Prediction of long-term impacts using environmental monitoring and modelling tools at two mine sites: Kittilä mine in Finland and Roșia Montana in Romania

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Abstract

Water sampling and laboratory analysis are laborious, span over a long period and require a large volume of samples to be collected and analysed. Therefore online monitoring devices could help narrowing down the suitable sampling sites and intervals, but also to react in case of any sudden changes in physico-chemical characters due to a failure of e.g. water treatment systems or a tailings dam. However, the current monitoring technology does not monitor accurately metal and metalloid concentrations, most field sensors have too short lifetime for online measuring, at least without continuous maintenance, and water analyses are still needed.

Long-term environmental impacts of gold mining and the suitability of new field equipment to monitor contaminant behaviour in recipient waterways were studied at two contrasting European gold mine sites: the operating Kittilä mine in Finland, and closed Roșia Montană mine in Romania. Whereas Romania has the largest gold resources in Europe, Kittilä mine is Europe's largest operating gold mine. The aim of the study was to understand how the mine waters are mixed and the contaminants diluted in recipient rivers and to provide information on how mine waters should be discharged to minimize environmental impacts of a mine. This was done by studying the electrical conductivity (EC) and flow velocities and patterns in recipient natural waters. EC is a general measure of total dissolved solids (e.g. salts, alkalis, chlorides, sulphides and carbonate compounds) in water, and natural waters tend to have low EC-levels, whereas elevated levels indicate often mineralisation or possible pollution.

Keywords
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Synopsis

1. *Purpose of research*

Long-term environmental impacts of gold mining and the suitability of new field equipment to monitor contaminant behaviour in recipient waterways were studied at two contrasting European gold mine sites: the operating Kittilä mine in Finland, and closed Roșia Montană mine in Romania. Whereas Romania has the largest gold resources in Europe, Kittilä mine is Europe's largest operating gold mine. The aim of the study was to understand how the mine waters are mixed and the contaminants diluted in recipient rivers and to provide information on how mine waters should be discharged to minimize environmental impacts of a mine.

2. *Material and analysis*

The mixing and dilution of mine waters in rivers was studied by measuring the electrical conductivity (EC) and flow velocities and patterns in recipient natural waters. EC is a general measure of total dissolved solids (e.g. salts, alkalis, chlorides, sulphides and carbonate compounds) in water, and natural waters tend to have low EC-levels, whereas elevated levels indicate often mineralisation or possible pollution. EC was measured vertically along the river and horizontally from river cross-sections by CastAway CTD (SonTek 2012) at both sites. The flow profiles on different parts of the river were measured by the Flow Tracker at both sites, and in Kittilä site also by River Surveyor M9 which measures also the velocity profiles and the shape of the river bottom. Additionally in Kittilä site, four continuous water quality monitoring devices were installed in mine water discharge sites as well as in upstream and downstream of River Seurujoki to measure long-term variations of water quality parameters in the river. The results obtained from field measurements were used together with the isotopic and geochemical analysis for hydrogeochemical modelling to predict the chemical transformation and long-term impacts of mining at study sites. The isotope and geochemical study results are presented in Papp et al. 2018. Also, the results of this study were utilized in ecological risk assessment presented in Baciu et al. 2018.

3. *Methods applicability*

Measurements with RiverSurveyor M9 were found to be challenging due to varying gradient of the river, un-uniform shape and dense vegetation of the riverbed or shallowness of the river. Therefore, finding a suitable site for measurements was difficult. However, those sites could be measured by the Flow tracker instead and in overall the measurements revealed valuable knowledge of the river flow patterns that affect greatly to mixing and dilution of mine water in natural waters.

Water depth proved to be the limiting factor also for the measurements with the Cast Away CTD device as parts of the river where the water level was less than the size or the required minimum depth of the device. Neverthless, the device was found to be technically applicable also to horizontal measurements in a stream, as long as the axis of the device was kept parallel to the stream so that water can freely flow through the flow-through cell of the device. The device is designed to measure vertical profiles. Overall the device was noted to be very functional for field measurements also in remote areas due to its small size, low weight and quick measurements.

The operation of the continuous measurement instruments proved to be problematic. In order to export the recorded data the Onset HOBO U24-001 loggers had to be taken out of the water. For an unknown reason this caused inaccurate measurements after the device was submerged again. In contrast, the YSI EXO2 functioned well also after the data was exported, apart from the nitrate results which differed from the laboratory results. However the device needed regular cleaning, calibration and due to the remote location and outsite of the reach of powergrid of the devices the batteries needed to be regularly replaced. The sensor is not designed to be used in mine water environments or to be calibrated at field which might explain the inaccuracy with the nitrate results.

Despite the above mentioned difficulties in field measurements, the combination of the different field measurements was found usefull tool to study mixing and dilution of mine waters in rivers. Furthermore, the study showed that at least in Kittilä site where the river is small and the flow velocities and the shape of the river vary a lot, the way of discharging is crucial for diminishing environmental effects. This kind of a study could be used when designing and optimising discharging methods for mine sites.

4. General evaluation and awareness

Water sampling and laboratory analysis are laborious, span over a long period and require a large volume of samples to be collected and analysed. Therefore online monitoring devices could help narrowing down the suitable sampling sites and intervals, but also to react in case of any sudden changes in physico-chemical characters due to a failure of e.g. water treatment systems or a tailings dam. However, the current monitoring technology does not monitor accurately metal and metalloid concentrations, most field sensors have too short lifetime for online measuring, at least without continuous maintenance, and water analyses are still needed. Furthermore, the monitoring area has to be carefully chosen so that all important sources that might interact are taken into consideration. The decision over the number of monitoring sites is challenging: too many sites results in high costs and time input; not enough monitoring sites results in detrimental data gaps. Therefore, the selection of monitoring sites is crucial. Also, if the mine expands, an assessment for the possible relocation of monitoring sites thoughout the mine life is needed.

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1 Introduction

The mining sector is a significant water user and a producer of wastewater, and water management is globally one of the most challenging stress factors in mining and mineral processing industry. Furthermore water is the greatest pathway for mine derived contaminants, and especially in pristine environments and water scarce areas, mining might have significant influence on local hydrological features and aquatic habitats (Environmental Law Alliance Worldwide 2010, Välisalo et al. 2014). Mine site is always a part of a catchment area in a meteoric water circulation system and its operation will alter the topographical and hydrological features through excavations, replacement of land masses and dewatering of the open pits and underground workings. Subsequently, also the hydrogeological circumstances such as infiltration, groundwater gradient, flow paths and velocities will change, affecting the surface and groundwater subsystems not only inside the mine site but also on its surroundings (Salonen et al. 2014).

The water quality depends highly on the mineralogy of the mined ore and typically, dewatering and process waters from sulphidic metal ore mines are saline due to elevated levels of sulphate (SO_4), earth alkali and alkali metals (e.g. sodium, potassium, magnesium, calcium). Additionally some emissions originate also from explosives (nitrates), processing (e.g. xanthates) and water treatment chemicals (e.g. aluminium and iron chlorides and sulphates, lime). The electrical conductivity (EC) correlates well with soluble salts and alkali and earth alkali metal concentrations in water (e.g. figure 3.1.2). Since EC tend to remain within a constant rate in natural waters, it is a useful general measure of water quality to be used as a baseline for comparing and detecting the influence of contamination sources such as mining. Furthermore, the CTD (EC, temperature, depth) sensors are nowadays rather reliable, inexpensive and easy to use and thus it is usually one of the monitored parameters in mines monitoring program. However, especially in natural, unconstructed streams, the depth and the shape of the river channel change constantly, altering also the water flow and mixing patterns. Subsequently, the water quality parameters neither divide evenly on the stream and choosing the monitoring location is challenging. Although CTD sensors and flow meters are widely used to monitor the water quality, the monitoring is often carried out by handful fixed stations around the mine site and they have not yet been widely combined with water velocity profiling which would reveal also the uneven flow patterns across the stream. On the other hand, the hydrological profiling device CastAway-CTD (SONTEK 2012), used in this study, is designed for instantaneous profiling of vertical conductivity profiles in deep waters such as seas or lakes (Restrepo and Kettner 2012, Nishenko S, Hogan and Kvitek 2012, Horner-Devine et al. 2009), not for horizontal profiling in small streams as in this study. Thus, this study tested the utility of combining EC data from CastAway-CTD measuring device and flow velocity

profiling data from the RiverSurveyor M9 (SONTEK 2011) device to indicate mine water plume mixing and dilution behaviour in stream waters. The RiverSurveyor M9 is an Acoustic Doppler Current Profiler (ADCP) device which measures water velocity, channel bathymetry and river discharge perpendicular to the current. To verify field measurements, water samples were taken in parallel with the CastAway-CTD assessments and analysed in the laboratory.

1.1 Aims of the study

The aim was to study mine water mixing and dilution processes in recipient rivers in order to 1) assess the long-term environmental impact and possible natural amelioration processes in the vicinity of old mine site and 2) provide information on how mine waters should be discharged to enhance the mixing and dilution processes to minimize adverse impacts on environment. Another objective was to test the applicability of different measuring devices to monitor the water quality parameters on field conditions and to compare the results to laboratory analysis results. The study was conducted by a combination of different monitoring devices at two case study sites: the Kittilä mine in Finland, and Roșia Montană mine in Romania. Characteristics from both sites are summarised in Table 2.1.1. The results obtained from field measurements were used together with the isotopic and geochemical analysis for hydrogeochemical modelling to predict the chemical transformation and long-term impacts of mining at study sites. The isotope and geochemical study results are presented in Larkins *et al.* 2017 and Papp *et al.* 2018. Also, the results of this study were utilized in ecological risk assessment studies which are published in Malinen 2015, and Baciu *et al.* 2018.

2 Mine water discharge studies at Kittilä mine Finland

2.1 Site background

The Kittilä mine is located in Finnish Lapland approximately 50 km northeast of the town of Kittilä (Figure 1.2.1). The climate is classified as subarctic, with yearly mean temperature being below 0 °C and snow cover ranging normally from October to May (Table 1.2.1). The vegetation zone is northern boreal and the wetlands surrounding the mine area consist of 1 to 2 m of peat over top of 3 to 6 m of moraine deposit. The soil surrounding the mine site is predominantly low permeability glacial till. There are not significant alluvial groundwater deposits in the mine vicinity. The mine site is within the lower reaches of the 307 km^2 Seurujoki River catchment, which drains to the Loukinen River south of the site (AVI 2013).

The Kittilä mine is currently the largest operating gold mine in Europe, with more than 2 million ounces of known gold resources. The average grade of proven and probable reserves is 4.9 g/t, and 3.5 g/t for additional resources (Wyche et al. 2015). The mineralization is classified as a Proterozoic orogenic gold deposit. Gold mineralization occurs along a 5 km stretch of the Kiistala shear zone within the Kittilä group of the Central Lapland Greenstone Belt (CLGB), and is associated with carbon (amorphous carbon and graphite), silica, albite alteration and carbonate

alteration of meta-sedimentary and volcanoclastic host rocks within the Kittlä group (Wyche et al. 2015, Lehtonen et al. 1998). These host rocks are in a transitional zone between Fe-rich to Mg-rich tholeiitic basalts, and consist of mafic tuff, black chert and banded iron formation (BIF). The gold is predominantly refractory, and exists within the lattice structures of arsenopyrite and pyrite. Sulphide content within the host rock ranges from 2 to 30%, and is on average 10% (Doucet et al. 2010).

Table 2.1.1 Summary of environmental and historical mine site conditions of the study sites

	Kittilä mine, Finland	**Roșia Montană mine, Romania**
Average annual temperature	-1.3 °C	7.4°C
Average annual precipitation/evaporation	Precipitation: 55 cm/yr Evaporation: 25 cm/yr	Precipitation: 74.5 cm/yr (SRK 2012)
Vegetation	Northern boreal vegetation	Nemoral formations (temperate forest – deciduous and coniferous)
Proximity to residential areas	50 km northeast of Kittilä, Finland (population 6421)	5 km northeast from Abrud, Romania (population 5000)
Economic mineralisation	Refractory gold (Au) within arsenopyrite and pyrite	Native gold, electrum gold (gold-silver) associated with sulphides (predominantly pyrite)
Host rock	hydrothermally altered meta-oceanic sediments with 10% sulphides within tholeiitic basalt (Proterozoic Kittilä group)	Neogene maar-diatreme volcanic complex intruding Cretaceous detrital sediments
Underground workings	exist beneath open pits and are being actively expanded	140 km of underground workings
Open pits	2 open pits totalling 35 ha	2 open pits totalling 24.95 ha
Mining operation dates	production began in 2009 and projected to continue to 2037	>2,000 years bp to 2006
Current mining activity	Underground mining ongoing with planned expansion	No current mining, but mining permit being sought by Roșia Montană Gold Corporation

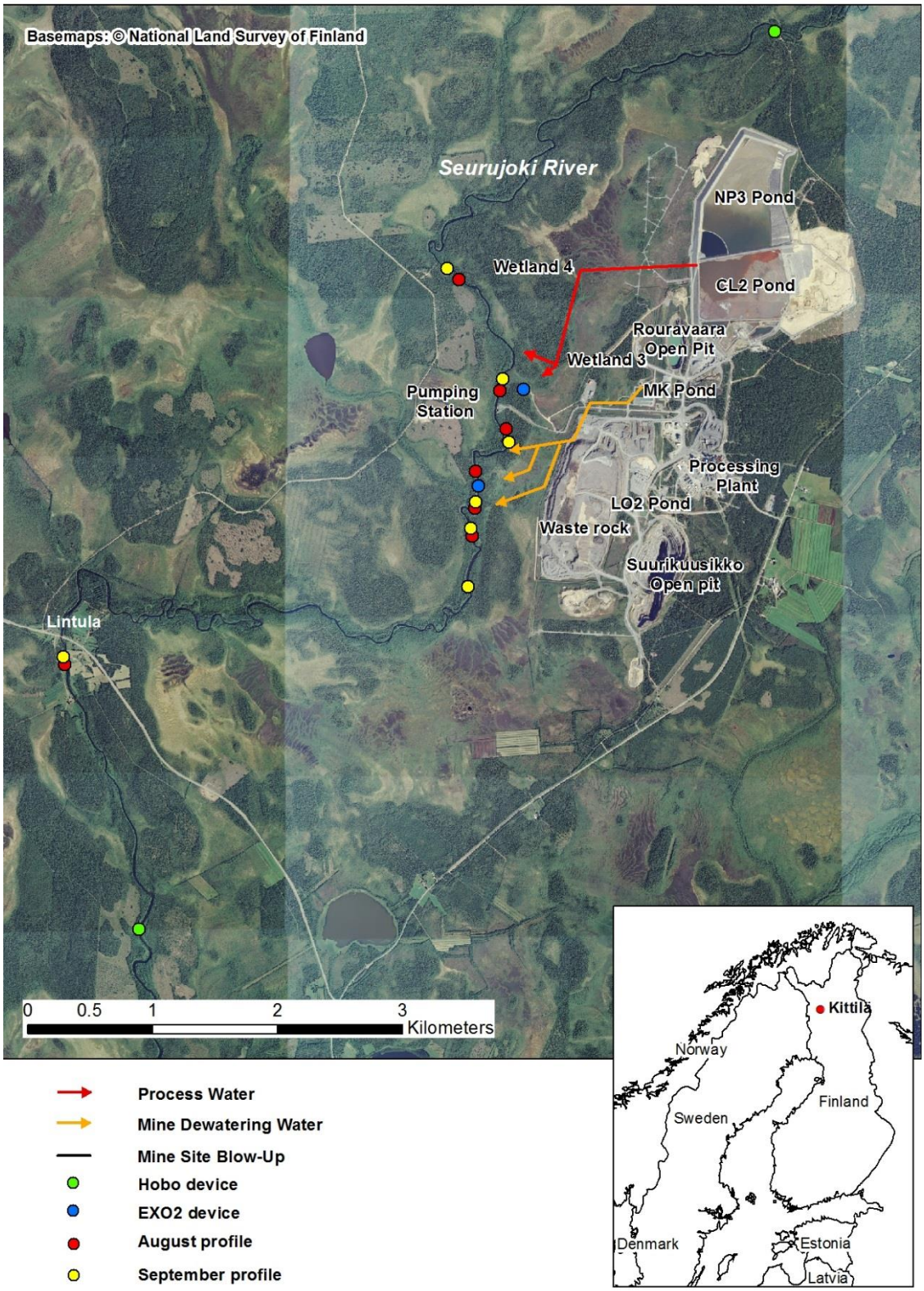

Figure 2.1.1. Location of Kittilä mine operations, mine water discharge flow paths, continuous water quality devices and the EC and flow-profiling sites.

Mining at Kittilä began in 2008 by Agnico Eagle, with the first commercial production of Au in early 2009. Initially ore was extracted from open pits. The Suurikuusiko open pit to the south, and the smaller Rouravaara open pit to the north were mined until 2012. Underground mining began in 2010 with about 8 km of underground tunnels mined per year. Underground stopes are backfilled with a tailings-cement paste and water from the NP3 pond. Approximately 1.4 million tons of ore are mined annually to produce approximately 6,000 kg Au (Agnico Eagle Finland 2015).The mining area encompasses 857 ha and includes the two open pits, underground workings, ore processing and water treatment facilities, two settling ponds, waste rock dumps, and other mine facilities (Figure 2.1.1).

Due to the refractory nature of the gold, cyanide leaching is required for gold extraction from ore. Ore beneficiation entails crushing, grinding, froth flotation, pressure oxidation, dissolution and electrowinning (Agnico Eagle Finland 2015). Approximately 3 Mm^3 of water is used annually during mineral beneficiation, 65% of which is recycled between tailings ponds and the beneficiation plant. The remaining 1.1 Mm^3 of beneficiation water is diverted from the river Seurujoki (AVI 2013) (Figure 1.2.2). Ore is transported from the mine to the semi-autogenous grinding mill by truck. Sulphide minerals are separated by froth flotation. The slurry extracted during flotation is neutralized and discharged to the NP3 tailings impoundment. Effluent from NP3 is discharged to an open fen-type peatland infiltration field, treatment wetland 4 (TW4), which drains to the Seurujoki River (Doucet et al. 2010). TW4 was designed to be 44 ha in area, but has been measured to currently be approximately 60 ha, with approximately 50% actively flowing area. Discharge of process water from NP3 to TW4 and on into the Seurujoki River began in 2010. The average discharge is 2,700 m^3/day (Pöyry 2012). The sulphide concentrate extracted during flotation is moved to a pressure oxidation autoclave for gold extraction. The gold concentrate is pumped to the carbon-in-leach (CIL) circuit in which gold is extracted from the slurry by cyanide leaching and adsorbed to carbon granules. The gold concentrate is further treated for gold recovery, and the cyanide leach tailings are moved to a reactor for cyanide destruction using the INCO method, following equation 1 (Agnico Eagle Finland 2015).

1) $(SO_2 + O_2 + H_2O + CN^- \xrightarrow{Cu^{+2}\ Catalyst} OCN^- + SO_4^{-2} + 2H^+)$

The INCO treated tailings and effluent from the cyanide leaching process are directed to the CIL2 and CIL3 (directly to the east of CIL2, not pictured in Figure 1) tailings ponds, which are in a closed circuit with the mill. (Agnico Eagle Finland 2015).

Mine dewatering and waste rock drainage waters are managed separately from process waters. Underground mine dewatering water is pumped to the MK pond, treated with PIX (ferrisulphate) coagulant, and discharged to the 5.5 ha peatland infiltration field, treatment wetland 3 (TW3). From TW3 effluent is routed to a second 17 ha peatland infiltration field, treatment wetland 1 (TW1), from which it subsequently drains to the Seurujoki River. Discharge of underground mine dewatering water to TW3 began in 2006 and is on average 6,500 m^3/day (Palmer et al. 2015). The Suurikuusikko open pit is dewatered to the LO2 storage pond. Open pit dewatering water from LO2 was discharged to treatment peatland TW3 until May 16, 2013, after which it has been

utilized in the mill for processing, for underground drilling, and has been pumped to the Rouravara open pit for storage. Seepage water from the waste rock facility is directed to the SISU pond. Excess water from the SISU pond will be directed to the CIL2 pond (Ramboll 2015). Additives are used throughout the beneficiation process, as well as for water treatment of both process and dewatering waters. Table 2.1.2 provides a list of industrial additives applied at the Kittilä site.

Table 2.1.2 Chemicals used during mineral beneficiation and water treatment at the Kittilä mine site (Pöyry 2009).

Chemical	Chemical formula	Use
foaming chemical MIBC	$C_6H_{14}O$	foaming
Xantate PAX	$C_5H_{11}OCS_2K$	foaming chemical
Sodium isobutyl xantate	$C_5H_{10}OS_2Na$	foaming chemical
Flocculent		thickening
Oxygen	O_2	autoclave
Hydrated lime	$Ca(OH)_2$	neutralization/pH increase
Burnt lime	CaO	pH adjust
Nitric acid	HNO_3	acid wash
Lye	NaOH	pH adjust
Cyanide	CN	Gold extraction
Activated carbon		CIL-circle gold extraction
Copper sulphate	$CuSO_4$	foaming, cyanide elimination
Metabisulphite SMBS	$Na_2S_2O_5$	cyanide elimination
Ferrisulphate PIX	$Fe_2(SO_4)_3$	water treatment

Water discharged from the Kittilä mine to treatment peatlands has an electrical conductivity of over ten-fold natural surface water in the area (Pöyry 2012). According to Larkins et al. 2017, process effluent and mine dewatering water are characterized by elevated metal and metalloid concentrations (As, Sb, Ni, Zn, Al, Cu, Mn, and Fe), as well as distinct ion composition in comparison to natural waters. Process water discharged to TW4 contains relatively high loads of SO_4, P, and N, while mine dewatering water discharged to TW3 contains relatively high metal loads (As, Sb, and Ni). Further, the quality of the mine dewatering water is variable, and depends largely on the lithology of the area being dewatered at a given time.

The mine waters are treated with PIX coagulant to remove suspended solids prior to discharge to treatment wetlands (Table 1.2.2). The effectiveness of treatment wetlands to attenuate contaminants is seasonally dependant in Finland, and is greatest during summer months during maximum biological activity. The treatment capacity of the wetlands is lowest during spring flooding, and it has been predicted that nutrients and contaminants could potentially be flushed from the wetlands to the River Seurujoki during these periods of high flow (Pöyry 2012, Palmer et al. 2015). Further, continual contaminant loading to treatment wetlands poses the potential to alter redox and pH conditions within the wetlands, and could result in mobilization of metals to the

surrounding environment. These conditions highlight how an understanding contaminant sources, pathways, and fluxes at the Kittilä site are crucial for guiding environmentally sustainable mining and water management practices.

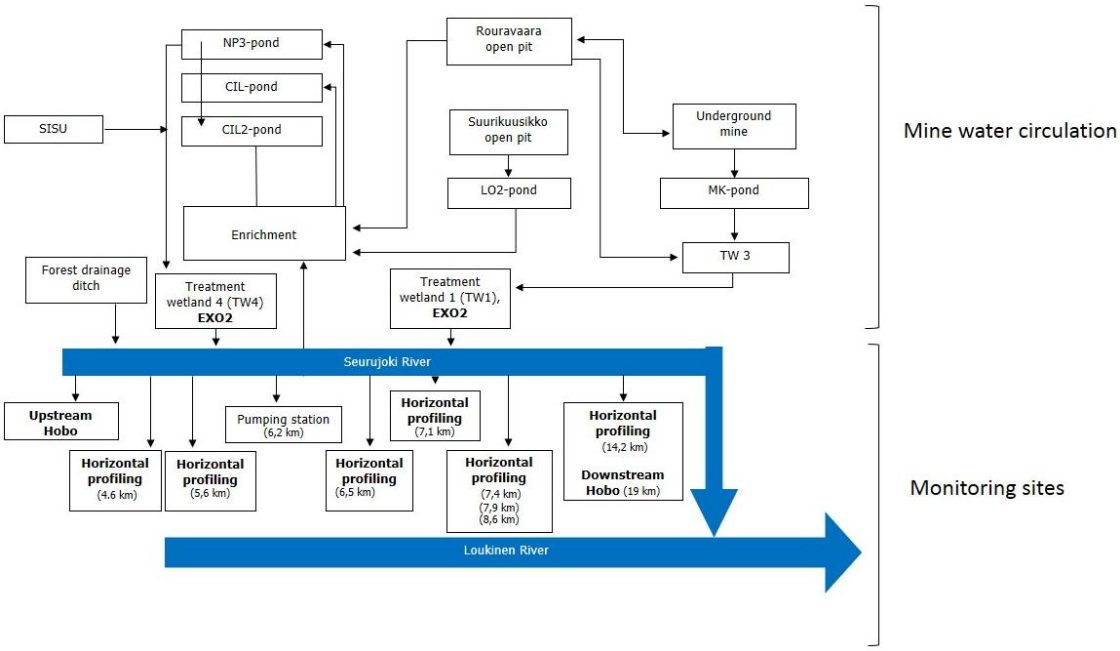

Figure 2.1.2 Mine water origins and flow paths relative to the Seurujoki and Loukinen Rivers. Approximate distance downstream from upstream Hobo monitoring point indicated in parentheses. (Adapted from Hämäläinen 2015a and Malinen 2016).

The Seurujoki River is naturally infertile, with clear water, but the mining operations have increased the concentrations of nitrogen compounds, SO_4, antimony (Sb), manganese (Mn) and some other metals in lower reaches (Pöyry 2012a). In addition to mining, forestry has changed the quality of the river water and the Seurujoki River is no longer in its natural state. According to the previous monitoring campaigns, the overall ecological status of the river remains good (AVI 2013b) but there has been changes in the diatom communities both in Seurujoki River and Loukinen River after opening the mine and the communities differ from the surrounding rivers. Thus the ecological status of the river is classified as poor. Fortunately, the ecological state of diatoms has balanced to its current state as there has not been any indication of changes in diatom communities between years 2010-2015. Furthermore, the company plans to open a treatment plant to treat the process waters to decrease the SO_4 concentrations, which will reduce also the concentrations of some metals and metalloids as the sulphate precipitates. (e.g. Hamari 2007, Kiviniemi 1999, Pöyry Finland Oy 2012-2013, Ramboll Finland Oy, 2014-2016). As the mine is expanding and as the mine workings extend deeper, the amount of dewatering waters increase. Anomalous concentrations of chloride (Cl) have been detected in some of the deepest extending boreholes. This type of saline groundwaters are common in Fennoscandian Shield and relate usually to glaciation and ancient Sea level fluctuations (e.g. Hyyppä 1984, Novakowski

1984, Nurmi et al. 1988, Frape et al 2003, Kietäväinen 2017). With increasing amount of dewatering waters especially the NO_3 emissions and salinity are expected to increase also in Seurujoki River (Pöyry 2012a, AVI 2013b), which may weaken the ecological status of the river. Mine water-surface water relationships, EC and flow profiling and continuous monitoring sites are illustrated in Figure 2.1.2.

2.2 Water quality monitoring

The aim of the study in Kittilä mine was to understand the mixing and dilution of dewatering and process waters in the recipient Seurujoki River and to provide information on how mine waters should be discharged to minimize environmental impacts. The horizontal CTD and flow velocity profiling campaigns were made simultaneously in August and September 2014 by CastAway-CTD and River Surveyor M9 (Figure 2.1.1a). Some of the flow velocity measurements in smaller tributaries were made by a Flow Tracker. The CastAway-CTD was used also to measure bathymetric i.e. vertical electric conductivity (EC) and temperature profiles along the river in June, July, August and September 2014 (Figure 2.1.1b). Additionally, four continuous water quality monitoring devices were installed to measure long-term variations of water quality parameters for approximately three months from June to August 2014. EC, pH, redox potential, dissolved oxygen, turbidity, nitrate concentration and temperature were measured from the process and dewatering water discharge ditches by two YSI EXO2 -multiparameter sondes probes (YSI incorporated 2009) and EC, T and depth in upstream and downstream of the Seurujoki River by two Oneset HOBO U24-001 conductivity loggers (Onset 2010). Along with the on-site measurements water samples were taken from the Seurujoki and the mine discharge waters in June and August 2014. The variables analyzed were Ag, Al, As, B, Ba, Bi, Cd, Co, Cr, Cu, I, K, Li, Mn, Mo, Ni, P, Pb, Rb, Sb, Se, Sr, Th, Tl, U, V, Zn, Ca, Fe, Mg, Na, Si, S, DOC, Br, Cl, F, SO_4, NO_3 and NO_2. The location for the profiles and sampling were chosen along the river from upstream to downstream so that the measurements would reveal the natural background state of the river, the influence of the mine and mixing and dilution processes in downstream (Figures 1.2.1 and 1.2.2). The raw data gathered during field campaigns was processed using Matlab software to produce scaled vertical profiles for conductivity and water temperature in the river, and to combine horizontal RiverSurveyor M9 water flow velocity measurements with horizontal conductivity casts made by the CastAway-CTD device (Räsänen *et al.* 2018).

The results of the monitoring studies were published in two thesis done by the students of Savonia University of applied sciences; “Effects of the Treated Drainage and Process Water in the Water System below the Kittilä Mine” (Hämäläinen 2015a) and “Impact of Water Balance and Flow Profile on Mixing and Diluting Substances in the Recipient River of Kittilä Mine” (Hämäläinen 2015b). An article was also submitted for a review in 2017 (Räsänen *et al.* 2018). Since the studies are well presented in the thesis (in Finnish) and in the article, in this report only a short introduction is presented. Furthermore, the results of the geochemical and isotopic studies are only cited here when relevant, and the more detailed results are presented in Larkins *et al.* 2017 and Papp *et al.* 2018. Additionally, ecological risk assessment studies were also carried out and are presented in more detailed in Malinen 2015 and Baciu et al. 2018.

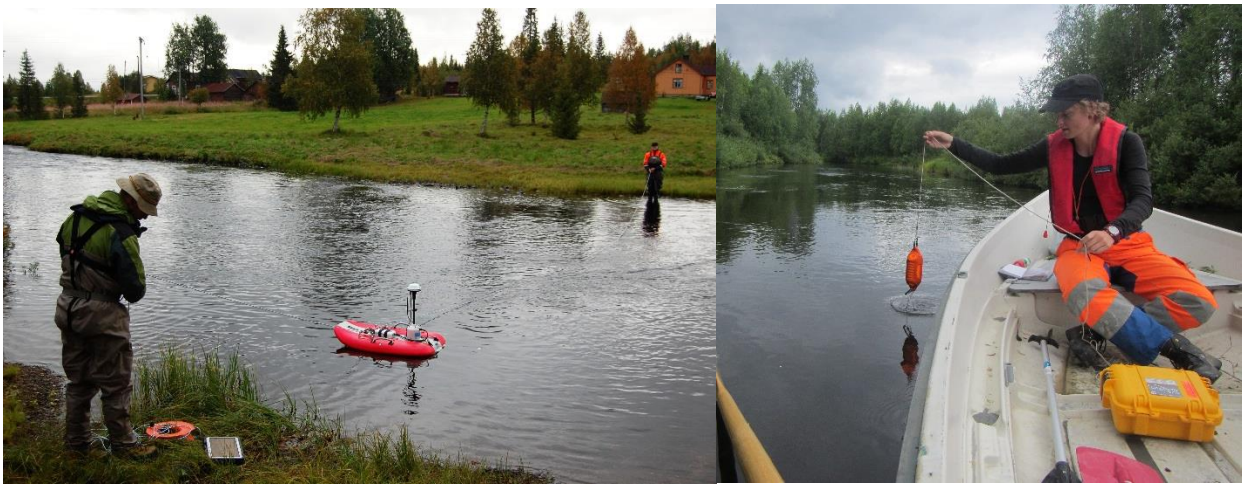

Figure 2.2.1 a) The horizontal flow velocity profiling by RiversSurveyor M9 device and b) The Vertical CTD profiling by CastAway-CTD device at Seurujoki River (Photos © GTK).

2.3 Mine's influence on the river Seurujoki.

The water flow of a river can be expected to increase downstream. This is due to the drainage basin of the river getting larger and larger as the river progresses (Leopold, 1953). Based on the water balance calculations and the flow measurements, at Seurujoki this is true only upstream from the process water discharge site but in the vicinity of the mine the claim is no longer valid even when the water intake and discharge of the mine are taken into account (Figure 2.3.1.4.1). This indicates that part of the water must enter a natural reservoir. This reservoir was observed to intake water in average at a rate of 0.44 m^3/s during September, which accounts for approximately 15% of the total flow of the river (Hämäläinen 2015b).

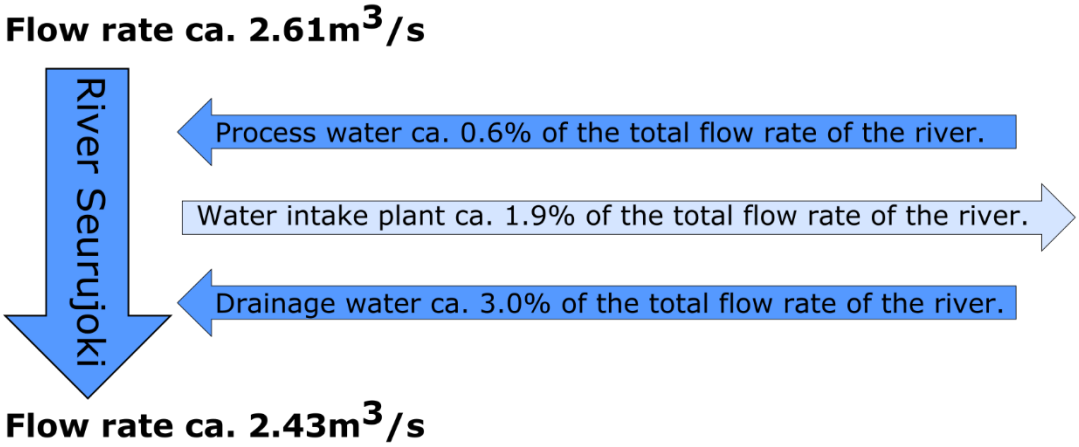

Figure 2.3.1. Water balance of the Kittilä mine (Hämäläinen 2015b).

During the study the M9 device seemed to slightly exaggerate the flow rates. When comparing results from the M9 with results from Talvitiemukka fixed measurement station operated by the ELY –center, the results were 37% higher in August and 11% in September. Yet the flow rate results of M9 aligned well with the measurements done by the very accurate permanent ultrasound flow rate measuring station of the mine. Furthermore, the load source estimates based on the isotope and geochemical tracers conducted at SUSMIN project were similar at each stage of mixing and supported the M9 measurements (Larkins et al. 2018). Later on, after calibration and maintenance of the measurement station, it turned out to be misbalanced which added reassurance on the accuracy of the M9 measurements.

A Cast Away CTD (conductivity, temperature and depth) - hydrographic instrument was used to measure a 14 km section of the river once a month on 16.6., 22.7., 26–27.8 and 17.9.2014. The device was used while rendering the horizontal electrical conductivity cross sections. Measurements were done across stream, in one continuous sweep, with 5 measurements per second interval. The device was hoisted into a long handle and was held upstream from the measurer, flow-through cell of the device parallel to the stream. The profiles were done following the shapes of the river bottom but without the device touching it. The device has been designed for vertical EC profile measurements and it hasn't been applied to horizontal cross river measurements before. The variables measured were temperature corrected electrical conductivity, salinity, acoustic velocity and depth. The measurements with the Cast Away CTD were conducted along the same cross-section as the flow rate measurements, which allowed correlation of EC profile with flow rate profile (Hämäläinen 2015a).

The YSI EXO2 -sondes probes were installed into the dewatering and process water discharge points of the mine (Figure 2.1.2). The Oneset HOBO U24-001 loggers were installed into two locations, one upstream, and one downstream from the mine. These locations were chosen in order to both gain baseline values and to detect the possible environmental influences of the mine at the same time.

The pH values of the discharge waters were observed to be close to neutral during the whole measurement period. This was expected as the mine regulates the values (Agnico Eagle Finland Oy, 2015). The redox-potential measured with YSI EXO2's was observed to be between 180–350 mV during the whole measurement period, with process waters having slightly higher values on average (Hämäläinen 2015a). According to Evangelou (1998) this makes the waters mildly oxidizing. The dissolved oxygen, also monitored with the YSI EXO2's, varied between 3.6 mg/l and 12.4 mg/l. The DO values varied considerably more in process waters when compared to dewatering waters (Hämäläinen 2015a).

Upstream from the mine, the highest EC values occurred near the surface of the river. Horizontally across the river, variation in the electrical conductivity wasn't significant. The natural electrical conductivity of the Seurujoki was between 50-100 µS/cm and the mine discharge increased the EC to a level of 180-230 µS/cm (Table 2.2.1). Vertically, the highest EC values were found near the river bottom (Hämäläinen 2015a). Moreover, the high conductivity correlates well with concentrations of different metals, magnesium (Mg), potassium (K), sodium (Na), calcium (Ca),

and SO_4 (Räsänen *et al*. 2018). This can be explained by the heavier, dissolved solids settling to the bottom of the river after discharging from the treatment wetlands.

Table 2.3.1. Electrical conductivity of the mine discharge and EC values from Seurujoki up- and downstream from the discharge release sites (Hämäläinen 2015a).

Month	Upstream from the discharge location (µS/cm)	Mine discharge (µS/cm)	Downstream from the discharge location (µS/cm)
June	54	3894	181
July	86	1191	141
August	82	1580	230
September	102	856	116

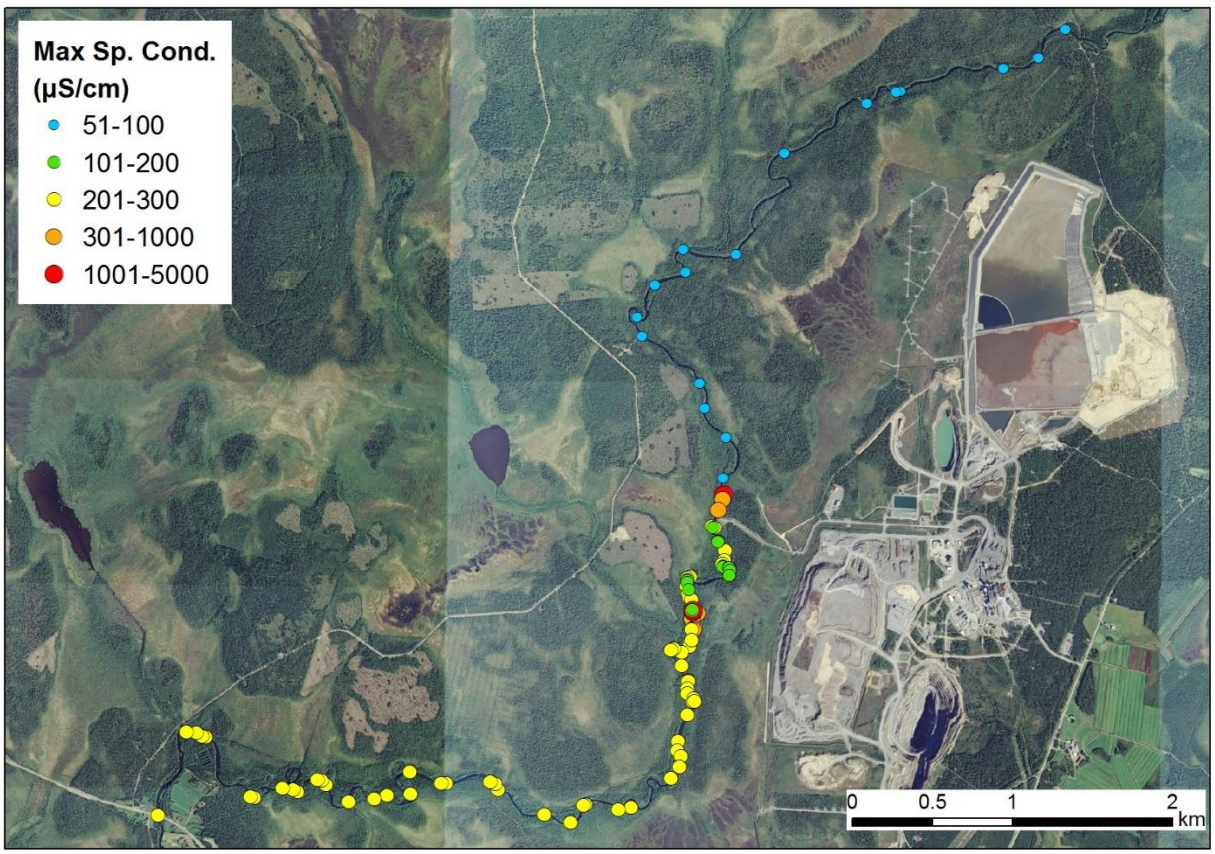

Figure 2.3.2 A map showing the change in River Seurujoki's EC resulting from the process- and dewatering water discharge in August 2014.

The dilution and mixing of dewatering waters in the river is slow in comparison to process waters. It takes approximately 300 meters downstream from the process water discharge point for the EC to level out across the whole river (Figure 2.3.2). For the dewatering waters this takes up to 9 kilometers. Of course the higher background values caused by the process water discharge might further hinder the dilution and mixing of the dewatering waters, but the most substantial reasons for the difference were observed to be *(1.)* the amount of water discharged, *(2.)* the differences in the river flow rates at the discharge sites and *(3.)* the different methods for discharging the waters (Hämäläinen 2015a):

1. The amount of discharged dewatering waters was approximately five times the amount of process waters. Even if the EC values of process waters are considerably higher in comparison to dewatering waters, the larger volumes of dewatering water pose a bigger impact on the river water quality.
2. Dewatering waters are being discharged into the river at places where the flow rate is naturally low (20% lower than at the process water discharge site). Lower river flow rates were observed to hinder the mixing and dilution of mine waters significantly. By discharging dewatering waters at places where the river flow rate is higher the mixing and dilution could be enhanced. At the process water discharge site the highest river flow rates occur at the mine's side of the river which further increases the mixing of process waters. Thus it is also important to consider the differences in the river flow across the horizontal profile of the stream.
3. Dewatering waters are discharged through multiple small ditches, while the process waters are led through one clear channel. The dilution and mixing of dewatering waters could be enhanced if they were discharged through one clear channel as well.

Due to the low flow rates of the discharge waters, the plume of high EC values (originating from the mine discharge) stays on the mine's side of the river. Currently the mine takes the freshwater it needs from the same side and from the stretch between the two discharge sites. The freshwater quality at the mine could be improved if the mine would take the water it needed from the opposite side of the river. Also, the mining company monitors the river water quality only on the western side of the river. It would be advisable to monitor the water quality also on the mine's side, due to the heterogeneity in the EC values (Hämäläinen 2015a and Hämäläinen 2015b).

The Kittilä mine company is assessing a possibility to discharge the mine effluent via pipeline to lower reach of the Loukinen River. This would not increase the contaminant load in the rivers but the adverse effects would be allocated to a smaller extension of the river systems. Moreover, the water volumes and flow velocities of the Loukinen River would most likely enable faster mixing and dilution than current discharging point in Seurujoki, and the adverse effects on the river systems would be diminished.

3 Mine water monitoring studies at Roșia Montană Romania

3.1 Site background

Roșia Montană is located in the Southern Apuseni Mountains (western Romania) and belongs to the Golden Quadrilateral, one of the most important gold areas and probably the biggest gold deposit in Europe. The hydrothermal activity that generated the deposit is related to the Neogene magmatism, responsible for all the mineralizations (precious and base metals) from the Apuseni Mountains. The basement in the region consists of Paleozoic and Precambrian rocks, covered by Cretaceous sediments, mainly in flysch facies. The basement and the sedimentary cover have been intruded by the Tertiary magmatites, mainly represented by andesites and dacites (Tamas, 2007). The mining tradition spans over two millennia, the ore being extracted discontinuously during this time. Very likely, gold mining started in the region before the Roman times; however the first systematic operations were conducted by the Romans. Through an extended network of galleries, they followed the gold-rich veins. Typical trapezoidal-shaped galleries are still in a very good condition, and can be visited. The mining operations have been performed underground till 1970, when the open pit extraction began. The concentrate was separated by flotation from the ore. At the end of the flotation process, gold and silver were recovered using conventional cyanide leaching techniques. In the last two decades, due to the economical context and to insufficiently adapted technology, mining operations were significantly reduced. The mine was closed in 2006, and currently the mining area is inactive.

As the mining activity was performed during the centuries with little or no consideration for the environment, there are significant environmental consequences. Acid mine drainage (AMD) and the related transfer of heavy metals represents the main pollutant factor that affects the environment in this mining area. Acid drainage forms as a consequence of the chemical reactions between water and rocks containing sulphur-bearing minerals, especially pyrite. Once exposed, pyrite reacts with air and water and forms sulphuric acid (H_2SO_4) and dissolved iron. Further on, the acid runoff dissolves heavy metals such as Cu, Pb, Zn, etc., contaminating the ground- and surface water. The acid water comes from the Cetate and Carnic open pits, from several open galleries, and from numerous waste dumps. There are some open galleries that release important amounts of acid water with a very low pH value below 3. These acid waters are collected by the main watercourses in the region (Roșia and Corna steams, and Abrud River) and high concentrations of elements such as Cu, Zn, Pb, Cd, Ni are present also in stream sediments, disturbing the aquatic environment (Florea et al. 2005; Bird et al. 2005).

3.2 Water quality monitoring

The mixing and dilution of mine derived contaminants and their impact on recipient river system were studied in May 2015 downstream of the former Rosia Montana goldmine. The hydrologic system around Roșia Montană is complex, including several natural rivers and streams with highly variable geometry and flow conditions. Therefore and due to time limitations, the CTD and flow velocity monitoring studies were conducted only around the confluence of Arieș and Abrud Rivers (Figure 3.1.1). Further studies on water and soil pollution as well as ecological risks around the

mine site were conducted around the area and are presented in Papp *et al*. 2018, Lazar *et al.* 2014, and in Baciu et al. 2018. The Arieș River is the main watercourse of the area, with over 3000 km^2 of drainage area and average flow rate ranging from 5 m^3/s to 63 m^3/s (Forray and Hallbauer 2000). Its main tributary, the Abrud River has rather low flow (0.01 to 2 m^3/s), from a drainage area of 274 km^2. The Abrud River is quite severely polluted due to its tributaries that drain all mine waters from the former Roșia Montană mining area (Bird 2005). Although Abrud River receives all the adjacent streams, in comparison to its mining influenced tributaries, it has the lowest SO_4 content, total dissolved solids, and heavy metal concentrations, due to the higher flow rate and water volume (Papp *et al.* 2018). The water quality difference between these two rivers is visible, as the mine-impacted water from Abrud River flows along the right bank of the Arieș River after the confluence (Figure 3.2.1).

Figure 3.2.1 The confluence of the mine-impacted Abrud River (flowing from the left) and the Aries River (Photo © UBB)

The field work was conducted by GTK and UBB in May 2015 and the risk assessment itself was performed for the SUSMIN project as part of an environmental engineering course by the students from Savonia University of Applied Sciences (Savolainen et al. 2016). The assessment was based on 24 water samples, 36 vertical and 6 horizontal EC measurements done with the CastAway CTD and three flow rate measurements conducted during the field work. The raw data gathered from the field measurements was processed by Matlab. Along with the estimation of environmental impacts, one goal was to evaluate the usefulness and accuracy of the CastAway CTD in mine environment studies together with similar studies conducted at the Kittilä gold mine (see chapter 2.1). This was done by comparing the temperature compensated EC results from the device to EC results from the samples analysed in the laboratory (Savolainen et al. 2016).

The deviation between the two sets of results varied between 7.8 – 22.2%, the CastAway CTD showing higher values than the laboratory measurements. The deviation was also observed to non-linearly increase with the EC values (Savolainen et al. 2016). Reasons for the deviation are uncertain, but some differences in sampling and measurement time, location and depth might explain some of the variation.

3.3 Mine's influence on the river system

The EC results from the CastAway CTD are shown in Figure 3.3.2 along with EC values of water samples measured in the laboratory. The laboratory samples indicate that high EC values originating from the mine are caused by a combination of SO_4, different metals, alkaline earth metals and alkali metals (Figures 3.3.1a and b) (Savolainen et al. 2016).

Considering human health, the most substantial contaminants at the site are lead and nickel (Papp *et al.* 2018). Additionally the concentrations of zinc and fluoride exceed the Canadian Water Quality Guidelines for the Protection of Aquatic Life (CCME 1999) and also high SO_4 levels might pose a risk to aquatic organisms in Abrud River and near the river confluence. However, the concentrations are elevated also in Arieș River upstream indicating naturally high background values due to geology. Furthermore, as the relatively small Abrud River (about 1 m^3/s) mixes with the considerably bigger Arieș River (more than 5 m^3/s), the concentrations of all contaminants quickly dilute to levels below 100 µg/l, while being several thousand µg/l in some of the tributaries of Abrud River. The quick dilution is also visible in the EC measurements (Figure 3.2.2) (Savolainen et al. 2016).

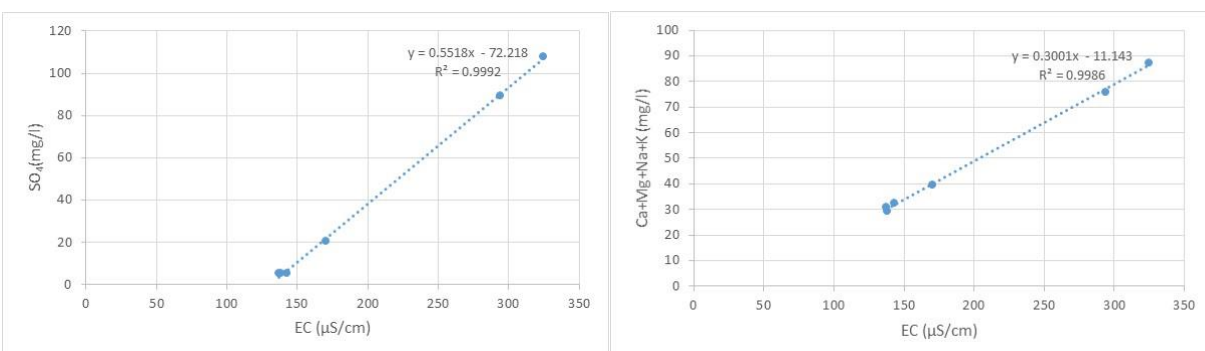

Figure 3.3.1 a) The correlation between SO_4 and EC, b) The correlation between alkali and earth alkali metals and EC

The former Roșia Montană mine site and its mining waste facilities clearly continue to affect the nearby river system and the most vulnerable are the small streams with too low flow and water volume to dilute the concentrations, in order to prevent the adverse impact on the aquatic life. At the confluence of Abrud and Arieș Rivers the contamination quickly dilutes due to higher water volume and flow. Nevertheless, the monitoring of surface water, groundwater, and mine water

quality is still necessary for designing appropriate measures to diminish the contaminant release that could harm the human health or the environment.

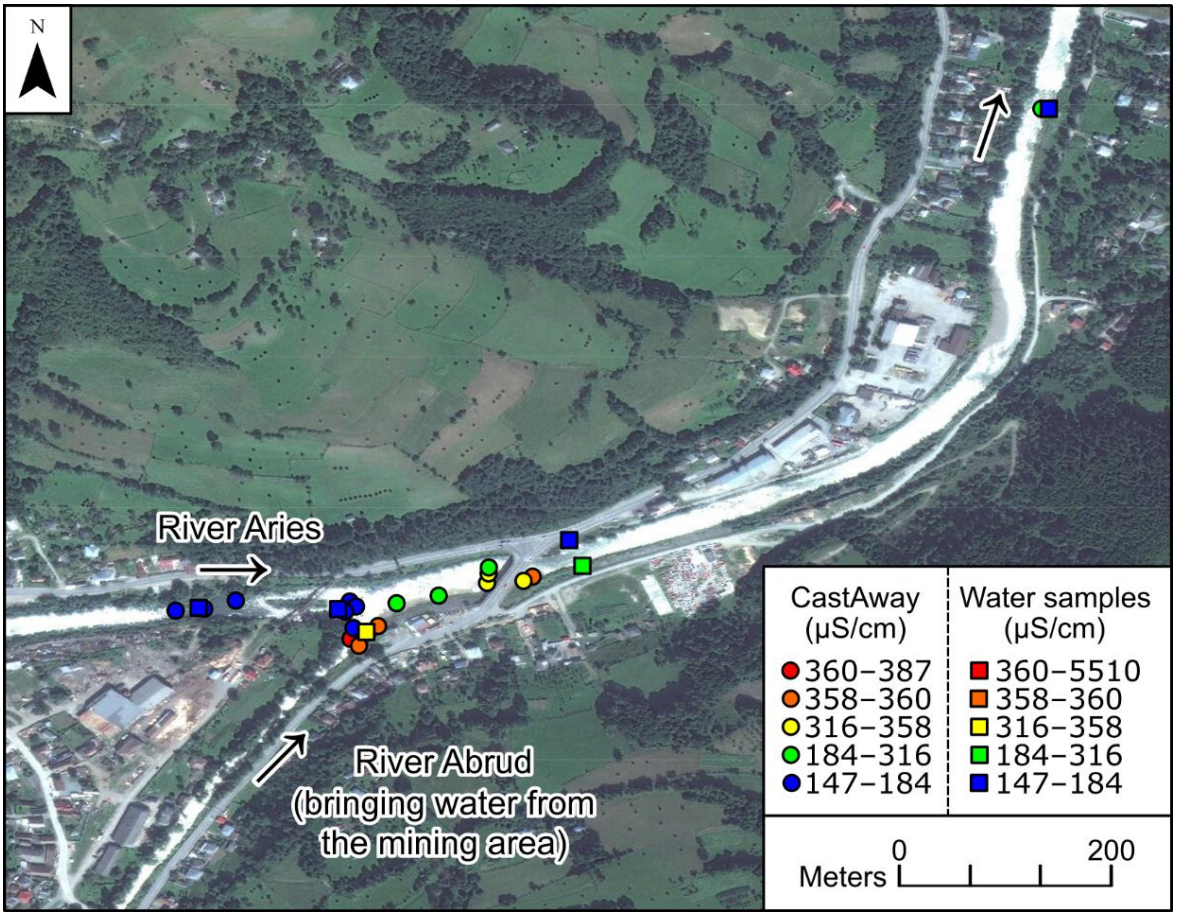

Figure 3.3.2 Electrical conductivity measurements and water sample locations near the confluence of Arieș and Abrud Rivers (Savolainen et al. 2016).

4 Conclusions

Measurements with RiverSurveyor M9 were found to be challenging to conduct at Seurujoki. The gradient of the river varies, the shape of the riverbed is un-uniform, the river is often very shallow and on some sites the river bottom is densely vegetated. Finding locations that filled at least the basic requirements for accurate measurements was hard and some of the measuring locations that were planned beforehand were deemed unsuitable and had to be abandoned or relocated.

The Cast Away CTD was found, along with normal EC measurements, to be technically applicable to horizontal measurements in a stream, as long as the orientation of the device is being considered. The device must be parallel to the stream so that water can freely flow through the flow-through cell of the device. The measurement should be conducted close to the river bottom, following the profile of the bottom. Water depth proved to be the limiting factor for the

measurements. Parts of the river where the water depth was less than 10 cm could not be measured due to the size of the device. Overall the device was noted to be very functional due to its small size, low weight and quick measurements.

The operation of the continuous measurement instruments proved to be problematic. The Oneset HOBO U24-001 loggers had to be taken out of the water in order to export the recorded data. For an unknown reason this caused inaccurate measurements after the device was submerged again and the data collected after late August 2014 had to be discarded. Similar difficulties had not been observed in previous studies. With the YSI EXO2's, the nitrate results differed from the laboratory results. The nitrate sensor was not designed to be used in mine water environments or to be calibrated at field which might explain the inaccuracy with the nitrate results. Furthermore, the device needed regular cleaning, calibration and due to the remote location and outside of the reach of power grid, the batteries needed to be regularly replaced.

Although the online monitoring devices could help narrowing down the suitable sampling sites and intervals, and also to react in case of any sudden changes in physico-chemical characters, the current monitoring technology does not monitor accurately metal and metalloid concentrations, most field sensors have too short lifetime for online measuring, at least without continuous maintenance, and water analyses are still needed. Also as evident at Kittilä site, the location of the monitors might affect the data obtained and all important sources that might interact should be taken into consideration.

Despite the above mentioned difficulties in field measurements, combination of CTD and flow velocity profiling of stream channel cross-sections proved to be a promising tool to assess the contaminant behaviour in stream waters. Monitoring revealed how changes in the stream morphology and flow velocity affect behaviour, mixing and dilution of contaminants especially in small tributary streams. In Kittilä, where the recipient, the Seurujoki River, is small and the flow velocities and the shape of the river vary a lot, the way of discharging affects crucially the mixing and dilution of the effluents. Lower river flow rates were observed to hinder the mixing and dilution of dewatering waters significantly. By discharging dewatering waters through one clear channel like the process and at places where the river flow rate is higher, the mixing and dilution could be significantly enhanced. The study highlights the importance of detailed hydrological and flow rate measurements in designing the location of mine water discharge ditch or pipeline to diminish environmental effects of mine discharge waters in recipient waterways.

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