming may be the only difference between recycled water and potable water in boilers. Low pressure boilers may be able to utilize the MF/RO water even without pre-treatment. (Victoria University and CSIRO 2008) The American Boiler Manufacturers' Association's water quality limits for boilers are shown in Table 9.

Table 9. The American Boiler Manufacturers' Association's water quality limits for boilers (GE Water 2013). 1) measured before oxygen scavenger addition, 2) without neutralization

DRUM OPERATING PRESSURE								
MPa	0-2.07	2.08-3.10	3.11-4.14	4.15-5.17	5.18-6.21	6.22-6.89	6.90-10.34	10.35-13.79
psig	0-300	301-450	451-600	601-750	751-900	901-1000	1001-1500	1501-2000
FEEDWATER								
Dissolved oxygen[1] (mg/L)	<0.040	<0.040	<0.007	<0.007	<0.007	<0.007	<0.007	<0.007
Total Fe (mg/L)	0.100	0.050	0.030	0.025	0.020	0.020	0.010	0.010
Total Cu (mg/L)	0.050	0.025	0.020	0.020	0.015	0.015	0.010	0.010
Total hardness (mg/L $CaCO_3$)	0.300	0.300	0.200	0.200	0.100	0.100	not detectable	
pH (25 °C)	7.5-10.0	7.5-10.0	7.5-10.0	7.5-10.0	7.5-10.0	8.5-9.5	9.0-9.6	9.0-9.6
Chemicals for preboiler system protection	use only volatile alkaline materials							
Nonvolatile TOC (mg/L C)	<1	<1	<0.5	<0.5	<0.5	as low as possible, <0.2		
Oily matter (mg/L)	<1	<1	<0.5	<0.5	<0.5	as low as possible, <0.2		
BOILER WATER								
Silica (mg/L SiO_2)	150	90	40	30	20	8	2	1
Total alkalinity (mg/L $CaCO_3$)	350	300	250	200	150	100	not detectable	
Free hydroxide alkalinity (mg/L $CaCO_3$)	not specified						not detectable	
Specific conductance[2] (µS/cm)	3500	3000	2500	2000	1500	1000	150	100

4.3 Flotation

Flotation has typically a solids density of 25-35% by mass. If water is not recycled or reused at all, flotation would thus require 1.9-3.0 m^3 water per each ton of ore processed. (Gunson et al. 2012) Flotation is one of the biggest water consuming unit processes in the mining and mineral processing chain (Table 2). For example, the total water consumption in the Minera Esperanza mine in Chile is approximately 630 L/s and the major part of the water (approximately 600 L/s) is used in the concentrator plant (ICMM 2012). Therefore, there is increasing need to recycle water from tailings dams and classification ponds (external recycle waters), thickener overflows, dewatered and filter products (internal recycle waters) (Levay et al. 2001; Muzenda 2010). Recycling of water within the flotation can be advantageous, since 1) the need to receive new water into the system is lowered, 2) the amount of discharged water is decreased, and 3) reagent consumption is decreased due to retention of some reagents (Slatter et al. 2009). However, process water contains several chemical compounds, which has raised concerns about the use of recycled process water in flotation.

Process water chemistry can have a critical impact on flotation efficiency. Ca^{2+} and SO_4^{2-} ions are typical components in the process water from flotation of sulphide minerals originating from the ore and flotation reagents (Ikumapayi et al. 2012). Minor species include reduced sulphur compounds such as SO_3^{2-}, $S_2O_3^{2-}$, $S_2O_5^{2-}$ and $S_4O_6^{2-}$, cations of ferrous and non-ferrous metals, anions of different compounds often of polymeric nature, frothing molecules, residual chemical reagents and products of their degradation (Ikumapayi 2013). Tables 10 and 11 show possible effects of the most important ions of concern, and typical flotation reagents in flotation, respectively. Organic compounds released from residual reagents in water, and dissolved inorganic species may alter water quality and flotation kinetics (Haran et al. 2008). In internal water recycling suspended solids levels tend to be high having a negative impact on flotation (Muzenda 2010). Some constituents have more effect on flotation than others. For example, sulphate tends to have a more negative effect on flotation than chloride. (Slatter et al. 2009) Bacteria-laden water, such as treated effluent, can have effect on flotation efficiency through microbiological activities (Liu et al. 2013). Precipitates such as calcium sulphate, magnesium carbonate, iron hydroxide and silica are the main contributions to the mineral surface contamination in many recycle streams (Muzenda 2010). When controlling the components in the process water properly, it is possible to recycle process water in the flotation circuit (Ikumapayi 2013).

Table 10. The effect of different components on selective flotation. (Rao and Finch 1989; Victoria University and CSIRO 2008; Muzenda 2010)

Component	**Effect**
Cu^{2+}, Fe^{2+}, Pb^{2+}	Undesired activation/flotation of sulphide minerals
S^{2-}	Undesired depression of sulphide minerals
Alkaline earth ions (Mg^{2+}, Ca^{2+} etc.)	Activation of the non-sulphide gangue, variation in the slurry pH and pulp potential, lower grade of sulphide concentrate obtained, lower recovery of oxides
Primary amines	High adsorption at fine particles causes slime flotation
Residual xanthates and their oxidation products	Selective absorbtion on most sulphides

Table 11. Typical flotation reagents and their consumptions (Lakefield and SENES 2002).

Use	Reagent	Purpose	Typical Consumption (kg/ton ore)
Copper flotation	AP3418A	Cu collector	0.040
	MIBC (methyl isobutyl carbonyl)	frother	0.035
Copper-molybdenum concentrator	Lime	pH modifier	0.295
	Dowfroth 250	frother	0.007
	Pine oil	frother	0.007
	Potassium Amyl Xanthate (PAX)	Cu-Mo collector	0.016
	Fuel oil	Mo collector	-
	Sodium hydrogen sulphide	Cu depressant	6.63 (kg/t concentrate)
Copper-nickel flotation	Potassium isobutyl xanthate	Cu-Ni collector	0.11
	Dow Froth 250C	frother	0.06
	CuSO4 (copper sulphate)	Ni activator	0.04
	NaCN (sodium cyanide)	Ni depressant	0.003
	Lime	pH modifier	1.6
	Percol	flocculant	0.002
	H2SO4 (sulphuric acid)	pH modifier	0.25
Copper-zinc flotation	Sodium isopropyl xanthate (SIX)	Cu-Zn collector	0.05
	MIBC	frother	0.03
	Na2SO3 (sodium sulphite)	Zn depressant	0.72
	CuSO4	Zn activator	0.93
	Lime	pH modifier	2.00
	Percol	flocculant	0.008
Copper-lead-zinc flotation	SIX	Cu-Pb-Zn collector	0.170
	PAX	Cu-Pb-Zn collector	0.042
	Soda ash	Cu-Pb pH modifier	2.5
	CuSO4	Zn activator	0.75
	Lime	Zn pH modifier	1.0
	Aerofloat 241	Pb collector	0.020
	Aero 3894	Cu collector	0.005
	Percol 351	flocculant	0.005
	SO2 (sulphur dioxide)	pyrite depressant	0.9
Lead-zinc flotation	SIX	Pb-Zn collector	0.97
	ZnSO4 (zinc sulphate)	Zn depressant	0.075
	NaCN	Zn depressant	0.040
	CuSO4	Zn activator	0.30
	MIBC	frother	0.014
	Percol	flocculant	0.012

The maintenance of consistent circuit water quality and elimination of short-term variation is essential in obtaining better flotation process performance. Uncontrolled variation in the concentrations, pH and Eh can result in losses of recovery, grade and separation efficiency, and in contamination of products. Surface coatings on value minerals, competitive adsorption of activators and reagents with other species, loss of reagents due to precipitation, overcoating and inadvertent reaction can cause losses of recovery. Non-selective coatings on both value minerals and gangue, ineffective separation of gangue minerals and ineffective activation can cause losses of grade. (Levay et al. 2001) However, in most of the cases where water quality has been found to affect flotation process, the precise reason for the effect has remained unknown (Muzenda 2010).

Flotation recovery of copper was increased by 4% in one processing plant, when the water supply was stabilized using different combinations of recycle streams. One recycle stream was completely removed from recycle since it contributed to the majority of precipitation and interference on the surface layers. (Levay et al. 2001) Muzenda (2010) recommended the use of a combination of process water and potable water in flotation circuits to balance their separate effects on flotation performance.

Tailings water treatment and recycling back to the flotation process is a common practice in mineral flotation plants. Recycling of process water tends to be more appropriate for the plants producing only one concentrate. When more than one concentrate is produced, recycled water has to be matched to the particular concentrate or be treated, so that deleterious reagents are not supplied into the other concentrate’s water supply. (Slatter et al. 2009) The effects of specific process water on flotation need to be evaluated case-by-case. Dissolved ions and flotation chemical additives can start to accumulate into the recycled water having either positive or negative effect on the process. Zinc ions in the recycle water are beneficial for selective separation of galena from sphalerite in the lead-zinc flotation separation. Calcium and sulphate ions in the process water can cause scaling problems and affect the mineral flotation separation. Process water with the recycle water from the tailings treatment can be saturated or supersaturated with gypsum and contain 800 ppm and 2800 ppm calcium and sulphate ions, respectively. Gypsum in recycle water affected the interactions between flotation reagents and sphalerite, and decreased flotation recovery. (Deng et al. 2013) However, calcium and thiosulphate ions were shown to have a positive effect on flotation in the study of Kirjavainen et al. (2002) by improving the flotability of sulphides after grinding in steel mill. Calcium was shown to activate especially nickel and copper sulphides, and thiosulphate reduced the effect of hydrophilic compounds on sulphide particles improving simultaneously flotation (Kirjavainen et al. 2002).

In the studies of Xu et al. (2012) the zinc concentrate water, zinc tailing water and effluent (see also Table 19) had negative effects on flotation of galena compared to distilled water, whereas lead concentrate water had a positive effect on flotation performance. Muzenda (2010) studied the effect of various recirculating mineral processing wastewater into flotation of platinum group metals flotation (Table 12, Figure 1). The results indicated higher recovery and increased mass pull with the potable water compared to recirculated waters, but also a lower concentrate grade. The presence of dissolved solids resulted in reduced recoveries but better concentrate grades. (Muzenda 2010) Chalcopyrite, galena and sphalerite minerals recoveries were better in process water than tap water in the studies of Ikumapayi (2013), which showed that process water could be recycled in flotation with no significant effect on grade and recovery of sulphide minerals. It was assumed that one of the reasons was the presence of rest reagents and high metal ions, which enhanced collector adsorption to xanthate. On the other hand, the use of process water in the flotation of galena indicated detrimental effects on the flotation process in the studies of Ikumapayi et al. (2012).

Table 12. Amandelbult concentrator recirculating mineral processing wastewater (adapted from Muzenda 2010).

Type of water sample	**pH**	**TDS (ppm)**	**Conductivity (uS/cm)**	**TSS (ppm)**	**Flotation recovery (%)**
Potable water	7.1	0	100	0	86.06
High rate thickener	9.91	2200	3200	70	68.8
Thickener #2	7.16	2200	3200	62	68.91
UG2 #1 Thickener	7.15	200	2700	59.5	48.65
Merensky thickener	7.17	1900	2800	129	66.74
Cloudy dam	7.5	2300	2700	44.5	64.21
Thickener #1	7.08	2400	2900	13	64.75
Return water	7.82	2400	3400	30	67.02
Sewage effluent	7.34	1200	1600	23	65.34

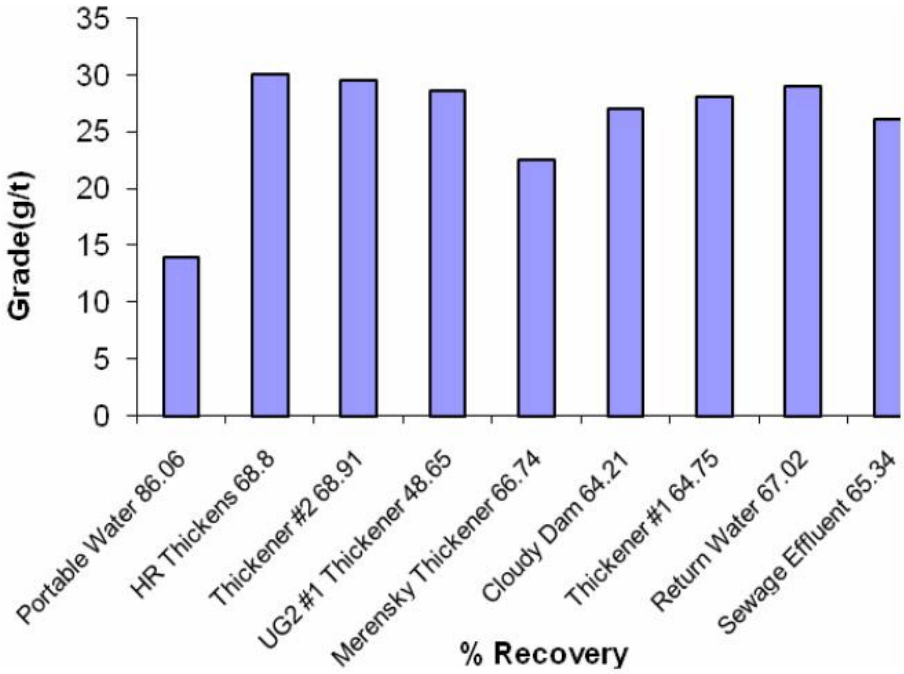


Figure 1. Grade versus recovery in flotation of PGMs with different waters (Muzenda 2010).

The work at Anglo Platinum plants since 1999 indicates that waters from thickener overflows and return dams have little negative effect on flotation and they can be used without further treatment. When thickeners don’t operate optimally, the suspended solid loading would increase having an impact on the reagent consumption of flotation. With return dam water the problems are likely organic in nature and they are produced from the degradation of different organic substances. (Slatter et al. 2009)

The only water available in some mines in Chile is seawater. For example, Minera Esperanza mine uses untreated seawater for flotation. Desalination plant using reverse osmosis is used to provide water for concentrate washing and cooling. (ICMM 2012) Washing is usually necessary to prevent corrosion problems later on during smelting. Las Luces plant has used sea water as process water since 1995. The grinding and flotation cells are fed with process water containing 46 g/ total dissolved salt. The concentration of dissolved salt has increased on average at the rate of 0.73 g/L per annum during the last 15 years of continuous seawater recycling. The increase in total salt content is largely a result of evaporation. The operational and capital investment costs of using seawater are higher due to the expenses required to combat the corrosive effect of seawater. A total dissolved salt content limit for the water used in copper flotation probably exists. (Moreno et al. 2011)

Recycling of the process water for flotation has the potential to decrease reagent consumption. The findings of Manono et al. (2013) suggest that the presence of high concentrations of ions in flotation plant water may be able to reduce the need for large additions of frother, which may enhance the profitability of the process. In the study of Ng'andu (2001) the use of underground mine water had deleterious effect on performance of the Mufulira flotation process because of its relatively low pH of about 7 enhancing deleterious electrochemical activity. However, when adding lime and raising the pH inside the primary grinding mills, the use of underground mine water was possible and the technique reduced the total lime consumption by 50% (Ng'andu 2001). These examples emphasize the fact that the whole process chain has to be taken into consideration, when planning water recycling in minerals processing. Examples of the reuse attempts of the use of process water in sulphide ore concentrators are listed in Table 13.

Table 13. Reuse attempts of process water in sulphide ore concentrators. (Ikumapayi 2013, Slatter et al. 2009)

Site	**Outcome**
Kristineberg, Sweden	-significant problems during pumping of the froth due to insufficient destruction of frothers and collectors in the tailings pond
Kristineberg, Stekenjokk	-no disturbance in grinding -no disturbance to pyrite flotation -when SO_4^{2-} >100 mg/L, selectivity against zinc in copper and zinc flotation decreased
Laisvall, Sweden	-deterioration of lead flotation and frothing due to precipitation of calcium carbonate in pipes and spray nozzles (carbonate from mine water)
Zinkgruvan, Sweden	-reduction in lead recovery -increase of zinc in lead concentrate -reuse of water stopped
Falun, Sweden	-reuse limited to 25% due to blockage of pipes by gypsum precipitate -saturation of calcium sulphate solution in the tailings pond water
Benambra, Australia	-lower recovery, grade and flotation kinetics with Melbourne process water
Kidd Creek, Canada	-process water 500 ppm thiosalt and 300 ppm calcium -improvement of flotation by enhancement of depression of pyrite and recovery of copper due to presence of thiosalt and calcium ions
Fankou, China	-rest collector in process water beneficial to lead flotation
Mufulira, Zambia	-low pH underground mine water reduced copper recovery and increased copper loss to tailings -deleterious effect removed by addition of quicklime in the primary mill
Rustenburg, South Africa	-tests to assess viability of using treated sewage effluent from the Rustenburg municipality -the overall platinum recovery and grade at similar level as with normal process water -slightly lower kinetic rate

Factors assosiated with water recycling in the flotation processes are so numerous, that a reasonable way to understand and manage these is required. One possibility is offered by electrochemistry, which can be used to measure for example potentials of different minerals, contact angle related properties and concentration of different chemicals direct in the slurry. It may be possible to find possible relationships between impurities in water and hydrofobicity / hydrofilicity as well as in flotability of individual minerals in the slurry. Such systems have been in use at least in Finland since late 1980s.

4.4 Leaching

Leaching processes can be divided into chemical leaching, pressure leaching (autoclave leaching) and bioleaching. The appropriate leaching method depends on the ore and metal to be extracted. Different methods in copper leaching from primary sulphides can be divided into predominantly sulphate and chloride processes. Sulphate processes can be further divided into atmospheric or super-atmospheric in pressure, and chemical or biological in the leaching. Some sulphate based copper processes are listed in Table 14. (Dreisinger 2006)

Table 14. Sulphate-based copper hydrometallurgy processes (adapted from Dreisinger 2006).

Process	**Temp. (ºC)**	**Pressure (atm)**	**Regrind D80 (µm)**	**Special conditions**
Activox process	90-110	10-12	5-10	Fine grinding combined with high oxygen overpressure overcomes chalcopyrite passivation
Albion process	85	1	5-10	Atmospheric ferric leaching of very finely ground concentrate
Anglo American – University of British Columbia Process	150	10-12	10-15	Modest regrind combined with surfactants for chalcopyrite leaching
Bactech/Mintek low temperature bioleach	35	1	5-10	Low T bioleach (35-50ºC) requires very fine grind to overcome chalcopyrite passivation.
BIOCOP^{TM}	65-80	1	37	High T bioleach (65-80ºC) uses thermophilic bacteria
CESL copper process	140-150	10-12	37	Chloride catalysed leach of chalcopyrite producing basic copper sulphate precipitate in the autoclave
Dynatec process	150	10-12	37	Chalcopyrite is leached using low grade coal as an additive
Mt. Gordon process	90	8	100	Pressure oxidation of chalcopyrite/pyrite ore or bulk concentrate in an iron sulphate rich electrolyte
PLATSOL process	220-230	30-40	15	Total pressure oxidation in the presence of 10-20 g/L NaCl. Precious metals leached at the same time as base metals
Sepon copper process	80 (Cu) 220-230 (FeS_2)	Atm 30-40	100 50	Atmospheric ferric leach for copper from chalcocite. Pressure oxidation of pyrite concentrate to make acid and ferric sulphate for copper leach.
Total pressure oxidation process	200-230	30-40	37	Extreme conditions of T and P designed to rapidly destroy chalcopyrite and other sulphides

Gold can be recovered by several methods (Figure 2). For over 100 years, cyanide has been the leach reagent of choice in gold mining. Substitutes for cyanide have been proposed and thiourea, thiocyanate and thiosulphate have been regarded as the most realistic substitutes. (Hilson and Monhemius 2006; Aylmore and Muir 2001) For refractory ores various methods exist for the oxidation of the gold containing mineral matrix and for more efficient use of cyanide. Different pretreatment methods in gold processing are shown in Figure 3.

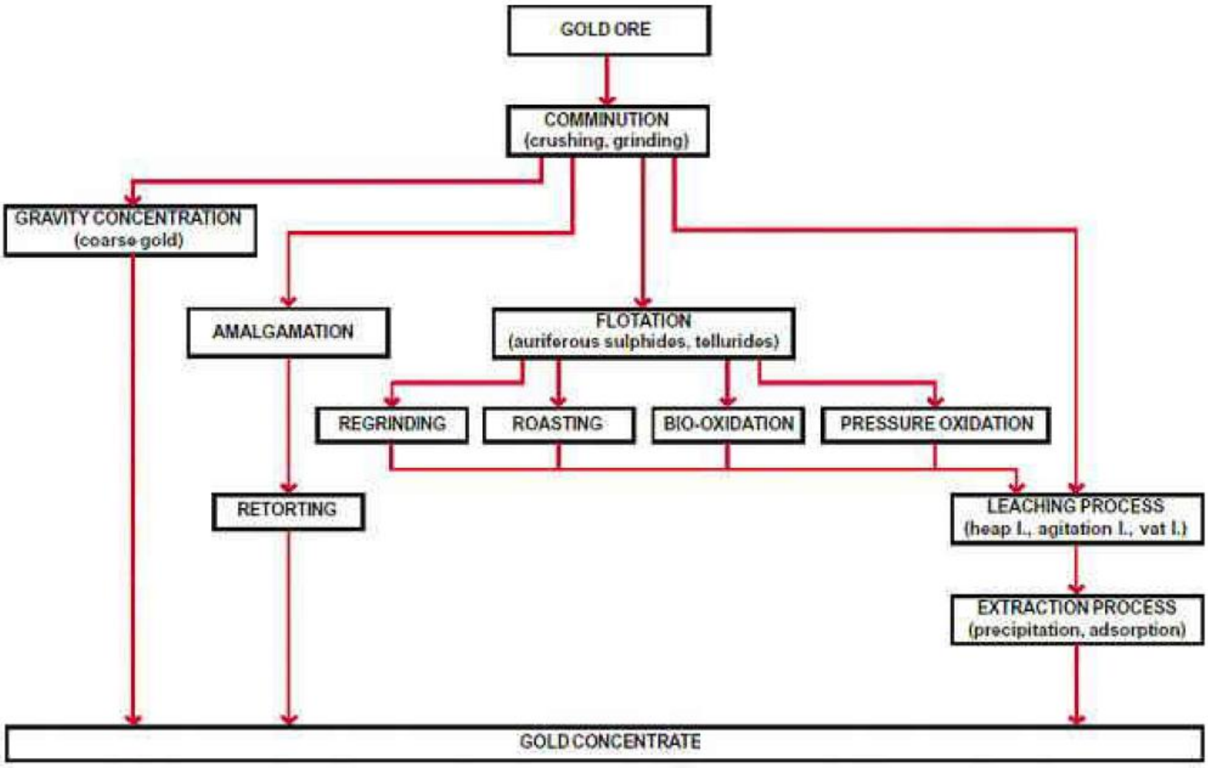


Figure 2. Basic flowchart for gold recovery (Eugene and Mujumbar 2009).

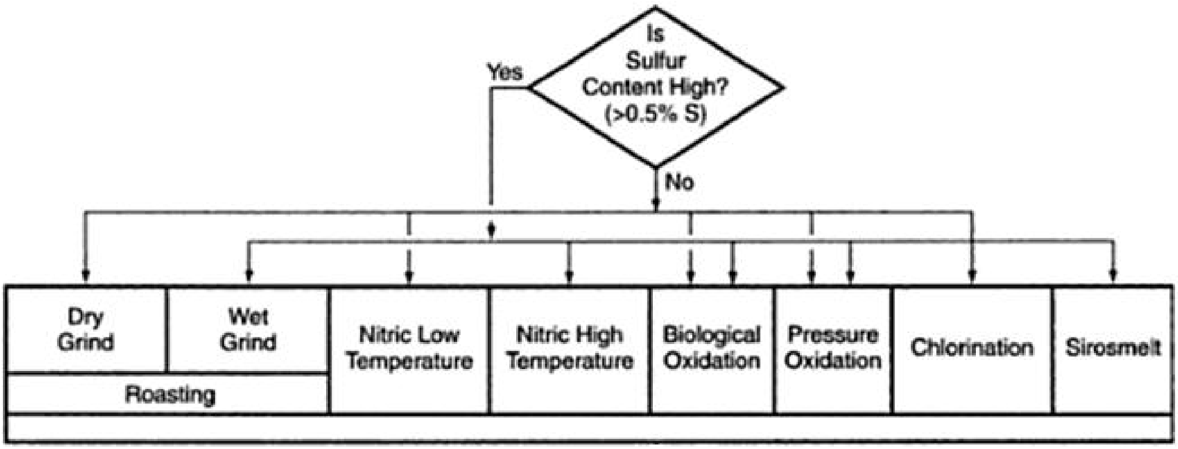


Figure 3. Pretreatment options in gold processing (Marsden and House 2006).

Cyanide losses are minimized in gold leaching by operating the leaching systems at a pH of above 10. Several compounds have effect on gold leaching. Chloride in autoclave feed water will form gold-chloride complexes in the autoclave, which reduce to gold on carbon in the ore. This gold is not dissolved in leaching operations and is lost to the tailings. Also metal concentrations in cyanide leaching have effect on leaching. For example, efficiency of the cyanide solution as a solvent decreased, when the recycled solution contained high concentration of zinc cyanide in the studies of Kurama and Catalsarik (2000). Lead ions (0.77 ppm) and ferrocyanide ions (200 ppm Fe) had a significant positive effect on gold dissolution in direct leaching experiments. Copper cyanide (50 ppm Cu) had a slightly negative effect on the gold dissolution. (Aghamirian and Yen 2005) Bahrami et al. (2007) used activated carbon to remove the dissolved metals from the process water prior to reusing the process water in the gold leaching step. The recoveries of Au and Ag were 93 and 71.7% when leaching with fresh water, and 91 and 66.2% when leaching with process water treated with activated carbon for 1 hour. When treated process water was used, the cyanide consumption was significantly reduced having a positive effect on chemicals consumption.

Sulphide ions in solution result in the passivation of the dissolution of gold in cyanide leaching. Lead can promote the removal of sulphide by precipitation as PbS. On the other hand, too much lead can result in passivation phenomenon in gold cyanide leaching. A general belief is that the presence of sulphur species in the cyanide leaching solution results in high consumption of cyanide and oxygen. The formation of copper cyanide species can result in low free cyanide species and reduce the gold leaching rate. (Dai and Jeffrey 2006)

In bioleaching, the tolerance of the microorganisms to different concentrations is crucial for successful operation. However, the microorganisms can be adapted to increasing concentrations of metals. The difference in tolerance between unadapted and adapted microorganisms can be significant. Bioheapleaching is based on recycling of the leaching liquor through the heap during several months and can generally tolerate relatively high concentrations of different compounds of recycled solutions. Table 15 summarizes the tolerance of mesophilic iron oxidizers to different ions. Table 16 shows the real concentrations of the pregnant leach solution of Talvivaara mine, where bioheapleaching is commercially utilized. In Talvivaara, 90% of pregnant leach solution is recycled back to the heap and 10% are piped to the metals recovery plant.

Table 15. Tolerance of mesophilic iron-oxidizers to leaching conditions. 1) Kinnunen 2004, 2) Breed and Hansford 1999, 3) Romero et al. 2003, 4) De et al. 1997, 5) Lawson et al. 1995, 6) Vardanyan and Akopyan 2003, 7) Das et al. 1997, 8) Fomchenko et al. 2003, 9) Chisholm et al. 1998, 10) Leduc et al. 1997, 11) Rossi 1990, 12) Sampson and Phillips 2001

Inhibitor	**Unit**	**Microbe**	**No effect**	**Partial inhibition**	**Total inhibition**	**Reference**
pH		*Leptospirillum ferriphilum*	0.9	0.7	0.5	1
		Leptospirillum ferrooxidans	1.1-1.7			2
Cl^-	g/L	*Leptospirillum ferriphilum*	5	10	20	1
		Leptospirillum –like strain	n.d.	10	12	3
		Acidithiobacillus ferrooxidans	0-0.01	0.4-10	3.6-12	3,4,5
Fe^{2+}	g/L	*Leptospirillum ferriphilum*	24			1
		Leptospirillum –like bacteria			15	6
Fe^{3+}	g/L	*Leptospirillum ferriphilum*	5	10	>20	1
		Acidithiobacillus ferrooxidans		0.2-20		7,8
Cu^{2+}	g/L	*Leptospirillum ferriphilum*	1-2	2-4		1
		Acidithiobacillus ferrooxidans	20*	0.6- >20, 25*		7,9, 10, 11
		Mixed mesophilic culture	0.2	1-4		12
		Leptospirillum ferrooxidans		0.06, 25**		11

*after adaptation, ** in mixed cultures

Table 16. Typical concentrations of the pregnant leach solution (PLS) in Talvivaara. (Talvivaara 2012).

Metal	**g/L**
Ni	1.5-3.5
Zn	4.0-7.5
Cu	0.5
Co	<0.3
U	0.01-0.03
Fe	10-20
Mn	3-8
Mg	3-8
Al	3-9
Ca	0.5-0.8
Na	0.3-0.7
As	<0.02
Cr	<0.02
Cd	<0.02

4.5 Chemical precipitation

Metal sulphides are generally less soluble than their corresponding hydroxide or carbonate precipitates (Table 17, Figure 4). Performance characteristics of chemical precipitation compared to different metal recovery techniques are shown in Table 18.

Table 17. Solubility products of metal hydroxides and sulphides (Dean 1999).

	Solubility product (mol /L)		
Metal	**MeOH**	**MeS**	**$MeCO_3$**
Al	1.3×10^{-33}	2.0×10^{-7}	-
Ag	2.0×10^{-8}	6.3×10^{-50}	8.5×10^{-12}
Co	5.9×10^{-15}	4.0×10^{-21}	1.4×10^{-13}
Cu	2.2×10^{-20}	6.3×10^{-36}	1.4×10^{-10}
Fe	4.9×10^{-17}	6.3×10^{-18}	3.1×10^{-11}
Mg	5.6×10^{-12}	-	6.8×10^{-6}
Mn	-	-	2.3×10^{-11}
Ni	5.5×10^{-16}	α-NiS 3.2×10^{-19} β-NiS 1.0×10^{-24} Y-NiS 2.0×10^{-26}	1.4×10^{-7}
Pb	1.4×10^{-15}	8.0×10^{-28}	7.4×10^{-14}
Zn	3.0×10^{-17}	α-ZnS 1.6×10^{-24} β-ZnS 2.5×10^{-22}	1.5×10^{-10}

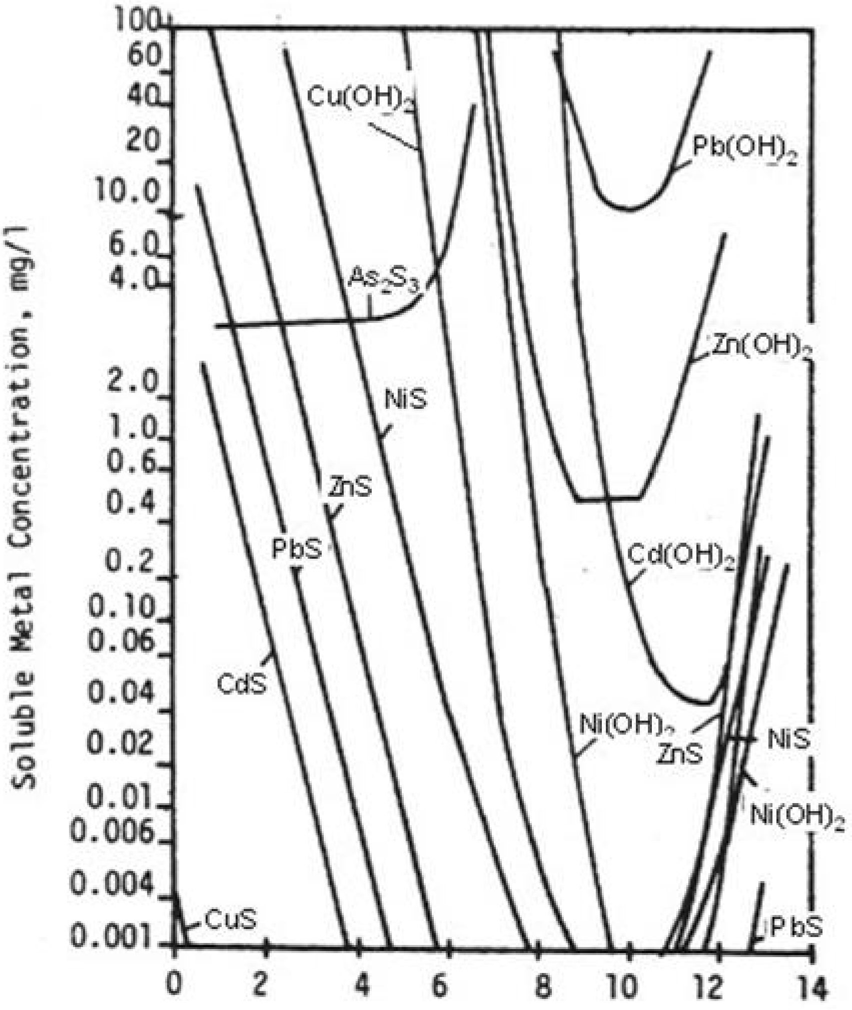


Figure 4. Comparison between the equilibrium concentrations of metal hydroxides and metal sulphides (BioMineWiki 2013).

Table 18. Performance characteristics of metal removal/recovery techniques (Kaksonen 2004).

	Performance characteristics					
Technique	**pH change**	**Metal selectivity**	**Influence of suspended solids**	**Tolerance of organic compounds**	**Working level for appropriate metal (mg/L)**	**End product**
Hydroxide precipitation	Limited tolerance	Non-selective	Tolerant	Tolerant, complexing agents may have adverse effect	>10	Gelatinous sludge
Sulphide precipitation	Limited tolerance	Limited selective, pH-dependant	Tolerant	Tolerant	>10	Dense sludge
Electrochemical operations	Tolerant	Moderate	Can be engineered to tolerate	Can be accommodated	>10	Metal deposit
Ion exchange	Limited tolerance	Chelate-resins can be selective	Fouled	Can be poisoned	<100	Concentrated liquid
Membrane processes	Limited tolerance	Moderate	Fouled	Intolerant	>10	Concentrated liquid
Adsorption	Limited tolerance	Moderate	Fouled	Can be poisoned	<10	Concentrated liquid or metal-containing adsorbent
Liquid-liquid extraction	Limited tolerance	Moderate	Tolerant	Tolerant	>10	Concentrated liquid
Foam flotation	Limited tolerance	Non-selective	Tolerant	Tolerant	>10	Dense sludge

4.6 Water chemistry in mines

Process water chemistry depends on ore type, gangue material, plant situation etc. Different mines and processing plants may experience different problems related to the same water chemistry. Table 19 shows examples of water chemistry of process or waste waters from different parts of the process chain in the mines.

Table 19. Process water chemistry. 1) Ikumapayi 2013, 2) Haran et al. 2008, 3) Dharmappa et al., 4) Levay et al. 2001, 5) Slatter et al. 2009, 6) Xu et al. 2012.

Species	Unit	Boliden process water, Sweden[1]	Benambra mine water from tailings pond, Australia[2]	Typical mine water from seepage of excavated area of the mine[3]	Circuit water[4]	Thickener O/F[4]	Decant pond return[4]	Amandelbult platinum mine flotation process water[5]
SO4	mg/L	200-1500	1100		14420	14114	17076	448
Ca	mg/L	100-500			120	56.4	135	100
Fe	mg/L	0.1-1300			6.16			
Na	mg/L				4350	4970	4540	271
K	mg/L				145	160	150	
COD (Cr)	mg/L	<30-130						
N	mg/L	0.1-10						
P	mg/L	<0.05-0.7						
Mg	mg/L	4.3-53			1820	1480	2250	
Ni	mg/L				4.15			
Mn	µg/L	4.4-8000						
Zn	µg/L	12-3900	0.12					
Al	µg/L	59-59000						
Cd	µg/L	0.12-5.2						
Co	µg/L	4-540						
Cu	µg/L	2.7-20000						
Hg	µg/L	<0.1-<0.13						
Cl^-	mg/L				2087	2340	2213	460
Conductivity (25 °C)	ms/m	96-160						
Specific conductivity	µs/cm @ 200°C		2800	600-10000				
pH			11.55	7-9.5	6.7	8.8	6.0	8.20
Eh mV SHE					440	338	264	
TDS	mg/L			500-2000	9900	11000	11000	1592
Suspended solids	mg/L			10-100				43
TOC	mg/L C							1.6

Table 19. Continues 2/2

Species	Unit	Amandelbult platinum mine return dam water[5]	Merensky flotation process water[5]	Lead concentrate wastewater Fankou Pb/Zn mine[6]	Zinc concentrate wastewater Fankou Pb/Zn mine[6]	Zinc tailing wastewater Fankou Pb/Zn mine[6]	Effluent Fankou Pb/Zn mine[6]
SO4	mg/L	628	1211				
S2-	mg/L			5.94	22.76	16.93	7.28
Ca	mg/L	89	575				
Fe	mg/L						
Na	mg/L	100	451				
K	mg/L						
COD (Cr)	mg/L						
N	mg/L						
P	mg/L			0.42	0.31	0.53	0.41
Pb	mg/L			19.06	22.05	95.42	9.94
Zn	mg/L			0.77	37.07	2.4	0.72
Mg	mg/L						
Ni	mg/L						
Mn	µg/L						
Zn	µg/L						
Al	µg/L						
Cd	µg/L						
Co	µg/L						
Cu	µg/L						
Hg	µg/L						
Cl^-	mg/L	471	1077	13.64	8.04	30.08	17.55
Conductivity (25°C)	ms/m						
Specific conductivity	µs/cm @ 200°C						
pH		9.25	7.18	11.78	12.14	12.45	12.02
Eh mV SHE							
TDS	mg/L	1936	3732				
Suspended solids	mg/L	22	34				
TOC	mg/L C	6.9	1.2				
BX	mg/L			1.06	0.68	1.35	0.74
DDTC	mg/L			77	23	95	94

4.7 Decision matrix for water recycling

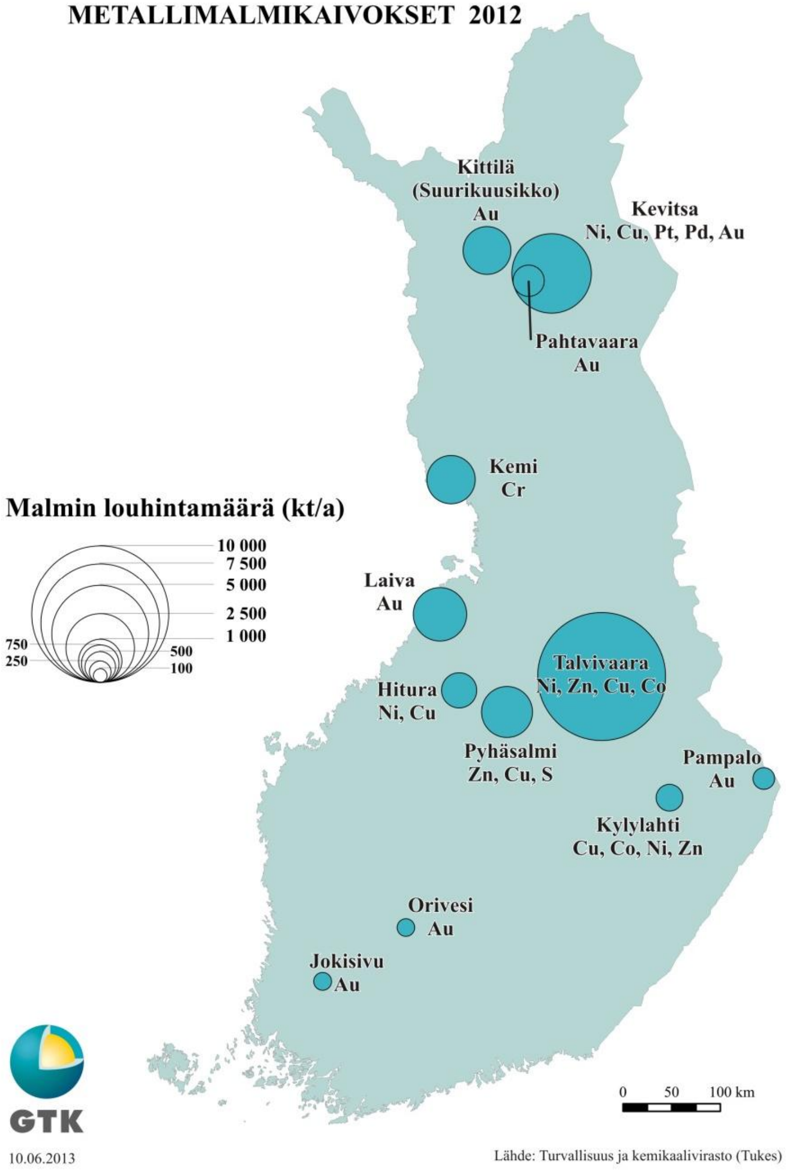
Several factors should be taken into account when considering the use of recycled water in processes. A decision matrix has been proposed in order to help in decision making (Table 20).

Table 20. Proposed decision matrix when considering using recycled water in processes (Victoria University and CSIRO 2008).

	Economics	**Quality**	**Wellbeing/health**
Reactants	Will less/more be required?	Will higher quality be required?	
Water	Will cost increase or decrease?	Will the quality be acceptable to the process? Will further treatment be required?	Will supply be consistent? What is the risk of cross-connection?
Energy	Will demand increase or decrease?	Will on site production be required?	
Staff/employees	Will there be pressure for increased wages and benefits?	Will training be required for users? Will specialists need to be hired?	What are the potential health effects and risks? What level of exposure will workers have?
Plant/equipment	Will maintenance costs increase? Will new plant be required? What will the retrofitting costs be?	Will higher quality materials be required in plant/equipment construction?	What is the risk of corrosion, biocorrosion, scaling, fouling etc?
Product	Will the price of the product be effected?	Will product quality be effected?	Are the runs guaranteed to produce usable product? Will there be consumer backlash against the product?
Trade waste	Will there be an increase in contaminant levels and what are the risks of fines?	Will there be more or less contaminants?	Will pipework need upgrading or greater maintenance?
Scheduled waste	Risk of fines? Increased costs of removal?	Will the nature of the waste change?	How will the waste impact the surroundings (smells etc)?
Company image	Will the green label increase sales? Will it be marketable? Possible incentives?	Will there be a greater brand respect?	Will this help meet company goals or mission statement? Eg “Grow me the money” recognition scheme.

5. Finnish metal mines

12 metallic mineral mines operate currently in Finland and several of them started the production in the last years (Figure 5, Table 21). The amount of mining operations is expected to further increase in the future. Half of the mines produce gold while the rest produce chromium, copper, nickel, zinc, sulphur, cobalt, silver and platinum group metals. The estimated turnover of the metal mining industry in Finland was approximately 960 million euros in 2011 (Uusisuo 2013). Environmental impact indicators related to water reported by metal mining companies in Finland are shown in Table 22. Processes in use in the mines were collected to the Table 23.



10.06.2013

Lähde: Turvallisuus ja kemikaalivirasto (Tukes)

Figure 5. Operating metal mines in Finland, year 2012 (Geological Survey of Finland 2013).

Table 21. Operating metal mines in Finland (adapted from PriceWaterhouse Coopers 2012 and Rytteri 2012).

Mine	**Company**	**Mineral**	**Production capacity**	**Net sales (2011) million $**	**Start year**	**Life of mine**	**Sustainability /Resp. report**
Suurikuusikko, Kittilä	Agnico-Eagle Finland Oy	Au 4,7 g/t	Au: 160 000 ounces	163,2	2009	Until 2044	Responsibility, 103 p. (GRI A)
Hitura, Nivala	Belvedere Mining Oy	Ni 0,6%, Cu 0,23%, Co, Pt, Pd	Ni: 2 500 t	22,6	1965	Until 2018	
Pahtavaara, Sodankylä	Lappland Goldminers Oy	Au 1,6 g/t	Au: 25 720 ounces	27,0	1996	At least 2 years	
Kemi, Keminmaa	Outokumpu Chrome Oy	Cr	1,3 million t	227,9	1966	Pending	Merged annual and CSR, 235 p. (GRI B+)
Jokisivu, Huittinen	Polar Mining Oy	Au 5,7 g/t	Au: 25 720 ounces (inc. Orivesi)	21,8 (inc. Orivesi)	2009	Until 2016	Included in annual, 3 p.
Orivesi	Polar Mining Oy	Au 5,7 and 7,3 g/t	See above	See above	1990	Until 2015	See above
Pyhäsalmi, Pyhäjärvi	Pyhäsalmi Mine Oy	Cu 1,1%, Zn 2,8%, S, Ag, Au	Cu: 14 000 t Zn: 32 300 t	169,9	1959	Until 2018	Sustainability, 74 p. (GRI B+)
Pampalo, Ilomantsi	Endomines Oy	Au 3,1 g/t	Au: 25 700-28 900 ounces	16,7	2011	n.a.	
Talvivaara, Sotkamo	Talvivaara Sotkamo Oy	Ni 0,23%, Zn 0,50%, Co 0,02%, Cu 0,13%, U 0,0018%	Ni: 50 000 t Zn: 100 000 t Cu: 15 000 t Co: 1 800 t	231,2	2008	2069	Included in annual, CSR, 23 p. (GRI C)
Laivakangas, Raahe	Nordic Mines Oy	Au 1,9 g/t	Au: 118 000 ounces	-(starting phase)	2011	2017	Included in annual, 2p.
Kevitsa, Sodankylä	Kevitsa Mining Oy	Cu 0,41%, Ni 0,30%, PGM, Au	Ni: 10 000 t Cu: 20 000 t	1,7 (starting phase)	2012	32 years	Sustainability report, 41 p. GHG report, 13 p.
Kylylahti, Polvijärvi	Kylylahti Copper Oy	Cu, Ni, Zn, Au	Cu: 8 000 t Au: 8 400 ounces Zn: 1 600 t	0,046 (starting phase)	2012	8-9 years	

Table 22. Environmental impact indicators related to water reported by companies (adapted from Rytteri 2012). X=reported, O=partially reported, Pyhäsalmi from Inmet to FQM in 2013.

Company	Outo-kumpu	Agnico-Eagle	Inmet	FQM	Talvi-vaara	Endo-mines	Altona Mining	Nordic Mines	Lappland Goldminers	Belvedere	Dragon Mining
Water withdrawn	X	X	X	O	X						
Water sources	X	X	X	O	X						
Water recycled	X	X	X	O							
Water discharged	X	X	X		X						

Table 23. Processes utilized by metal mines operating in Finland (Companies webpages 2013, Outokumpu sustainability report 2012, Aluehallintovirasto Pohjois-Suomi 2010, Pöyry 2012, Pöyry 2011, Vainionpää 2007). ECG=Excavation, crushing + grinding

Mine	**Operations**	**Water usage (million m^3/year)**	**Recycling rate (%)**
Kittilä Suurikuusikko	ECG - flotation - autoclave oxidation - cyanide leaching – recovery – electrolysis – smelting	1.2 m^3/ton ore	65%
Pahtavaara Sodankylä	ECG - gravimetric separation - flotation		
Jokisivu Huittinen	Excavation (concentration in Sastamala)		
Orivesi	Excavation (concentration in Sastamala)		
Pampalo Ilomantsi	ECG - gravimetric separation - flotation	2.5 m^3/ton of ore	96%
Laivakangas Raahe	ECG – flotation – gravimetric separation – cyanide leaching – recovery – smelting	1.3	
Kemi	ECG – gravimetric separation	1.4 in the mine	95% recycled rainwater
		2.0 in concentration	100%
Hitura	ECG – flotation		100% of process waters through tailings 5% of mine drainage water 95% of surface and rain waters of tailings area
Pyhäsalmi	ECG – flotation	6.0	internal recycling of process water in concentration15-20%
Talvivaara	Excavation – crushing – agglomeration – bioheapleaching – sulphide precipitation	6.0	
Kylylahti	ECG – flotation		
Kevitsa	ECG – flotation	1.1 (2.3 m^3/ton ore)	90%

5.1 Kemi

The Kemi chrome mine is the only mine of its type located within the European Union. Concentration processes at the mine are based on gravimetric separation. Therefore, only water and small amounts of flocculant are used. The concentrations of nitrogen, solids, calcium and iron in watercourses are slightly elevated. The total amount of water used in Kemi chrome mine in 2012 was approximately 1.4 million m^3, of which 95% was recycled rainwater. The ore concentration process uses approximately 2 million m^3 of water annually. All this water is recirculated via a settling-pool system covering more than 200 hectares. (Outokumpu sustainability report 2012)

5.2 Pyhäsalmi

Pyhäsalmi mine uses approximately 6 million m^3 lake water annually, of which over 90% is used for concentration process (process shown in Figure 6). The amount of internally recycled process water in the concentration is 15-20%. Mine water is acidic with elevated metal, sulphate and nitrogen concentrations, and it is not possible to utilize mine water without treatment in the concentration process. Tailings pond water is kept strongly alkaline, which precipitates the metals from the water. Recycling of process water is challenging due to calcium and sulphate, which can precipitate as gypsum and block pipes and devices. In addition, calcium precipitates in the presence of carbon dioxide as carbonates, which causes blockages as well. Suspended solids, pH, dissolved metals and ions in the recycled process water can cause difficulties in flotation. However, the use of recycled water was not shown to have any negative effect on the copper and zinc recoveries in flotation experiments. (Aluehallintovirasto Pohjois-Suomi 2010)

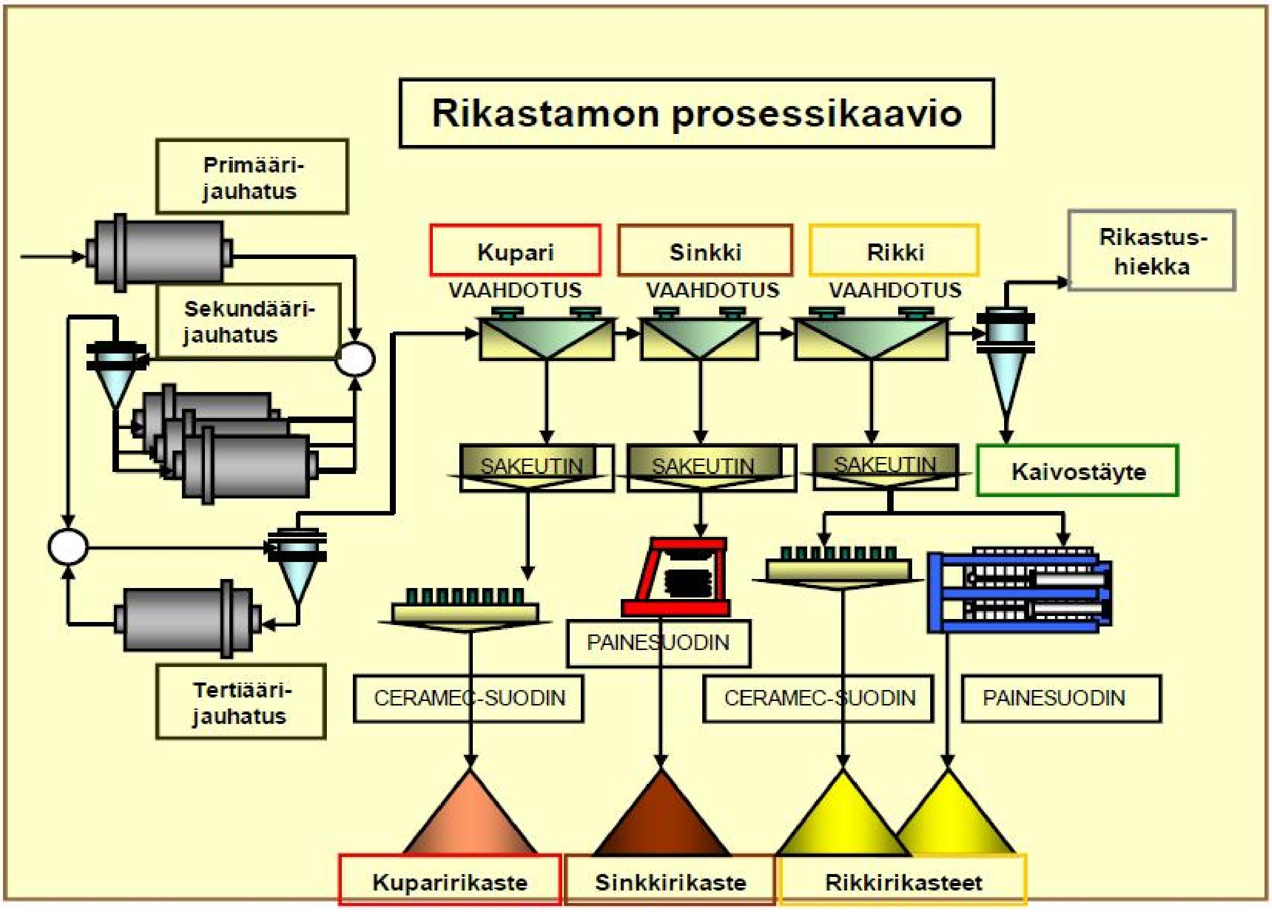


Figure 6. Pyhäsalmi mine concentration process flow sheet (Inmet Mining 2012).

5.3 Kittilä

In Kittilä mine, approximately 85% of process waste water is produced in flotation and pumped into the neutralization pond (process shown in Figure 7). 15% of process waste water is produced in the cyanidation unit and pumped into the CIL-pond after the cyanide destruction unit. Waters from the CIL-pond are entirely recycled back to the process. A part of the neutralized waters from NP-pond are recycled back to the process through the CIL-pond. The rest is discharged to the nearby river system. The approximate water recycling rate is 65%. Recycled process water contains increased concentrations of chloride, which can have detrimental effect on autoclaves and decrease gold recoveries. Therefore, the increase of process water recycling is not possible as long as chloride is not removed from the recycled process waters. Agnico-Eagle has studied the possibility to use mine water instead of fresh water from river in the process. Fresh water consumption has been approximately 1.2 m^3/ton ore. Kittilä mine's water balance is illustrated in Figure 8. (Pöyry 2012)

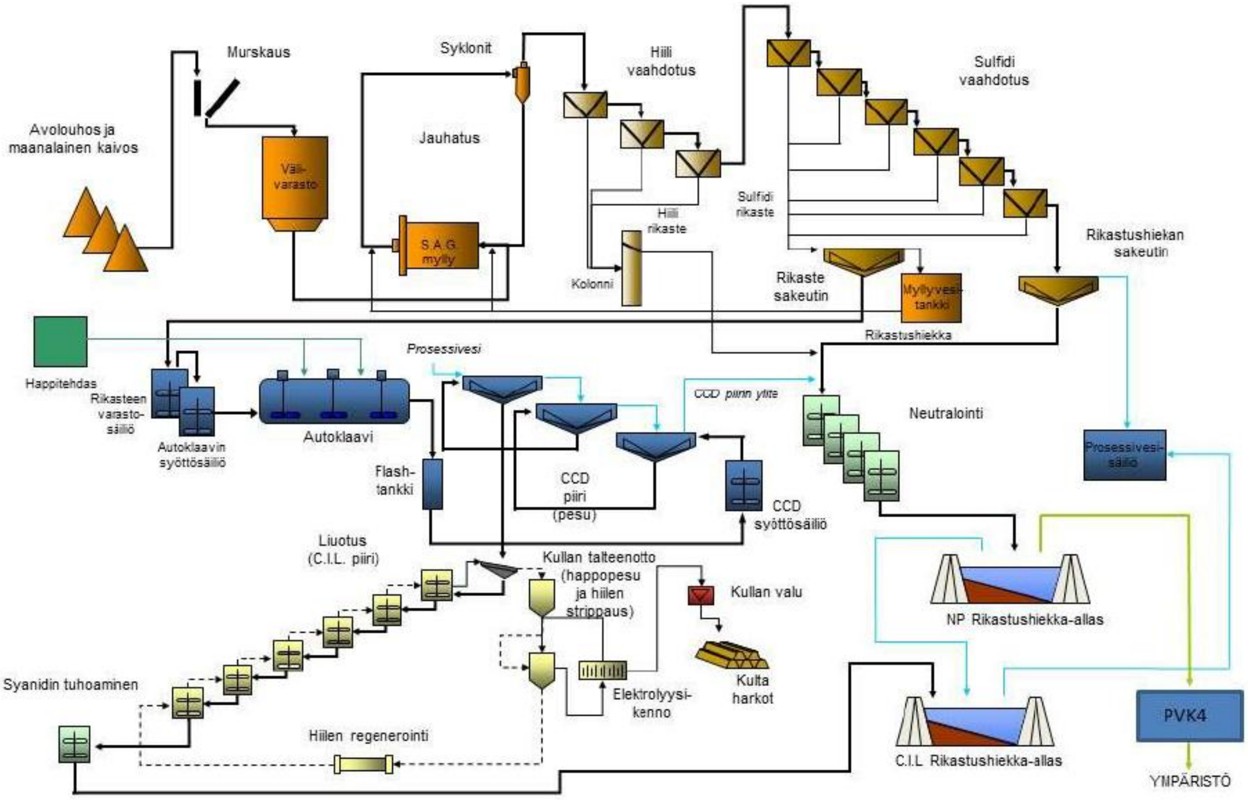


Figure 7. Process flow sheet of Kittilä gold mine (Agnico Eagle 2012).

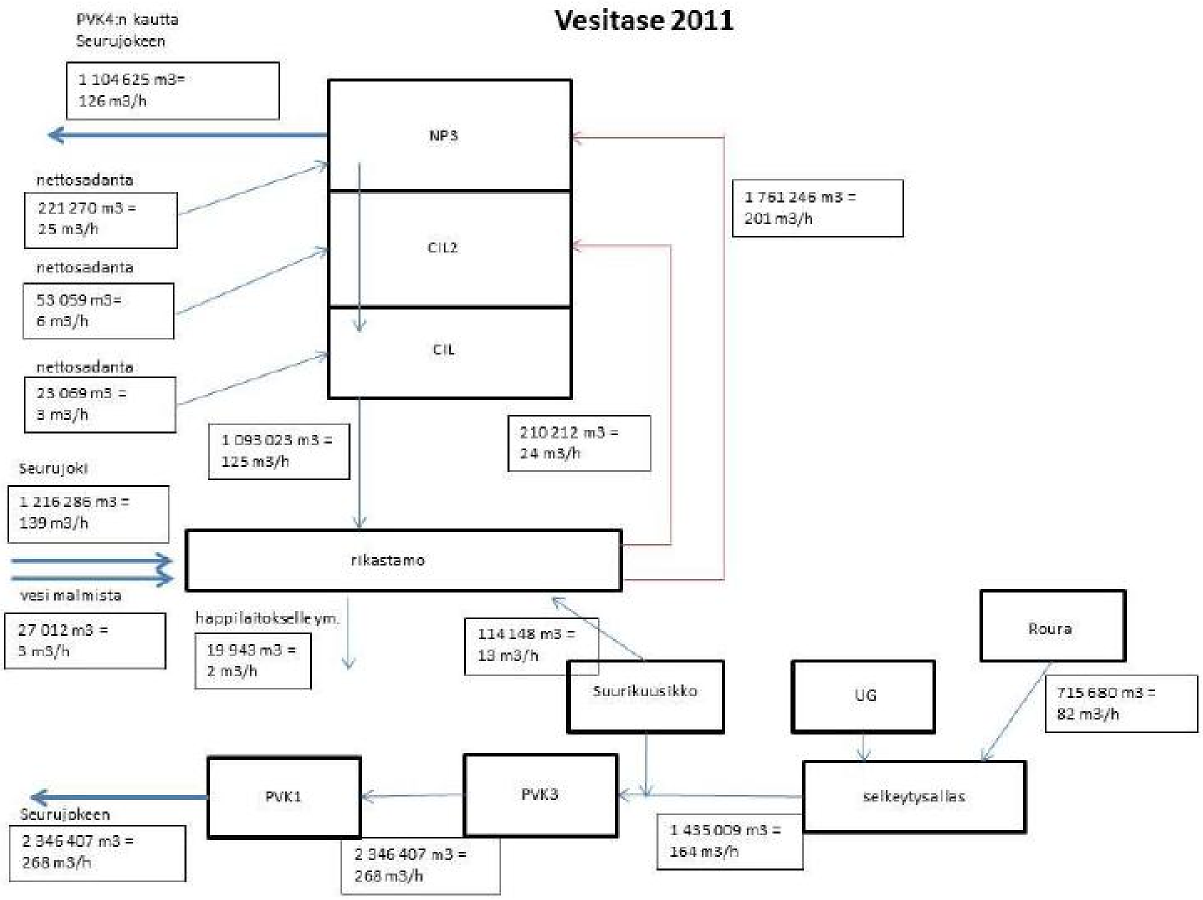


Figure 8. Water balance of Kittilä mine in 2011 (Pöyry 2012).

5.4 Hitura

Hitura mine has reached 100% recycling of process waters through the tailings area. 5% of mine drainage water and 95% of surface and rain waters of tailings area are recycled to the process, respectively. (Belvedere Resources 2011; Vainionpää 2007) The chloride concentration of the tailings pond water is approximately 2000 ppm. Recycling of chloride containing tailings pond water into flotation influences also concentrate chloride content. Chloride content of the concentrate is approximately 1000 ppm. Often there is a limit for the chloride content in smelters. For Harjavalta smelter, the upper limit is 500 ppm chloride in concentrate. However, there has not been any limit for Hitura's concentrate. (AVI 2012)

5.5 Talvivaara

Process flow sheet, recovery process and water flows in Talvivaara mine are shown in Figures 9, 10 and 11, respectively. The intake of fresh water from lake Kolmisoppi was 3,1 million m^3 in 2011, which corresponds to approximately 350 m^3/h. Total water consumption was 6.0 million m^3. (Talvivaara 2013) Water flow from bioleaching to metals recovery has been approximately 1200-1600 m^3/h. The biggest part of the water is returned to bioleaching after metals recovery.

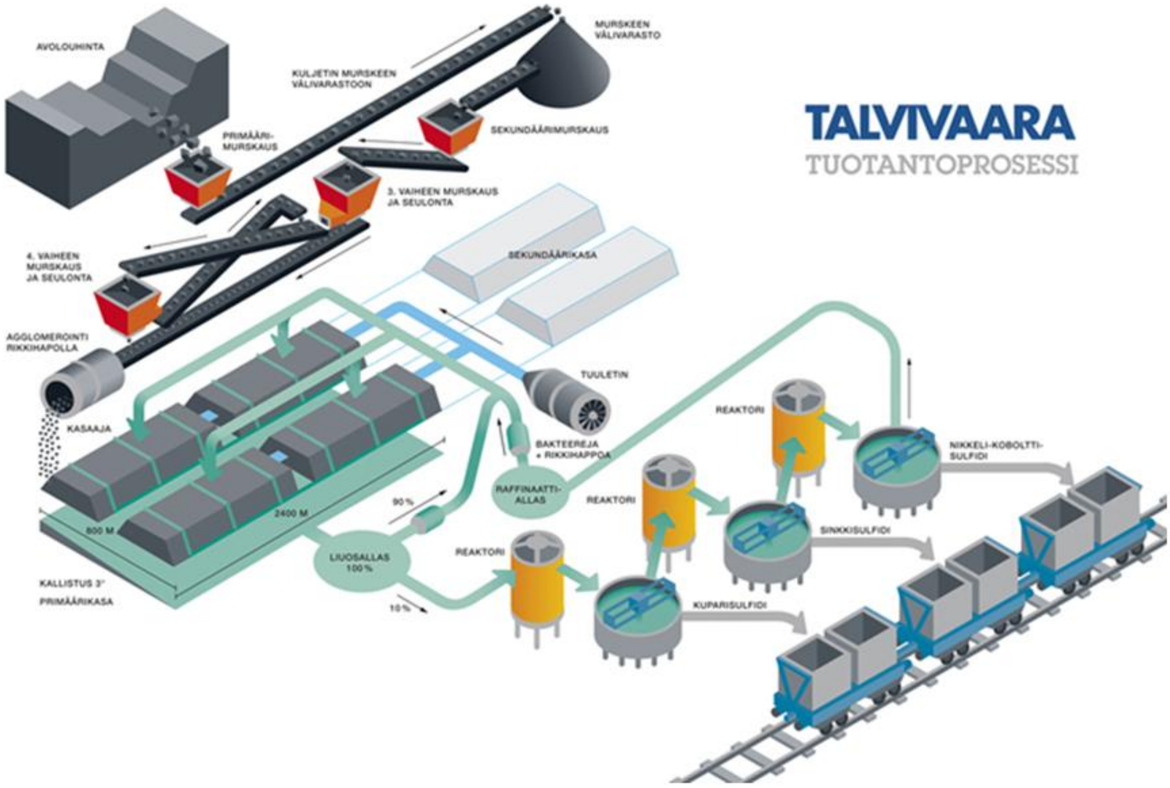


Figure 9. Talvivaara process (Talvivaara 2013).

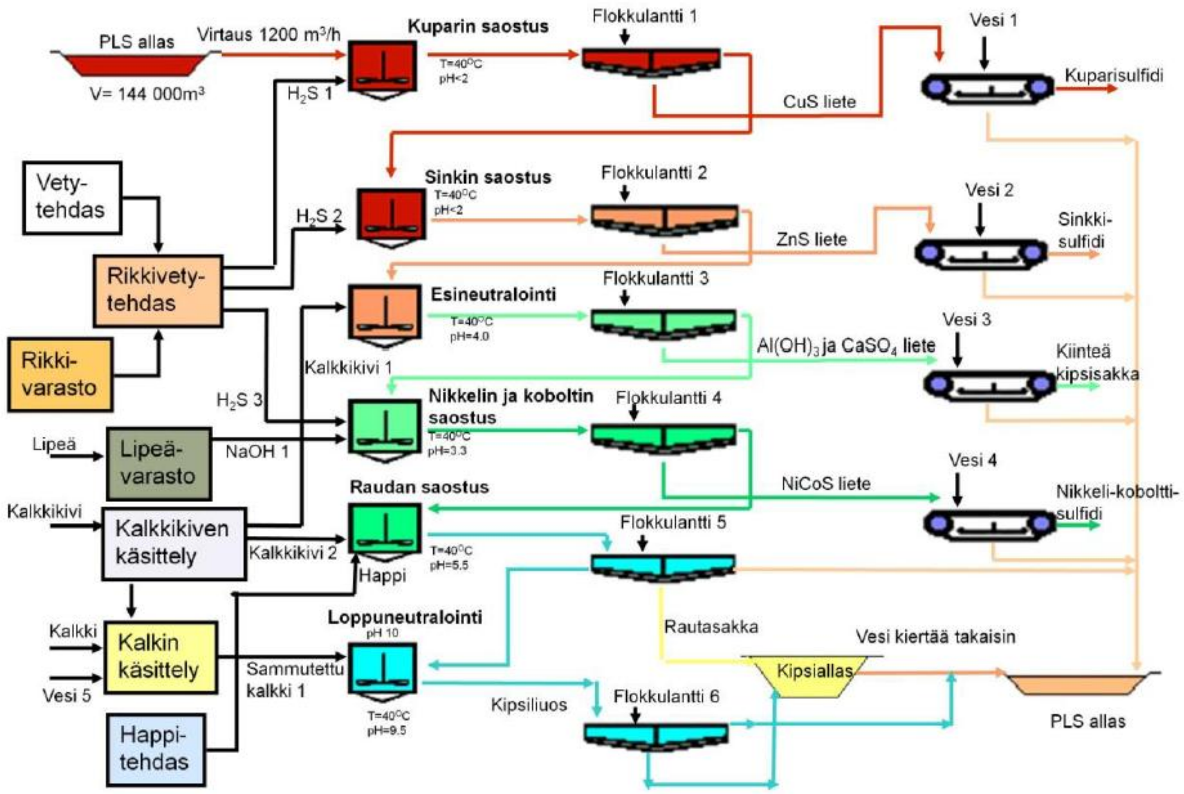


Figure 10. Talvivaara metals recovery process (Myöhänen 2010).

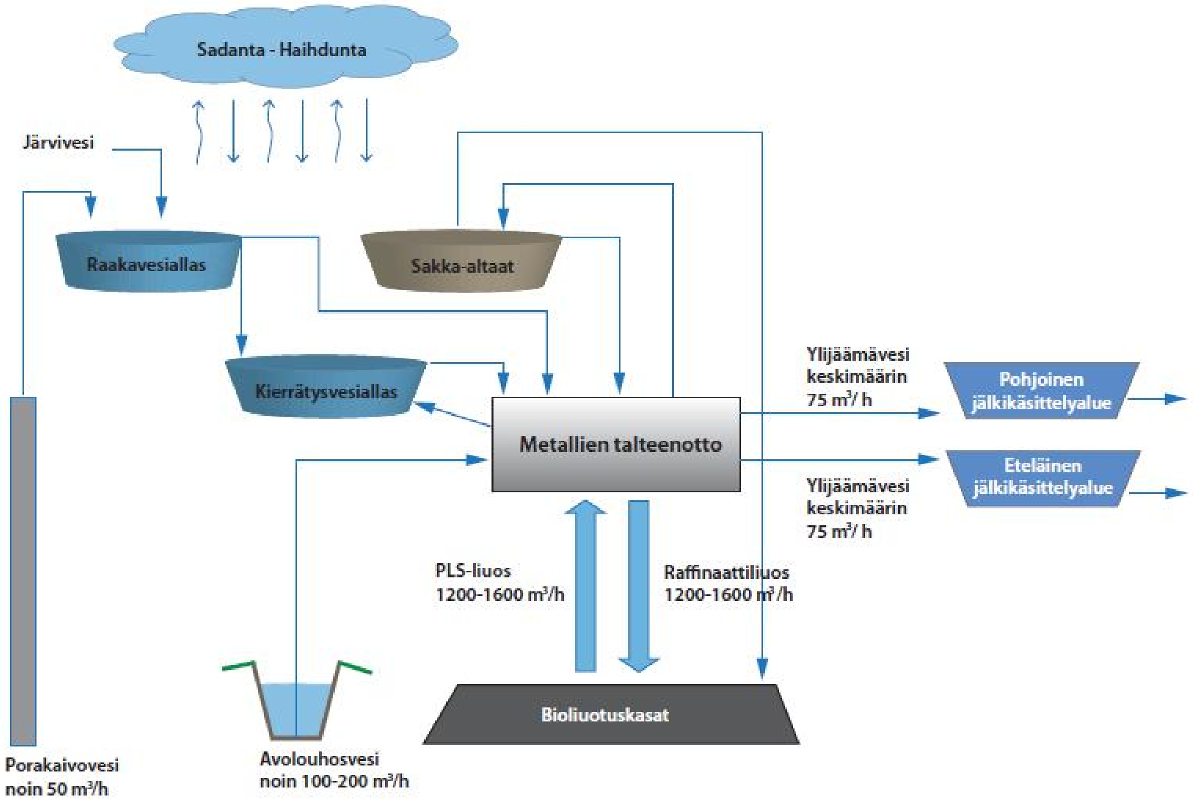


Figure 11. Water flows in Talvivaara mine (Talvivaara 2012).

Bioheapleaching process is based on recycling of the leaching solution through the primary and secondary heaps during several months to years. In Talvivaara, 90% of pregnant leach solution is recycled back to the heap and 10% are piped to the metals recovery plant. The concentrations of the pregnant leach solution vary depending on the ore and leaching phase. Typical PLS concentrations in Talvivaara were shown in Table 16. (Talvivaara 2013)

Overflow from final neutralization stage can be recycled back to the process. Recycling is possible into places, where recycling does not form gypsum or other problems due to metal sulphate concentrations. In order to increase recycling rate, process needs to be modified to remove suspended solids from the solution. Talvivaara has estimated that approximately 100-200 m^3/h of the overflow from final neutralization is recycled back to the process. Approximately 1.3 million m^3/year (144 m^3/h) surplus water has to be removed from the process.

5.6 Kevitsa

In Kevitsa mine, the total water requirement is 2.3 m^3/ton ore. No water is added to mining operations or to primary crushing. Milling consumes the biggest amount of water, but recycled lower quality water is applicable for milling unit process. Overflow from tailings pond is pumped to water storage pond and almost 90% is recycled back to the flotation unit. Clean fresh water is needed for chemicals production, in filtering and for pumps. Clean fresh water requirement is approximately 10% of the total water usage. (Pöyry 2011) Kevitsa mine process is shown in Figure 12 and water balance in Figure 13.

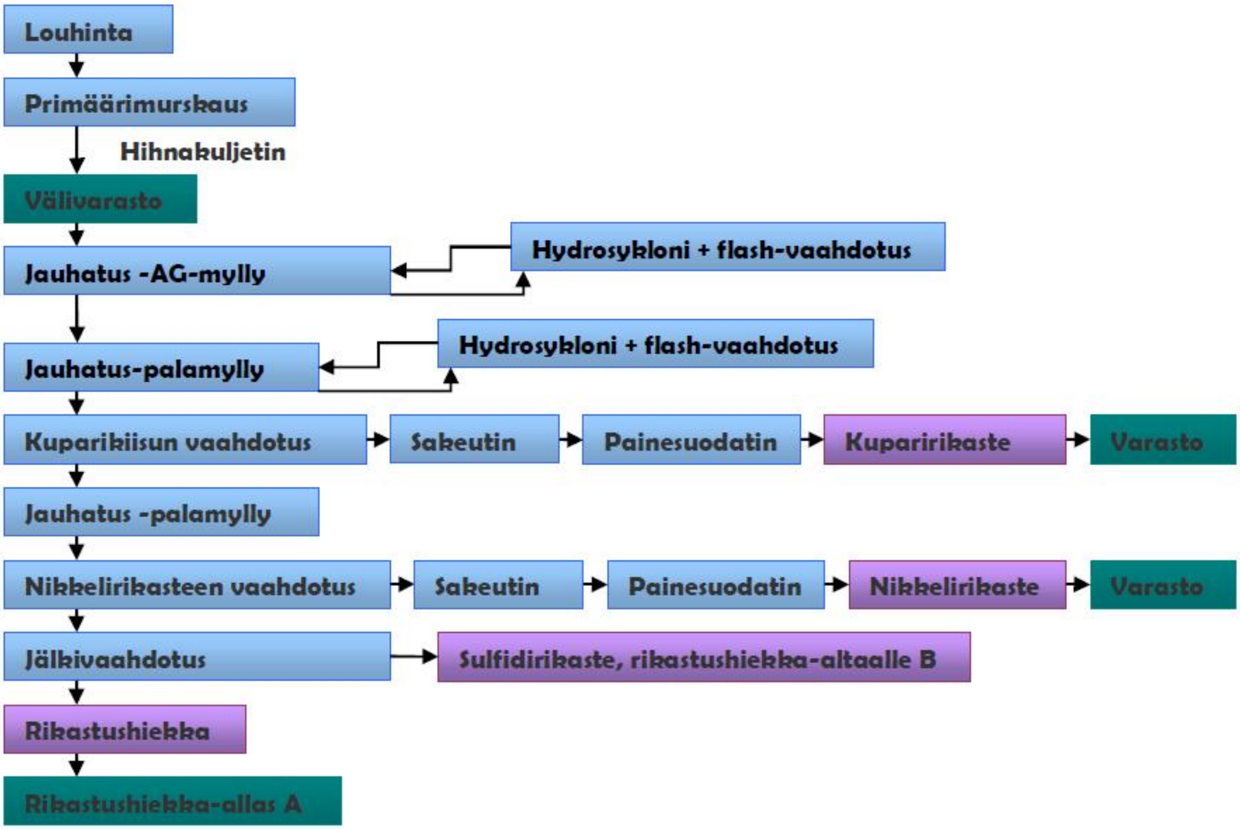


Figure 12. Kevitsa mine process (Pöyry 2011).

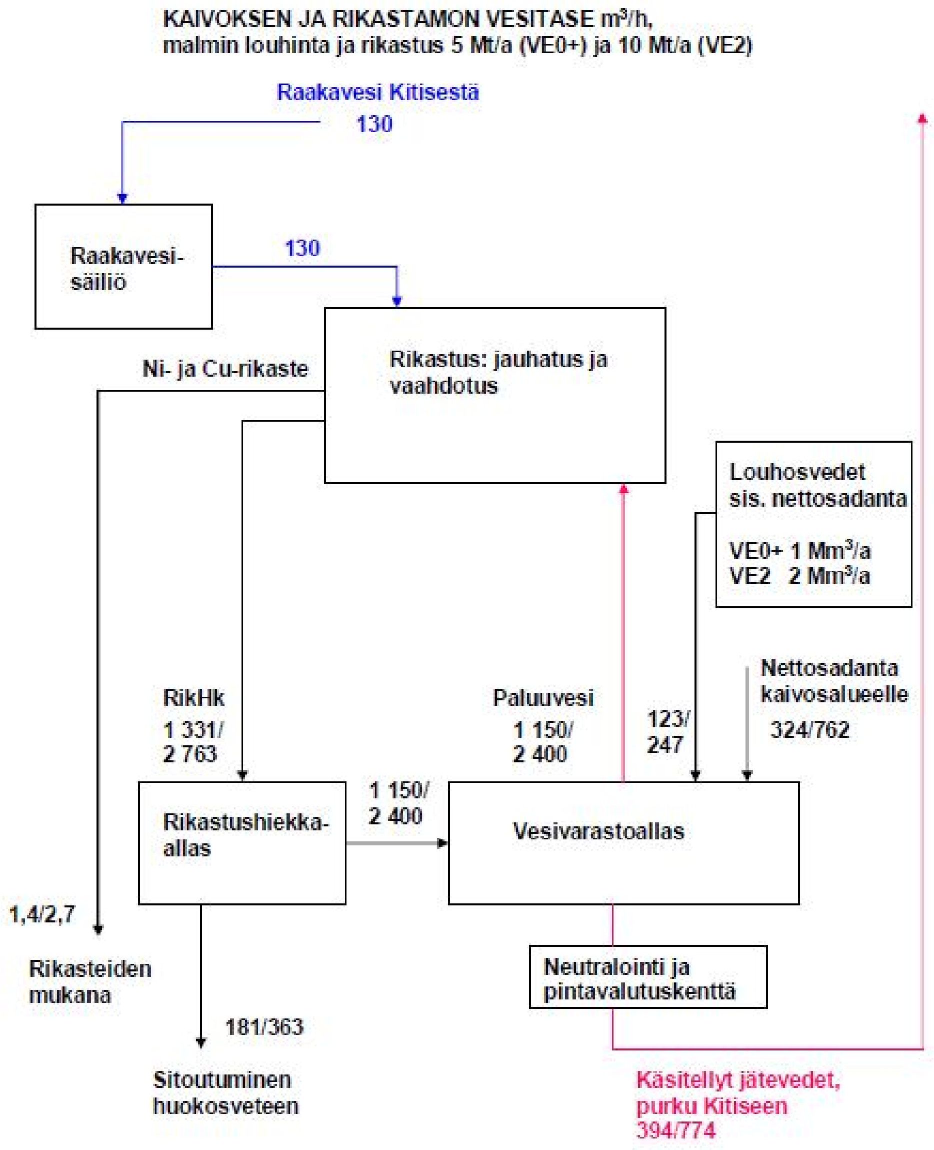


Figure 13. Kevitsa mine water balance (Pöyry 2011).

5.7 Pampalo

Pampalo process flow sheet is shown in Figure 14 and water usage in Figure 15. Water use in Pampalo mine was 2.5 m^3/ton of ore in 2011. 520 000 m^3/a recycled water from the clarification pond and 22 000 m^3/a fresh water were utilized. The internal water recirculation was thus 96%. Pampalo mine has operated with a closed water circuit so far. All water is recycled back from clarification pond to the concentrators. (Endomines 2012) Pampalo process waste water chemistry is shown in Table 24.

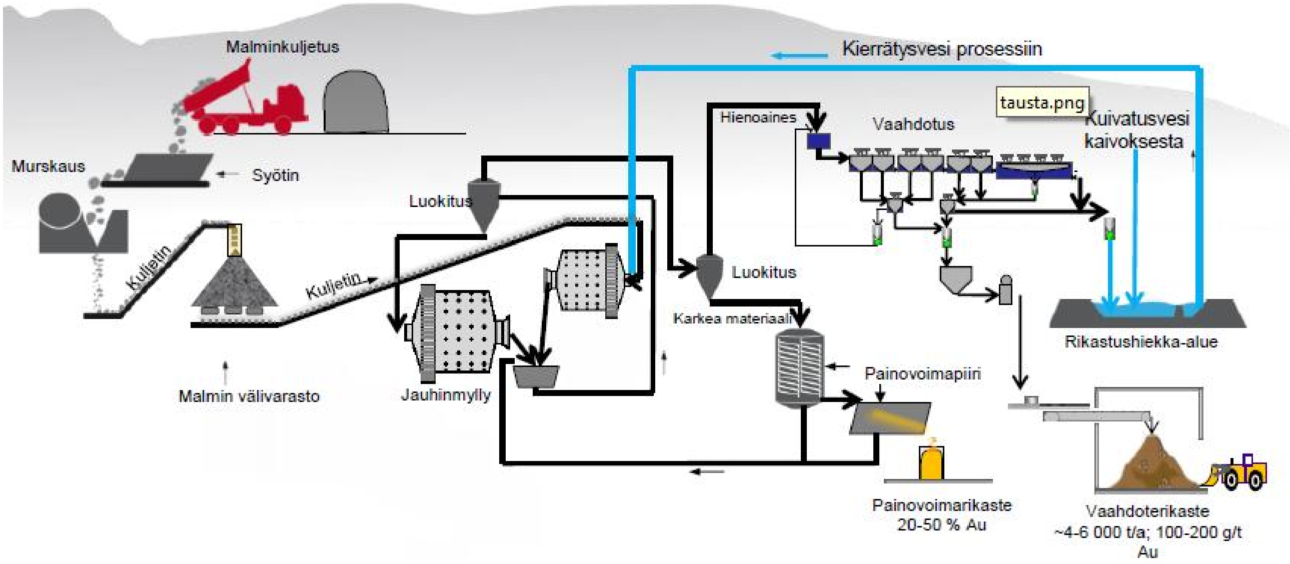


Figure 14. Pampalo concentration process (Ekberg 2013).

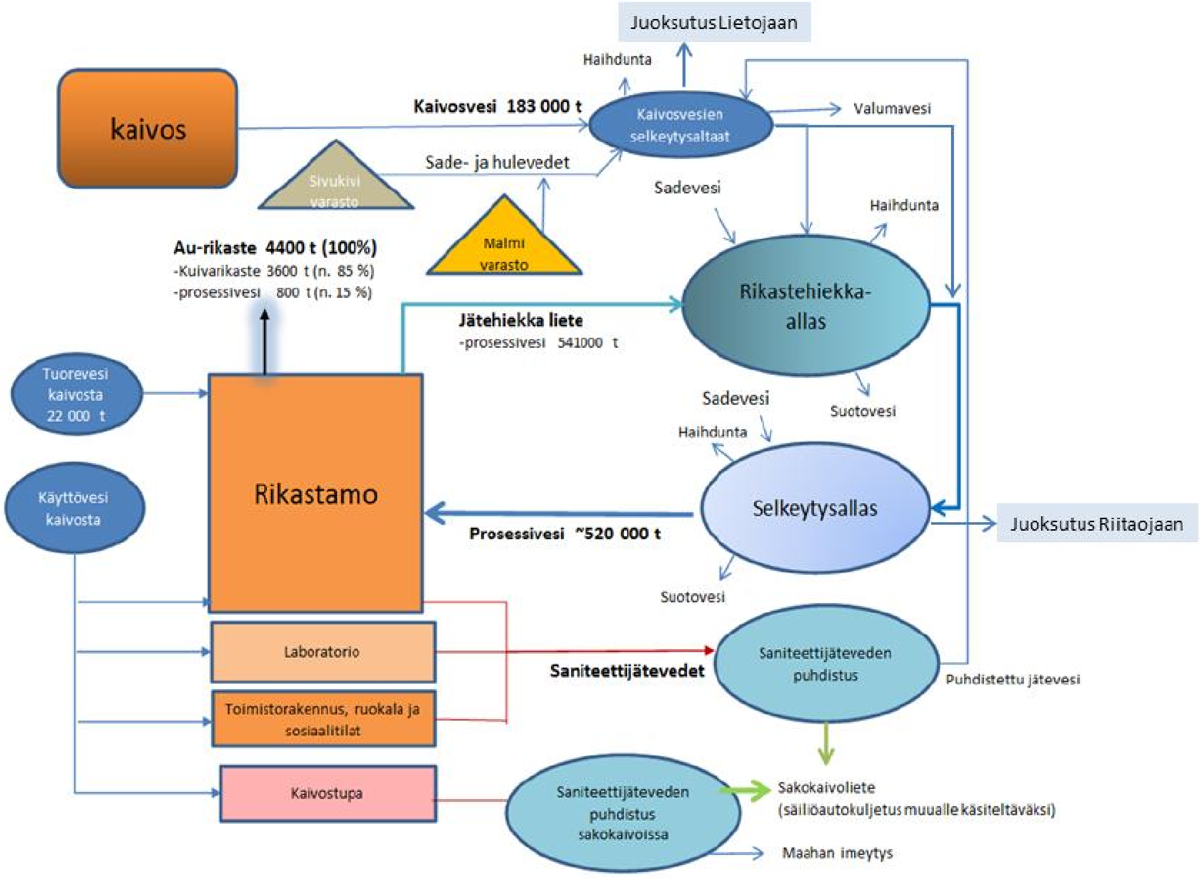


Figure 15. Water usage in Pampalo mine, year 2011. Water discharge into Lietoja and Riitoja starts in the autumn 2013. (Endomines 2012)

Table 24. Process waste water chemistry (Endomines 2012).

		Process waste water		**Water after clarification pond**
		Filtered 0,45 µm	**Settled**	
Compound	Unit			
As	µg/L	8,3	9,4	8
Cd	µg/L	0,07	0,07	0,1
Co	µg/L	0,22	0,67	
Cr	µg/L	<0,2	8,1	4
Cu	µg/L	2,7	3,9	5
Ni	µg/L	2,0	5,2	6
Pb	µg/L	0,49	3,2	2,2
V	µg/L	2,8	9,3	
Al	µg/L	59	2000	
Ba	µg/L	110	140	
Fe	µg/L	9	1500	1020
Mn	µg/L	9,8	56	
Sr	µg/L	2700	2800	
Ti	µg/L	<0,1	59	
Zn	µg/L	<2	2	<10
U	µg/L	7,2	8,4	
Se	µg/L	0,2	<0,2	
SO4	mg/L	190	190	65
Tot P	mg/L	-	0,46	0,13
Tot N	mg/L	-	21	3,3

5.8 Laivakangas

Laiva mine processing plant is shown in Figure 16. Water balance in the Laiva mine is positive and excess water is pumped into the sea. According to the plans the amount of water discharged into the sea is 175 m^3/h and 1.3 million m^3/year. Average mine water and water pond qualities are shown in Table 25. Process waters are recycled in the process, but the risk for accumulation of process chemicals in the process exists. Since the process has been operating for a shorter time, information of this is not currently available. (Nordic Mines 2012)

Table 25. Water qualities at Laiva mine (Nordic Mines 2012).

Measurement	**Unit**	**Mine water**	**Water pond**
pH		6.5-7.5	6.5-8
Conductivity	mS/L	47	52
Tot N	mg/L	3.9	5.8
Tot P	mg/L	0.2	0.08
WAD cyanide	mg/L		<0.01
As	mg/L	0.04	0.02
Cu	mg/L	0.07	0.02
Fe	mg/L	19	1.4
Mn	mg/L	0.3	0.14
SO_4^{2-}	mg/L	38	151
V	mg/L	0.02	<0.005

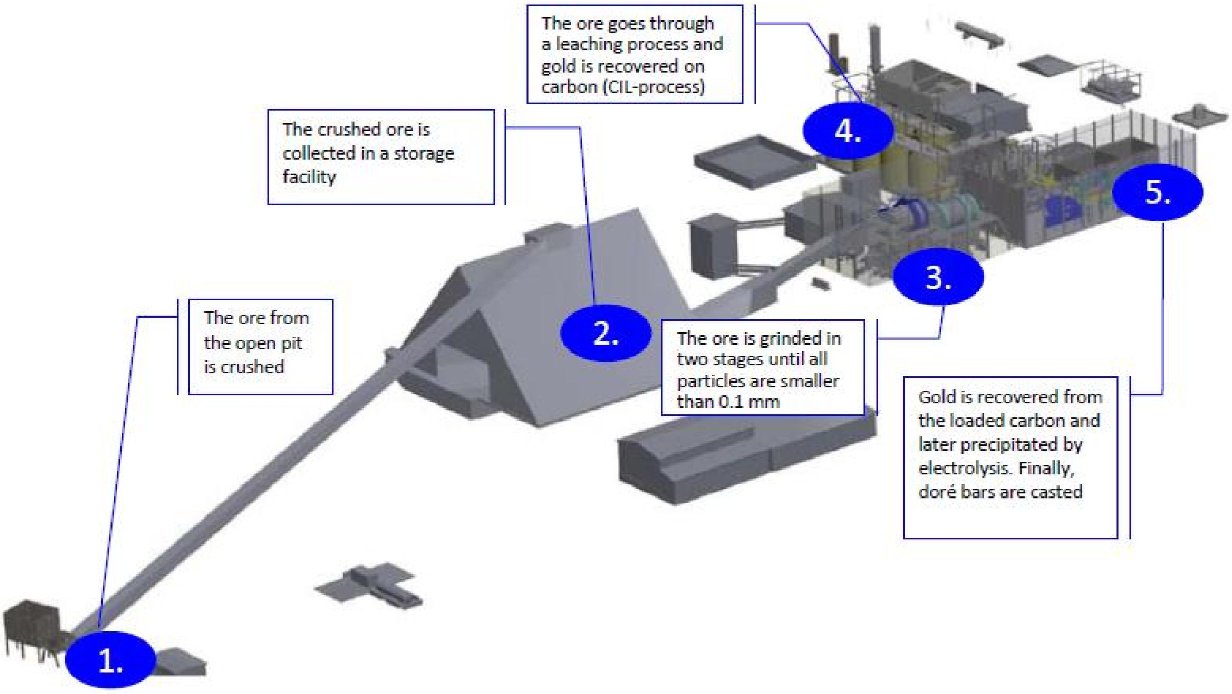


Figure 16. Laiva mine processing plant (Söderholm 2013).

6. Conclusions

Stricter effluent discharge limits have been proposed for metal mines in many countries. In Finland, sulphate concentration of the effluents has been in public focus. In some Finnish mines the challenge has been the excess of water after heavy rains and melting of snow. Globally, in many arid areas the challenge is on the contrary water scarcity. In both these cases, tendency and need in the mines is to reuse and recycle more water in order to gain public and regulatory acceptance. Sometimes lower quality water can be recycled directly back to the process, but often there is a need for different water treatment processes. New water treatment technologies such as forward osmosis may have potential applications also in the mining industry.

Understanding of the effects on process performance is crucial when deciding over water recycling. Extraction, leaching, flotation and hydro-blasting represent over 80% of total water demand in mining. Therefore, the recycling of water in these processes has most influence in the water usage. The whole process chain has to be taken into consideration, when planning water recycling in minerals processing. Recycling of water in the mining industry is always case-specific, but good examples of successful operations in the world exist. Environmentally beneficial water recycling and reuse projects can also return a significant economic benefit.

Identified challenges related to mine water recycling in Finnish mines were pH, suspended solids and elevated metal, sulphate, chloride and nitrogen concentrations, which can disturb the process performance. Calcium and sulphate can precipitate as gypsum and block pipes and devices. Recycling is possible into places, where recycling does not form gypsum or other problems due to metal sulphate concentrations. Chloride can have in some processes detrimental effect on autoclaves and decrease gold recoveries. Recycling of chloride containing tailings pond water into flotation influences also concentrate chloride content. Often there is a limit for the chloride content in smelters.

Kittilä, Pyhäsalmi and Talvivaara mines were chosen as cases for further studies, since they represent a large variety of processing technologies. In these mines, large total quantities of water are used in the processes. Kittilä represents gold ore processing, Pyhäsalmi represents a typical base metal processing plant with flotation cells, and Talvivaara represents a multi metal mine where a new bioheapleaching process for nickel recovery is in use. These cases give further insight into the water reuse and recycling concept in the mining industry.

References

Aghamirian M.M. and Yen W.T. 2005. A study of gold anodic behaviour in the presence of various ions and sulphide minerals in cyanide solution. Minerals Engineering 18: 89–102.

Agnico Eagle. 2012.

Aluehallintovirasto, Pohjois-Suomi. 2010. Päätös nro 40/10/1. Selvitys prosessiveden kierrätyksen ja jäteveden käsittelyn tehostamisen mahdollisuuksista Pyhäsalmen kaivoksella, Pyhäjärvi.

Aluehallintovirasto, Pohjois-Suomi. 2012. Lupapäätös nro 51/12/1. Hituran kaivoksen ympäristöluvan lupamääräyksen 4 määräajan jatkaminen, Nivala.

Aylmore M.G. and Muir D.M. 2001. Thiosulfate leaching of gold – A review. Minerals Engineering 14 (2): 135–174.

Bahrami A., Hosseini M.R. and Razmi K. 2007. An investigation on reusing process water in gold cyanidation. Mine Water Environ 26: 191–194.

Belvedere Resources. Sustainability report 2011.

BioMineWiki. 2013. Sulfide versus hydroxide precipitation. http://wiki.biomine.skelleftea.se/wiki/index.php /Sulfide_versus_hydroxide_precipitation [accessed 28th August, 2013]

Breed A.W. and Hansford G.S. 1999. Effect of pH on ferrous-iron oxidation kinetics of Leptospirillum ferrooxidans in continuous culture. Biochemical Engineering Journal 3: 193–201.

Chisholm I.A., Leduc L.G. and Ferroni G.D. 1998. Metal resistance and plasmid DNA in Thiobacillus ferrooxidans. Antonie van Leeuwenhoek 73: 245–254.

Dai X. and Jeffrey M.I. 2006. The effect of sulphide minerals on the leaching of gold in aerated cyanide solutions. Hydrometallurgy 82: 118–125.

Das A., Modak J.M. and Natarajan K.A. 1997. Studies on multi-metal ion tolerance of Thiobacillus ferrooxidans. Minerals Engineering 10: 743–749.

De G.C., Oliver D.J. and Pesic B.M. 1997. Effect of heavy metals on the ferrous iron oxidizing ability of Thiobacillus ferrooxidans. Hydrometallurgy 44: 53–63.

Dean J.A. 1999. Lange’s handbook of chemistry. 15th edition. New York, McGraw-Hill Inc.

Deng M., Liu Q. and Xu Z. 2013. Impact of gypsum supersaturated water on the uptake of copper and xanthate on sphalerite. Minerals Engineering 49: 165–171.

Dharmappa H.B., Sivakumar M. and Singh R. Wastewater recycle, reuse and reclamation – Vol. I, Wastewater characteristic management and reuse in mining & mineral processing industries.

Dreisinger D. 2006. Copper leaching from primary sulphides: Options for biological and chemical extraction of copper. Hydrometallurgy 83(1-4): 10–20.

Ekberg M. 2013. Etsintäyhtiöstä kaivosyhtiöksi – Endomines ja Pampalon kultakaivos. Maaliskuu 2013. Tampereen sijoitusmessut.

Endomines Oy. 2012. Hakemus Pampalon kaivoksen ympäristöluvan tarkistamiseksi ja muuttamiseksi. 2.3.2012.

Environment Canada. 2012. 10-year review of metal mining effluent regulations. Discussion paper. December 14, 2012.

Environment Canada. 2013. http://www.ec.gc.ca/eau-water/default.asp?lang=En&n=851B096C-1 [accessed 5 July 2013]

Eugene W.W.L. and Mujumbar A.S. 2009. Gold extraction and recovery processes. M2TC Report. Minerals, Metals and Materials Technology Centre, National University of Singapore.

Fleming H. and Radakovich R. Water Management in Mining Operations. Hatch Water. Mining Magazine Congress 2011, Johannesburg, South Africa, October 24-25, 2011.

Fomchenko N.V., Slavkina O.V. and Biryukov V.V. 2003. Biological oxidation of sulfide raw material using a culture of Thiobacillus ferrooxidans under various conditions of leaching. Applied Biochemistry and Microbiology 39: 82–86.

GE Water. Handbook of Industrial Water Treatment. http://www.gewater.com/handbook/index.jsp [accessed 4 July 2013]

Geological Survey of Finland. 2013. http://www.gtk.fi/geologia/luonnonvarat/metallit/ [accessed 9.8.2013]

Gunson A.J., Klein B., Veiga M. and Dunbar S. 2012. Reducing mine water requirements. Journal of Cleaner Production 21: 71–82.

Haran N.P., Boyapati E.R., Boontanjai C. and Swaminathan C. 2008. Kinetics studies on effect of recycled water on flotation of copper tailings from Benambra Mines, Victoria. Development in Chemical Engineering and Mineral Processing 4 (3-4): 197–211.

Hilson G. and Monhemius A.J. 2006. Alternatives to cyanide in the gold mining industry: what prospects for the future? Review article. Journal of Cleaner Production 14: 1158–1167.

Ikumapayi F.K. 2013. Recycling process water in complex sulphide ore flotation. Mineral Processing , Division of Sustainable Engineering, Luleå University of Technology. April 2013. Doctoral thesis.

Ikumapayi F., Mäkitalo M., Johansson B. and Rao K.H. 2012. Recycling of process water in sulphide flotation: Effect of calcium and sulphate ions on flotation of galena. Minerals Engineering 39: 77–88.

ICMM, 2012. International Council on Mining & Metals. Report, Water management in mining: a selection of case studies. May 2012. 32 p.

Inmet Mining, 2012. Company brochure.

Kaksonen A. 2004. The performance, kinetics and microbiology of sulfidogenic fluidized-bed reactors treating acidic metal- and sulphate-containing wastewater. Doctoral thesis. Tampere University of Technology, Publication 489.

Kinnunen P. 2004. High-rate ferric sulphate generation and chalcopyrite concentrate leaching by acidophilic microorganisms. Doctoral thesis, Tampere University of Technology.

Kirjavainen V., Schreithofer N. and Heiskanen K. 2002. Effect of calcium and thiosulfate ions on flotation selectivity of nickel-copper ores. Minerals Engineering 15: 1–5.

Kurama H. and Catalsarik T. 2000. Removal of zinc cyanide from a leach solution by an anionic ion-exchange resin. Desalination 129: 1–6.

Lakefield Research Limited & SENES Consultants Limited. 2002. Applicable technologies for the management of mining effluents in the northwest territories. Department of Indian and Northern Affairs Canada. April 2002. QS-Y201-000-EE-A1.

Lawson E.N., Nicholas C.J. and Pellat H. 1995. The toxic effects of chloride ions on Thiobacillus ferrooxidans. In: Biohydrometallurgical Processing, Vargas T., Jerez C.A., Wiertz J.V. and Toledo H. (eds.). University of Chile, pp. 165–174.

Leduc L.G., Ferroni G.D. and Trevors J.T. 1997. Resistance to heavy metals in different strains of Thiobacillus ferrooxidans. World Journal of Microbiology and Biotechnology 13: 453–455.

Levay G., Smart R.St.C. and Skinner W.M. 2001. The impact of water quality on flotation performance. The Jounal of The South African Institute of Mining and Metallurgy 101 (2): 69–76.

Liu W., Moran C.J. and Vink S. 2013. Managing the potential risks of using bacteria-laden water in mineral processing to protect freshwater. Environmental Science & Technology 47: 6582–6588.

Manono M.S., Corin K.C. and Wiese J.G. 2013. The effect of ionic strength of plant water on foam stability: A 2-phase flotation study. Minerals Engineering 40: 42–47.

Marsden J.O. and House C.I. 2006. The chemistry of gold extraction. 2nd edition. Society for Mining, Metallurgy, and Exploration, Inc. USA.

Minerals Council of Australia. 2006. Strategic water management in the minerals industry. 36 p.http://www.ret.gov.au/resources/Documents/mcmpr/Strategic_Framework_for_Water_Management_in_the_Minerals_Industry.pdf (accessed 10.3.2013)

Mining, People and the Environment, 2013. http://www.mpe-magazine.com/reports/reduce,-reuse,-recycle (accessed 6.3.2013)

Miranda M. and Sauer A. 2010. Mine the gap: Connecting water risks and disclosure in the mining sector. WRI working paper. World Resources Institute, Washington, DC.

Moreno P.A., Aral H., Cuevas J., Monardes A., Adaro M., Norgate T. and Bruckard W. 2011. The use of seawater as process water at Las Luces copper-molybdenum beneficiation plant in Taltal (Chile). Minerals Engineering 24: 852–858.

Muzenda E. 2010. An investigation into the effect of water quality on flotation performance. World Academy of Science, Engineering and Technology 45: 237–241.

Myöhänen M. 2010. Partikkelianalysaattorilaitteiston kehitys. Insinöörityö, Kajaanin ammattikorkeakoulu.

Ng'andu D.E. 2001. The effect of underground mine water on performance of the Mufulira flotation process. The Journal of The South African Institute of Mining and Metallurgy. October 2001: 367–380.

Nordic Mines Oy. 2012. Laiva-kaivoksen ympäristöluvan muutoshakemus. 20.3.2012.

Norgate T.E. and Lovel R. 2004. Water use in metal production: A life cycle perspective. DMR-2505 report. CSIRO Minerals. September 2004.

Outokumpu. Sustainability report 2012.

PriceWaterhouse Coopers. 2012. The Finnish Mining Industry. An Overview - 2012. 12 October 2012.

Pöyry Finland Oy. 2011. Kevitsan kaivoksen laajennus. FQM Kevitsa Mining Oy, Ympäristövaikutusten arviointiselostus. 5.4.2011

Pöyry Finland Oy. 2012. Agnico-Eagle Finland Oy, Kittilän kaivoksen laajennus. YVA-selostus. 26.4.2012

Rao S.R. and Finch J.A. 1989. A review of water re-use in flotation. Minerals Engineering 2: 65–85.

Romero J., Yañez C., Vásquez M., Moore E.R.B. and Espejo R.T. 2003. Characterization and identification of an iron-oxidizing, Leptospirillum-like bacterium, present in the high sulfate leaching solution of a commercial bioleaching plant. Research in Microbiology 154: 353–359.

Rossi G. 1990. Biohydrometallurgy. McGraw-Hill, Hamburg.

Rubio R.F. 2012. Mining: The challenge knocks on our door. Mine Water Environ 31: 69–73.

Rytteri T. 2012. Social responsibility strategies for the public relations of mining companies in Finland. Conference on socially and environmentally responsible mining, November 27-28, 2012. Espoo, Finland.

Sampson M.I. and Phillips C.V. 2001. Influence of base metals on the oxidising ability of acidophilic bacteria during the oxidation of ferrous sulfate and mineral sulfide concentrates, using mesophiles and moderate thermophiles. Minerals Engineering 14: 317–340.

Slatter K.A., Plint N.D., Cole M., Dilsook V., de Vaux D., Palm N. and Oostendorp. 2009. Water management in Anglo Platinum process operations: Effects of water quality on process operations. Abstracts of the International Mine Water Conference, 19th-23rd October 2009, Pretoria, South Africa. pp. 46–55.

Söderholm K. 2013. Prospects of the mining industry in the Nordic countries and sub-contractor opportunities. EnergyMatchMetal 2013, Vaasa 20.3.2013.

Talvivaara. 2012. Kaivoksen laajennuksen ympäristövaikutusten arviointi. Arviointiohjelma. 24.2.2012. N-Paino Oy, Lahti.

Talvivaara. 2013. www.talvivaara.com [accessed 8.8.2013]

United States. Code of Federal Regulations, Title 40, part 440. Ore mining and dressing point source category.

USGS. 2013. Mining water use. http://ga.water.usgs.gov/edu/wumi.html [accessed 5 July 2013]

Uusisuo M. 2013. Mining industry. Sector report 1/2013. Ministry of Employment and the Economy, Finland.

Vainionpää P. 2007. Hitura Mining Oy. Rikastushiekka-alueiden YVA-arviointiohjelma. 13.8.2007.

Vardanyan N.S. and Akopyan V.P. 2003. Leptospirillum-like bacteria and evaluation of their role in pyrite oxidation. Microbiology 72: 438–442. Translated from Mikrobiologiya 72: 493–497.

Victoria University and CSIRO. 2008. Guidance for the use of recycled water by industry. Institute for Sustainability and Innovation, Victoria University. CSIRO Land and Water – For the Smart Water Fund.

Westerstrand M. and Öhlander B. 2011. Geochemical effects of increased production on recirculated process water at the Kiirunavaara iron mine, northern Sweden. Mine Water Environ 30: 252–262.

Whittington B.I., McDonald R.G., Johnson J.A. and Muir D.M. 2003. Pressure acid leaching of arid-region nickel laterite ore. Part I: effect of water quality. Hydrometallurgy 70: 31–46.

World Bank Group. 1998. Base metal and iron ore mining. Pollution prevention and abatement handbook. Project guidelines: Industry sector guidelines. Effective July 1998.

Xu J., Liu R., Sun W., Hu Y. and Dai J. 2012. Effect of mineral processing wastewater on electrochemistry of galena. Journal of Environmental Science and Engineering A 1: 279–285.