GEOLOGICAL SURVEY OF FINLAND
Report of Investigation 218
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Kemi Mine

Envimine project –Developing environmental and geodynamic safety related to mine closure in the Barents region

Ulpu Väisänen (ed.), Hannu Hirvasniemi, Pentti Kouri,
Juho Kupila, Laura Lauri and Marja Liisa Räisänen

GTK

Kolarctic
ENPI CBC | CROSS-BORDER COOPERATION

GEOLOGIAN TUTKIMUSKESKUS **GEOLOGICAL SURVEY OF FINLAND**

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Front cover: Aerial photo of the Kemi Mine.
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In this report, the results of geochemical studies in the Kemi Mine area as a part of the mining environmental project of ENVIMINE are presented. The project was carried out in 2012–2014, in cooperation between the Geological Survey of Finland (GTK), Luleå University of Technology (LTU), Sweden, and the Mining Institute, Kola Science Centre, Russian Academy of Sciences (MI KSC RAS), Russia. The study area in Russia was the closed mine of Umbozero and in Sweden the closed mine of Laver.

The Kemi Mine was chosen as the study area of Finland due to the abundance of monitoring data on its environmental impacts, and information on the present state. The mine provides an example of what type of data is collected during mining, and how it can be exploited during mine closure.

One aim of the project was to update the database on the mine site by means of previous and new research data. New research included mapping of surficial deposits, fieldwork and geochemical sampling. Geochemical studies were conducted by analysing organic bottom sediments in the tailings and streams and surface waters in the mine sites and reference areas. Based on water analyses at the Kemi Mine, indicative elements for tailings water contamination were nitrate (NO_3), sodium (Na) and chromium (Cr). The concentrations of the effluents markedly decreased in downstream waters of the mine. Cr was mainly bound to solid particles in waters of the facility and downstream creek waters. Therefore, Cr in downstream waters does not cause toxic impacts on the biota. The chemical behaviour of the several trace metals, especially manganese (Mn), zinc (Zn) and lead (Pb), but also copper (Cu), molybdenum (Mo), arsenic (As) and selenium (Se), suggests that they could originate from peat in the neighbouring bog rather than from the tailings facility. This argument is based on their mobility (acetate extractability) in peat next to the facility. The results demonstrated that most of the phosphorus (P) in the stream sediments is discharged from the drained bogs next to the facility. The occasional increase in P concentrations in the settling pond and seepage well waters originated from the pad peat sediments rather than from the tailings fines. Overall, it can be concluded that the potential impact of tailings effluents on watercourses is more connected with turbidity (fine solids, salinity), despite the NO_3 effluent. Cr effluents into downstream watercourses consist of Cr-bearing solid particles, which appear to be inert in the neutral creek waters. This project was co-funded by the European Union, through the Kolarctic ENPI CBC 2007–2013 Programme.

Keywords (GeoRef Thesaurus, AGI): mines, chromite ores, mining waste, environmental effects, soils, bedrock, surface water, ground water, vegetation, air, Kemi, Lapland, Finland

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Kaivosympäristöhanke ENVIMINE toteutettiin vuosina 2012–2014, yhteistyössä Geologian tutkimuskeskuksen (GTK), Luulajan teknillisen yliopiston (Luleå Tekniska Universitet LTU, Ruotsi) ja Venäjän Kaivosinstituutin (Mining Institute, Kola Science Centre, Russian Academy of Sciences MI KSC RAS, Russia) kanssa.

Tutkimusalueet olivat Suomessa Kemin kromikaivos (Outokumpu Chrome Oy) sekä suljetut kaivokset Umbozero Venäjällä ja Laver Ruotsissa. Tutkimuskohteista tehtiin päivitetyt tietokannat pohjautuen sekä aikaisempiin aineistoihin että projektin uusiin tutkimustuloksiin. Kaivos- ja referenssialueilla tehtiin geokemiallisia tutkimuksia, näytteenottoa ja analysointia vesistä, maaperäkerrostumista ja pohjasedimenteistä. Tässä raportissa on kuvattu geokemialliset tutkimukset Kemin kaivoksella, Suomessa. Se valittiin tutkimuskohteeksi, koska kaivoksella on laaja seurantatutkimusaineisto kaivoksen ympäristövaikutuksista ja nykytilasta. Kemin kaivos toimii esimerkkinä siitä, mitä tietoa sen toiminnoista ja ympäristöstä kaivoksen elinaikana kerätään ja miten niitä voidaan hyödyntää sulkemistilanteessa.

Kemin kaivoksella tehtiin geokemiallisia tutkimuksia, otettiin näytteitä analyysejä varten pinta- ja pohjavesistä, maaperäkerrostumista ja orgaanisista purosedimenteistä. Tutkimusten mukaan rikastushiekka-altaiden veden pilaantumista osoittavat indikaattorit ovat NO_3, Na ja Cr. Vesien pitoisuudet pienenivät huomattavasti kaivoksesta etelään vesistöjen alajuoksulla. Cr on pääasiassa sitoutunut veden kiintoainekseen altaissa ja purovesien alajuoksulla. Tämän vuoksi Cr ei aiheuta vesistöjen alajuoksulla haittavaikutuksia eliöstöön. Useat hivenalkuaineet, erityisesti Mn, Zn ja Pb, mutta myös Cu, Mo, As ja Se, ovat peräisin pikemminkin paikallisista turvekerrostumista kuin rikastushiekka-altaista. Tämä perustelu pohjautuu niiden liikkuvuuteen (asetaattiuutot) turvekerrostumissa rikastushiekka-altaiden läheisyydessä. Tutkimustulosten mukaan suurin osa purosedimenttien fosforista vapautuu ojitetuilta soilta rikastushiekka-altaiden läheisyydestä. Satunnaiset kohonneet fosforipitoisuudet rikastushiekka-altaassa ja sen padon viereisessä suotovesikaivossa ovat peräisin todennäköisemmin altaan pohjan turvekerrostumista kuin rikastushiekan hienoaineksesta. Johtopäätöksenä voidaan todeta, että rikastushiekka-altaiden päästöjen potentiaalinen vaikutus vesistöihin liittyy pääasiassa sameuteen (hieno kiintoaines, suolapitoisuus), lukuun ottamatta NO_3-päästöjä. Kromipäästöt alajuoksun vesistöihin koostuvat kromipitoisista kiinteistä hiukkasista, jotka ovat ilmeisesti reagoimattomia neutraaleissa purovesissä. Hanke on saanut rahoitusta EU:lta, ja se kuului Kolarctic ENPI CBC 2007–2013-ohjelmaan.

Asiasanat (Geosanasto, GTK): kaivokset, kromimalmit, kaivosjäte, ympäristövaikutukset, maaperä, kallioperä, pintavesi, pohjavesi, kasvillisuus, ilma, Kemi, Lappi, Suomi

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1 INTRODUCTION

The Barents region is an important source of natural resources, and the mining industry has become increasingly important to the economy of the region. The area has been active in terms of mining in the past and it still has great potential for new discoveries and the development of new mines. However, challenges associated with mine closure will arise due to industrial and environmental safety regulations, constraining negative mining-induced impacts on the surrounding water, soil and air. It is important to find solutions for land remediation, including tailings impoundments and waste rock dumps, which are a hazard to environmental safety due to the contamination of surface water and groundwater, dust releases and potential failures of dams. Mining environmental studies have previously been conducted on many closed mines in Finland and Sweden, but there is also a great need for studies on closed mines in Russia. The Geological Survey of Finland (GTK) has carried out environmental studies on mines in Northern Finland, such as the Kevitsa Mine (Väisänen & Lanne 2005, Väisänen & Muurinen 2006, Väisänen et al. 2008, Pietilä et al. 2014) and the closed mine of Rautuvaara, Kolari (Räisänen et al. 2007).

The project *Mining environmental research in the Barents region* (ENVIMINE) was carried out in cooperation between Finland, Russia and Sweden in 2012–2014. The study area in Finland was

Fig.1. The study areas of the project: Kemi Mine, Laver Mine and Umbozero Mine.

the active chrome mine of Kemi, located in Northern Finland near the city of Kemi. It is the only chrome mine in the European Union and has been in production since 1968. The Kemi Mine was also an associate of the project. The other study areas were the closed mines of Umbozero in Murmansk region, Russia, and Laver in Norbotten, Sweden (Fig.1). The Umbozero Mine, with loparite ore, producing rare earth metals, was in operation from 1984–2004, and the copper mine of Laver from 1936–1946. An aerial photo of the Kemi Mine is displayed on the cover page.

The objectives of the project, presented in the project plan of ENVIMINE (Annex 1 of the Grant Contract), were to develop methodology for environmentally safe mine closure under the specific climatic and natural conditions in the Barents region, and to produce information for target groups and stakeholders with an interest in the mining environment. The aims were to create an updated database of the mine sites and develop multilateral relations between Finnish, Russian and Swedish organizations responsible for environmental management. The aim was also to develop and carry out environmental research with the best available techniques (BAT), and to exchange experiences and scientific knowledge.

Field studies for the project were carried out in all the partner countries. However, in this report provides a description of the studies and results concerning the Kemi Mine in Finland. Field studies on the Kemi Mine were carried out in 2013–2014. Geochemical studies were conducted by analysing organic bottom sediments in the tailings and streams. Surface waters were analysed at the mine sites and reference areas. The aims were to determine the concentrations and origin of heavy metals and other contaminating elements and compounds dissolving in waters and flowing into the environment, and to define the water flow directions in the area.

Conclusions and recommendations for aftercare plans and monitoring programmes for the study areas of the closed mines, Laver in Sweden and Umbozero in Russia, were also aims of the project (Väisänen et al. 2014). The research data used in this report are partly monitoring data of the Kemi Mine and new data of GTK. The project was co-funded by the European Union, Kolarctic ENPI CBC Programme.

2 DESCRIPTION OF THE KEMI MINE STUDY AREA

The Kemi Mine of Outokumpu Chrome Oy is situated 8 km to the east of the centre of Kemi (Fig. 2). The nearest inhabited areas are situated to southwest and north of the mine, at a distance of 2–2.5 km. Kemi airport is located 5 km to the west of the mine. The landscape is characterized by flat areas with small hills and lowlands with swamps or paludified forests. The vegetation of the area is lush, due to calcareous rocks. Differences in topography are mostly only between 10–15 m. The mine site and most parts of the surroundings are situated approximately 20–30 m a.s.l. The long-term average temperature during the years 1981–2010 was +1.7 °C and precipitation 580 mm/year. Approximately half of the precipitation falls as snow. The thickness of the snow cover is 700–800 mm. The prevailing wind directions are variably from the north, northeast, south and southeast. (Pöyry Finland Oy 2014)

2.1 Bedrock

The 1:100 000 bedrock map (Perttunen 1971) and explanation (Perttunen 1991) of the Kemi area published by GTK were used as the main sources of information in the following review. The bedrock in the study area can be divided into three main units: (1) the Archaean >2.7 Ga Pudasjärvi gneiss complex, (2) the ~2.43 Ga mafic layered intrusions and (3) the mostly metasupracrustal rocks of the Peräpohja schist belt that are <2.4 Ga in age (Fig. 3).

The Archaean Pudasjärvi Complex consists of granitoids, gneisses and greenstone belt fragments that are all older than ~2.7 Ga. The 3.5 Ga Siurua trondhjemite gneiss, the oldest known rock formation in Finland, is situated within the Pudasjärvi complex in its eastern part (Mutanen & Huhma

Fig. 2. Map of Kemi and the surroundings (Outokumpu Chrome Oy 2009).

2003). In the study area, the Archaean rocks comprise Neoarchaean (~2.7–2.8 Ga) tonalites, diorites and leucogranitoids that are medium-grained, foliated, banded and commonly migmatized. The main minerals in most gneiss types are quartz, plagioclase and K-feldspar in various proportions, in addition to which the rocks contain biotite, chlorite and amphibole as the ferromagnesian minerals. Amphibolite and hornblendite inclusions are typically present within the other rock types. The large leucogranite area marked in the geological map (Fig. 3) may not be defined as clearly in the field; rather, the rocks within the area marked as granite generally contain more K-feldspar than the surrounding tonalite areas, but the contacts between the rock types are gradational.

Giant mafic layered intrusions were emplaced within the rifted Archaean crust of the Fennoscandian shield in the early Palaeoproterozoic (Iljina & Hanski 2005, Lauri et al. 2012). The Kemi intrusion that hosts the Cr mine forms a part of a chain of intrusions that extends from the Tornio area in western Lapland through northern Finland to the Koillismaa area in the east and to the Kola Peninsula in Russia. According to Alapieti et al. (1989), the Kemi intrusion is a lenticular body ~15 km long and 2 km wide in the middle. The lowermost 500 m, which hosts the Kemi Cr deposit, consists of ultramafic rocks. At least 15 chromitite interlayers (0.002–90 m thick) are known within the ultramafic zone. The upper part of the intrusion is composed of gabbros, gabbronorites, leucogabbros and anorthosites. The best age estimate for the Kemi intrusion is the $^{207}Pb/^{206}Pb$ age of 2430 ± 4 Ma measured from the least discordant zircon fraction of sample A662 Elijärvi (Perttunen & Vaasjoki 2001).

The supracrustal rocks of the Peräpohja Belt were deposited above the Archaean gneisses and the mafic layered intrusions, which were already subject to erosion before the sedimentation commenced (Perttunen 1991). The stratigraphy begins with a basal conglomerate (Sompujärvi formation) that contains clasts from the underlying layered intrusions, limiting the age of the Peräpohja Belt to <2.4 Ga. In the study area, the rocks of the

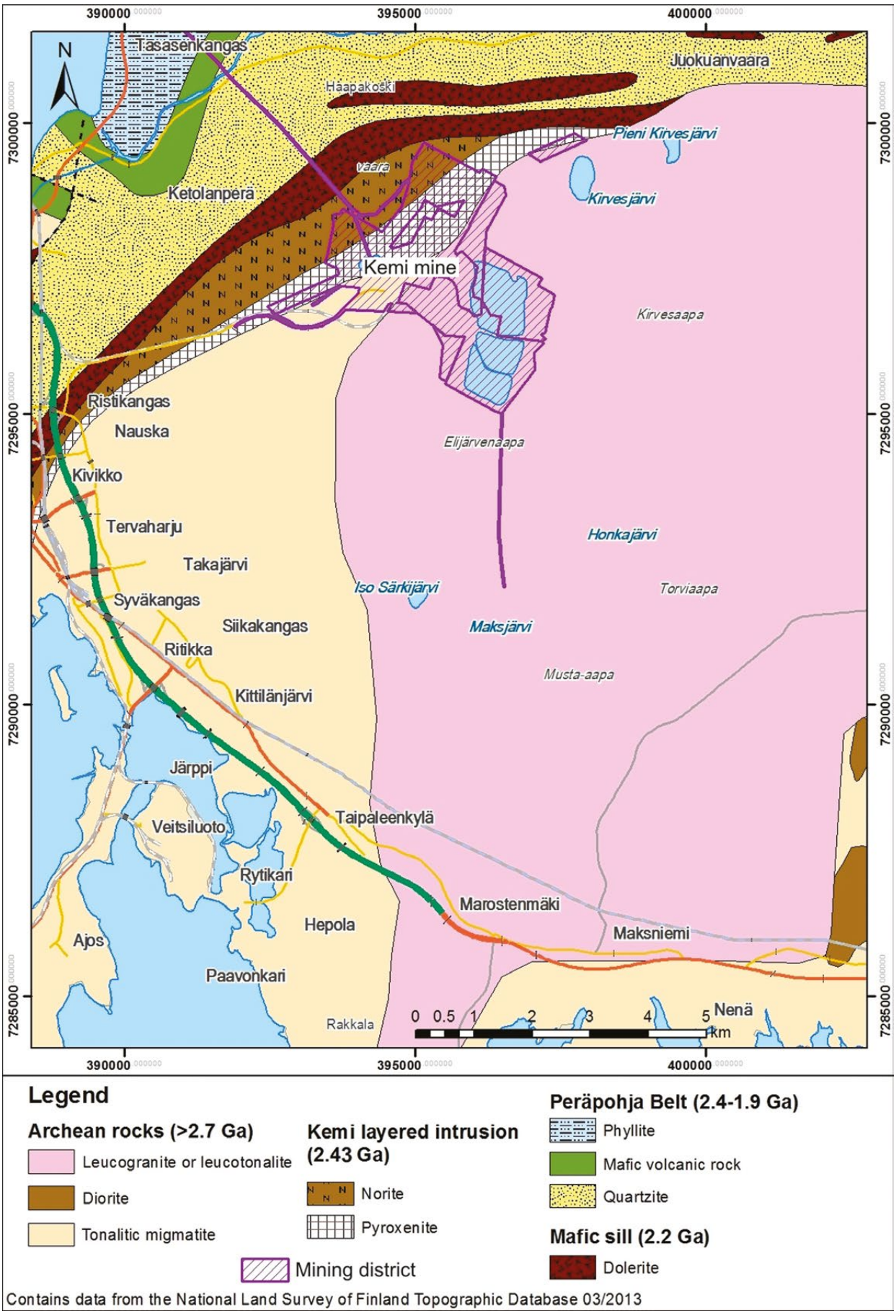


Fig. 3. Bedrock of the Kemi Mine site and surroundings. Extracted from the digital bedrock map database DigiKP of GTK. The Kemi mining concession is taken from the mining register of Tukes (extracted 5.9.2014).

Peräpohja Belt are present in the northern parts (Fig. 3). The quartzite unit that covers most of the area N of the Kemi Cr mine belongs to the Palokivalo formation (see Hanski et al. 2005 and references therein). It consists of light grey clastic quartzite that commonly shows sedimentary structures such as layering, cross-bedding and ripples marks. The quartzite may contain some K-feldspar and sericite. The quartzite is overlain by mafic volcanic rocks of the Jouttiaapa formation. The formation consists of 0.5–60 m thick lava flows that occasionally have amygdules in the bottom and top parts. The rocks have undergone greenschist facies metamorphism and consist of actinolite, albite, epidote and chlorite. The amygdules may contain zeolites such as analcime or laumontite. The mafic volcanic rocks of the Jouttiaapa formation are succeeded by mica schists of the Martimo formation, which are present in the upper NW corner of the study area. The Martimo formation consists of phyllites and mica schists, which were deposited in a deepening marine basin by turbidity currents. The main minerals are quartz and micas (sericite, chlorite and biotite).

The Kemi intrusion and the quartzite of the Palokivalo formation are separated from each other by a mafic dolerite sill (Fig. 3). These dolerites mark a widespread magmatic event at ~2.2 Ga, which extends from Central Lapland to the Peräpohja and Kuusamo areas and to the Koli area in eastern Finland (Hanski et al. 2010). The dolerite magmas intruded the quartzites as sills that are commonly gravity differentiated so that the sills from bottom to top comprise olivine, olivine–clinopyroxene, clinopyroxene, clinopyroxene–magnetite and plagioclase–clinopyroxene–magnetite cumulates. The quartzites in the study area host several dolerite sills that all belong to the 2.2 Ga swarm.

2.2 Quaternary deposits and hydrogeological conditions

The main surficial deposits in the study area and surroundings are till and peat. Sand and gravel deposits are situated scattered over the whole area. Till and sand areas are in many places covered with peat deposits, their thickness mostly being less than 1 m. A glaciofluvial formation of gravel and sand extends from the northwestern part of the area to the southern part. There are numerous bedrock outcrops in the area, and minor areas of fine-grained sediments (Fig. 4). Kirvesaapa, a Natura 2000 protected area, is situated east of the mine site. The private nature conservation area of Purolehto is located next to Iso-Ruonaoja, 5.5 km downstream of the mine.

The Kemi Mine and surrounding areas belong to the catchment area of Iso-Ruonaoja. The size of the whole catchment area is 60.71 km^2, and lakes cover 1.4 % of this. The former lake Elijärvi has been drained. The main flow direction of groundwater in the mining district is southeast of the mine (Outokumpu Chrome Oy 2009). Iso-Ruonaoja flows to the southwest, into the bay of Hepolahti, which is connected to the Gulf of Bothnia. The catchment area of Iso-Ruonaoja is swampy and the water is slightly acidic, containing humus. Iso-Ruonaoja and Hepolahti are popular fishing areas (Pohjois-Suomen Aluehallintovirasto 2010).

The water table at the mine site has been monitored in 8 groundwater observation wells since 2004. The water table is high in the mine area, showing a good correlation between the soil type, bedrock level and topographic position. The locations of the wells are presented in Figures 5 and 10. Annual variation in the level of the water table is <1 m, except at the site 4, where it varies by between 1–3 m (Figs 5–9). According to Outokumpu Chrome Oy (2013), the water table in the groundwater observation wells varied during 2013 from +20.00 to 31.01 m (N_{43}). The water table was highest at observation well PV6, as also in earlier years. PV6 is situated on the western side of the mine. The lowest water table was in observation well PV2, situated on the southern side of clarification pond 5. In July 2013, the water table varied in depth from 0.3–1.45 m, except in observation well PV1, where the water table was at the level of the ground surface. According to observations, the impacts of the mine on the water table in the surroundings have been very small. Changes in the water table are mainly due to seasonal changes and the amount of precipitation.

Three groundwater areas are situated in surroundings of the mine. Ristikangas-Ketolanperä-Salmenkylänkangas is an important groundwater area (Class I), located to the west of the mine. The shortest distance to the mine site is 500 m. The

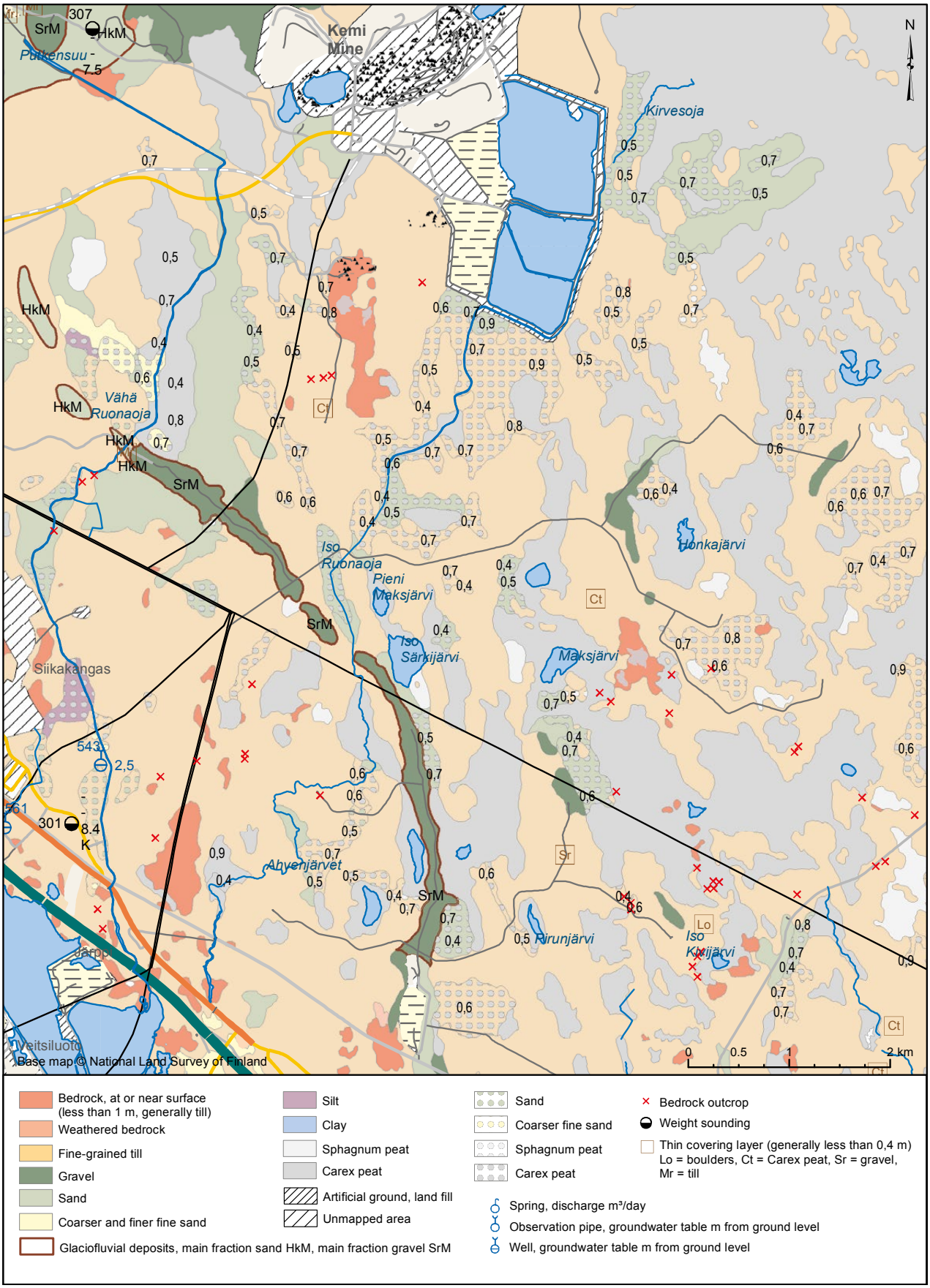


Fig. 4. Quaternary deposits of the Kemi Mine site and surroundings (the map compiled by Raija Pietilä, according to the data of GTK).

size of the groundwater area is 526 ha, and the total area of the formation is 4.2 km². Two other groundwater areas are situated further from the mine, the shortest distance being 3 km (Outokumpu Chrome Oy 2009).

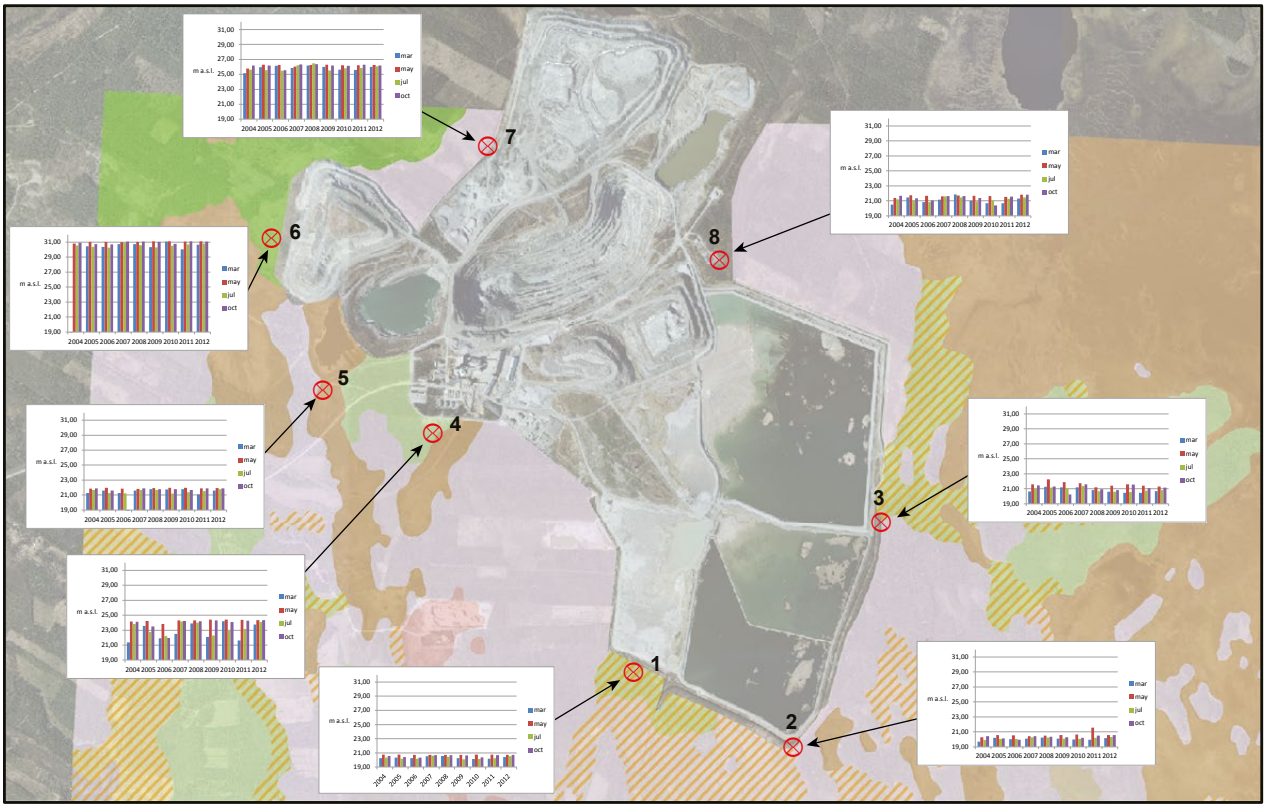
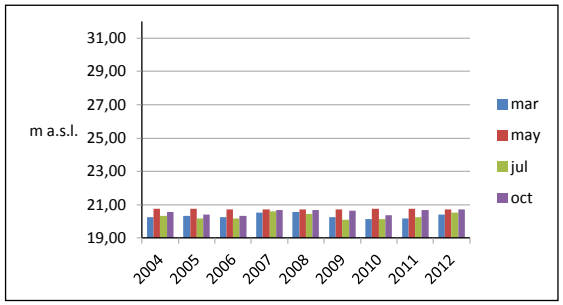
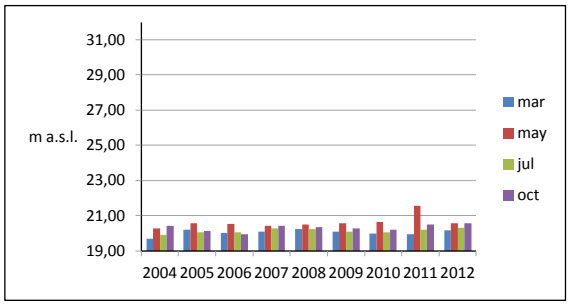


Fig. 5. General view of the groundwater monitoring sites at the Kemi Mine with the annual groundwater level in 2004–2012. Sampling was carried out in March, May, July and October.

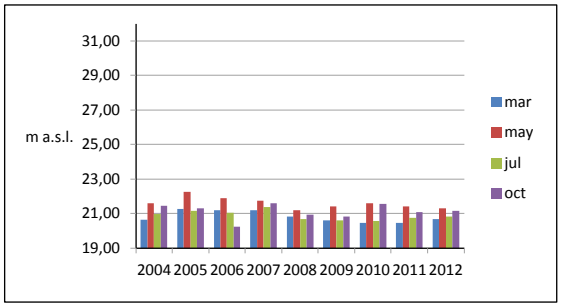


Groundwater monitoring site 1.
Ground level 20.43 m a.s.l.
- 0 - 0.4 m peat
- 0.4 - 2 m sand
- 2 - 7 m sandy moraine
- 7 m→bedrock

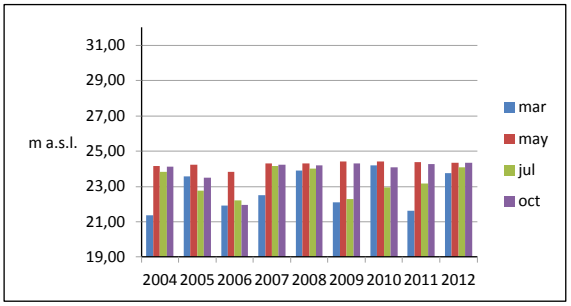


Groundwater monitoring site 2.
Ground level 21.45 m a.s.l.
- 0 - 0.4 m peat
- 0.4 - 1.6 m sand
- 1.6 - 3.7 m sandy moraine
- 3.7 m→bedrock

Fig. 6. Water table and thicknesses of surficial deposits at groundwater monitoring sites 1 and 2, Kemi Mine.

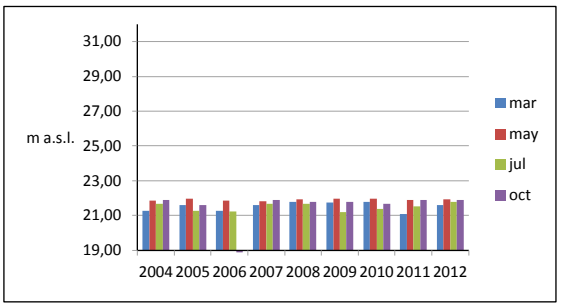


Groundwater monitoring site 3.
Ground level 22.43 m a.s.l.
- 0 - 0.2 m humus
- 0.2 - 1.3 m sand
- 1.3 - 3.3 m sandy moraine
- 3.3 m→bedrock

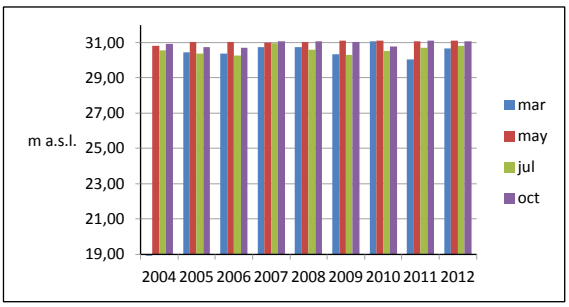


Groundwater monitoring site 4.
Ground level 24.55 m a.s.l.
- 0 - 0.4 m peat
- 0.4 - 3 m sandy moraine
- 3 m→bedrock

Fig. 7. Water table and thicknesses of surficial deposits at groundwater monitoring sites 3 and 4, Kemi Mine.

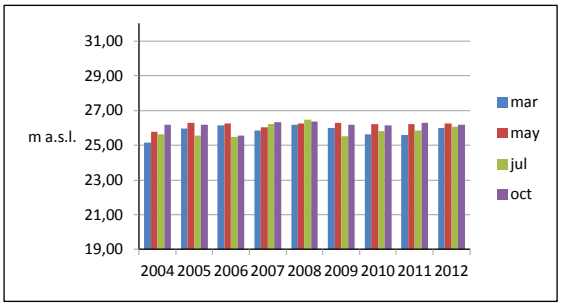


Groundwater monitoring site 5.
Ground level 21.87 m a.s.l.
- 0 - 0.5 m peat
- 0.5 - 1.3 m sand
- 1.3 - 4.3 m sandy moraine
- 4.3 m→bedrock

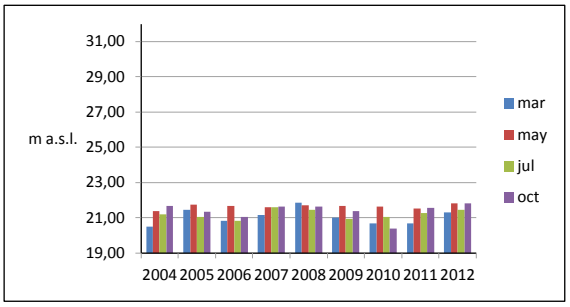


Groundwater monitoring site 6.
Ground level 31.4 m a.s.l.
- 0 - 0.1 m humus
- 0.1 - 6 m sandy moraine
- 6 m→bedrock

Fig. 8. Water table and thicknesses of surficial deposits at groundwater monitoring sites 5 and 6, Kemi Mine.



Groundwater monitoring site 7.
Ground level 27.37 m a.s.l.
- 0 - 0.2 m humus
- 0.2 - 7 m sandy moraine
- 1.3 - 4.3 m sandy moraine
- 7 m→bedrock



Groundwater monitoring site 8.
Ground level 22.05 m a.s.l.
- 0 - 0.7 m peat
- 0.7 - 1.5 m sand
- 1.5 - 10 m sandy moraine
- 10 m→bedrock

Fig. 9. Water table and thicknesses of surficial deposits at groundwater monitoring sites 7 and 8, Kemi Mine.

3 FACTS ON THE KEMI MINE AND ORE PRODUCTION

The chromite ore of the Kemi Mine was originally found in 1959 by Martti Matilainen, a diver. Geologist Aarno Kahma from GTK investigated this promising ore discovery, and delivered the data to Outokumpu Oy. Investigations were carried out until 1962, and a road and railway connections were built to the area. The formation of the chrome ore is about 15 km long, situated from under the city of Kemi to the area of Elijärvi and Kirvesjärvi. The stratigraphic thickness of the formation varies from 200 m to approximately 2 km, and it is thickest in the mine site. The formation is part of a chain of magmatic intrusions, aged about 2.4 billion years (Outokumpu Chrome Oy 2009). Seismic studies have indicated that the ore deposit extends to a depth of several kilometres (Kauppila et al. 2013).

Open pit mining at the Kemi Mine started in 1968. Underground mining started in 2003, and all production has been from the underground mine since 2006. In the future, approximately 2.7 Mt/a of ore will be processed (Outokumpu Chrome Oy 2009). In 2014, updated estimations of ore reserves were 50.1 Mt and mineral resources 97.8 Mt. All gangue will be used for backfilling of the underground mine. The size of the tailings area is 290 hectares, including the areas of the clarification ponds. The enrichment process has produced approximately 500 000 tons of tailings annually (Table 1), and 1.2 Mt since enlargement (Pohjois-Suomen Aluehallintovirasto 2010). The ore consists of chromite, tremolite, chlorite, talc, carbonates and serpentinite. Rocks of the "Kemi layered intrusion" consist of gabbro, peridotite, serpentinite and chrome ore. The average chromium oxide (Cr_2O_3) content of the ore is 26.5 %. The waste rock is comprised of talc-carbonate rock, pyroxenite, peridotite- and talc serpentinite, granite-gneiss, albite- and dolerite-dyke rocks. The Kemi Mine is presently the only oxide mine in Finland (Kauppila et al. 2013).

The products are lumpy ore and fine concentrate. In 2013, 1 760 026 tons of ore was mined, and the amount of waste rock was 924 156 tons. About 145 000 tons of waste rock were added to the waste rock pile, 15 880 tons of granite was transferred into the store and 763 264 tons was used for filling mine shafts. Some waste rock was sold and approximately 99 000 tons were crushed for chips, mainly for road building and gritting. In 2012, the deepest mine shafts extended to a depth of 600 metres.

Table 1. Summary of operation before expansion and estimations of operation after expansion of the mine (Outokumpu Chrome Oy 2009, Pohjois-Suomen Aluehallintovirasto 2010).

	Operation before expansion	**Expansion (estimations according to YVA)**
Mine	Underground mine, open pit quarries 83 ha	Quarrying will continue deeper; the area of the mine will not grow.
Amount of quarrying	1 300 000 t/year	2 700 000 t/year
Buildings	5 700 m^2	Expansion appr. 6 000 m^2 more
Production capacity	650 000 t/year	1 300 000 t/year
Landfill of waste rock	Landfill areas 150 ha	No new landfills; waste rock of old landfills will also be placed in mine shafts.
Amount of lump rock	160 000 t/year	270 000 t/year
Amount of waste rock	400 000 t/year	1 000 000 t/year
Tailings	290 ha	No more tailings will be built during expansion.
Amount of tailings	500 000 t/year; total in 2010 8.7 Mt in the tailings	1.2 million t/year
Use of water	2 600 000 m^3/year	5 000 000 m^3/year (will be less according to the latest information)
Energy consumption	40 000 MWh/year	80 000 MWh/year
Traffic	Trucking 45 loads/day or train transport 2 loads/day	Trucking 90 loads/day or train transport 4 loads/day

Many service operations are presently situated underground, such as the crushing plant, transportation equipment and other services required by infrastructure facilities and equipment. Concentration of the ore occurs in two stages, with methods based on gravity separation. The stages are lump concentration and fine concentration (Kauppila et al. 2013). Chromite ore is concentrated in the concentration plant of the Kemi Mine and transported to the Tornio ferrochrome works. After enlargement, the mine production will be doubled. Estimated ore and mineral reserves for mining are probably enough for tens of years (Outokumpu Chrome Oy 2009).

The Kemi Mine has 7 tailings ponds. Two ponds (numbers 4 and 5) are clarification basins, while the others are tailings basins (Fig. 10). Tailings material and waters from the concentration plant are directed to the clarification ponds. The amount of tailings material pumped to the tailings basins was 975 701 tons in 2013. Circulation of waters from pond 5 started in 1991. Tailings pond number 1 (size 22 ha) has been filled and landscaped (Pöyry Finland Oy 2014). Tailings ponds 2–3 (25 ha) and 6 are almost full. Tailings pond 7 (108 ha) has been used since 2008 (Outokumpu Chrome Oy 2009). The clarification ponds of the Kemi Mine have abundant birdlife, and rare birds are also resident there. The fish in the ponds, such as pike, perch, roach and crucian carp, originate from Iso-Ruonaoja. The nutrient-rich water of the ponds is the reason for richness of the birdlife (Rauhala & Ylimaunu 2006).

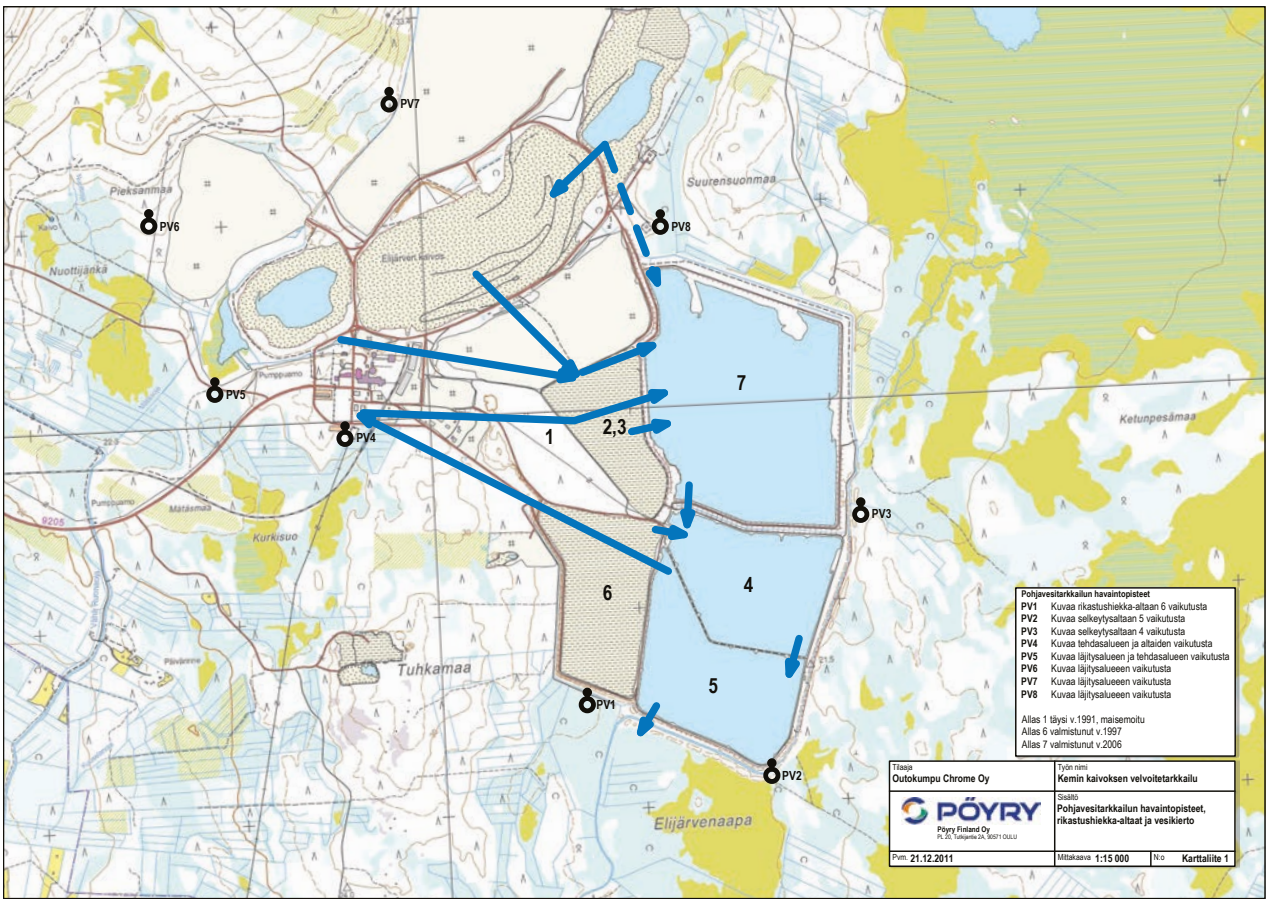


Fig. 10. Tailings basins, groundwater monitoring sites since 2004 and water flow directions (blue arrows) at the Kemi Mine (Pöyry Finland Oy 2014).

4 ENVIRONMENTAL IMPACTS

Environmental impacts in the Kemi Mine are minor due to the oxide ore type. Weathering has not caused acidification or the dissolution of heavy metals. Resistance against acidification is good due to the basic rocks in the area. The ore, barren rock obtained in open-pit mining and tailings are in practice insoluble, and the dissolving minerals are mainly carbonates. Environmental impacts are minimal because the processing of concentrates does not involve chemicals, except flocculants. The processes are based on gravimetric separation. Environmental impacts have also been controlled by circulating waters in the mine.

4.1 Emissions

Generally, mining causes emissions to the air from blasting, ore crushing, grinding and concentrating, drying of concentrates, heating, traffic, and the storage of tailings and waste rock. The most significant air emissions are the blasting gases carbon dioxide (CO_2), nitrogen (N_2), carbon monoxide (CO) and nitrogen oxides (NO_x), exhaust gases (CO_2, CO), hydrocarbons, NO_x and sulphide dioxide (SO_2), fine particles, process gases, particulate emissions and mineral dust. Mineral dust emissions are produced by excavation, transport, loading, crushing, grinding and drying, piling of waste rock and the storage of concentrate and tailings. The composition of mineral dust corresponds to finely ground ore and the associated waste rock (Kauppila et al. 2013). Emissions have decreased in past years, mainly due to the decreased transport of waste rock from the open pit (Nikula 2012).

The Kemi Mine has used various types of explosives. The oil emulsion explosive Kemiitti 810 has been considered to be environmentally the most friendly, due to its stable structure in wet conditions (Oy Forcit Ab 2012, Vuolio 2001). N emissions from old explosives have been found, especially in old waste rock piles. Lately, explosives have been practically insoluble in water, and emissions from explosives have diminished, since all mine operations are now underground.

The load of SO_2 decreased during the 2000s from 30 tons/year to 7 tons/year, and the load of NO_x from 25 tons/year to 12 tons/year. Emissions of CO_2 decreased by 50 % to 6700 tons/year (in 2008), due to the use of propane in heating of the underground mine since 2005. Internal traffic has also decreased (Pohjois-Suomen Aluehallintovirasto 2010).

Examples of contemporary means for mitigating airborne emissions and associated environmental impacts used in the Kemi Mine according to Kauppila et al. (2013) are as follows:

- Dust removal systems operate in the mine and concentration plant.
- Dusting of roads and waste areas is prevented by sprinkling and using dust-binding agents.
- Concentrates are stored indoors. Loading areas are asphalt surfaced and are regularly washed during the summer. Concentrate, stored outdoors, is sprinkled in the summer.
- Hydrate lime has been tested in the tailings pond for the prevention of dust (could also be used in closed mines).
- Covering and landscaping of the tailings has been carried out as soon as these are full.
- A contingency system is in place in case of environmental damage.

Examples of methods used for the mitigation of water and wastewater loading and the consequential environmental impacts of these are as follows:

- Almost all the water (98 %) required for the concentration process is recycled.
- All surface water of the mining area is conducted to the settling pond.
- A contingency plan is in place in case of environmental damage.

The impacts of the underground mine will also be quite small following enlargement. Some increase in emissions to air will occur due to the increasing need for fuel. Dust and gas emissions of the enrichment plant will also slightly increase. Emissions to waters are minor (Pohjois-Suomen Aluehallintovirasto 2010).

4.2 Waste rock and tailings

The main metals in both the waste rock and tailings are chromium (Cr) and nickel (Ni). Cr is bound to oxide minerals and magnesium (Mg) to silicates. The iron sulphide concentration of the waste rock is low. The high concentrations of carbonates in waste rock neutralize the acidity of infiltrated water inside the piles. The amounts of waste rock, lumpy rock and tailings produced by the Kemi Mine in 2003–2008 are presented in Table 2.

Table 2. Mine wastes of the Kemi Mine in 2003–2008 according to Pohjois-Suomen Aluehallintovirasto (2010).

Waste 1000 tons	2003	2004	2005	2006	2007	2008
Waste rock	3985	3422	561	270	407	498
Lumpy rock	88	80	87	132	141	159
Tailings	466	545	490	493	509	501

The emissions from and solubility of tailings and waste rock have been investigated by means of CEN, a rapid batch leaching test. The solubility of metals from the tailings is low. Metals in the waste rock and tailings are in a slightly soluble form, and a limited amount of nitrogen residues from explosives has dissolved in the circulated water. Nutrients in the overflow have slightly increased eutrophication in ditches and brooks, but the impacts rapidly diminish downstream, close to the sea. The impacts of Iso-Ruonaoja in the gulf of Hepolahti, Gulf of Bothnia, are hardly detectable (Pohjois-Suomen Aluehallintovirasto 2010).

The bottom of the tailings consists of the original soil of the area, while the compact parts of the dams are comprised of till. Part of waters in the tailings flows to the environment through controlled overflow, and infiltration also occurs through the bottom and dams.

4.3 Waters

Water is required in various mining processes, for instance, for the concentrator, underground quarrying and in sanitary facilities. Process water consumption in the concentrator totals about 2 500 000 m^3/year and in underground quarrying 100 000 m^3/year (Outokumpu Chrome Oy 2009).

Tailings material is pumped to tailings basin 7, from where the waters flow to clarification basin 4, and further to basin 5 (Fig. 10). Part of water is taken from the basins back to the enrichment plant, while the rest flows via Iso-Ruonaoja to Hepolahti (Pohjois-Suomen Aluehallintovirasto 2010). Waters from the mine site that flow to the environment include overflow and leachate from the clarification ponds, and runoff waters from the mine, including waters from the Viianmaa open pit. The main effluents are solids, calcium (Ca), nitrogen (N) and iron (Fe) (Pöyry Finland Oy 2014).

Old explosives produce N effluents in waters, and infiltration waters contain phosphorus (P). N concentrations have been high in the open pit of Viianmaa due to the remnants of explosives. The effluent load in waters is formed of overflow from clarification pond 5, leachate waters from the tailings and clarification ponds, and runoff waters from the mine area. Some impacts of the mine on water quality have been observed in Iso-Ruonaoja, downstream of the mine, including higher Ca, N and in the summer P concentrations (Pöyry Finland Oy 2014). Some zinc (Zn) and Cr, partly bound to solids, has spread to the environment (Outokumpu Chrome Oy 2009). Leachate waters through the dams were estimated to total approximately 769 000 m^3 in 2013. Controlled overflow from basin 5 was approximately 1 098 000 m^3. The effluent load during the years 2003–2009 is presented in Table 3 (Pöyry Finland Oy 2014). The effluent load of the mine is calculated by measuring the discharge of Kirvesoja, upstream of the mine, and Iso-Ruonaoja, downstream of the mine, and by calculating changes in water quality caused by the mine, based on changes in concentrations and discharges (Outokumpu Chrome Oy 2009). Calculations of the concentration differences between substances were performed by Pöyry Environment Oy.

Table 3. Discharged amount of water and effluent load of the Kemi Mine in 2000–2013 (- denotes concentrations under the limit of the assay, or that the calculated effluent load is negative), according to Pöyry Finland Oy (2014).

Year	Discharge	Effluent load									
	m³/a	Solids t/a	Tot P kg/a	Tot N kg/a	Ca t/a	Fe t/a	Zn tot kg/a	Cr tot* kg/a	Cr diss** kg/a	Ni tot kg/a	Ni diss kg/a
2000	4 200 000	33	355	20 494	191	11	-	79	-		
2001	2 900 000	21	332	18 369	182	15	5.0	5.2	0.5		
2002	2 050 000	10	273	12 788	183	4.0	4.6	5.6	-	31	27
2003	1 330 000	49	268	10 121	183	0.9	6.1	14.5	3.7	41	27
2004	2 100 000	115	581	18 577	300	7.6	3.8	8.2	12	78	
2005	2 300 000	21	409	17 592	220	6.2	68	12	-	57	
2006	1 800 000	38	291	8 566	176	4.3	-	5.7	0.6	31	
2007	940 000	75	673	10 376	388	22	-	109	12	135	
2008	1 400 000	34	679	10 023	420	33	-	28	5.1	67	
2009	1 240 000	38	455	6 555	353	12	-	33	5.6	61	
2010	1 100 000	31	640	5 786	419	13	-	25	5.9	52	
2011	1 400 000	68	633	9 457	437	26	-	-	0.4	67	
2012	3 450 000	-	941	21 283	519	-	121	35	13	99	69
2013	2 810 588	43	295	17 233	434	22	26	37	6.4	91	73

*tot = total, **diss = dissolved

5 MONITORING PROGRAMMES AT THE KEMI MINE

The Kemi Mine has a monitoring programme for the assessment of environmental impacts, including emissions, water quality, dust, noise, vibration, the composition of tailings and waste rock. Heavy metal concentrations in moss and some food plants have also been investigated. Water quality and the water table have been monitored in 8 groundwater observation wells 4–12 times per year and in watercourses in the environment since 2004. Water has been circulated in the mine since 1991. Overflow waters, wastewater quality and impacts on watercourses are checked according to the monitoring programme.

5.1 Water quality

Water samples are analysed once per month from the clarifying pond (P2), Kirvesoja (P1) and Iso-Ruonaoja (P3), nine times per year downstream of Iso-Ruonaoja (P5), and four times per year in Hepolahti (P4) (Fig. 11). Water quality of the Viianmaa quarry is monitored once a month. Water from the quarry flows either to tailings basin 7 or to the surrounding watercourses. Leachate water wells for monitoring leachate from the basin have been built around tailings basin 7.

Measurements and analyses of waters include: temperature, dissolved oxygen, chemical oxygen consumption, pH, electrical conductivity, solids, total N , ammonium N (NH_4-N), nitrate N (NO_3-N), nitrite N (NO_2-N), total P, phosphate P (PO_4-P), chlorides (Cl), Fe, Ca, total and dissolved Cr, Ni, Zn and faecal coliform bacteria. Total Cr, Ni and Zn concentrations and dissolved Cr are analysed 4 times per year (Outokumpu Chrome Oy 2009). The water quality in 2013 is presented in Table 4.

In the winter, mine waters have some impacts on the water quality of Iso-Ruonaoja: higher pH values due to calcium concentrations, higher electrical conductivities and nutrient contents, and lower oxygen contents have been recorded. Sometimes, the winter concentrations of PO_4–P and total P, NH_4, N and Fe have been higher downstream of the mine than in the clarification pond or in Kirvesoja, probably due to leachate waters

from the clarification pond. In the winter, a major part of N exists as NO_3. In the summer, the oxygen concentrations in Iso-Ruonaoja are mainly high. Higher solids (18–33 mg/L) in July–August 2013 were due to algae, not inorganic material. The annual average did not exceed 10 mg/L, which is the maximum average limit according to the permit decision. Some Cr, Ni and vanadium (V) have been found in the sediments of Hepolahti, Gulf of Bothnia. However, they have not changed the ecosystem of Hepolahti. In 2013, impacts of the mine could be seen in Iso-Ruonaoja as a higher pH value, electrical conductivity and N concentrations compared to values in Kirvesoja, upstream of the mine. Cl, Ca, Cr, Zn and Ni concentrations were also higher in Iso-Ruonaoja than upstream of the mine. Further downstream of Iso-Ruonaoja, concentrations were lower, but there were still elevated electrical conductivities and concentrations of Cl, Ca, Zn and Ni compared to waters upstream of the mine. Concentrations of P, Fe and solids have recently been lower downstream of Iso-Ruonaoja (Pöyry Finland Oy 2014).

Table 4. Water quality in Kirvesoja, Iso-Ruonaoja and Hepolahti in 2013 according to Pöyry Finland Oy (2014).

	Faecal coliform bacteria, pc/100 mL	**O_2 mg/L**	**O_2 %**	**pH***	**Electr. cond. mS/m ***	**Solids mg/L**	**N tot µg/L ***	**NH_4-N µg/L ***	**$NO_{2,3}$-N µg/L ***	**P tot µg/L ***	**PO_4-P µg/L ***
Kirvesoja P1	N = 12										
Average	36	7.8	62	6.4	7.6	2.8	621	64	49	21	11
Min	0	5.2	50	5.9	2.5	<1	350	<5	<5	5	<2
Max	200	10	74	6.8	21	8.5	1 100	230	490	46	33
Iso-Ruona-oja	P3 N = 12										
Average	24	6.7	54	7.3	61	4.9	1 494	348	710	45	37
Min	0	3	21	6.9	30	<1	830	60	110	20	5
Max	100	9.4	70	7.7	91	12	2 400	770	1500	80	71
Iso-Ruona-oja	P5 N = 9										
Average	47	10.1	84	7.6	50	4.1	1 173	165	505	34	22
Min	0	8.4	68	7.1	24	1.4	760	12	86	18	7
Max	118	11.8	96	8	75	8.8	1 900	600	1 300	58	45
Hepolahti P4	N = 4										
Average	4	9	83	7.8	33	3.1	795	120	212	26	10
Min	0	8.5	63	7.5	18	2	390	10	<5	14	4
Max	7	9.7	94	8.1	60	4.4	1 500	430	840	37	27
Clarification pond 5	1		61	8.2	99	10	1 825			34	

Table 4. Cont.

	COD Mn ** mg/L	Cl mg/L	Ca mg/L	Fe µg/L	Cr dissolved µg/L	Cr µg/L	Ni dissolved µg/L	Ni µg/L	Zn µg/L
Kirvesoja P1	N = 12								
Average	19	7.7	3.7	2 308	0.88	0.75	0.36	0.31	5.3
Min	7.4	0.7	1.5	710	0.5	0.3	<0.25	<0.25	3.8
Max	26	26	8.6	6 000	1.4	1.2	0.7	0.5	7.2
Iso-Ruona-oja	P3 N = 12								
Average	13	86	26	2 967	2	0.9	5.1	4.3	6.6
Min	7.3	44	12	1 400	1.1	0.6	<3	1.7	3.3
Max	19	140	39	4 600	3.7	1.4	8.3	7.4	12
Iso-Ruona-oja	P5 N = 9								
Average	15	69	23	2 544	2.3	1	5.1	3.5	18.5
Min	8.1	30	12	1 600	1.8	0.8	3	1.8	5.6
Max	22	120	35	3 600	3.1	1.5	6.8	4.5	43
Hepolahti P4	N = 4								
Average	12	44	16	1 318	1.9	0.6	2.8	2.3	5.3
Min	8.2	22	11	770	1.3	0.6	2	1.4	3.6
Max	15	93	26	2 100	2.5	0.6	3.5	3.1	7
Clarification Pond 5	10		22	107	2.4	7			3.3

*Accredited method
Methods:
Temperature and water lever: field measurements
Coliform bacteria: SFS 4088:2001
O2: SFS-EN 25813:1996
O2 Satur. %: SFS-EN 25813:1996
pH: SFS 3021:1979
EC mS/m: SFS-EN 27888:1994, temperature compensation
Solids: SFS-EN 872:2005
Tot. N: internal method O-Y-088
NH_4-N: internal method O-Y-077
$NO_{2,3}$-N: internal method O-Y-078
Kok. P: internal method O-Y-089
PO_4-P: internal method O-Y-079
**COD Mn = oxidized organic material in water

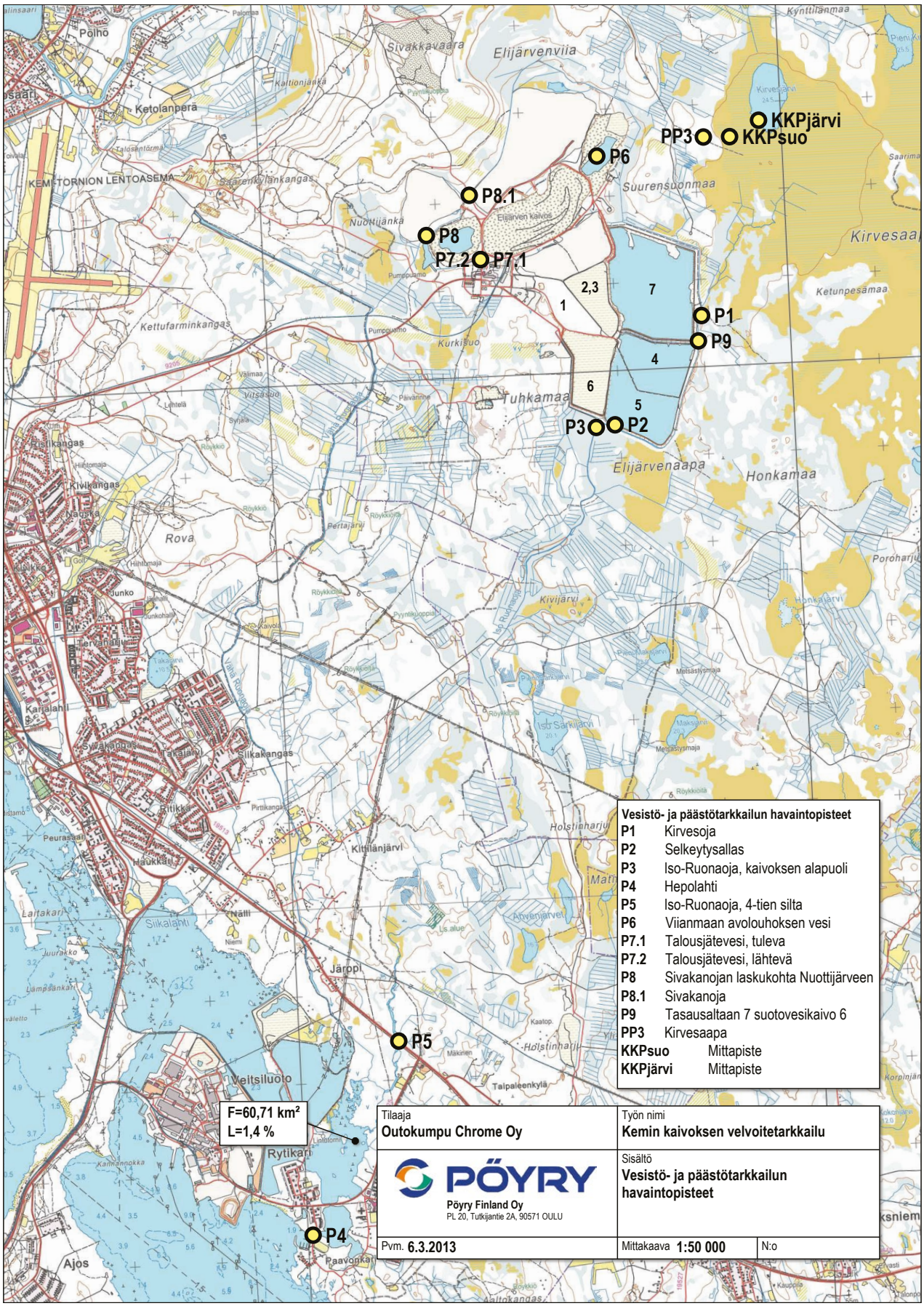


Fig. 11. Monitoring sites of surface waters at the Kemi Mine according to Pöyry Finland Oy (2014).

Water quality in groundwater observation wells PV1–PV8 in 2013 is presented in Table 5 and the location of the monitoring wells in Figure 10. Water quality was analysed four times in 2013.The results show that iron concentrations were high, partly due to the low oxygen contents. In unoxidized conditions, Fe is dissolved in water, while in the presence of oxygen Fe reacts to form a precipitate. Some Ni and NH_4-N concentrations were higher than the maximum limit of drinking water.

Table 5. Water quality in the groundwater observation wells PV1-PV8 at the Kemi Mine in 2013, according to Pöyry Finland Oy (2014), and recommendations for household water quality (Sosiaali- ja terveysministeriö 2000 and 2001, decrees STM 461/2000 and 401/2001).

	t °C	O_2 mg/L	O_2 %	Electr. cond. mS/m	P dissolved µg/L	N dissolved µg/L	NH_4-N dissolved µg/L	Cl dissolved µg/L	Fe dissolved µg/L
STM 461/2000				250			400	250	200
PV1									
Average	4.2	0.9	7	79	15	378	280	135	1 130
Min.	3.0	0.5	3	78	9	340	250	130	780
Max.	5.5	1.3	10	79	24	440	310	150	1 700
PV2									
Average	5.0	6.2	49	8.5	19	1 265	42	1.1	1 280
Min.	3.4	1.6	12	6	8	760	20	0.9	620
Max	7.3	9.5	74	14	34	2 200	59	1.3	1 700
PV3/2									
Average	6.5	3.1	25	6.6	59	743	72	0.9	4 150
Min.	1.9	2.5	22	5.9	44	630	43	0.7	2 500
Max	9.7	3.6	28	7.5	88	880	140	1.1	5 700
PV4									
Average	5.6	3.1	30	7.9	23	1 033	72	0.7	3 658
Min.	2.7	<0.2	3	3.7	7	540	16	0.5	730
Max	9.4	9.7	74	13	32	1 300	170	1	7 400
PV5									
Average	5.6	<0.2	<1	18	31	1 500	103	1.8	13 750
Min.	3.3	<0.2	<1	15	22	1 400	73	1.6	12 000
Max	8.7	<0.2	<1	20	51	1 600	130	2	16 000
PV6									
Average	5.8	3.7	30	6.1	4.5	540	32	0.8	433
Min.	2.3	1.8	15	4.5	3	470	10	0.4	380
Max	8.5	8	65	7.6	8	630	68	1.3	500
PV7									
Average	4.7	1.4	11	35	15	130	70	3.9	47
Min.	3.7	1.3	10	35	11	80	51	1.6	<10
Max	5.9	1.5	12	35	18	190	95	10	140
PV8/2									
Average	6.6	2	19	67	46	4 600	735	6.3	6 450
Min.	2.8	<0.2	<1	54	22	1 700	600	3.6	2 200
Max	13	6	44	77	64	11 000	880	8.1	14 000

Table 5. Cont.

	Cr dissolved µg/L	Cr tot. µg/L	Ni dissolved µg/L	Ni tot. µg/L	Zn dissolved µg/L	Zn tot. µg/L	Ca dissolved mg/L	Mg dissolved mg/L
STM 461/2000	50	50	20	20				
PV1								
Average	0.2	0.6	0.3	1.1	2.6	18	61	16
Min.	<0.2	0.4	<0.2	0.4	1.2	1.7	56	16
Max.	0.3	0.7	0.5	1.5	5.7	35	63	16
PV2								
Average	8.9	13	19	21	20	22	8.6	3.8
Min.	6	6.9	7.8	7.8	5	5.9	6.4	2.1
Max	13	17	31	36	54	60	13	7
PV3/2								
Average	11	35	10	21	14	36	6.4	2.5
Min.	9.1	26	8.8	18	11	28	5.7	2.4
Max	14	46	11	27	18	55	7.7	2.9
PV4								
Average	14	16	10	11	31	37	6.7	5.7
Min.	4.6	6.1	5.1	5.8	14	12	3.2	3
Max	22	24	15	15	62	78	9.2	7.9
PV5								
Average	8.3	11	1.9	5	66	226	25	6.8
Min.	5.7	6.7	1.1	1.5	21	55	22	5.7
Max	12	16	2.6	14	170	390	26	7.9
PV6								
Average	4.6	7.8	3.8	5.6	7.2	10	6	3.1
Min.	4	6.9	3.1	4.8	5	6	4.2	2.2
Max	5.1	8.4	4.4	6.4	10	12	7.9	3.8
PV7								
Average	<0.2	0.7	<0.2	0.5	1.9	5	37	15
Min.	<0.2	0.5	<0.2	0.3	<0.5	4	37	15
Max	<0.2	0.9	<0.2	0.8	4.9	7	38	15
PV8/2								
Average	2.4	198	3.5	117	7.7	176	42	13
Min.	1.6	22	1.2	13	1.6	25	39	13
Max	3.4	420	7	240	23	360	46	14

Wastewaters entering and leaving the wastewater treatment plant are analysed 4 times per year. Temperature, pH, electrical conductivity and biological oxygen consumption (BOD_{7ATU}) are measured, and analyses of P, total N, NH_4-N, Cl, Fe, dissolved Cr, Ni and Zn are also conducted. The waters flow to the clarification ponds, not directly to watercourses (Nikula 2012). The discharge of Kirvesoja is measured every month while sampling, and the amount of water is measured at monitoring site P3. Overflow from basin 5 is regularly measured. The amount of water pumped from the Viianmaa open pit and waters flowing to basin 4 are measured once a month (Pohjois-Suomen Aluehallintovirasto 2010).

Monitoring of dams is carried out once a year, and periodic monitoring once every 5 years. The condition of the tailings dams and the quality of waters flowing to the watercourses are visually inspected daily. Checking of dust is carried out daily and dust-binding material is used if necessary (Outokumpu Chrome Oy 2009).

5.2 Surficial deposits, vegetation and air

The composition and solubility of the tailings have been monitored according to the monitoring programme. Due to the ore type and concentration process, the solubility of Cr, Ni and Zn is very low without any notable changes. The waste management plan was prepared in 2011, including the landscaping plan for the waste rock piles (Nikula 2012).

Air quality, which is monitored yearly, has improved since the end of open pit mining (Outokumpu Chrome Oy 2009, Pohjois-Suomen Aluehallintovirasto 2010). In the 2000s, SO_2, NO_2 and CO_2 emissions considerably diminished (Table 6) due to the reduced fuel consumption and improved energy efficiency, and also the reduced transportation of waste rock. Using propane instead of heavy fuel oil for heating the underground mine since 2005 has reduced SO_2 emissions (Outokumpu Chrome Oy 2009, Pohjois-Suomen Aluehallintovirasto 2010).

Particle emissions have been measured once every 5 years by analysing metal concentrations in moss (red-stemmed feather, *Pleurozium schreberi*) since 1985. Samples of red-stemmed feather moss were taken along radial lines up to 50 km from the mine. Cr concentrations in the Gulf of Bothnia were measured in 1985. Since then, concentrations on the coast have considerably decreased to the level of 2–4 µg/g. Higher concentrations have been recorded at the most 2 km from the mine. Concentrations in most parts of Finland are at least 4–6 µg/g. Ni concentrations have been observed to decrease as a function of distance from the mine. Slightly elevated concentrations have been recorded 2–4 km from the mine, but the concentrations have remained at a constant level. Zn concentrations were <60 µg/g. They were considerably lower in 2000 than in 1990, representing the background concentrations in reference areas (Outokumpu Chrome Oy 2009).

Concentrations of Cr and Ni displayed no marked changes in 1990, 1995, 2000 and 2005. Particular emissions have decreased during this period, which should also affect the impacts on moss. Concentrations in moss were also analysed in 2010.

Concentrations of heavy metals were determined in food plants in 2002. Cr and Ni concentrations were higher near the mine compared to the reference areas. Concentrations in soil were approximately at the average level. Impacts of dust and noise are monitored to a distance of 1 km from the mine. Dust contents have diminished in past years due to the decline in the transportation of waste rock and maintenance work on roads, watering of the product storage area, and partly due to underground mining. Both mining and precrushing are carried out underground. Dust produced by crushing is removed by wet scrubbers, which are also used on the ground surface. Some dust emissions occur from tailings and waste rock piles, and also from loading material. Watering and covering of the piles has reduced dust emissions. Metals are easily bound and enriched in organic material of the surficial deposits, but in acidic conditions metals dissolve in water and are transported deeper into the Quaternary deposits. No deterioration of trees was found in monitoring conducted in 2009 (Pohjois-Suomen Aluehallintovirasto 2010).

Table 6. Emissions of sulphur oxides, nitrogen oxides and carbon dioxide from heavy and light fuel oil and diesel in 2004–2011 (tons per year).

	2004	2005	2006	2007	2008	2009	2010	2011	Expanded production
SO_2	21	12	9	7	7	8	7	5.2	8
NO_2	32	19	10	12	12	10	15	14.4	18
CO_2	14 800	9 400	5 800	6 900	6 693	5 804	8 500	8 222	9 616

6 DATA FROM STUDIES CONDUCTED BY GTK

Investigations carried out by GTK have included analyses of waters, organic stream sediments and peat in the mine site and reference areas. Water samples for analyses were taken from settling ponds, the Iso-Ruonaoja creek downstream of the mine, and in reference areas in the Kirvesoja creek and bog ditch waters upstream of the mine. Tailings pore water and the seepage well water were additionally analysed. Sediment samples were taken from a settling pond, the Iso-Ruonaoja creek next to the dam of the tailings and downstream of the mine. Peat samples were taken from a bog northeast of the tailings facility and the Elijärvenaapa bog, at the Kemi mine site. The sampling sites are shown in Figs 12–13 and pictures of field working in Figs 14–18.

The water temperature, pH value, electrical conductivity and dissolved oxygen were measured at each sampling site, the field instrument being a WTW Multi 3430 Digital pH/D.O./conductivity meter. The tailings sample was taken from the outfall into a bucket and allowed to settle before separating the tailings water and solid samples. Water samples were taken into plastic bottles by taking untreated aliquots of 0.5 litres, which were used for anion determinations. An aliquot of 100 mL was then taken from each sample after filtering using BD Plastipak disposable syringes and Whatman GmbH disposable filters and acidified with 0.5 mL of 65 % suprapur nitric acid for elemental analysis. Organic stream sediments were taken using a manual tube sampler or a net with a 0.06 mm pore size at sampling sites with thin sediments. The samples were taken into plastic bags. Peat samples were taken with a manual drill designed for peat sampling. All samples were stored in a cool box before sending to the laboratory. Sampling of water and stream sediments was modified after the methods described by Lahermo et al. (1996). The analytical methods are briefly described in Table 7. Water flow directions at the mine site and in the surrounding area were determined by means of monitoring data on the water level in the groundwater observation wells at the Kemi Mine.

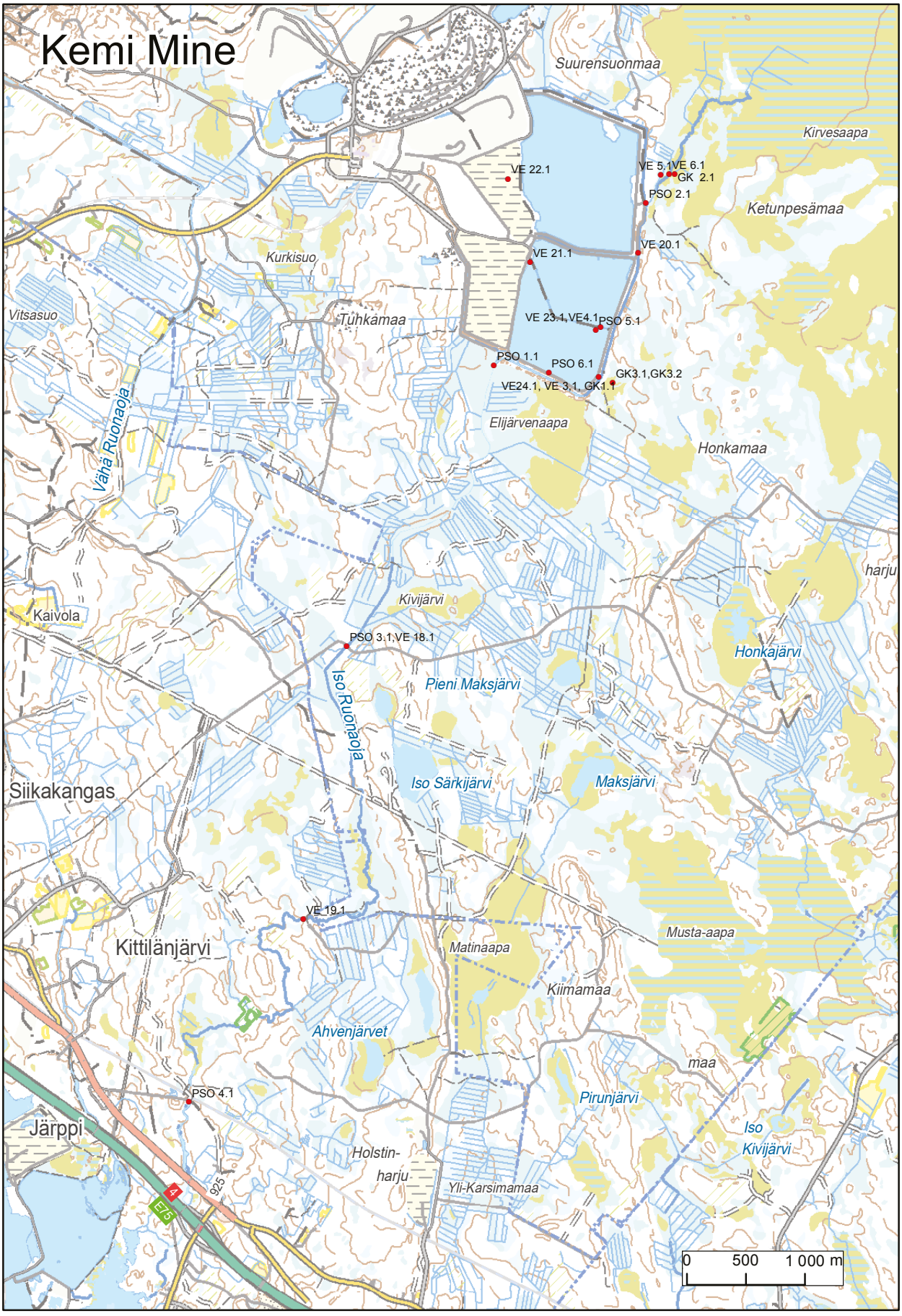


Fig. 12. Sampling sites of GTK in 2013–2014. VE = water sampling site, PSO = organic stream/bottom sediment, GK = geochemical sample (peat, sediment). Base map©National Land Survey of Finland.

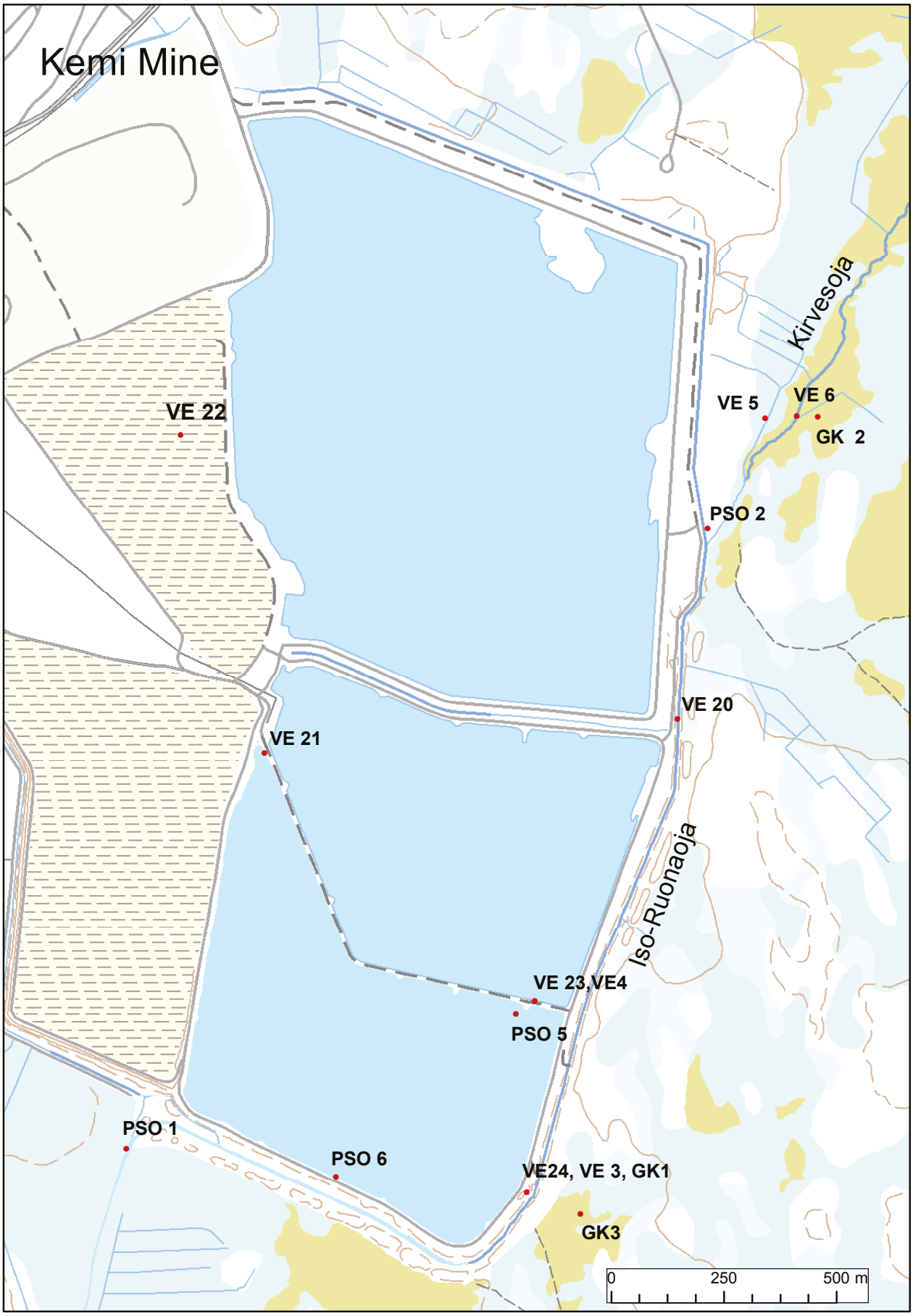


Fig. 13. Sampling sites of GTK in the tailings area and near surroundings in 2013–2014. VE = water sampling site, PSO = organic stream/bottom sediment, GK = geochemical sample (peat, sediment). Base map©National Land Survey of Finland.

Table 7. Pretreatment and analysis methods for sediment and water samples.

Sample amount	Code	Pretreatment, extraction method	Measurements
Sediment and peat samples			
6	820L	Freeze-dried and sieved <2.0 mm, pyrolytic decomposition	CN analyser
10	503PM	Freeze-dried and sieved <2.0 mm, and conc. nitrogen and extraction assisted microwave[1)]	32 elements with ICP-OES and MS-ICP
8	201PM	Freeze-dried and sieved <2.0 mm, and 1-M NH_4 acetate extraction, for stream sediments solid:solution ratio = 1:10, and for peat samples, solid:solution ratio = 1:60	33 elements with ICP-OES and MS-ICP
4	214PM	Freeze-dried and sieved <2.0 mm, and 0.01 M NH_4Cl extraction, solid:solution ratio = 1:50	33 elements with ICP-OES and MS-ICP
Water samples			
11	139PM	100 mL water, filtered (0.45 µm) and water acidified with suprapur nitrogen acid (0.5 mL)	33 elements with ICP-OES and MS-ICP
11	150PM	100 mL water, non-filtered and acidified with suprapur nitrogen acid (0.5 mL), and conc. nitrogen acid decomposition	34 elements with ICP-OES and MS-ICP
11	143R	0.5 L water, non-filtered	Anions (SO_4, NO_3, Cl, Br, F) with IC
11	143T	0.5 L water, non-filtered	Alkalinity SFS-EN ISO 9963-1:1996, $KMnO_4$ SFS 3036: 1981
11	143C	0.5 L water, non-filtered	PO_4-P, SFS 3025:1986
7	142L-DOC	100 mL water, filtered (0.45 µm) and acidified with suprapur phosphorus acid (1 mL)	C analyser
7	142L-TOC	100 mL water, non-filtered and acidified with suprapur phosphorus acid (1 mL)	C analyser
11		WTW meter MULTI 3430	Field measurements: pH, electrical conductivity, dissolved oxygen

1) Niskavaara 1995
2) Räisänen et al. 1997, Heikkinen & Räisänen 2009

Fig. 14. Sampling organic stream sediments near the Kemi Mine by drilling through the ice. March 2013. Photo: Ulpu Väisänen.

Fig. 15. Sampling organic stream sediments. Iso-Ruonaoja, September 2013. Photo: Ulpu Väisänen.

Fig. 16. Sampling water from a creek near the Kemi Mine. June 2014. Photo: Ulpu Väisänen.

Fig. 17. Field measurements of water samples at the Kemi-Mine. Photo: Ulpu Väisänen.

Fig. 18. Data storage in the field. Photo: Ulpu Väisänen.

6.1 Chemical composition of stream sediments in the Kirvesoja ditch and Iso-Ruonaoja creek

Pad sediments in settling pond 5 consist of peat, mud and mineral matter (including secondary inorganic precipitates) discharged from the tailings impoundment. Since the samples were taken close to the dams, their composition does not unambiguously depict the sediment quality in the whole pond area (see Fig. 13). This finding is based on the heterogeneity of element distributions in two pad sediment samples (see Tables 8 and 9b). One of the pad sediments (PSO6) consisted of 48 % organic C (peat) and the other (PSO5) only about 6 %. Furthermore, the peaty sediment had abnormally high concentrations of N (2.4 %), sulphur (S, 1.8 %), P (0.1 %), Fe (1.0 %), Ca (1.4 %), sodium (Na, 0.3 %) and Mg (0.6 %) compared to the sediment poor in organic matter (0.3 % N, 0.1 % S, 0.02 % P, 0.2 % Fe, 0.1 % Ca, 0.02 % Na, 0.09 % Mg). It can be assumed that N and Na, and some of the Ca and Mg, mainly originated from the ore blasting and processing (e.g. chemical remains, released from crushed mineral crystal edges). By comparison, the abnormal quantity of P and Fe could have originated from the local peat, on which the settling pond has been constructed (Fig. 19a-b). The peat in the Elijärvenaapa bog next to the settling pond contained 0.1-0.2 % P and 0.9-1.2 % Fe. Furthermore, most of the S originated from the local peat, since Cr_2O_3 ore and the tailings waste contain low amounts of sulphide minerals (S < 0.02 %, unpublished tailings chemical data, Outokumpu Chrome Oy, Kemi Mine).

Table 8. Carbon, N, S and P concentrations in pad sediments from settling pond 5, stream sediment samples from the Kirvesoja and Iso-Ruonaoja creeks, and peat samples from the bog northeast of the tailings facility and from the Elijärvenaapa mire, in the Kemi Mine area (see sampling sites in Figs 12–13).

	C	N	S	P
		%		
Pad sediments, settling pond 5				
Peat & mud sediment (PSO5)	5.97	0.26	0.10	0.02
Peat & mud sediment (PSO6)	48.2	2.40	1.83	0.10
Stream sediment samples				
Background, Kirvesoja creek (PSO2)	1.13	0.06	0.03	0.01
Peat & mud sediment, seepage ditch (GK1)	-	-	0.17	0.02
Iso-Ruonaoja, upstream (PSO1)	0.76	0.04	0.08	0.03
Iso-Ruonaoja, midstream (PSO3)	1.28	0.05	0.08	0.03
Iso-Ruonaoja, downstream (PSO4)	6.81	0.37	0.40	0.05
Peat samples				
Background bog, next to Kirvesoja creek (GK2)	-	-	0.24	0.15
Upper peat (0-1.5 m), Elijärvenaapa (GK3)	-	-	0.29	0.16
Lower peat (0.5-1 m), Elijärvenaapa (GK3)	-	-	0.42	0.11

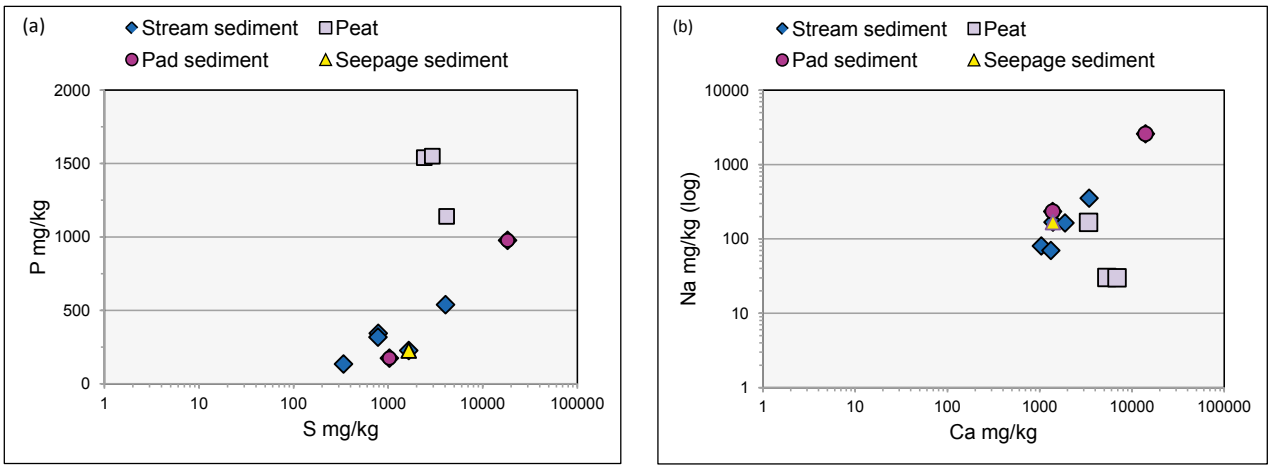


Fig. 19. Distributions of (a) acid extractable P and S concentrations, and (b) those of acid-extractable Na and Ca concentrations in samples of stream, peat, pad and seepage sediments at the Kemi Mine.

Table 9. Acid-extractable element concentrations of (a) stream sediment samples and (b) pad and seepage sediment samples and peat samples in the Kemi Mine area. Sampling sites PSO1, PSO3 and PSO4 are situated south of the tailings basins (see sampling sites in Figs 12–13).

(a)

	Kirvesoja creek	**Iso-Ruonaoja creek**		
mg/kg	Reference (PSO2)	Upstream (PSO1)	Midstream (PSO3)	Downstream (PSO4)
Fe	4 060	12 200	11 200	28 600
Al	2 220	4 030	3 690	8 410
Mg	1 220	3 690	5 430	9 120
Ca	1 040	1 880	1 320	3 430
K	215	710	368	1 150
Na	80	164	70	353
Cr	7.7	182	508	960
Mn	39	90	97	928
Zn	11	16	20	120
Ni	3.8	21	48	92
Co	1.6	3.7	3.7	26
Cu	1.7	5.5	7.8	27
Pb	1.5	1.6	2.2	11
As	1.3	2.9	3.0	6.5
Se	0.32	0.50	0.52	0.83
Mo	0.05	0.13	0.22	0.86
Cd	0.07	0.06	0.07	0.46
Th	1.7	2.0	3.1	3.1
U	0.28	0.51	0.44	1.1

(b)

	Pad sediments, pond 5		**Seepage ditch**	**Reference bog (GK2)**	**Elijärvenaapa bog (GK3.1, GK3.2)**	
mg/kg	Peat & mud (PSO5)	Peat & mud (PSO6)	Peat & mud (GK1)	Upper peat 0–0.5 m	Upper peat 0–0.5 m	Lower peat 0.5–1 m
Fe	2 180	10 400	4 740	14 000	9 230	10 900
Al	1 490	2 820	2 010	4 480	4 760	6 980
Mg	880	5 740	1 450	652	702	841
Ca	1 380	14 000	1 390	3 380	5 340	6 880
K	156	929	412	323	141	<50
Na	234	2 590	168	167	30	30
Cr	17	88	18	33	26	36
Mn	20	66	32	107	179	214
Zn	7.0	22	7.0	8.2	12	6.3
Ni	3.9	31	5.7	3.1	7.3	20
Co	0.37	2.9	1.5	0.72	3.4	9.4
Cu	4.0	22	2.6	4.0	17	37
Pb	2.4	27	0.9	7.7	13	3.1
As	0.94	6.2	0.49	3.8	3.1	4.5
Se	0.34	1.0	0.31	1.2	1.1	1.7
Mo	0.44	4.7	0.08	0.52	0.94	1.3
Cd	0.03	0.61	<0.01	0.09	0.28	0.39
Th	1.6	0.9	2.0	2.5	1.4	2.8
U	0.43	1.1	0.33	1.2	0.80	1.9

Similarly to the peat chemistry in the neighbouring bogs, stream sediments in the Iso-Ruonaoja creek were enriched in Fe and Mn, especially the sediment taken from the furthest site downstream (Table 9, and see Mn in Fig. 20). However, the Iso-Ruonaoja stream sediments had higher concentrations of main and trace elements than the Kirvesoja stream sediment in the reference area (Table 9a). Overall, the stream sediments have a higher mineral matter content than pad, seepage and peat sediments. This interpretation is based on the higher concentrations of Al, Mg and potassium (K) (referring to mica and chlorite silicates) in the stream sediments than in the pad, seepage and peat sediments (Table 9).

The acid-extractable concentration of Cr varied between 20 mg/kg and 80 mg/kg in pad sediments of settling pond 5 (Table 9). The highest Cr concentration was recorded in the organic carbon-rich sediment. A similar relationship with the organic carbon (C) content was also observed for other trace elements, manganese (Mn), Ni, copper (Cu), Pb, Zn, As and molybdenum (Mo) (Table 9b). However, the peat in the reference bog and Elijärvenaapa bog next to the facility had almost equal amounts of several trace metals, e.g. Cr, Ni, Cu, lead (Pb) and Zn. By contrast, the peat was rich in Mn (Table 9b). It had on average more arsenic (As), selenium (Se), cadmium (Cd), thorium (Th) and uranium (U) than the pad and seepage sediments (Fig. 20). Compared to the pad, seepage and peat sediments, the Iso-Ruonaoja stream sediments were enriched in Cr, Mn, Zn, Ni and cobalt (Co) (Fig. 20). Overall, the Iso-Ruonaoja sediments had on average higher trace element concentrations than the Kirvesoja stream sediment (PSO2), which represented the background levels (Fig. 20, Table 9).

The content of the acetate-extractable fraction depicts elements that are chemically adsorbed on solid, organic and inorganic particles and the composition of non-crystalline precipitates (e.g. Fe and Al and other metal hydroxides). The fraction also includes water-soluble and easily leachable (physically adsorbed) elements bound with weak bonds on surfaces of solid particles. The composition of the chemical adsorption fraction generally depicts the elements mobilized by effluents from industrial processes, soil drainage (land use) and dusting.

The chemical adsorption fraction of the pad sediments (settling pond 5) mainly consisted of Ca, Mg, and Na, and variably K, S, Fe and aluminium (Al), respectively (Table 10). By contrast, stream sediments downstream of the Iso-Ruonaoja creek had the highest Fe and Mn contents, but much less Ca, Mg and Na. The peat in the neighbouring bogs also contained a great deal of chemically adsorbed Fe and Mn, as well as Ca, Al and magnesium (Mg). It is noteworthy that a high portion (>75 %, except sample GK1) of acid-extractable Ca and Na was dissolved in acetate from pad, seepage and peat sediments, whereas their acetate extractability in the stream sediment samples was <50 % (Figure 21a). Compared to Ca and Na, the acetate extractability of Al and Fe was low, less than 40 %. Based on the results, the content of non-crystalline Fe precipitates (= acetate-extractable Fe) was low in pad sediments. Seepage, stream and peat sediments contained some non-crystalline Fe, which obviously indicates weathering of Fe bearing minerals such as Fe sulphides. In contrast to Fe, Al has minor extractability in acetate, except from peat samples (Fig. 21a). This indicates that Al in the pad, seepage and stream sediments is mostly in a crystalline form (silicates, crystalline Al oxyhydroxides). The peat sediments had some non-crystalline Al as well as Fe, i.e. Al and Fe organocomplexes.

Sediment and peat samples had hardly any acetate-extractable Cr compared to other trace metals

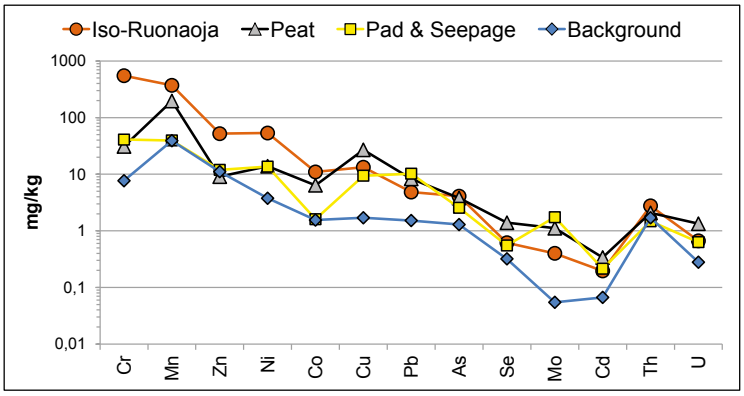


Fig. 20. Distributions of acid-extractable trace element (Cr, Mn, Zn, Ni, Co, Cu, Pb, As, Se, Mo, Cd, Th, U) concentrations in stream sediments of the Iso-Ruonaoja creek (PSO1, PSO3, PSO4), peat layers of the Elijärvenaapa bog (GK3.1, GK3.2), pad and seepage sediments of the settling pond (PSO5, PSO6, GK1) and in Kirvesoja stream sediment (reference, PSO2) in the Kemi Mine area. The concentrations are calculated as means for each sample group.

(Table 10, Fig. 21b). The pad, seepage and stream sediments had small concentrations (<2 mg/kg) of acetate-extractable trace elements, except for those of Mn, Zn, Ni and Pb (Table 10). The content of acetate-extractable Mn was 3–40 mg/kg in pad and seepage sediments, but much higher in peat sediments (100–210 mg/kg). An abnormally high concentration of acetate-extractable Mn, 610 mg/kg, was measured from the Iso-Ruonaoja sediment at the furthest site downstream, whereas in the other stream sediment samples the concentration was only 30 mg/kg. Acetate-extractable concentrations of Zn and Ni were highest (14 mg/kg) in the Iso-Ruonaoja sediment at the furthest site downstream and lowest in one of the pad sediments, as well as in the seepage sediment and peat layer at the reference bog site. The acetate-extractable Pb level was highest (4–8 mg/kg) in the upper peat layers, the organic-rich pad sediment and the Iso-Ruonaoja sediment at the furthest site downstream. In the other samples, the Pb concentration was <1 mg/kg.

The above findings indicate that acetate-extractable trace metals (Mn, Zn, Ni, Pb) obviously originated from drainage (i.e. oxidation) of the sulphide-bearing bog (Elijärvenaapa). The oxidation of sulphides is followed by the release of metals trapped in peat. The ammonium chloride (NH_4Cl) extraction method was used for peat samples to measure the element concentrations in the water soluble and easily leachable fraction (physically adsorbed elements, Table 11). The results demonstrate that the sulphur content is lower in the upper than the lower peat layer, indicating the oxidation of sulphides due to drainage of the bog. In contrast, some Fe was adsorbed in the upper peat layer sample at the reference bog site, whereas at the sampling sites in the Elijärvenaapa bog, its concentration was somewhat lower in the upper than the lower peat layer sample. A similar trend was observed for Al and Mn. Concentrations of trace elements were relatively low and in most cases under the lowest detection limit of the method.

It can be concluded that the discharges from the both drainage of the bog and the tailings facility have impacts on the sediment chemistry of the Iso-Ruonaoja creek. The enrichment of Cr and Na in the stream sediments indicates the impact of the tailings and settling pond effluents, whereas several sulphide trace metals originated from peat forming the pad sediment of the ponds and via drainage from neighbouring bogs rather than from the tailings effluents. It should be noted that this interpretation is suggestive due to the small number of sediment samples analysed.

Table 10. Acetate-extractable concentrations of (a) samples of the seepage and stream sediments and (b) those of pad sediments and peat in the Kemi Mine area (see samplings sites in Figs 12–13).

(a)

	Seepage ditch	**Iso-Ruonaoja creek**	
mg/kg	Peat & mud sediment (GK1)	Midstream (PSO3)	Downstream (PSO4)
Fe	1 870	2 600	9 190
S	440	67	308
Al	45	116	499
Mg	196	71	252
Ca	501	409	1 580
K	42	27	103
Na	126	22	175
P	20	23	34
Mn	2.8	30	611
Cr	0.54	1.6	2.6
Zn	3.3	2.1	14
Ni	0.5	2.1	9.6
Cu	0.57	0.05	<0.03
Co	<0.03	0.44	6.5
As	0.11	0.40	0.76
Mo	0.01	0.01	0.02
Se	<0.09	0.03	0.06
Pb	0.24	0.87	3.8
Cd	<0.006	0.01	0.01

Table 10. Cont.
(b)

	Pad sediments, settling pond 5		Reference bog (GK2)	Elijärvenaapa bog (GK3.1, GK3.2)	
mg/kg	Peat & mud (PSO5)	Peat & mud (PSO6)	Upper peat 0–0.5 m	Upper peat 0–0.5 m	Lower peat 0.5–1 m
Fe	225	38.8	5 950	3 030	2 730
S	64	414	58	53	164
Al	145	75.6	1 210	1 080	1 710
Mg	402	4 320	644	708	865
Ca	1 080	10 400	2 970	4 640	5 900
K	68	769	282	102	<20
Na	203	2 410	171	29	22
P	14	26	31	27	<10
Mn	8.3	42	98	171	208
Cr	0.3	0.32	1.0	0.8	1.7
Zn	0.08	1.6	6.3	7.8	3.2
Ni	0.4	1.5	0.5	1.3	3.8
Cu	0.04	0.19	0.5	1.0	2.0
Co	<0.1	0.24	0.27	1.70	4.1
As	0.23	1.4	0.95	0.85	1.8
Mo	0.01	0.02	0.01	0.02	0.02
Se	0.03	0.04	0.30	0.18	0.40
Pb	0.83	5.0	4.2	7.6	1.7
Cd	0.01	0.02	0.06	0.22	0.29

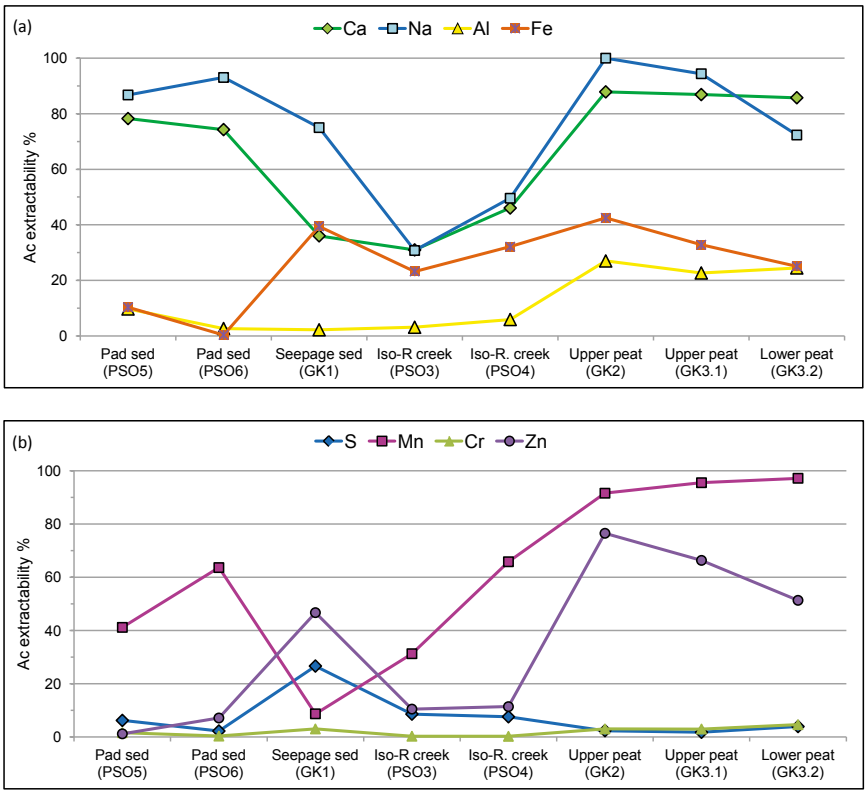


Fig. 21. Percent acetate extractability of (a) Ca, Na, Al and Fe, and (b) S, Mn, Cr and Zn concentrations from their acid-extractable concentrations in samples of pad and seepage sediments (PSO5, PSO6, GK1), stream sediments (PSO3, PSO4, Iso-R creek = Iso-Ruonaoja creek) and peat samples taken from a bog northeast of the tailings facility (GK2, reference) and the Elijärvenaapa bog (GK3.1, GK3.2) in the Kemi Mine area (see sampling sites in Figs 12–13).

Table 11. pH and element concentrations of the physical adsorption fraction (NH_4Cl extractable) of a peaty seepage sediment and peat samples taken from the bog northeast of the tailings facility (reference) and from the Elijärvenaapa bog in the Kemi Mine area (see samplings sites in Figs 12–13).

	Seepage ditch (GK1)	**Reference bog (GK2)**	**Elinjärvenaapa bog (GK3.1, GK3.2)**	
mg/kg	Peat & mud sediment	Upper peat 0–0.5 m	Upper layer 0–0.5 m	Lower peat 0.5–1 m
pH	6.0	4.9	4.6	4.5
S	399	30	26	166
Fe	24	130	17	25
Al	<5	13	12	21
Ca	295	676	912	1100
Mg	144	286	278	335
Na	100	159	34	34
K	42	286	82	21
P	<10	<10	12	<10
Cr	<0.25	<0.25	<0.25	<0.25
Mn	1.2	23	32	40
Zn	<1	1.0	<1	<1
Cu	1.0	2.6	1.9	1.8
Ni	0.2	<0.15	0.2	1.0
Co	<0.025	0.11	0.46	1.4
As	<0.025	0.31	0.16	0.49
Mo	<0.01	0.01	0.02	0.02
Pb	<0.025	0.04	<0.025	<0.025
Se	<0.072	<0.072	<0.072	<0.072

6.2 Chemical composition of tailings and stream waters

The pH of the tailings pore water and settling pond waters was basic (8.7–9.4, Table 12). It dropped to neutral when discharged from the pond (Table 12). At the reference sites, the pH of the Kirvesoja creek water and bog ditch water was slightly acid (5.6–6.5). The electrical conductivity of the tailings pore water was about 100 mS/m, whereas that of settling pond water varied between 89 mS/m and 114 mS/m. In contrast, the seepage waters had on average somewhat greater conductivity (85–130 mS/m) than the settling pond waters. The conductivity, however, decreased (64–65 mS/m) downstream in the Iso-Ruonaoja creek. Expectedly, the lowest conductivities (20–40 mS/m) were in the water samples taken from the reference sites.

The greatest alkalinity (3.7–3.9 mmol/L) was measured from waters seeping from settling pond 5 (Table 12). The tailings pore water and settling pond waters had somewhat lower alkalinity (1.9–2.6 mmol/L). The Iso-Ruonaoja creek had higher alkalinity (2.7–3.0 mmol/L) than the settling pond waters. Surface waters at the reference sites had the lowest alkalinity (0.2–0.3 mmol/L).

The potassium permanganate ($KMnO_4$) number depicts the consumption of oxygen in surface water, and it is therefore associated with the organic matter content of the water. The highest $KMnO_4$ number (90–110 mg/L) was measured from the surface waters of the reference sites and the lowest (10–30 mg/L) from the waters of the tailings and settling ponds. The seepage waters had a somewhat higher $KMnO_4$ number (20–40 mg/L) than the waters in the settling pond. The $KMnO_4$ number at the downstream site in the Iso-Ruonaoja creek was about 45 mg/L, indicating the impact of the bog waters.

Table 12. Temperature, pH, electrical conductivity (EC), alkalinity and $KMnO_4$ number of the water samples taken from the tailings facility (tailings pore water, settling and seepage waters), Kirvesoja creek (ref = reference), a bog ditch and Iso-Ruonaoja creek in the Kemi Mine area (see samplings sites in Figs 12–13).

	Sample code	Measure date	Temp. °C	pH	EC mS/m	Alkalinity mmol/L	$KMnO_4$ mg/L
Kirvesoja, upstream (backgr)	VE6	11.06.2014	13.7	5.6	25.7	0.15	110
Bog ditch, reference	VE5	11.06.2014	14.0	6.5	41.6	0.26	89
Tailings pore water (pond 7)	VE22	04.09.2013	20.7	9.4	104	2.00	11
Settling water (pond 4)	VE23	04.09.2013	15.2	9.2	104	2.57	18
	VE4	11.06.2014	18.0	8.7	114	1.90	13
Settling water (pond 5)	VE21	04.09.2013	15.3	9.7	88.8	2.55	29
Seepage well	VE20	04.09.2013	11.4	7.1	121	3.89	27
Seepage ditch	VE24	04.09.2013	12.3	7.4	85.1	3.77	41
	VE3	11.06.2014	11.5	7.4	132	3.70	22
Iso-Ruonajoki, midstream	VE18	03.09.2013	9.6	7.4	64.8	2.98	46
Iso-Ruonajoki, downstream	VE19	03.09.2013	9.7	7.8	64.1	2.74	45

The chemistry of the tailings pore water and settling pond waters, as well as the seepage waters, was characterized by high concentrations of anions, e.g. Cl, NO_3, sulphate (SO_4), and soluble alkaline and earth alkaline metals (Na, K, Ca, Mg, i.e. base cations) compared to the surface water chemistry at the reference sites and the Iso-Ruonaoja creek (Fig. 22, Table 13). Notably, the Iso-Ruonaoja creek waters had higher anion and base cation concentrations than the Kirvesoja and bog ditch waters at the reference site. The above-mentioned variables are indicative of mining impacts, i.e. effluents from chemical remains and elements released during ore processing.

Table 13. Mean concentrations of (a) anions SO_4, NO_3, Cl, bromide (Br), fluoride (F), iodine (I), and (b) soluble main and trace elements, and (c) total concentrations of main and trace elements of stream waters (reference, Iso-Ruonaoja), tailings pore water (T pore water), and settling pond and seepage waters in the Kemi Mine area. N refers to the number of the samples. See locations of the samples in Figures 12–13.

(a)

		Reference	T pore water	Settling pond	Seepage	Iso-Ruonaoja
Sample codes		VE6, VE5	VE22	VE23, VE4, VE21	VE20, VE24, VE3	VE18, VE19
Sample amount		2	1	3	3	2
SO_4	mg/L	0.57	124	103	83.7	29.5
$S\text{-}SO_4$ [1)]	mg/L	0.19	41.4	34.4	27.9	9.85
S	mg/L	<1	44.0	36.3	26.4	10.3
NO_3	mg/L	<0.2	35.0	8.35	4.69	1.88
Cl	mg/L	0.905	156	167	171	90.1
Br	mg/L	<0.1	1.07	0.86	0.88	0.58
F	mg/L	<0.1	0.23	<0.2	<0.2	<0.2
I	mg/L	<2	8.1	8.2	16	8.3

[1)] SO_4 concentration divided by 2.996

Table 13. Cont.

(b)

		Reference	T pore water	Settling pond	Seepage	Iso-Ruonaoja
Sample codes		VE6, VE5	VE22	VE23, VE4, VE21	VE20, VE24, VE3	VE18, VE19
Sample amount		2	1	3	3	2
Ca	mg/L	2.27	12.3	28.7	37.8	28.9
Mg	mg/L	1.04	13.2	24.1	27.6	16.1
Na	mg/L	3.09	157	125	133	68.1
K	mg/L	0.51	24	23.3	23.7	7.84
Si	mg/L	1.62	6.52	0.56	4.96	5.07
Fe	mg/L	0.93	<0.05	<0.05	0.77	1.76
P	mg/L	17	18	22	588	39
Sr	µg/L	15.35	1 390	1 161	1 026	370.5
Al	µg/L	51	6.8	24	21	20
Mn	µg/L	20	0.2	2.2	172	45
Zn	µg/L	9.4	1.9	2.5	4.5	3.6
Cr	µg/L	0.9	2.6	1.0	1.2	1.0
Ni	µg/L	<0.05	3.6	4.5	3.7	2.5
Cu	µg/L	<0.1	1.2	0.7	0.8	1.6
Co	µg/L	0.1	0.2	0.2	0.2	0.1
As	µg/L	0.4	2.3	1.4	0.6	0.4
Mo	µg/L	0.2	8.2	6.0	1.4	0.8
V	µg/L	0.3	4.5	1.6	3.9	1.7
Sb	µg/L	0.04	2.5	0.6	0.1	0.1
Se	µg/L	<0.5	3.5	3.1	3.1	1.5

(c)

		Reference	T pore water	Settling pond	Seepage	Iso-Ruonaoja
Sample codes		VE6, VE5	VE22	VE23, VE4, VE21	VE20, VE24, VE3	VE18, VE19
Sample amount		2	1	3	3	2
S	mg/L	0.29	41.9	36.7	26.5	10.6
Ca	mg/L	2.28	12.3	29.0	38.2	29.8
Mg	mg/L	1.27	13.4	23.7	27.8	15.6
Na	mg/L	3.08	149	123	128	66.3
K	mg/L	0.54	37.3	23.3	24.2	8.30
Si	mg/L	1.42	7.04	<0.7	4.47	4.91
Fe	mg/L	1.23	0.14	<0.03	0.96	3.10
P	mg/L	4.47	0.12	0.13	0.24	0.16
Sr	µg/L	14.0	1 460	1 147	1 004	369
Al	µg/L	61	187	42	34	40
Mn	µg/L	20	1.14	5.3	174	50
Zn	µg/L	27	10	9.6	12	13
Cr	µg/L	<2	100	5.9	2.2	1.4
Ni	µg/L	<3	9.7	5.2	4.2	<3
Cu	µg/L	2.1	1.4	1.6	1.9	1.8
Co	µg/L	<2	1.6	0.8	1.0	0.2
As	µg/L	0.4	2.4	1.4	0.7	0.6
Mo	µg/L	<0.2	12	6.9	1.6	1.1
V	µg/L	<0.5	4.0	1.4	3.6	2.0
Sb	µg/L	<0.2	2.5	0.5	<0.2	<0.2
Se	µg/L	<5	<5	6.6	6.5	5.6

The soluble concentrations of several trace metals and metalloids were, however, low in all the surface waters (Table 13b). Therefore, trace element distributions were examined by fractionating concentrations into solid and soluble fractions. The element concentrations of filtered water samples are assumed to represent the composition of the soluble fraction. The content of the solid fraction was determined by deducting the element concentration of the filtered sample from the total concentration of the unfiltered sample. Based on the fractionation, alkaline and alkaline earth metals (Na, K, Ca, Mg) and sulphur mainly occurred in a soluble form in the waters of all the sampling sites, whereas Al and P and several trace elements (Cr, Ni, Mo, Zn, Mn, Cu, Se) occurred both in a soluble form and bound to solid particles in the waters (Figs 22–25; see also Table 13b-c).

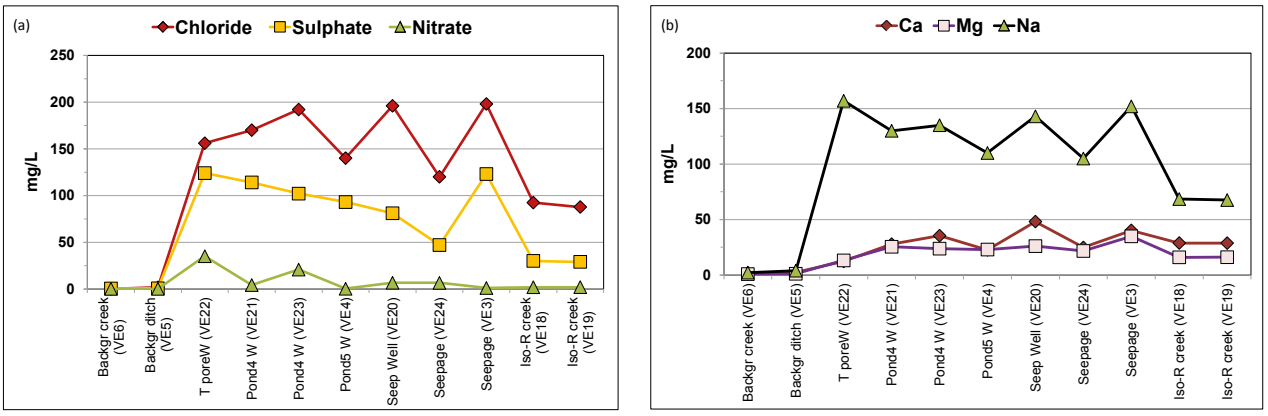


Fig. 22. Distributions of (a) anions (Cl, SO_4 and NO_3) and (b) soluble concentrations of Ca, Mg and Na at the water sampling sites starting from left: Kirvesoja creek (VE6) and bog ditch waters (VE5), tailings pore water (T poreW VE22), waters of settling ponds 4 and 5 (Pond4 W VE23 and VE4, Pond5 W P5 VE21), seepage well water (Seep Well VE20), and Iso-Ruonaoja creek waters (Iso-R creek VE18 and VE19) in the Kemi Mine area (see sampling sites in Figs 12–13).

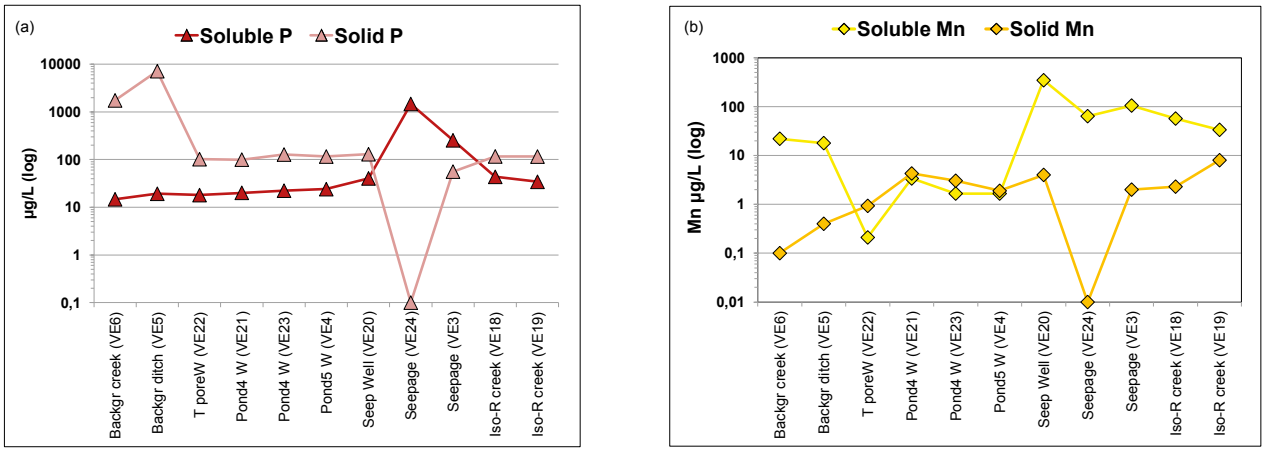


Fig. 23. Distributions of (a) soluble and particle-bound P concentrations and (b) soluble and particle-bound Mn concentrations in surface waters in the Kemi mine area. See keys for water sampling sites in Figure 22 and site locations in Figs 12–13.

In reference waters, most Al was dissolved (50 µg/L) and minor amount (10 µg/L) bound to solid particles (Table 13b-c). In contrast, the tailings pore water and settling pond waters had a three times higher concentration of particle-bound Al (60 µg/L on average) than dissolved Al (20 µg/L on average), whereas the seepage waters and Iso-Ruonaoja creek waters had lower Al concentrations (≤20 µg/L) in the both soluble and solid fractions than the waters at the reference sites and waters in the facility. The findings suggest that Al-bearing discharges from the facility mainly consist of Al-bearing minerals (and/or Al organocompounds), which settle out in downstream watercourses.

The soluble concentrations of P (590 µg/L) were on average highest in seepage waters and lowest in waters at the reference sites (Table 13b-c). Actually, the soluble P concentrations of the seepage waters varied from 40 µg/L in the seepage well water to 250–1470 µg/L in the seepage ditch waters (Fig. 23a). The soluble concentrations of P were almost the same for tailings pore and settling pond waters and Iso-Ruonaoja creek waters. By contrast, concentrations of particle-bound P were abnormally high in waters at the reference sites and relatively low in all the other waters (Fig. 23a). This suggests that P originated from peat in the neighbouring bog, as also revealed by the P content of the pad sediments.

Overall, the behaviour of soluble and solid Mn displayed similar trend to P (Fig. 23b). The soluble Mn concentrations were greater in waters of the seepage sites and the reference sites. The tailings pore water had the lowest soluble Mn concentration. The soluble Mn concentration increased slightly in waters of the settling ponds and remained at almost the same level in the downstream waters of the Iso-Ruonaoja creek. In contrast to P, a relatively small quantity of Mn was bound to solid particles of the waters.

Cr was mainly bound to solid particles in the tailings pore water and waters of the settling pond (Fig. 24a). The concentrations of soluble Cr remained relatively low (<2 µg/L) in the all water samples. The exception was the tailings pore water, which contained 2.6 µg/L soluble Cr. In contrast to Cr, the concentration of soluble Ni gradually increased from the tailings pore water (2.6 µg/L) to the settling pond waters, and it was highest (9.3 µg/l) in the seepage well water (Fig. 24b). Ni concentrations of waters at the reference sites were below the lowest detection limit (<0.05 µg/L). Seepage ditch waters contained <1.5 µg/L, and the Iso-Ruonaoja creek waters on average 2.5 µg/L. Ni was only bound to solid particles in the tailings pore water.

The chemical behaviour of Zn followed that of Mn, indicating the peat as its source. However, the concentrations were relatively low (soluble Zn <7 µgL, solid Zn <11 µg/L), except for waters at the reference sites (on average 9 µg/L soluble Zn and 18 µg/L solid Zn). Soluble concentrations of As, Se and Mo, even in small quantities, were clearly greater in tailings pore water and settling pond waters than in the creek waters at the reference site and downstream (Fig. 25). In contrast, the solubility of Pb was relatively low in the waters of the facility, whereas it was slightly elevated in waters at the reference sites and the seepage well. Soluble concentrations of Cu and Co were <1 µg/L in most of the samples.

Furthermore, concentrations of particle-bound As and Pb were <0.3 µg/L in all samples, whereas 1.5–2.6 µg/L particle-bound Cu and Co occurred in waters at some sampling sites of the facility and downstream. Concentrations of particle-bound Mo and Se varied from 0.3–3.6 µg/L and 2.5–6.7 µg/L, respectively in the tailings pore, settling pond and seepage waters, whereas the creek waters downstream had less particle-bound Mo (<0.5 µg/L) than Se (1.5-4.3 µg/L). The above concentrations of particle-bound trace elements are,

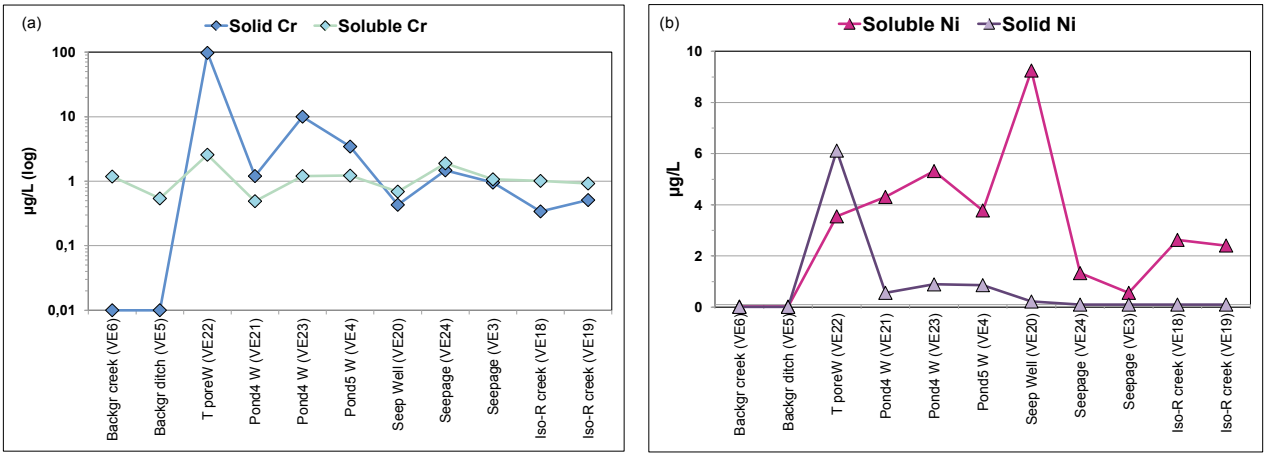


Fig. 24. Distributions of (a) soluble and particle-bound Cr concentrations and (b) soluble and particle-bound Ni concentrations in surface waters in the Kemi mine area. See keys for water sampling sites in Figure 17 and site locations in Figs 12–13.

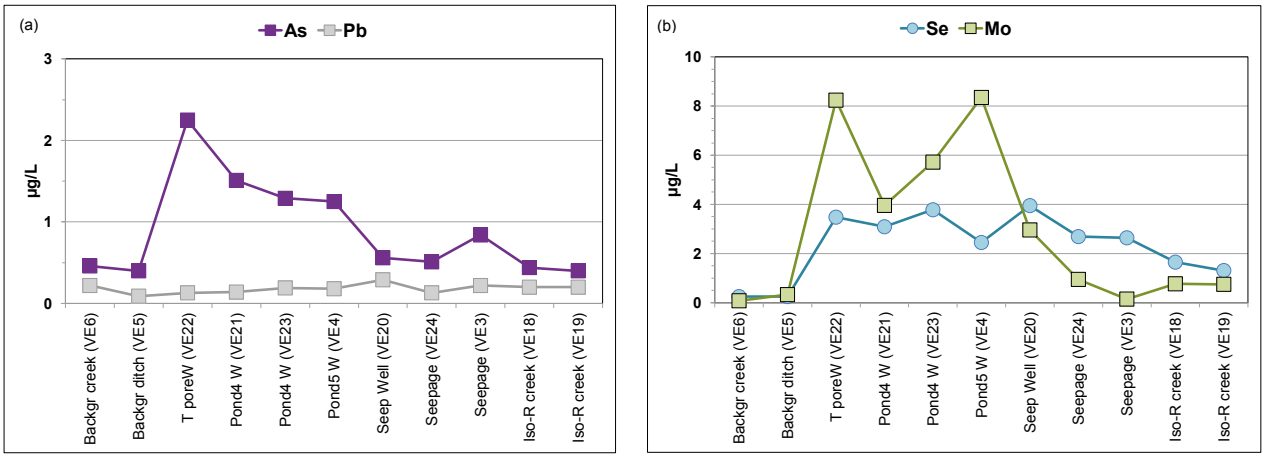


Fig. 25. Distribution of soluble (a) As and Pb and (b) Se and Mo concentrations in surface waters in the Kemi Mine area. See keys for water sampling sites in Figure 22 and site locations in Figs 12–13.

however, indicative due to the poor accuracy and precision of their MS-ICP determinations for unfiltered water samples.

It can be concluded that the contamination of tailings waters can be distinguished from receiving stream waters by their elevated concentrations of N and Na, and particle-bound Cr. The origin of several trace elements (e.g. Mn, Zn, Ni, Zn, Cu, Co, Pb, As, Mo, Se) in settling pond and seepage waters appears to be linked to the chemistry of the peaty pad sediments underlying the ponds rather than the tailings waste and process waters, as the chemical content of the peat samples indicated. A similar interpretation obviously applies for the creek waters downstream. Nevertheless, some of trace metals (e.g. Ni, Mo, Se) could have originated from both sources (tailings and peat).

7 CONCLUSIONS AND DISCUSSION

7.1 Conclusions and discussion on the geochemical results of the Kemi Mine study case

The chemical impacts of tailings and settling ponds on watercourses are mainly estimated based on the surface water data. The geochemistry of sediment samples provided only some indicators of element sources. The most striking source of trace metals (and metalloids), P, Fe and S was the local peat, which forms the pad of the settling ponds. The peat is characterized by acid rock drainage phenomena, resulting in acidic effluents rich in metals and metalloids flowing into the Iso-Ruonaoja creek, which also receives effluents from the tailings and wastewater facility. This obscures the actual impacts of tailings waste and process waters on downstream watercourses.

According to water analysis data, indicative elements for contamination with tailings water are NO_3, Na and Cr. The highest concentrations of NO_3 and Na were measured in the tailings pore water, settling pond and seepage waters and the lowest in the waters at the reference sites. The concentrations of the effluents markedly decreased in downstream waters of the Iso-Ruonaoja creek. However, the Iso-Ruonaoja creek waters had ten to a hundred times more Na and NO_3, respectively, than waters at the reference sites. Furthermore, some of the Ca and Mg in the downstream creek waters could originate from ore blasting and processing (release from crushed mineral edges).

Cr was mainly bound to solid particles in the waters of the facility and the downstream creek waters. Its solubility was relatively low at all the sampling sites. The chemical behaviour of Cr in the waters suggests that Cr-bearing fine-grained matter discharged from the settling ponds is accumulating in still water sites of the Iso-Ruonaoja creek. This was observed at the furthest downstream site of the creek. Furthermore, Cr-bearing particles (oxide and silicate minerals) appear to be chemically inert in the stream sediment environment. Therefore, it is suggested that Cr in down-

stream water does not cause toxic impacts on the biota. In contrast to Cr, Ni showed its mobile character in the neutral conditions of the seepage waters compared to basic conditions of the tailings pore water. However, concentrations of soluble Ni in the receiving creek water (Iso-Ruonaoja) were low (<3 µg/L), being below the environmental threshold value (<21 µg/L, Vna1022/2006, changes Vna342/2009, 868/2010 and 1562).

The chemical behaviour of the several trace metals, especially Mn, Zn and Pb, but also Cu, Mo, As and Se, suggests that they originate from the local peat rather than from the tailings facility. This argument is based on their mobility (acetate extractability) in peat layers next to the facility. However, the interpretation should be considered as indicative, since this study did not include comparative samples from fine tailings and fine sediment matter from the wastewater clarification pond.

Furthermore, results showed that most of P in the stream sediments is discharged from the drained bogs next to the facility. The occasional increase in P concentrations in the settling pond and seepage well waters originated from the pad peat sediments rather than from the tailings fines. This is based on the chemical behaviour of P in the peat layers of the bogs next to the tailings facility. The behaviour of P as well as that of Mn, Fe and S is markedly dependent on the oxidizing and reducing potential at a sampling site. Unfortunately, redox potentials were not measured at either water or sediment sampling sites, and we could not therefore separate the actual effect of peat chemistry on tailings effluents and their interaction with bog drainage effluents in the Iso-Ruonaoja creek (outside the facility).

Overall, it can be concluded that the potential impact of tailings effluents on watercourses is more connected with turbidity (fine solids, salinity), despite the NO_3 effluent. Cr effluents entering downstream watercourses consist of Cr-bearing solid particles, which appear to be inert in the neutral creek waters. Furthermore, soluble concentrations of other traces in the creek waters were relatively low. Therefore, it can be concluded that the potential trace metal and metalloid effluents from the facility do not form a toxic risk to the biota in the downstream watercourses. The above conclusions are suggestive due to the small amount of chemical data.

7.2 General conclusions on sustainable mining at Kemi

The best available techniques (BAT) have been taken into consideration in the following stages and processes according to Outokumpu Chrome Oy (2009):

- The amount of actual waste is minor.
- The impacts of explosives are minimized.
- Waste rock has been re-used in different sites, and is used for filling shafts. Utilization of tailings has been investigated, possibly for enrichment with the developed techniques.
- Emissions have been taken into consideration together with process development.
- Good techniques produce good enrichment results (top notch).
- Energy consumption has diminished during underground mining.
- Risks have been identified in the environmental system.
- The development of techniques will be monitored.

The Kemi Mine is continually developing material and energy efficiency. This also means lower emissions and waste, and more internal material and energy flows. Particle emissions have diminished since open pit mining was ended. The tool in environmental issues is the certified ISO 14001 system, which is regularly audited by an outside expert. Several innovative technologies are used in the production chain in the Kemi Mine.

Risk analyses and a protection plan have been prepared for the mine. Environmental aspects are checked at least once a year. The composition and solubility of tailings has to be monitored by means of analyses of comprehensive aggregate samples.

Closure of the tailings and settling pond facility and landscaping have been planned for the Kemi Mine (Outokumpu Chrome Oy 2012). The main closure actions according to Plan VO2 (more extensive) consist of lowering of the water table in the tailings area and the use of dry cover for landscaping. The cover material will consist of till from the moraine area next to basin 6. The till composition and its suitability for covering were investigated in 2006 by Ramboll Finland Oy. In addition, a peat

layer will be constructed on the till cover to promote vegetating (grass) and prevent dusting and soil erosion. The alternative plan, VO1, is more compact and, for instance, waste rock exploitation should be easier. Post-monitoring programmes will be planned after mine closure. According to the present data and predictions, mining will continue for decades.

The tailings waste is classified as inert mine waste based on the low sulphide sulphur content and low solubility of potential toxic metals (Outokumpu Chrome Oy 2012). According to this study and the earlier monitoring data, environmental risks to the downstream watercourses are mainly caused by N compounds. Expectedly, the N load will gradually decrease after active mining ends and the facility is covered. In addition to N, turbidity (solid fine particles and base cations) may lower the water quality of the downstream watercourses. This study demonstrated that the local peat, both underlying the ponds and via drainage of the bogs next to the facility, is a significant contamination source for surface waters. We suggest that this fact should also be considered when selecting peat material for covering from local bogs.

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APPENDIX 1

Organic stream sediments (2 samples), Kemi, March 2013. U=duplicate analysis.

Sample ID	As mg/kg + 503M2	Be mg/kg + 503M2	Bi mg/kg + 503M2	Cd mg/kg + 503M2	Mo mg/kg + 503M2	Pb mg/kg + 503M2	Sb mg/kg + 503M2	Se mg/kg + 503M2	Th mg/kg + 503M2	Tl mg/kg + 503M2	U mg/kg + 503M2	Al mg/kg + 503P
PSO1	2.85	0.1	<0.1	0.06	0.13	1.62	<0.05	0.5	2.03	0.06	0.51	4030
PSO1 U	3.66	0.2	<0.1	0.08	0.22	2.14	<0.05	0.6	2.39	0.07	0.60	5310
PSO2	1.29	<0.1	<0.1	0.07	0.05	1.52	<0.05	0.3	1.70	0.03	0.28	2220

Sample ID	B mg/kg + 503P	Ba mg/kg + 503P	Ca mg/kg + 503P	Co mg/kg + 503P	Cr mg/kg + 503P	Cu mg/kg + 503P	Fe mg/kg + 503P	K mg/kg + 503P	Li mg/kg + 503P	Mg mg/kg + 503P	Mn mg/kg + 503P	Na mg/kg + 503P
PSO1	<5	28.8	1880	3.7	182.0	5.5	12200	710	4	3690	90	164
PSO1 U	<5	39.9	2580	4.9	280.0	7.4	16800	970	5	4990	121	217
PSO2	<5	10.4	1040	1.6	7.7	1.7	4060	215	2	1220	39	80

Sample ID	Ni mg/kg + 503P	P mg/kg + 503P	Rb mg/kg + 503P	S mg/kg + 503P	Sr mg/kg + 503P	Ti mg/kg + 503P	V mg/kg + 503P	Zn mg/kg + 503P	C % + 820L	N % + 820L
PSO1	21	344	4	785	11.3	401	17.6	16	0.76	0.04
PSO1 U	29	479	6	1160	15.9	568	24.5	21	0.75	0.04
PSO2	4	135	<1	337	6.5	233	6.9	11	1.13	0.06

APPENDIX 2

Organic stream sediments (4 samples), Kemi, September2013. U=duplicate analysis.

Sample ID	As	Be	Bi	Cd	Cu	Li	Mo	Rb	Sb	Se	Th	Tl
	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg
	201M	201M	201M	201M	201M	201M	201M	201M	201M	201M	201M	201M
PSO3	0.401	0.02	<0.01	0.010	0.05	<0.01	0.011	0.064	<0.005	0.03	0.058	0.001
PSO3 U	0.408	0.02	<0.01	0.010	0.04	<0.01	0.012	0.064	<0.005	0.03	0.059	0.001
PSO4	0.755	0.05	<0.01	0.011	<0.03	<0.01	0.022	0.179	0.009	0.06	0.133	0.005
PSO5	0.234	0.02	<0.01	0.007	0.04	<0.01	0.013	0.121	0.006	0.03	0.038	<0.001
PSO6	1.380	0.02	<0.01	0.021	0.19	<0.01	0.019	1.170	0.025	0.04	0.011	0.009

Sample ID	U	Al	B	Ba	Ca	Co	Cr	Fe	K	Mg	Mn	Na
	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg
	201M	201P	201P	201P	201P	201P	201P	201P	201P	201P	201P	201P
PSO3	0.091	116	<0.5	11	409	0.4	1.6	2600	27	71	30.3	22
PSO3 U	0.095	119	<0.5	11	422	0.4	1.6	2610	25	74	31.1	21
PSO4	0.427	499	1.1	50	1580	6.5	2.6	9190	103	252	611.0	175
PSO5	0.075	145	0.7	11	1080	<0.1	0.3	225	68	402	8.3	203
PSO6	0.199	75.6	7.1	45	10400	0.2	0.3	38.8	769	4320	42.2	2410

Sample ID	Ni	P	Pb	S	Si	Sr	Ti	V	Zn	As	Be	Bi
	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg
	201P	201P	201P	201P	201P	201P	201P	201P	201P	+ 503M	+ 503M	+ 503M
PSO3	2.1	23	0.9	67	41	4.9	0.29	2.9	2.11	2.96	0.1	<0.1
PSO3 U	2.2	24	0.8	69	42	5.0	0.24	3.1	2.12	2.72	0.1	<0.1
PSO4	9.6	34	3.8	308	134	19.1	0.57	6.6	13.70	6.47	0.2	<0.1
PSO5	0.4	14	0.8	64	12	28.4	0.45	3.2	0.08	0.94	<0.1	<0.1
PSO6	1.5	26	5.0	414	54	272.0	0.19	0.9	1.56	6.23	0.1	0.2

Appendix 2 cont.

Sample ID	Cd mg/kg + 503M	Li mg/kg + 503M	Mo mg/kg + 503M	Pb mg/kg + 503M	Rb mg/kg + 503M	Sb mg/kg + 503M	Se mg/kg + 503M	Th mg/kg + 503M	Tl mg/kg + 503M	U mg/kg + 503M	Al mg/kg + 503P	B mg/kg + 503P
PSO3	0.07	3.6	0.22	2.19	3.28	<0.05	0.5	3.12	<0.01	0.44	3690	<5
PSO3 U	0.05	3.7	0.20	1.95	3.38	<0.05	0.4	2.03	<0.01	0.52	3580	<5
PSO4	0.46	6.6	0.86	10.70	8.49	<0.05	0.8	3.14	0.11	1.05	8410	<5
PSO5	0.03	1.2	0.44	2.36	0.95	<0.05	0.3	1.56	<0.01	0.43	1490	<5
PSO6	0.61	0.6	4.70	27.40	3.30	0.50	1.0	0.88	0.16	1.13	2820	18

Sample ID	Ba mg/kg + 503P	Ca mg/kg + 503P	Co mg/kg + 503P	Cr mg/kg + 503P	Cu mg/kg + 503P	Fe mg/kg + 503P	K mg/kg + 503P	Mg mg/kg + 503P	Mn mg/kg + 503P	Na mg/kg + 503P	Ni mg/kg + 503P	P mg/kg + 503P
PSO3	25.6	1320	3.7	508.0	7.8	11200	368	5430	97	70	48	318
PSO3 U	23.0	1220	3.5	495.0	6.9	10200	363	5120	85	75	44	277
PSO4	106.0	3430	25.5	960.0	26.5	28600	1150	9120	928	353	92	539
PSO5	17.7	1380	0.4	17.4	4.0	2180	156	880	20	234	4	175
PSO6	91.5	14000	2.9	87.5	21.6	10400	929	5740	66	2590	31	977

Sample ID	S mg/kg + 503P	Sr mg/kg + 503P	Ti mg/kg + 503P	V mg/kg + 503P	Zn mg/kg + 503P	C % + 820L	N % + 820L
PSO3	780	8.9	242	14.2	20	1.28	0.05
PSO3 U	645	8.2	248	13.5	19	1.33	0.05
PSO4	4040	32.3	509	37.5	120	6.81	0.37
PSO5	1030	31.5	167	12.8	7	5.97	0.26
PSO6	18300	382.0	101	27.9	22	48.20	2.40

APPENDIX 3

Stream sediment (1 sample) and peat (3 samples of 2 sites), Kemi, June 2014. U=duplicate analysis.

Sample ID	As	Bi	Cd	Co	Cr	Cu	Li	Mo	Ni	Pb	Rb	Sb
	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg
	201M	201M	201M	201M	201M	201M	201M	201M	201M	201M	201M	201M
GK1	0.11	<0.07	<0.006	<0.03	0.5	0.6	0.47	0.01	0.5	0.24	0.15	<0.03
GK1 U	0.10	<0.07	<0.006	<0.03	0.5	0.4	0.48	0.02	0.3	0.22	0.14	<0.03
GK2	0.95	<0.07	0.060	0.27	1.0	0.5	0.46	0.01	0.5	4.20	0.95	<0.03
GK3.1	0.85	<0.07	0.222	1.70	0.8	1.0	0.45	0.02	1.3	7.64	0.32	<0.03
GK3.2	1.77	<0.07	0.289	4.12	1.7	2.0	0.45	0.02	3.8	1.70	0.07	<0.03

Sample ID	Se	Th	Tl	U	Al	B	Ba	Be	Ca	Fe	K	Mg
	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg
	201M	201M	201M	201M	201P	201P	201P	201P	201P	201P	201P	201P
GK1	<0.09	0.09	<0.006	0.023	45	<2	7.6	<0.1	501	1870	42	196
GK1 U	<0.09	0.08	<0.006	0.021	42	<2	6.8	<0.1	452	1650	45	178
GK2	0.30	0.22	0.022	0.208	1210	<2	57.7	0.15	2970	5950	282	644
GK3.1	0.18	0.15	0.045	0.152	1080	<2	36.2	<0.1	4640	3030	102	708
GK3.2	0.40	0.32	0.063	0.801	1710	<2	46.8	0.12	5900	2730	<20	865

Sample ID	Mn	Na	P	S	Si	Sr	Ti	V	Zn	pH	As	Bi
	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	pH	mg/kg	mg/kg
	201P	201P	201P	201P	201P	201P	201P	201P	201P	214I	214M	214M
GK1	2.8	126	20	440	<20	16	1	4	3.3	6.01	<0.025	<0.056
GK1 U	2.4	110	17	397	<20	14	1	3	1.3	6.3	<0.025	<0.056
GK2	98.0	171	31	58	48	27	4	22	6.3	4.88	0.31	<0.056
GK3.1	171.0	29	27	53	33	23	2	11	7.8	4.64	0.16	<0.056
GK3.2	208.0	22	<10	164	38	31	4	21	3.2	4.54	0.49	<0.056

Appendix 3 cont.

Sample ID	Cd	Co	Cr	Cu	Li	Mo	Ni	Pb	Rb	Sb	Se	Th
	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg
	214M	214M	214M	214M	214M	214M	214M	214M	214M	214M	214M	214M
GK1	<0.005	<0.025	<0.25	1.0	0.1	<0.01	0.2	<0.025	0.39	<0.025	<0.072	<0.01
GK1 U	<0.005	<0.025	<0.25	1.3	0.1	<0.01	<0.15	<0.025	0.37	<0.025	<0.072	<0.01
GK2	0.01	0.11	<0.25	2.6	<0.05	0.01	<0.15	0.04	2.62	<0.025	<0.072	<0.01
GK3.1	0.03	0.46	<0.25	1.9	<0.05	0.02	0.2	<0.025	0.81	0.03	<0.072	<0.01
GK3.2	0.04	1.44	<0.25	1.8	0.1	0.02	1.0	<0.025	0.19	<0.025	<0.072	<0.01

Sample ID	Tl	U	Al	B	Ba	Be	Ca	Fe	K	Mg	Mn	Na
	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg
	214M	214M	214P	214P	214P	214P	214P	214P	214P	214P	214P	214P
GK1	<0.005	<0.005	<5	<2	2.3	<0.1	295	24	42	144	1.2	100
GK1 U	<0.005	<0.005	<5	<2	2.3	<0.1	294	26	45	143	1.2	102
GK2	0.03	<0.005	13	<2	6.7	<0.1	676	130	286	286	22.9	159
GK3.1	0.06	<0.005	12	<2	3.5	<0.1	912	17	82	278	32.4	34
GK3.2	0.09	<0.005	21	<2	4.3	<0.1	1100	25	21	335	40.4	34

Sample ID	P	S	Si	Sr	Ti	V	Zn	Ag	As	Bi	Cd	Li
	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg
	214P	214P	214P	214P	214P	214P	214P	503M	503M	503M	503M	503M
GK1	<10	399	<20	9.3	<0.5	<0.2	<1	0.04	0.49	<0.1	<0.01	2.7
GK1 U	<10	397	<20	9.3	<0.5	<0.2	1.1	0.02	0.61	<0.1	0.01	2.6
GK2	<10	30	44	6.0	<0.5	0.8	1.0	0.03	3.79	<0.1	0.09	0.2
GK3.1	12	26	30	4.5	<0.5	0.6	<1	0.02	3.12	0.1	0.28	0.2
GK3.2	<10	166	36	5.6	<0.5	1.0	<1	0.03	4.46	<0.1	0.39	0.3

Appendix 3 cont.

Sample ID	Mo mg/kg 503M	Pb mg/kg 503M	Rb mg/kg 503M	Sb mg/kg 503M	Se mg/kg 503M	Th mg/kg 503M	Tl mg/kg 503M	U mg/kg 503M	Al mg/kg + 503P	B mg/kg + 503P	Ba mg/kg + 503P	Be mg/kg + 503P
GK1	0.08	0.91	3.13	<0.05	0.3	1.99	0.03	0.33	2010	<5	12	<0.2
GK1 U	0.08	1.21	3.34	<0.05	0.5	4.03	0.03	0.44	1890	<5	12	<0.2
GK2	0.52	7.74	1.41	0.17	1.2	2.48	0.04	1.20	4480	<5	84	0.36
GK3.1	0.94	13.40	0.79	0.21	1.1	1.38	0.09	0.80	4760	<5	56	0.24
GK3.2	1.28	3.14	0.47	0.09	1.7	2.77	0.13	1.87	6980	<5	75	0.37

Sample ID	Ca mg/kg + 503P	Co mg/kg + 503P	Cr mg/kg + 503P	Cu mg/kg + 503P	Fe mg/kg + 503P	K mg/kg + 503P	Mg mg/kg + 503P	Mn mg/kg + 503P	Na mg/kg + 503P	Ni mg/kg + 503P	P mg/kg + 503P	S mg/kg + 503P
GK1	1390	1.5	18	2.6	4740	412	1450	32	168	5.7	227	1650
GK1 U	1540	1.3	18	2.8	4810	358	1400	33	162	5.5	290	1700
GK2	3380	0.7	33	4.0	14000	323	652	107	167	3.1	1540	2410
GK3.1	5340	3.4	26	17.0	9230	141	702	179	30	7.3	1550	2930
GK3.2	6880	9.4	36	36.9	10900	<50	841	214	30	20.4	1140	4150

Sample ID	Sr mg/kg + 503P	Ti mg/kg + 503P	V mg/kg + 503P	Zn mg/kg + 503P
GK1	17	267	9.7	7
GK1 U	18	297	9.9	6
GK2	32	304	61.6	8
GK3.1	27	210	43.1	12
GK3.2	37	351	101.0	6

APPENDIX 4

Water samples (7 pieces), Kemi, September 2013. U=duplicate analysis.

Sample ID	Ag µg/l + 139M	Al µg/l + 139M	As µg/l + 139M	B µg/l + 139M	Ba µg/l + 139M	Be µg/l + 139M	Bi µg/l + 139M	Cd µg/l + 139M	Co µg/l + 139M	Cr µg/l + 139M	Cu µg/l + 139M	I µg/l + 139M
VE18	0.02	20.5	0.44	35.9	57.5	<0.1	0.40	<0.02	0.12	1.01	1.93	8.17
VE18 U	0.02	21.5	0.49	38.4	59.8	<0.1	0.46	<0.02	0.12	1.09	1.96	10.6
VE19	0.01	19.0	0.40	30.6	49.7	<0.1	0.37	<0.02	0.11	0.92	1.36	8.50
VE20	<0.01	10.5	0.56	63.8	96.8	<0.1	0.33	<0.02	0.32	0.69	1.46	22.1
VE21	<0.01	45.9	1.51	49.6	48.1	<0.1	0.57	<0.02	0.13	0.49	0.73	7.62
VE22	0.01	6.77	2.25	65.0	84.7	<0.1	0.30	0.02	0.15	2.57	1.20	8.09
VE23	<0.01	15.8	1.29	52.6	57.4	<0.1	0.45	<0.02	0.13	1.20	0.89	7.87
VE24	<0.01	35.4	0.51	84.4	53.8	<0.1	0.41	<0.02	0.09	1.89	0.44	13.5

Sample ID	K mg/l + 139M	Li µg/l + 139M	Mn µg/l + 139M	Mo µg/l + 139M	Ni µg/l + 139M	P µg/l + 139M	Pb µg/l + 139M	Rb µg/l + 139M	Sb µg/l + 139M	Se µg/l + 139M	Sr µg/l + 139M	Th µg/l + 139M
VE18	8.10	2.70	56.9	0.77	2.63	43.5	0.20	9.24	0.10	1.65	382	0.82
VE18 U	8.60	2.87	59.2	0.80	2.91	47.5	0.23	9.67	0.10	2.00	402	0.96
VE19	7.57	2.59	33.5	0.75	2.41	34.2	0.20	8.58	0.08	1.31	359	0.64
VE20	18.0	3.91	346	2.96	9.25	40.3	0.29	25.3	0.29	3.95	1030	0.54
VE21	17.4	2.58	3.38	3.96	4.31	24.0	0.18	29.8	0.48	3.09	863	0.20
VE22	24.0	2.97	0.21	8.24	3.55	18.0	0.13	41.1	2.48	3.48	1390	0.10
VE23	21.4	3.10	1.66	5.72	5.32	20.1	0.14	35.9	0.59	3.78	1220	0.14
VE24	20.5	1.91	63.7	0.95	1.33	1470	0.13	31.4	<0.02	2.69	768	0.38

Appendix 4 cont.

Sample ID	Tl	U	V	Zn	Ca	Fe	Mg	Na	Si	S	PO4	Br
	µg/l	µg/l	µg/l	µg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l
	+ 139M	+ 139M	+ 139M	+ 139M	+ 139P	+ 139P	+ 139P	+ 139P	+ 139P	+ 139P	143C	+ 143R
VE18	0.14	0.24	1.77	4.63	28.9	1.78	16.0	68.5	5.06	10.6	0.05	0.6
VE18 U	0.15	0.25	2.04	5.04	29.8	1.82	16.8	72.8	5.28	10.9	0.05	0.6
VE19	0.12	0.22	1.54	2.65	28.8	1.74	16.1	67.6	5.08	9.98	0.07	0.6
VE20	0.16	0.48	1.84	3.48	48.2	1.71	26.1	143	5.29	28.4	<0.02	1.3
VE21	0.09	0.25	2.75	1.58	22.7	<0.05	23.0	110	1.18	32.7	<0.02	0.9
VE22	0.13	0.01	4.46	1.85	12.3	<0.05	13.2	157	6.52	44.0	<0.02	1.1
VE23	0.11	0.23	1.32	2.44	27.9	<0.05	25.5	130	0.26	41.0	<0.02	1.2
VE24	0.10	0.04	6.77	3.12	24.9	0.10	21.7	105	5.47	7.54	0.29	0.8

Sample ID	Cl	F	SO4	NO3	Alk	KMnO4	Al	As	B	Ba	Be	Bi
	mg/l	mg/l	mg/l	mg/l	mmol/l	mg/l	µg/l	µg/l	µg/l	µg/l	µg/l	µg/l
	+ 143R	+ 143R	+ 143R	+ 143R	143T	143T	150M	150M	150M	150M	150M	150M
VE18	92	<0.2	30	1.8	2.98	46	39.9	0.58	52.1	53.4	<0.5	0.55
VE18 U	93	<0.2	30	1.8	2.85	47	44.1	0.68	55.1	56.3	<0.5	0.44
VE19	88	<0.2	29	1.9	2.74	45	40.4	0.62	51.9	50.8	<0.5	0.47
VE20	196	<0.2	81	6.6	3.89	27	21.3	0.72	86.8	91.3	<0.5	0.42
VE21	140	<0.2	93	<0.4	2.55	29	56.8	1.60	69.1	46.3	<0.5	0.38
VE22	156	0.2	124	35	2.00	11	187	2.40	76.0	90.0	<0.5	<0.2
VE23	170	<0.2	114	4.2	2.57	18	43.9	1.41	74.8	56.4	<0.5	0.41
VE24	120	<0.2	47	6.5	3.77	41	47.7	0.61	103	50.7	<0.5	0.40

Appendix 4 cont.

Sample ID	Cd µg/l 150M	Ag µg/l 150M	Co µg/l 150M	Cr µg/l 150M	Cu µg/l 150M	K mg/l 150M	Li µg/l 150M	Mn µg/l 150M	Mo µg/l 150M	Ni µg/l 150M	Pb µg/l 150M	Rb µg/l 150M
VE18	<0.1	0.05	0.23	1.35	1.85	8.53	3.19	59.2	1.09	<3	<0.6	9.49
VE18 U	<0.1	<0.05	0.21	2.03	1.99	8.99	3.42	62.0	1.43	<3	0.62	10.1
VE19	<0.1	<0.05	0.24	1.43	1.67	8.07	3.21	41.5	1.18	<3	<0.6	9.35
VE20	<0.1	<0.05	0.45	1.12	1.64	17.2	4.59	350	4.35	9.47	0.63	25.5
VE21	<0.1	<0.05	0.22	1.69	<1	16.8	3.05	7.66	5.27	4.87	<0.6	30.7
VE22	<0.1	<0.05	1.61	100	1.36	37.3	4.62	1.14	11.8	9.67	<0.6	23.2
VE23	<0.1	<0.05	0.23	11.2	1.40	20.9	3.84	4.70	6.89	6.21	<0.6	38.0
VE24	<0.1	<0.05	0.21	3.36	1.06	20.0	2.40	63.7	0.35	<3	<0.6	32.1

Sample ID	Sb µg/l 150M	Se µg/l 150M	Sr µg/l 150M	Th µg/l 150M	Tl µg/l 150M	U µg/l 150M	V µg/l 150M	Zn µg/l 150M	Ca mg/l 150P	Fe mg/l 150P	Mg mg/l 150P	Na mg/l 150P
VE18	<0.2	<5	372	1.25	0.16	0.21	2.08	15.3	29.9	3.20	15.6	68.6
VE18 U	<0.2	<5	391	0.98	0.06	0.25	2.11	18.8	30.4	3.27	15.9	68.8
VE19	<0.2	5.57	366	1.13	0.11	0.23	1.83	10.2	29.6	2.99	15.6	63.9
VE20	0.23	10.6	949	0.93	0.11	0.48	1.75	10.4	48.6	2.20	26.4	137
VE21	0.40	7.02	830	0.63	0.08	0.26	2.30	9.57	23.0	0.05	23.1	108
VE22	2.49	<5	1460	<0.2	0.06	0.01	4.00	10.3	12.3	0.14	13.4	149
VE23	0.49	10.2	1200	0.67	0.10	0.25	1.25	9.92	27.6	0.06	24.9	123
VE24	<0.2	6.47	733	0.99	0.08	0.05	5.76	13.7	24.2	0.11	20.3	94.4

Appendix 4 cont.

Sample ID	P mg/l 150P	S mg/l 150P	Si mg/l 150P	pH*	EC* mS/m
VE18	0.16	10.8	4.98	7.38	64.8
VE18 U	0.16	10.8	5.05		
VE19	0.15	10.4	4.84	7.75	64.1
VE20	0.17	27.9	4.99	7.13	120.6
VE21	0.14	33.2	1.16	9.67	88.8
VE22	0.12	41.9	7.04	9.38	104.3
VE23	0.12	39.5	<0.7	9.22	104
VE24	0.25	7.19	4.92	7.35	85.1

*Field measurement

APPENDIX 5

Water samples (4 pieces), Kemi, June 2014. U=duplicate analysis.

Sample ID	Ag µg/l + 139M	Al µg/l + 139M	As µg/l + 139M	B µg/l + 139M	Ba µg/l + 139M	Be µg/l + 139M	Bi µg/l + 139M	Cd µg/l + 139M	Co µg/l + 139M	Cr µg/l + 139M	Cu µg/l + 139M	I µg/l + 139M
VE3	0.01	16.5	0.84	50.8	84.5	<0.1	<0.02	0.02	0.18	1.07	0.37	10.9
VE3 U	0.01	15	0.81	55.4	91.4	<0.1	<0.02	<0.02	0.15	1	0.31	10.1
VE4	<0.01	10.5	1.25	64.6	85.6	<0.1	<0.02	0.02	0.21	1.22	0.44	9.12
VE5	0.3	24.6	0.4	3.16	5.56	<0.1	<0.02	<0.02	0.15	0.54	<0.1	2.07
VE6	0.01	77.1	0.46	1.39	6.71	<0.1	<0.02	<0.02	0.14	1.18	0.13	<2

Sample ID	K mg/l + 139M	Li µg/l + 139M	Mn µg/l + 139M	Mo µg/l + 139M	Ni µg/l + 139M	P µg/l + 139M	Pb µg/l + 139M	Rb µg/l + 139M	Sb µg/l + 139M	Se µg/l + 139M	Sr µg/l + 139M	Th µg/l + 139M
VE3	32.6	2.1	105	0.15	0.56	254	0.22	33.3	0.02	2.64	1280	0.02
VE3 U	30.3	1.91	96.6	0.18	0.83	230	0.18	30.7	0.03	2.62	1180	0.01
VE4	31.2	2.79	1.66	8.35	3.78	22.3	0.19	34.7	0.79	2.45	1400	<0.01
VE5	0.85	0.62	17.9	0.33	<0.05	19.2	0.09	0.17	0.03	<0.5	15.2	0.01
VE6	0.17	0.33	22	0.08	<0.05	14.7	0.22	0.06	0.04	<0.5	15.5	0.01

Sample ID	Tl µg/l + 139M	U µg/l + 139M	V µg/l + 139M	Zn µg/l + 139M	Ca mg/l + 139Pp	Fe mg/l + 139Pp	Mg mg/l + 139Pp	Na mg/l + 139Pp	S mg/l + 139Pp	Si mg/l + 139Pp	Br mg/l + 143R	Cl mg/l + 143R
VE3	0.18	0.04	3.2	6.93	40.3	0.5	34.9	152	43.3	4.11	<1	198
VE3 U	0.14	0.05	3.02	6.39	40.2	0.52	34.8	152	42.8	4.1	<1	193
VE4	0.12	0.14	0.71	3.59	35.5	<0.05	23.8	135	35.3	0.23	<1	192
VE5	0.02	<0.01	0.25	7.44	2.53	0.72	1.18	3.95	<1	1.26	<0.1	1.71
VE6	<0.01	<0.01	0.36	11.4	2.01	1.13	0.9	2.22	<1	1.97	<0.1	<0.2

Appendix 5 cont.

Sample ID	F	NO3	SO4	Ag	Al	As	B	Ba	Be	Bi	Cd	Co
	mg/l	mg/l	mg/l	µg/l	µg/l	µg/l	µg/l	µg/l	µg/l	µg/l	µg/l	µg/l
	+ 143R	+ 143R	+ 143R	150M	150M	150M	150M	150M	150M	150M	150M	150M
VE3	<1	<2	123	0.06	33.3	0.91	54.5	90.5	<0.5	<0.2	<0.1	2.29
VE3 U	<1	<2	123	<0.05	46	0.87	50.6	84.5	<0.5	<0.2	<0.1	2.27
VE4	<1	20.7	102	<0.05	25.8	1.28	63.6	80.9	<0.5	<0.2	<0.1	2.07
VE5	<0.1	<0.2	0.66	<0.05	37.1	0.36	<4	5.19	<0.5	<0.2	<0.1	<2
VE6	<0.1	<0.2	0.48	0.06	85.4	0.44	<4	6.48	<0.5	<0.2	<0.1	<2

Sample ID	Cr	Cu	K	Li	Mn	Mo	Ni	Pb	Rb	Sb	Se	Sr
	µg/l	µg/l	mg/l	µg/l	µg/l	µg/l	µg/l	µg/l	µg/l	µg/l	µg/l	µg/l
	150M	150M	150M	150M	150M	150M	150M	150M	150M	150M	150M	150M
VE3	2.02	2.98	35.3	2.04	107	<0.2	<3	<1	33.1	<0.2	<5	1330
VE3 U	6.66	2.66	32.8	1.88	101	<0.2	<3	<1	31.1	0.26	<5	1250
VE4	4.66	2.86	32.1	2.71	3.55	8.68	4.64	<1	33.4	0.75	<5	1410
VE5	<2	2.02	0.54	0.51	18.3	<0.2	<3	<1	0.15	<0.2	<5	13.2
VE6	<2	2.25	0.54	<0.5	22.1	<0.2	<3	<1	<0.1	<0.2	<5	14.7

Sample ID	Th	Tl	U	V	Zn	Ca	Fe	Mg	Na	P	S	Si
	µg/l	µg/l	µg/l	µg/l	µg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l
	150M	150M	150M	150M	150M	150Pp	150Pp	150Pp	150Pp	150Pp	150Pp	150Pp
VE3	<0.2	0.23	0.04	3.43	10.6	41.8	0.58	36.6	153	0.31	44.4	3.51
VE3 U	<0.2	0.16	0.04	3.23	9.32	42	0.61	36.9	153	0.31	46	3.54
VE4	<0.2	0.14	0.13	0.73	9.35	36.4	<0.03	23.1	137	<0.3	37.5	<0.7
VE5	<0.2	<0.02	<0.01	<0.5	36.9	2.51	1.2	1.4	3.9	7.18	0.29	1.17
VE6	<0.2	<0.02	<0.01	<0.5	17.6	2.05	1.26	1.13	2.25	1.76	0.28	1.67

Appendix 5 cont.

Sample ID	pH*	EC*	PO4-P*	Alkalinity*	KMnO4 number*
		mS/m	mg/L	mmol/L	mg/L
VE3	7.6	128.7	0.099	3.7	22
VE3 U					
VE4	8.8	110.9	<0.01	1.9	13
VE5	6.4	3.8	<0.01	0.26	89
VE6	6.1	2.4	<0.01	0.15	110

*Accredited analysis method

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The Barents region is an important source of natural resources and the area has great potential for the mining industry. However, challenges associated with mine closure will arise due to mining-induced impacts on the surrounding water, soil and air, and possible impacts on biota. The Geological Survey of Finland carried out environmental studies at the Kemi Mine, as a part of a project on active and closed mines. The project was carried out in cooperation between Russia and Sweden. The Russian partner was the Mining Institute from Apatity, Murmansk region, and the Swedish partner was Luleå University of Technology. The geochemical studies on the active chromite mine of Kemi focused on the origin of elevated concentrations of some elements in waters and organic stream sediments at the mine site and in its surroundings. Chemical impacts of tailings and settling ponds on watercourses were estimated based on surface water and organic stream sediment data. The studies provided new data on the composition and geochemical features of the pad of the settling ponds and local peat, and their impacts on water quality in the downstream watercourses.

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