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Turunen, K., Räsänen, T., Hämäläinen, E. et al. Analysing Contaminant Mixing and Dilution in River Waters Influenced by Mine Water Discharges. Water Air Soil Pollut 231, 317 (2020). https://doi.org/10.1007/s11270-020-04683-y

Analysing Contaminant Mixing and Dilution in River Waters Influenced by Mine Water Discharges

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Abstract Mine water discharges can cause negative effects on recipient rivers. The magnitude of the effects depends on how quickly and efficiently contaminants dilute in the river. Electrical conductivity (EC) is linked to the water quality and can be utilized as a general tool to compare and detect the contaminant sources and concentration changes derived from mine water discharge. Hydrological and flow velocity profiling devices were tested to assess the impact as well as mixing and dilution of mine effluent discharge in a river next to a gold mine in Finland. Additionally, flow rate and velocity profiles of the cross-sections were measured. Recently, the greatest ecological impacts had been detected in the vicinity of the dewatering discharge point, which has the highest sulphate concentrations in rivers. According to EC measurements of this study, these were the same locations, where the mine effluent did not dilute and mix efficiently due to lower flow velocities and lesser turbulence. Further, EC values displayed a significant positive correlation with sulphate, magnesium, potassium, sodium, and calcium, whereas a lower correlation was observed with the trace elements. The tested study method revealed how changes in the river morphology and flow velocity affect behaviour, mixing, and dilution processes. Mixing and dilution of contaminants depended on the discharge location and method as well as on the density differences between the mine water discharge and fresh river water. This study highlights the importance of detailed hydrological and flow rate measurements when designing the location of mine water discharge to recipient rivers.

Keywords Mine water · Contamination · Sulphate · Electrical conductivity · Environmental monitoring

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1 Introduction

Mine water discharges are recognized as being responsible for the greatest environmental impact of mining (Environmental Law Alliance Worldwide 2010). The occurrence and concentrations of harmful metals, sulphates, and nutrients can be linked not only to the geology and mineralogy of the ore deposit but also to the water treatment efficiency and the chemicals used in mineral beneficiation. Traditionally, the acidity of the metal-rich mine drainage has been accounted for as the main contributor to adverse impact on freshwater

ecosystems. However, the role of secondary salinisation and elevated sulphate concentrations have also found to play important role in degradation of freshwater ecosystems (Cañedo-Argüelles et al. 2013; Porter-Goff et al. 2013; Zhao et al. 2017). Recent research shows that elevated sulphate concentrations increase also phosphate availability and mobility from sediment and thus susceptibility to eutrophication as well as mercury mobilization through methylation (cf. Meays and Nordin 2013), yet there are no water quality guidelines for sulphate concentrations in surface waters in most of countries.

Assessing the short- and long-term effects of mine water discharge to recipient rivers and lakes plays an important role in mine environmental impact assessment (EIA) procedure and in the overall water management of a mine. Furthermore, the information of mixing and dilution conditions in rivers is crucial in designing the location and method of mine water discharge to recipient river to avoid the adverse impacts on freshwater ecosystems. Therefore, reliable monitoring methods are needed in order to obtain a holistic view about the contaminant load and the seasonal variation in mixing and dilution processes in recipient water bodies. However, the water sampling and laboratory analysis are laborious, span over a long period, and require a large volume of samples to be collected and analysed. Furthermore, in natural rivers, the depth and the shape of the river channel change constantly, which alters also the water flow patterns and it is challenging to make reliable measurements of water quality indicators. Thus, monitoring location has to be carefully chosen to ensure consideration of all important factors and contaminant sources influencing the outcome.

Traditionally mixing and transport behaviour of contaminants have been studied by using tracers that are injected steady rate from a point source located at the proposed discharge point. Mine water discharge from sulphidic metal ore mines is typically saline due to elevated levels of sulphate (SO_4), earth alkali, and alkali metals (e.g. sodium, potassium, magnesium, calcium). Sulphate has been shown to be one of the primary indicators for detecting mine-derived pollution in rivers, even before detecting changes in acidity and pH (e.g. Parker and Carey 1980; Rikard and Kunkle 1990). Unlike most of the other ions, sulphate is neither greatly affected by pH fluctuation nor removed by precipitation or sorption (Gray 1996). The electrical conductivity (EC) describes the amount of soluble salts such as sulphate, sodium, potassium, magnesium, and calcium in water. In contrast to mine water, the EC in natural rivers and rivers is affected primarily by the geology of the watershed and EC tends to remain within a rather constant range. Thus, EC is a useful general measure of river water quality that can be used as a baseline for comparing and detecting the influence of contamination sources in rivers that already has the contaminant source (e.g. Younger 1995; Banks et al. 1997; Heikkinen et al. 2008). In addition, EC is a rather simple, and cheap parameter to monitor with handheld or online CTD sensors. Because it also correlates with many mine-derived solutes, it helps narrow down the sites for more advanced studies and is therefore one of the most common water quality parameters routinely monitored at mine sites.

Acoustic Doppler current profiler (ADCP) measurements have attracted considerable popularity because of their capabilities to efficiently measure river discharges, channel bathymetry and flow velocity profiles from a vessel such as motorized boat moving across rivers in a direction perpendicular to the current (Williams et al. 2013, Scully and Geyer 2012; Szupiany et al. 2007, Muste and Spasojevic 2004, Yorke and Oberg 2002). Further, combining electrical conductivity data from CTD sensors with water velocity profiling data from the ADCP device has been proven to be a useful tool to study sediment and contaminant fluxes as well as stratification in oceans and lakes (e.g. Mueller and Wagner 2009; Vaz et al. 2012). However, the method has not yet been widely applied in studying rivers receiving mine water discharge, but EC and flow velocity rates are monitored usually with fixed stations, which do not take into account the channel bathymetry and its effect on mixing and dilution. EC was chosen as the key indicator for this study, because the earlier studies conducted at the Kittilä gold mine in Northern Finland (e.g. LVT 2007; Pöyry 2008; Palmer et al. 2015) had shown that sulphate has the greatest impact on the ecology of the nearby the Seurujoki River, whereas other contaminants such as Sb, As, and Ni are retained in the treatment wetlands. The earlier studies also indicated that despite their lower contaminant concentrations, dewatering water had a greater impact on the ecology than process water. In order to indicate contaminant mixing and dilution behaviour in rivers and in different discharge locations, the aforementioned combination of methods

was tested. This study aimed also to evaluate the usability of the method in planning discharge locations for mine water pipelines or ditches in order to enhance the mixing and dilution processes resulting in a lesser impact on the river ecosystem. Assessing the river and contaminant transport dynamics will also help in setting and improving the water quality monitoring schemes of the mine. Combining the monitoring method with the water chemistry analysis will also help to assess whether the recently set sulphate concentration limit for the environmental permit of the mine is adequate to diminish the adverse impact on the river ecosystem.

2 Methods

2.1 Study Site

The study site was the Seurujoki River, which is the recipient river of mine water discharged from the Kittilä gold mine. The mine is located in Central Lapland, in Northern Finland, about 170 km north of the Arctic Circle and the town of Rovaniemi (Fig. 1). The Suurikuusikko deposit is one of the largest known gold deposits in Finland and the Kittilä Mine is currently the largest operating gold mine in Europe producing about 4500 kg of gold every year (Ramboll 2015a). The mining company, Agnico Eagle Finland Oy, started the construction of the mine in 2006, the gold extraction commenced in 2008 and the mine achieved commercial production in 2009. The underground mining started 2010 and since open pit mining at Kittilä was terminated in 2012, the mine is now only operating underground, with a mine lifetime estimated through 2037 (Eilu and Pankka 2009).

The Kittilä municipality area is sparsely populated, the nearest village Rouravaara being about 1 km to the east of the mine, but the nearest residential houses are located about half a kilometre from the mine site. The principal land uses near the mine site are reindeer herding, forestry, and some agriculture. The mine area is surrounded by a natural wetland area with 1–2-m-thick peat deposits. In some places, there are quaternary, low-permeable (10^{-9}–10^{-5} m/s) sandy and gravelly till deposits (Pöyry Finland Oy 2012). The till beds are mainly 3–6 m thick but in places where there are weathered and fracture zones of bedrock, the till beds may be 20 m deep. The thickness of the top layer of the

weathered bedrock varies and in some areas it has been weathered almost to clay. The area is classified as sub-arctic and the annual mean temperature is − 1 °C. The annual mean precipitation is about 500–600 mm and evaporation 200–300 mm (Pöyry Finland Oy 2012).

The Seurujoki River is located 500 m off the mine site. The river has ice cover during the winter months, from November to May (Lahermo et al. 1996; Pöyry Finland Oy 2012). The water quality in Seurujoki is good, clear, and low in nutrients, but due to its location in the Central Lapland Greenstone Belt, it has naturally high As, Sb, and Zn concentrations. In addition to mining, the water quality in Seurujoki is affected by forestry practices and natural loads from peatlands.

According to Larkins et al. 2018, process effluent and dewatering waters of the mine are characterized by elevated metal and metalloid concentrations, especially As and Sb, as well as distinct ion composition in comparison with natural waters. The process effluent is described as magnesium-sulphate dominated and dewatering waters as calcium-sulphate dominated whereas the ambient natural waters tend to be calcium and bicarbonate dominated. Elevated concentrations of sulphate, As, and Sb are related to the ore mineralogy and the oxidation of sulphide minerals such as pyrite (FeS_2), arsenopyrite (AsFeS), and stibnite (Sb_2S_3). Calcium (Ca) and magnesium (Mg) are related to the dissolution of ankerite $Ca(Fe,Mg,Mn)(CO_3)_2$, dolomite ($CaMg(CO_3)_2$) and calcite ($CaCO_3$), whereas potassium (K) and sodium (Na) are linked not only to the weathering of albite ($NaAlSi_3O_8$) and muscovite ($KAl_2(AlSi_3O10)(F,OH)_2$) but also to the residues of Na and K-xanthates used as collectors in the flotation process. (Pöyry 2012a; Wyche et al. 2015; Larkins et al. 2018).

Pretreated process effluent water and mine dewatering water are directed to treatment wetlands; these are used to delay the flow of mine water and to improve the water quality before discharging into the Seurujoki River. Process effluent water is directed to an open fen type of treatment wetland 4 which has a size of 44 ha (Palmer et al. 2015) (Fig. 1). According to the study of Palmer et al. (2015), the hydraulic load is 2713 m^3/day, the surface load is 0.34–0.59 mm/h, with the residence time varying between 7 and 42 days. Dewatering water from the underground mine is directed first to treatment wetland 3 and then to treatment wetland 1. The process water is discharged into the Seurujoki River through one constructed ditch from
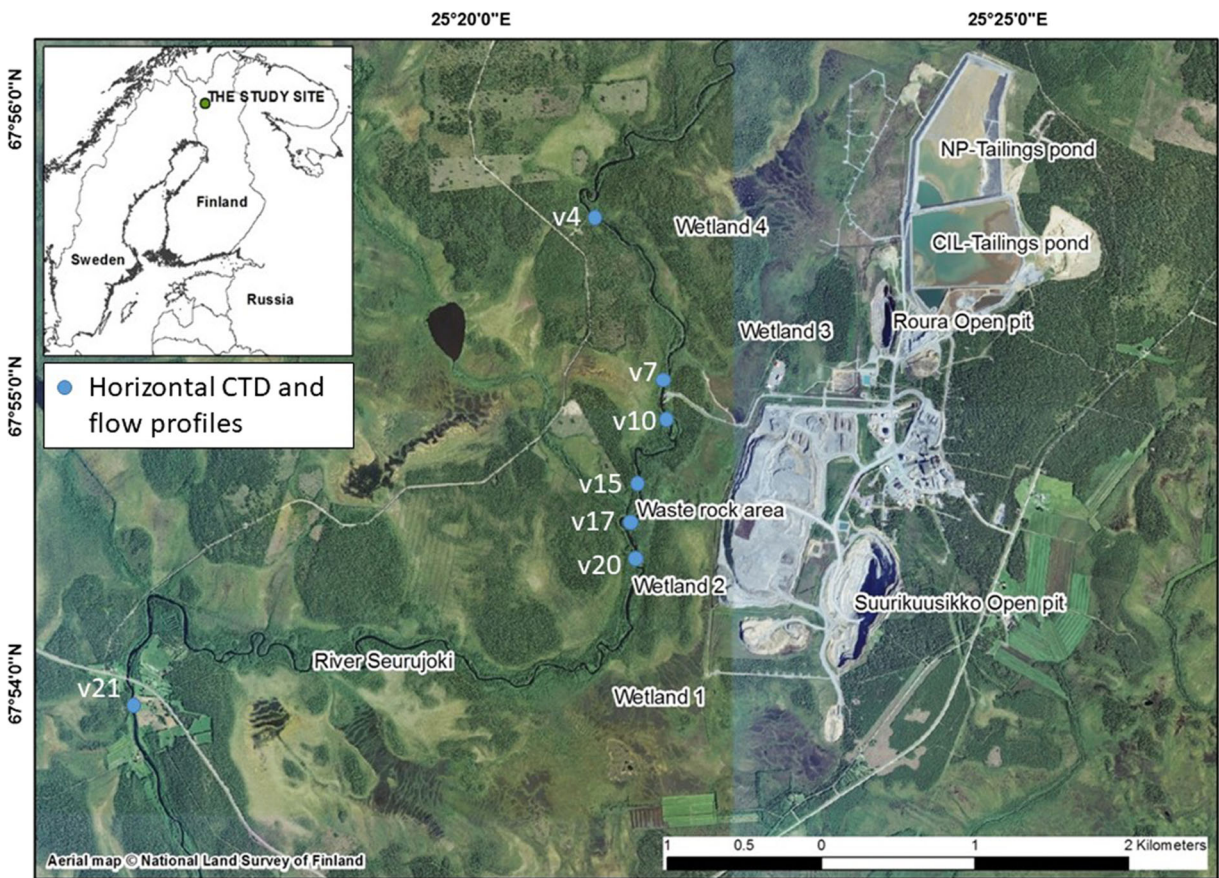
Fig. 1 Location of the Kittilä mine, the mine operations, treatment wetlands and recipient the Seurujoki River. The blue dots represent the river cross-sections selected for horizontal CTD measurements and flow profiles with the ADCP device. Vertical CTD profiles were also measured in these locations

treatment wetland 4, whereas the dewatering water is discharged through several small natural ditches through treatment wetland 1. The locations of the treatment wetlands are presented in Fig. 1. Approximately three billion cubic meters of water are used in the beneficiation process annually. About 65% of the water is recycled between the beneficiation plant and the tailings pond (NP-pond) with the 1.1 billion cubic meters being taken as raw water from the Seurujoki River (AVI 2013). In 2014 approximately 3.2 million m^3 of mine water, from which 24% process effluent water and 76% mine dewatering water were discharged to the Seurujoki River (Ramboll 2015a). According to Larkins et al. (2018), the contribution of the mine water to the Seurujoki River is on average 4%. According to Palmer et al. (2015), the treatment wetlands retain up to 95% of As, Sb, and Ni, whereas SO_4 and Fe are not retained, but leaching from the wetland to the Seurujoki River.

2.2 Measurements and Analyses

In this study, the mixing and dilution of mine water discharge in the recipient river, the Seurujoki River, was studied using EC as an indicator of mine water plume. The EC was measured by a hydrological profiling device, CastAway-CTD (SONTEK 2012), which is a rather new piece of equipment intended for instantaneous profiling of vertical conductivity profiles in deep waters such as seas or lakes (Restrepo and Kettner 2012; Horner-Devine et al. 2009). However, the suitability of CastAway-CTD in studying small river water has not yet been evaluated. To verify field measurements, water samples were taken in parallel with the CTD assessments and analysed in the laboratory. In addition, parallel to CTD measurements, the flow velocity profiles were measured by Acoustic Doppler Current Profiler (ADCP) device, RiverSurveyor M9 (SONTEK 2011). Figure 2 presents an outline of the practical aspects of the study.
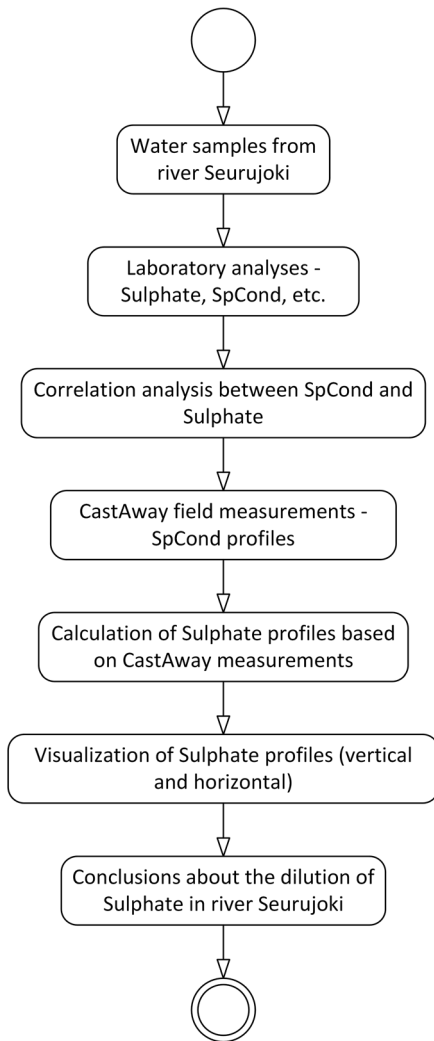
Fig. 2 Outline of practical aspects of the study

A field campaign was conducted at the Seurujoki River in August 2014. The CTD device was used to measure bathymetric, i.e. vertical electrical conductivity and temperature profiles from a canoe and horizontal changes of electrical conductivity and temperature from selected river cross-sections. Figure 1 presents these cross-sections and locations of the following measuring points:

- v4 describes the background (natural state of the river).
- v7 is process water discharge point.
- v10 is about 0.5 km below process water discharge point.
- v15 is the main dewatering water discharge point.

- v17 is close to smaller dewatering water discharge ditches.
- v20 is located 1 km downriver from v15, also smaller dewatering water discharge ditches.
- v21 is located 8 km downriver from v7.

In Fig. 1, the mine area is located on the right side of the Seurujoki River. The average discharge of the Seurujoki River in August 2014 was 2.08 m^3/s. In addition, the annual average discharge in 2014 was 2.23 m^3/s and maximum was 34.48 m^3/s. Monthly precipitation was 54.6 mm and average temperature was 12.0 °C in August 2014 measured in Kittilä, Pokka weather station.

In this study, the CTD device was used also to measure horizontal conductivity and temperature profile of the river. This was used together with vertical profiles in order to obtain more specific information about how the contaminants were being mixed and diluted. The CastAway-CTD is a handheld, small device designed for profiling to depths up to 100 m. The device measures temperature, salinity, conductivity, and sound of speed using 5-Hz response and sampling rate. It has also built-in GPS which provides location information.

RiverSurveyor M9 device was used to measure flow velocity for the same selected river cross-sections (Fig. 3). The measurement is based on ADCP technology (Acoustic Doppler Current Profiler); this makes it possible to measure water flow velocity, channel bathymetry, and river discharges (Yorke et al. 2002). In the RiverSurveyor M9, the profiler is mounted on a powerboat, which enables rapid and accurate discharge measurements in unsteady flow conditions. ADCP devices provide also data on the width of the river for the cross-sections and this was used to fix the location of the measurement sites. The CastAway-CTD device also has built-in GPS but its accuracy was not sufficient enough for combining directly CTD conductivity measurements with ADCP flow velocity measurements. The CTD device records measurement time for each measurement and this was utilized to pinpoint the location of each measurement in order to combine data from both devices in the same cross-section. The profiling was carried out back and forth two to six times on each cross-section according to the accuracy given by the ADCP device. Should there have been too many outliers or the accuracy too low, the profiling was repeated.

During the field campaign, water samples were taken from several locations in the Seurujoki River, in order to
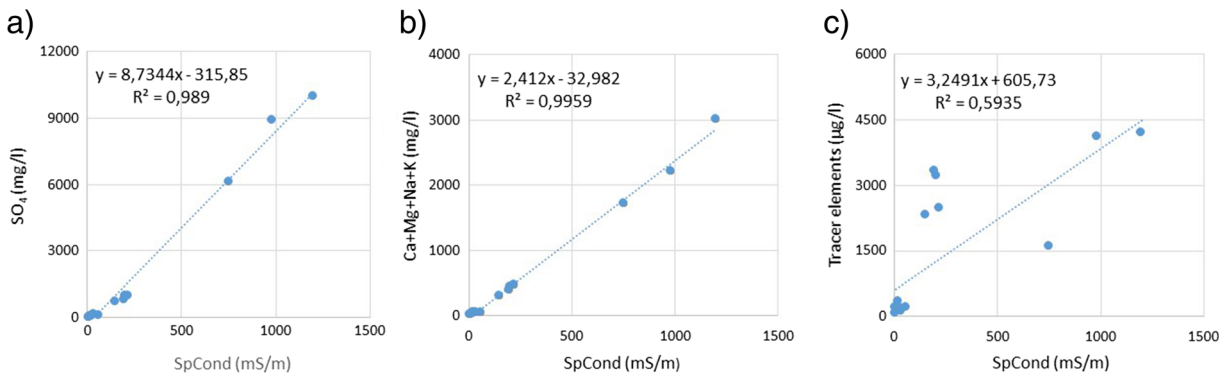
a)

b)

c)

Fig. 3 Correlation between **a** sulphate (mg/L), **b** sum concentration of Ca, Mg, Na and K (mg/L), and **c** sum concentration of trace elements (µg/L) with specific electrical conductance (SpCond) (µS/cm) in the Seurujoki River based on water samples taken in August 2014

verify the measurements as well as to assess whether the results correlate with the concentrations (mainly SO_4, Ca, Mg, Na, K). The water samples for soluble metals and metalloids analysis were pretreated immediately after sampling by ultrafiltration (0.2 µm) with acid preservation (metals and metalloids: 0.5 ml nitric acid/100 ml). Samples for analysing the anions and alkalinity were not pretreated. Alkalinity was measured on site with a Hach titrator and physico-chemical properties (pH, Eh, EC, DO, T) were measured by the YSI-Professional Plus instrument. All water samples were analysed in the accredited Labtium laboratory. The concentrations of total and soluble metal and metalloid were determined by inductively coupled plasma optical emission spectroscopy (ICP-OES) or inductively coupled plasma mass spectrometry (ICP-MS) depending on the concentrations (high concentrations by ICP-OES) and anion concentrations by ion chromatography.

2.3 Data Processing and Analysis

Field campaign produced raw data from CTD casts and ADCP measurements. The CTD results are presented as maximum values measured per transect, while outliers were discarded. Matlab software was used to produce scaled vertical profiles for conductivity and water temperature in the river. Furthermore, Matlab was used to combine horizontal ADCP water flow velocity measurements with horizontal conductivity casts taken with the CTD device. The depth of river water varies, creating challenges in comparing CTD measurements taken from different locations. In this study, one of the aims was to resolve how the possible contaminants are mixed and diluted in the river water. Therefore, the vertical and

horizontal conductivity measurements were used together with ADCP water flow velocity values. In order to compare results of different measuring locations and to make it possible to combine output from CTD device with ADCP data, some data preprocessing was necessary. Vertical conductivity profiles for different measurement locations relative to river depth were created using these data processing actions:

1. Scaling the absolute depth values (meters) into relative values (percentage)
2. Classifying (binning) measured conductivity and temperature values using relative depth values into 10 depth classes
3. Constructing illustration (figure) where conductivity and temperature measurements for different measuring locations are presented relative to river depth

The same kind of data processing was done also for creating horizontal profiles. CTD data and ADCP measurements were combined. Data was processed in order to produce a horizontal profile for water flow velocity (ADCP) and specific electrical conductivity (CTD) measurements for the same measured cross-sections. ADCP measures also the width of the river, which was divided into 20 sections and this was used in combining measurements. Horizontal conductivity profiles for the cross-sections relative to river width were created using following data processing actions:

1. Classifying (binning) measured water flow velocity (m/s) using river width values into 20 width sections
2. CTD device recordings of measurement time for each measurement which was used as an indicator

for the measurement location during the cast. Measurement time was classified into 20 classes and measured conductivity (µS/cm) values were incorporated into these 20 width classes.

3. Combining the water flow velocity and conductivity values relative to river width and presenting them in one figure with a depth profile of the river

The results of data processing are presented in Figs. 6 and 8 where both vertical and horizontal profiles are shown.

3 Results

3.1 Electrical Conductivity Changes and Relation to Water Quality

The correlation between specific electrical conductivity and chemical compounds was analysed using water samples taken during August 2014 (Fig. 3). According to the correlation coefficient, EC values display a significant positive correlation ($R^2 = 0.98$) with the amount of sulphate in the river water. Also, total concentrations of magnesium, potassium, sodium, calcium show a significant positive correlation ($R^2 = 0.99$) with EC, whereas a lower correlation was observed with the trace elements ($R^2 = 0.59$).

Maximum specific electrical conductivity (Max Sp. Cond.) values measured per river cross-section with CTD device showed that natural level of EC in the Seurujoki River varies between 50 and 100 µS/cm; the average was 85 µS/cm in August 2014 (Fig. 4 and Fig. 5). The maximum of specific EC of treated process water discharged into the Seurujoki River was 10,300 µS/cm (measured using YSI-Professional Plus, YSI Incorporated 2009). The level of specific EC decreased during dilution when the process water was discharged into the Seurujoki River. In Fig. 4, the effect of dilution can be seen; at the discharge point (v7), the value was about 5000 µS/cm, whereas 400 m downriver, the specific EC had been reduced to a level of 100–300 µS/cm. The specific EC of underground mine dewatering water was 1600 µS/cm in the discharge point (v15). Figure 4 and Fig. 5 reveal that before the influence of the mining discharges, the EC was evenly divided along the entire width of the river bed with the natural value of EC being about 85 µS/cm.

Linear regression was used to calculate the variation of sulphate concentration in the Seurujoki River based on maximum specific EC values measured by the CTD device in August 2014. According to Canadian water quality criteria, the long-term average of freshwater total SO_4^{2-} level should not exceed 128 mg/l for very soft and 218 mg/l for soft to moderately soft water (CCME 2014). The results show that in the vicinity of mine process effluent water and dewatering water discharge locations (Fig. 5) sulphate concentrations are higher than the Canadian water quality criteria for soft to moderately soft water (CCME 2014). After the process, effluent water discharge point sulphate concentration dilutes quite rapidly to level 51 to 218 mg/l. However, as the dilution of sulphate concentration below 128 mg/L takes about 200 m distance downriver, mixing and dilution is less efficient after the mine dewatering water discharge point, taking up to 8 km. This indicates that the flow is more turbulent in the vicinity of the process water discharge point than in the dewatering water discharge point.

3.2 Vertical and Horizontal Profiling of River Electrical Conductivity

The depth of the Seurujoki River varied in the measuring locations between 0.68 and 0.9 m with the width varying between 11 and 21 m. In addition, the water flow velocity fluctuated between 0.44 and 0.59 m per second. One of our aims was to study how the EC and temperature profile change after the mine water discharge points. Figure 6 depicts the scaled values for vertical profiles. In variance scaling of variables, data is scaled to zero mean and variance of one. While the water temperature profiles have not changed from their natural state, the EC profile has changed. The profile at the (v4) measuring point presents the background i.e. natural state whereas (v21) is 8 km downriver from the process effluent water discharge point, exhibiting an EC profile similar to the background. Between these locations the EC varies considerably; for example, at the process water discharge point (v7), the maximum EC values were measured from surface water. In contrast, the maximum EC value in dewatering water discharge point was located on the bottom of the river.

Figure 8 presents the horizontal EC and temperature profiles determined by the CTD device for the same six cross-sections of the river. Figure 8 includes also the channel geometry and flow velocities measured by the
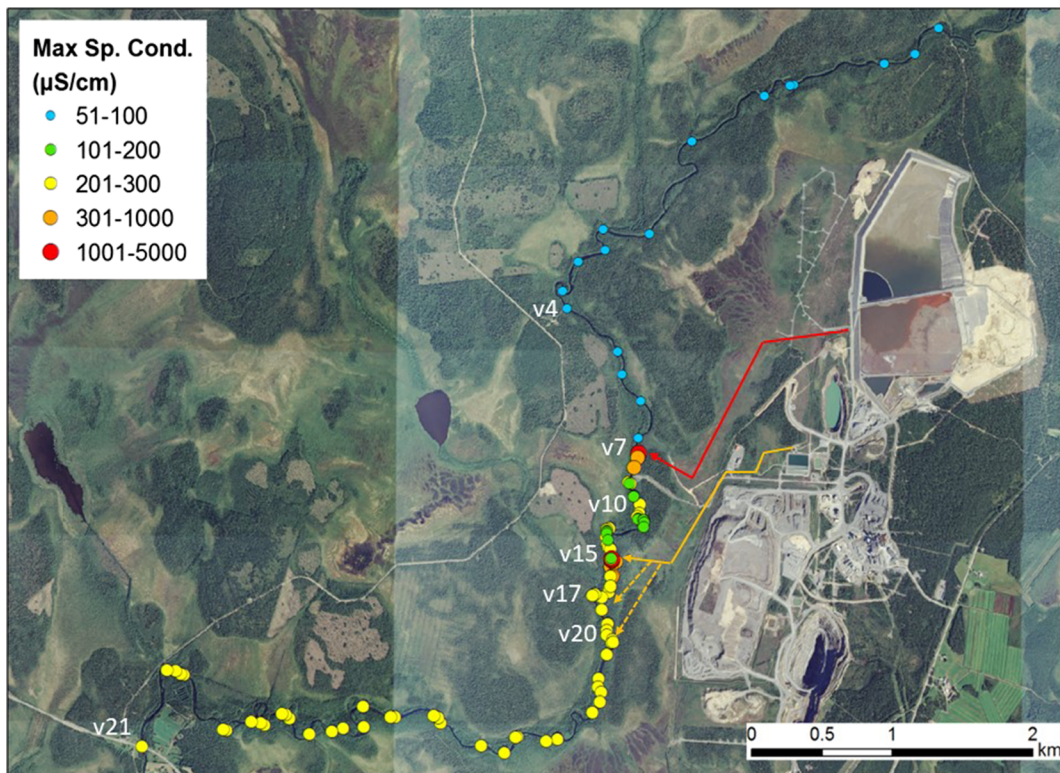
Fig. 4 Maximum specific electrical conductivity (Max Sp.Cond.) per transect in the Seurujoki River measured by the CastAway-CTD device in the Seurujoki River in August 2014. The blue dots represent the natural background values of the river, while red and yellow dots represent the mine impacted part of the River. The mine water discharge routes are marked with red (process water) and yellow (dewatering water) arrows. Points v4–v21 represent the CTD and flow profiling sites

ADCP device. In the natural state of the river (v4), electrical conductivity was stable across the whole width of the river. It was stable also in the cross-section located 8 km downriver from process water discharge point (v21). However, in the measuring locations where process (v7) and dewatering (v15) waters were being discharged, the maximum amount of EC was located heavily on the mine side of the river, where the actual discharging ditches are located. The same behaviour of EC also was observed at measuring points (v10, v20) which are located 1 km downriver from the main discharge locations.

Although the process water plume dilutes effectively, it is not fully mixed since 1 km downriver, in v10, EC increases on the bottom of the river (Fig. 6). Despite the lateral mixing and dilution of the process water plume, the saline (more dense) process water easily stratifies on the river bottom underlying fresh, less dense water, when the river flow turbulence decreases. The density of the process water derives from its total dissolved solid (TDS) content, which is a thousand times greater than in

the background (Fig. 7). The density gradient may suppress the vertical mixing and thus reduce vertical dispersion. In mine dewatering water discharge point (v15), river flow velocity is also lower since the river channel is wider than in the process effluent discharge point (v7) and twice the width of the background point (v4) (Fig. 8). Also, the deeper part of the main channel in dewatering water discharge point (v15), where the flow velocity is highest, is very narrow and further from the mine side of the river than in process effluent discharge point (v7), resulting in lesser mixing of the discharge. Due to width of the river channel in v15 the distance needed for lateral mixing is longer than in process water discharge point (v7). In addition, the volume of mine dewatering water, triple the volume of process effluent water, as well as the different discharge method effects the behaviour of contaminant plume. The mine dewatering water discharge creates longitudinal concentration gradients to river and the mine water plume is stratified on the river bottom underlying, less dense fresh water, in dewatering water discharge point
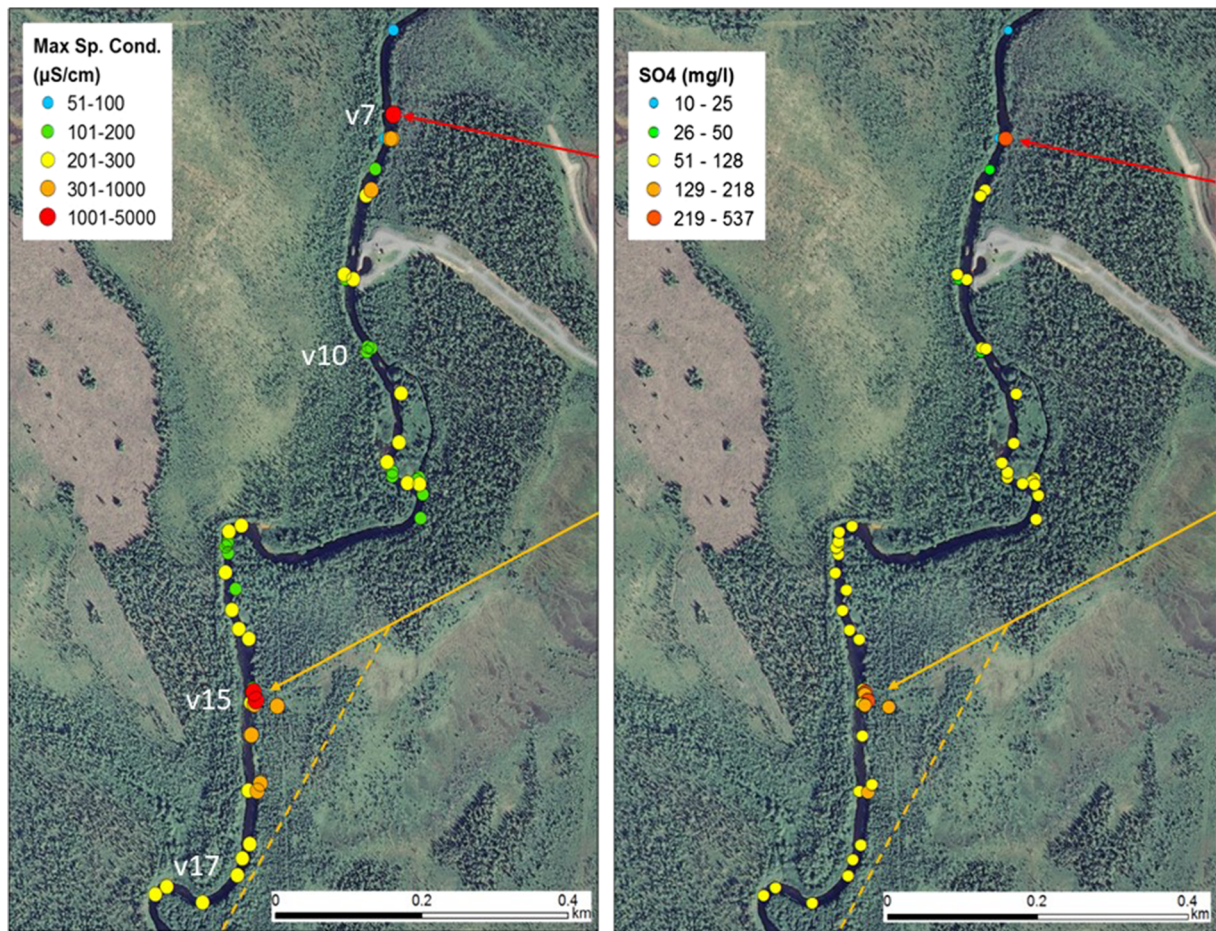
Fig. 5 Maximum specific electrical conductivity (Max Sp. Cond.) and SO$_4$ concentrations in the Seurujoki River close to the mine water discharge sites as measured by the CastAway-CTD device in August 2014. The highest values are shown with red markings, these are measured at the process water discharge point (red arrow) and the mine water discharge point (yellow arrows). v7–v17 represents the CTD and flow profiling sites

(v15). As seen in Fig. 6, 1 km downriver from the dewatering water discharge point, in v20, situation changes and the EC is higher in the surface water. This is consequence of both vertical and lateral mixing but also discharge of mine dewatering water through several natural ditches to the surface of the river.

According to Socolofsky and Jirka (2005), the theoretical distance needed for full vertical mixing can be simplified to equation: $L_x = 12h$, where h is the depth. Since the elevation of measured river cross-sections varies between 0.7 and 0.9 m (Fig. 8), the theoretical distance for vertical mixing is only 8–11 m. However, the width of the river channel varies considerably, between 11 m in point v4 (background), before the mine water discharge point, and 21 m, in dewatering water discharge point (v15). Theoretically, lateral mixing can

be calculated and simplified as $L_y = W^2/3h$, where W is the river width and h is the river depth (Socolofsky and Jirka 2005). Calculated lateral mixing distance in geomorphological conditions for mine process effluent water discharge point is 70 m, whereas mine dewatering discharge point the lateral mixing distance is 200 m. The CDT measurements (Figs. 5 and 6) indicate similar distances for lateral mixing, in general. However, the vertical CDT study (Fig. 6) showed vertical stratification due to salinity of mine dewatering waters.

4 Discussion

Mine water discharges are believed to exert the most significant environmental impact of mining during a
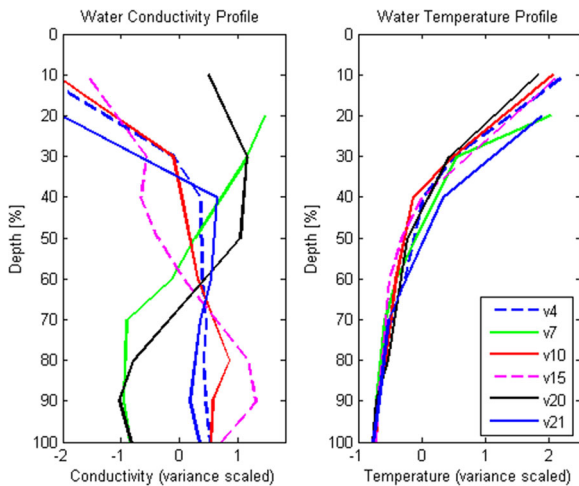
Fig. 6 Vertical profiles of specific conductance, water flow velocity and depth for cross-sections v4 (natural state of the river), v7 (process water discharge point), v10, v15 (main dewatering water discharge point), v20, and v21

mine's operational phase (Environmental Law Alliance Worldwide 2010). Thus, assessing how and to what extent mine waters pollute recipient rivers and lakes are a crucial part of the mine's water management programme and impact assessment. This study showed that the aforementioned issues can be assessed by

combining CTD and flow velocity studies. Awareness of water flow direction and velocities as well as the water quality (e.g. EC) variations are important if one wishes to clarify the mixing and dilution processes of contaminants in the river.

In this study, the electrical conductivity profiles measured with the CTD device detected the vertical and horizontal variation of EC values which revealed information about the distribution of contaminants in the river. The ADCP device was used successfully to measure water flow patterns in six cross-sections of a river in order to estimate the transverse mixing processes. The data from field measurements was combined with detailed water quality analysis (water samples analysed in a laboratory) and were processed using data analysis to produce more holistic information about the behaviour, mixing and dilution of contaminants in the river. The mine water discharge increased the conductivity in the Seurujoki River from natural levels of 50–100 μS/cm to a level of 210–280 μS/cm in downstream, the maximum being 10,300 μS/cm in process water discharge. According to the river water sampling conducted at the site in 2014, the high conductivity was attributable to the levels of magnesium, potassium, sodium, calcium, and sulphate. In contrast, there was no significant correlation
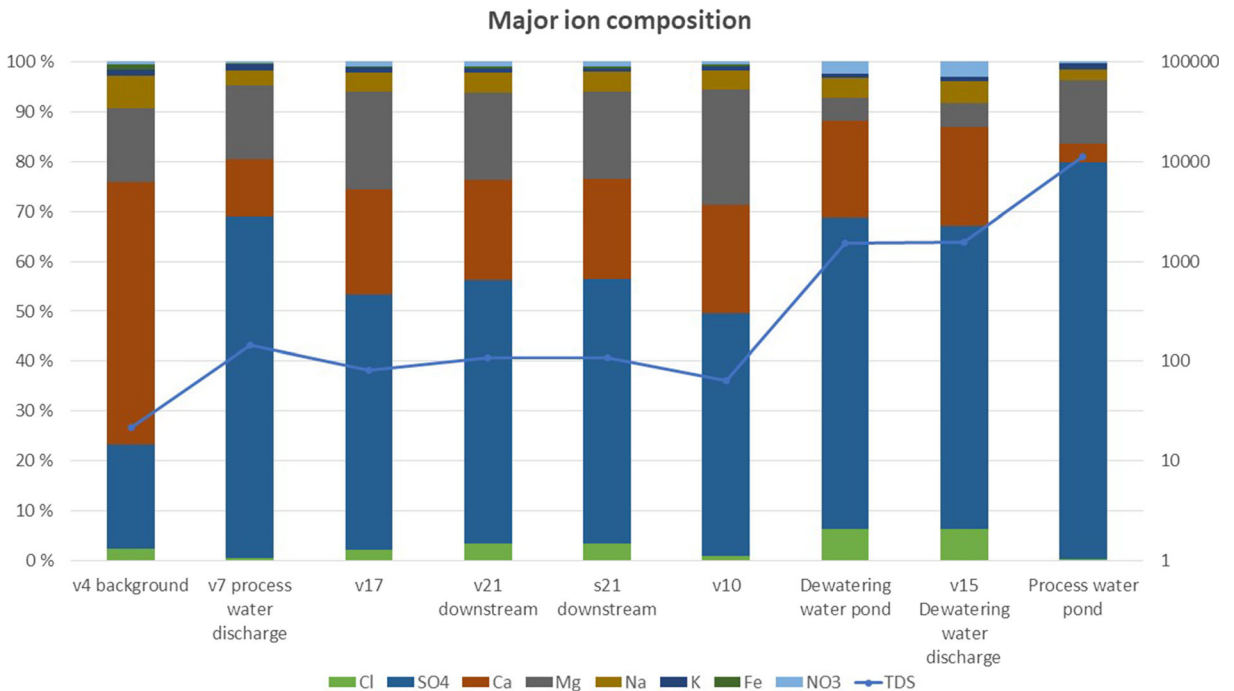

Fig. 7 The correlation of the major Ion composition (%) and total dissolved solids (TDS, mg/L) of natural river water and mine impacted process and dewatering water at the Kittilä mine
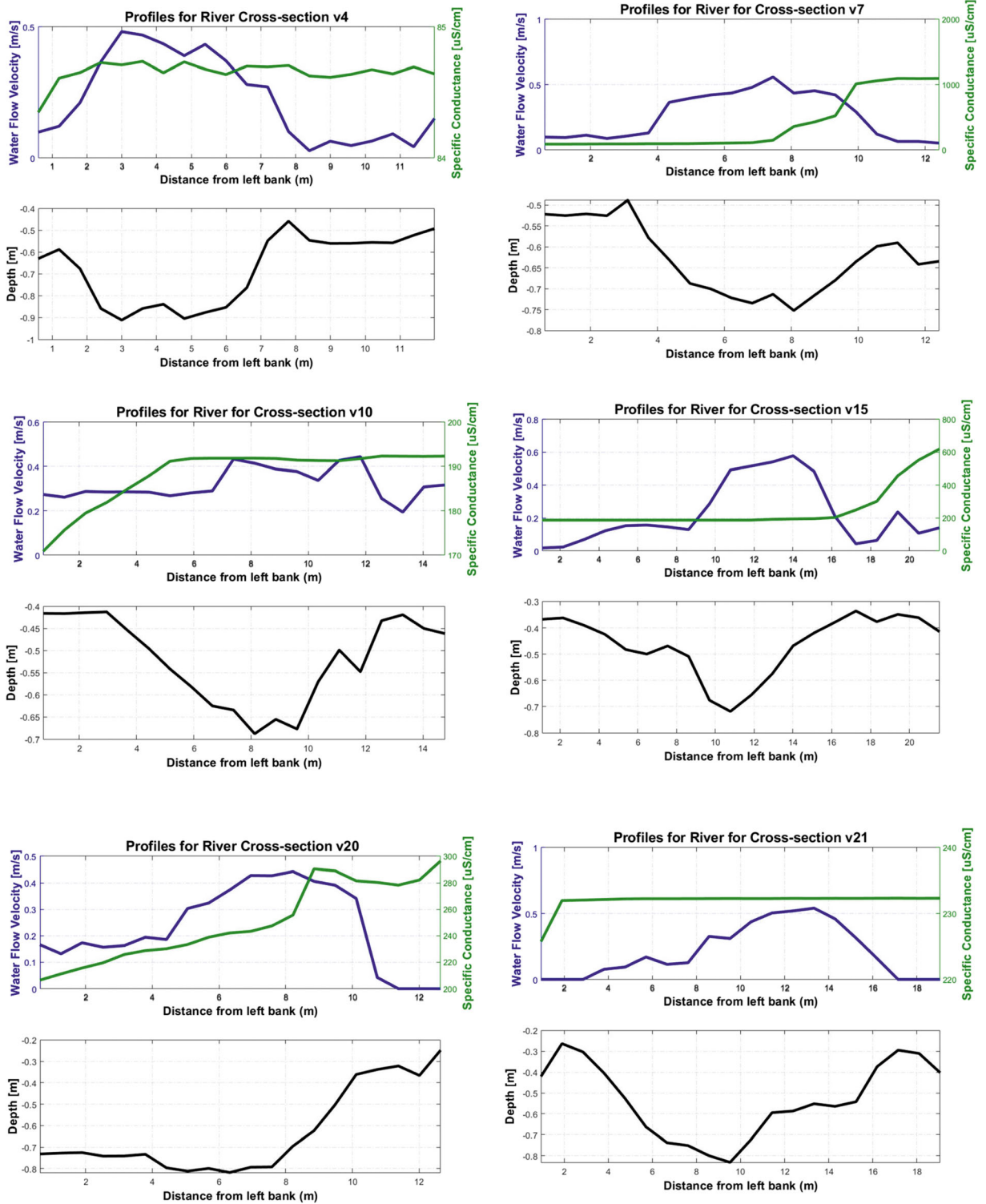
Fig. 8 Vertical profiles of specific conductance, water flow velocity and depth for west-east cross-sections v4 (background), v7 (process water discharge point), v10, v15 (dewatering water discharge point), v20, and v21

with trace elements. The distance needed for mine process and dewatering water plumes to be fully vertically mixed in the river depends on the channel depth. In natural rivers, the cross-section varies with depth, and the fall-line tends to meander. These factors enhance transverse mixing in the river. The mine waters mixed and diluted slowly in the Seurujoki River. There was also variation on the tendency to dilute and mix in the river between process and dewatering water. Although the dewatering water was less conductive i.e. saline than the process water, its impact on the Seurujoki River was greater. This is believed to be due to the fact that the volume of dewatering water was triple the volume of process effluent water and they were discharged continually through several natural ditches along the Seurujoki River. In contrast, process water was discharged along one ditch and a stronger flow to the river is likely to enhance the mixing and dilution processes. Further, because the mine water plume is not uniformly distributed across the cross-section at discharge point, but discharge on the river surface through the ditches, there are vertical concentration gradients. Different advection velocities cause strong vertical concentration gradients and large diffusive vertical flux. As the plume continues to move downriver, lateral turbulent diffusion smoothes out the vertical concentration gradients and mixes the plume in the transverse direction, far enough downriver. Therefore, if the discharge of mine waters to the Seurujoki River could be channelled along clear ditches, and at the points where the river flow is naturally vigorous, the mixing and dilution in the river would be intensified.

According to other studies (e.g. LVT 2007; Pöyry 2008, 2009, 2011, 2012a, 2013; WSP Environmental 2010; Ramboll 2014, 2015b) the greatest ecological impacts are mainly located in the vicinity of the dewatering discharge point. In these same locations, the sulphate concentrations in the Seurujoki River varied from 3.5 to 331 mg/l in June 2014 and from 4.1 to 628 mg/l in August 2014, with the maximum concentrations being detected at the dewatering water discharge point and 600 m downriver. Although sulphur is a ubiquitous element in freshwater environments, it is also considered as a potentially harmful contaminant (e.g. Monheimer 1975; Davies and Hall 2007; Meays and Nordin 2013). In fact, earlier studies (e.g. Pöyry 2012b; AVI 2013) have shown that sulphate is one of the most significant mine-derived contaminants causing an adverse ecological impact in the Seurujoki River.

Moreover, Davies and Hall (2007) found that the toxicity of sulphate to aquatic organisms was influenced by the calcium-magnesium ratio and the alkalinity of the water i.e. the lower the ratio and alkalinity, the higher the toxicity of SO_4 (Meays and Nordin 2013). The calcium-magnesium ratio in the Kittilä mine and river water varies from 0.12619 to 1.71667, and when combined with its alkalinity, this means that the water varies between being between very soft (0–30 mg/l $CaCO_3$) and moderately soft (31–75 mg/l $CaCO_3$). Thus, it is possible that these properties might increase further the toxicity of sulphate to aquatic organisms. Finnish guideline values for sulphate in natural waters were set recently. However, the mining company has environmental permit where the sulphate limit is being set at 2000 mg/l for monthly average concentrations discharged to treatment wetlands (AVI 2013), which exceeds the Canadian water quality criteria for the long-term average of freshwater total SO_4 -levels (CCME 2014). This supports the conclusion of adverse ecological effects due to incomplete mixing and dilution of contaminants in River Seurujoki. The improved discharge method would most likely decrease also the sulphate-derived ecological risks along the entire river ecosystem.

Although it is challenging to conduct the ADCP surveys in open channel flow due to the variable shape of the channel and flow characteristics such as strong turbulence, the method overcomes the disability of previously used devices such as electromagnetic current meter (ECM) or Acoustic Doppler Velocimeter (ADV), which are more laborious and slower to use and not suitable for deep water applications. Furthermore, the RiverSurveyor M9 device (SONTEK 2011) used in this study is suitable for open channel flow measurements since the data can be quickly collected as long as the person conducting the measurements possesses the necessary skills and technical knowledge to operate the device. However, since the dense vegetation and shallow depth of the river hamper the usability of both of the methods, all the desirable points of the river could not be monitored in this study. As concluded also by earlier studies (e.g. Nystrom et al. 2007; Kasvi et al. 2014; Flener et al. 2015), the ability of the ADCP devices to measure near-bed velocities is also limited approx. to 0.25 m above the riverbed (Nystrom et al. 2007). Therefore, the method is limited to deeper, less vegetated rivers, and for smaller waterways, some other methods such as ECM or ADV should be applied as was

done in this study. Also, as with all flow measurements and especially in case of natural, meandering rivers, such as the Seurujoki River, the measured flow field does not represent the dominating flow velocity and direction, but only a snapshot of a certain moment (Szupiany et al. 2007; Muste et al. 2004; Claude et al. 2014).

This CTD device has been used earlier mainly for vertical (bathymetric) water quality profiling in seas and in large lakes (e.g. Horner-Devine et al. 2009; Restrepo and Kettner 2012; Prouty et al. 2017). However, according to our results, the device is also highly suitable for horizontal EC profiling of the cross-section of the river. The method revealed how changes in the river morphology and flow velocity affect behaviour, mixing, and dilution processes, which affects the magnitude of the negative impacts. The mixing and dilution of contaminants depended on the discharge location and method as well as on the density differences between the mine water discharge and fresh river water. Selection of optimal location for mine water discharge ditch or pipeline that allows the fullest possible use of turbulent diffusion is an imported part of the EIA procedure to minimize the impacts on surface water. Therefore, it is important to conduct detailed hydrological and flow rate measurements when designing the location of mine water discharge ditch or pipeline to recipient rivers.

5 Conclusion

Combining moving-vessel ADCP measurements with EC profiling and hydrochemical analysis of water quality proved to be effective tool to study mine water plume behaviour and dynamics of mixing and dilution processes in the Seurujoki River. Also, compared with previously used methods such as ECM or ADV, a moving-vessel ADCP proved to be more effective and versatile method to study the flow velocities and river dynamics. CastAway-CTD (SONTEK 2012) is designed for bathymetric profiling but according to the result of this study, the device is also suitable for horizontal EC profiling at the cross-section of the river.

In conclusion, it is envisaged that the results of this study may prove useful in the following ways: 1) to improve water sampling procedures (selecting proper sampling locations) for more representative sampling, 2) to design better discharging locations and procedures in order to maximize dilution of contaminants and 3) to

plan optimal continuous monitoring sites as well as determining the best locations for installing the measuring devices. These actions will contribute to reducing the environmental impact of the discharged mine water and also improve the reliability of the environmental monitoring system. Even though the devices are not understandably applicable to be used for routine monitoring required by the environmental permit at mine sites, these kind of studies can be used to assess the accuracy of existing water quality policies and permits applied at mine sites and also for making future water management decisions and planning. Authors also recommend the method combination to be used in EIA procedure of metal ore mines when designing mine water discharge methods and locations and assessing the environmental impact of mine waters to recipient rivers.

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