Thermal infrared remote sensing in assessing ground/ surface water resources related to the Hannukainen mining development site, Northern Finland

Anne Rautio, Kirsti Korkka-Niemi, Veli-Pekka Salonen

Department of Geosciences and Geography, P.O. Box 64, University of Helsinki, FI-00014, Helsinki, Finland, anne.rautio@helsinki.fi

Abstract The potential impacts of mining activities are often connected with groundwater and surface water systems, as well as their interactions, which may be inadequately understood. Thermal infrared remote sensing was found to be a highly applicable method to indicate the active connections of groundwater and surface water resources in our study area, and could be an applicable method for use both in baseline studies and later in environmental monitoring. This research provided new insights into water management in subarctic environments, and the results could be used to locate mining infrastructure in areas with special concerns over water related issues.

Key words thermal infrared (TIR), groundwater, surface water, interactions, mining activities

Introduction

Environmental issues are playing an increasingly important role in planning large-scale mining activities, where potential impacts are often related to water management and water-related issues. This is especially the case in areas where the mining development sites host complicated aquifer systems with notable connections to natural surface water bodies.

Hannukainen is an old mining area in Northern Finland, and there are plans to restart the mining of iron oxide copper gold (IOCG) ore deposits within the next couple of years. The preliminary plans include a processing plant and tailings management facility (TMF) for housing 11.1 Mt of tailings with a high sulphur grade having the potential to produce acid mine drainage (AMD) (SRK 2014). One of the alternative areas for the new mining activities, option (1A), is surrounded by three valuable and vulnerable rivers (Valkeajoki, Äkäsjoki and Kuerjoki) and three brooks (Kivivuopionoja W, Kivivuopionoja N and Laurinoja) (fig. 1). The Quaternary sediments are exceptionally thick and permeable, hosting large groundwater reserves with complex groundwater flow conditions (Salonen *et al*.. 2014a, b). Therefore, it is essential to understand the interactions between surface water and groundwater for the proactive design and planning of mining activities in the sensitive study area.

Low-altitude helicopter-based thermal infrared (TIR) imagery has proved to be a useful and applicable tool to locate groundwater discharging into terrestrial and aquatic environments at different scales (local, watershed) under favourable imagery conditions, i.e. when a sufficient temperature contrast exists between the groundwater and soil surface or surface water (Torgersen *et al*.. 2001, Dugdale *et al*.. 2013, Rautio *et al*.. 2015). The technical developments of TIR cameras and unmanned aerial vehicles (UAVs), as well as lowered acquisition costs, have increasingly enabled their utilization in research.

The main aims of this study were to improve the general understanding of groundwater–surface water interactions under planned mine development, which will potentially affect the quality of water reserves. An additional objective was to assess the applicability of the UAV-based TIR survey method in environmental studies on a subarctic catchment (fig. 2).

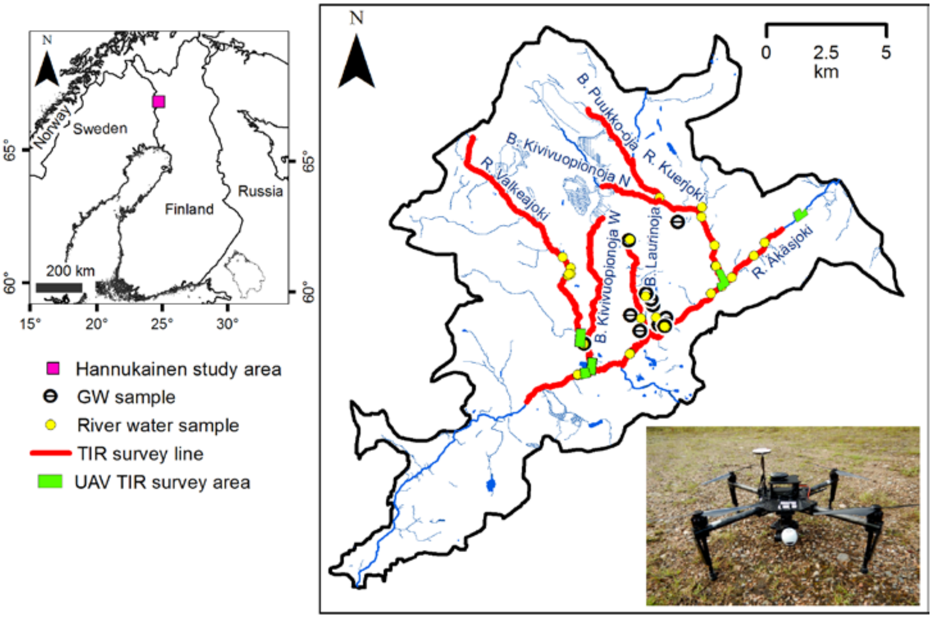

***Figure 1**. The coverage of helicopter-based TIR survey flight lines in 2012 and 2013, and UAV TIR survey areas, including the TMF 1A option and stable isotope water samples, as well as the used UAV platform (Matrice 100) with TIR and RGB cameras (Topographic Database © NLS 2016; Watershed Database © SYKE 2010).*

Material and methods

Thermal infrared (TIR) remote sensing (helicopter and UAV) was conducted to identify groundwater discharge sites, to map spatial surface temperature patterns along the sub-arctic rivers and compare the different TIR platforms in the proximity of the Hannukainen mining development area (fig. 1). In Finland, the optimal TIR imagery conditions, due to the maximum annual temperature difference between groundwater (+4 to +6 °C) and surface water (> +15 °C), exist in summer.

Altogether, the partly overlapping helicopter TIR surveys covered 61 km of rivers, as well as the riparian areas alongside the channels in 2012 (52 km) and 2013 (31 km). Helicopter TIR surveys were acquired from 60 to 270 m above the ground surface (m a.g.s.), producing a ground resolution of 0.08–0.35 m. The ground speed was maintained at 50 km h^{-1} over narrow, meandering streams and increased to 90 km h^{-1} over wide, straight river sections. A FLIR ThermaCAM P60 (320 × 240 pixels, 7.5–13 µm, 24 × 18 degrees) TIR camera together with an HDR-CX700 digital video camera were used to acquire imagery, and the cameras were held in a near-vertical position on the side of the helicopter. The acquisition time and the position were tagged into the digital image files from a built-in GPS. The data collection of thermal and digital video cameras was synchronized to the nearest second to correlate the thermal and visible band imagery during post-flight image processing. The FLIR ThermaCAM P60 was capable of detecting temperature differences of 0.08 ˚C with an accuracy of ±2.0 ˚C or ±2.0% of the reading.

UAV-TIR (fig. 1) consisted of a Matrice 100 platform (DJI) with a Xenmuse X3 gimbal and camera (DJI) and a FLIR TAU2 640 TIR camera integrated with a ThermalCapture module (TeAx Technology UG). The FLIR TAU2 640 has a pixel resolution of 640 x 512, a spectral range of 7.5–13.5 µm and a field of view of 45° x 37°. The FLIR TAU2 640 is capable of detecting temperature differences of ±0.05 ˚C with an accuracy of ±5.0 ˚C or 5.0% of the reading, as reported by the manufacturer. An UAV-TIR survey was acquired from 100 m above the ground surface (m a.g.s.) and the ground speed was approximately 3.5 m s^{-1} following premeditated flight route points. Thermal images were collected digitally and recorded from the sensor to the ThermalCapture at a rate of 8 frames s^{-1}, which guaranteed 75% overlap between the image frames. The thermal image frames were mosaicked and georeferenced with Pix4D software in post-processing of the survey data. The flight altitude of 100 m a.g.s. produced a ground resolution of 13 cm and the UAV-TIR survey covered the river and wetland areas of approximately 1.6 km^2 (fig. 1).

In addition, the stable isotopic compositions (δD, $\delta^{18}O$) were used as tracers to verify the observed groundwater discharge into the river system. When the end members differ sufficiently, the stable isotopic composition can be applied in groundwater–surface water interaction studies (Rautio and Korkka-Niemi 2015; Rautio *et al.*. 2015). The $\delta^{18}O$ and δD compositions were analysed from a total of 33 samples collected during the field campaigns in 2011, 2012 and 2013 (fig. 1). The samples were analysed with a Picarro L2120-i analyser at the University of Helsinki.

Results

Based on low temperature anomalies detected in the helicopter TIR survey, more than 500 groundwater discharge sites were located along the studied river and brooks. Moreover, the longitudinal minimum radiant temperature (T_{minr}) patterns of the studied rivers were highly variable. The River Valkeajoki and the brook Kivivuopionoja W were cold tributaries (approximately 10 ˚C average T_{minr}), suggesting a strong groundwater influence and a hydraulic connection with underlying aquifers. The River Kuerjoki also had a relatively cool stream (approximately 13 ˚C average T_{minr}), suggesting some groundwater component in the river flow. The $\delta^{18}O$ and δD compositions revealed differences between the studied rivers and supported the TIR results concerning the groundwater component in the studied rivers (Fig. 2). The UAV-TIR revealed low temperature anomalies in the same locations as the helicopter TIR surveys, but in more detail.

Thermal anomalies were classified into three categories: (1) discrete anomalies, (2) cold creeks and tributaries discharging into a main brook/river channel, and (3) diffuse anomalies (figs 3, 4) (Rautio *et al.*. 2015). A thermal anomaly was defined as a difference of at least 2 ˚C, 3 ˚C and 3 ˚C between the minimum radiant temperature of the observed anomaly and the air temperature during the TIR surveys in 2012, 2013 and 2016, respectively. The defined temperature buffers (2 ˚C, 3 ˚C and 3 ˚C) aimed to take into consideration the different weather conditions during the surveys and to exclude the shade-induced anomalies from groundwater discharge in results.

Discussion

The automated post-processing and georeferencing of the UAV-TIR survey data (Pix4D) were considerably faster compared to the manual image-by-image post-processing of helicopter TIR data. Tentatively, the georeferenced TIR data provide highly detailed thermal information and appear to be applicable in spatial analysis (fig. 4). However, the areal coverage is considerably smaller and the survey duration is longer with UAVs, mainly due to the lower ground speed compared to helicopters. UAVs are capable of flying at a considerable speed (50 kmh^{-1}) with a payload, but the TIR data quality deteriorates as the instability of the gimbal increases with increasing speed. Therefore, it is necessary to prioritize the imagery targets if the area of interest has a large areal coverage. Moreover, according to the Finnish Transport Safety Agency (Trafi), the UAV operator needs to maintain visual contact (visual line-of-sight, VLOS) with the platform without technical aids and a permit is needed to fly beyond the visual line-of-sight (BVLOS). The ground resolution of the TIR camera with UAVs is relatively high, generally under 0.20 m, due to the maximum image acquisition altitude of 150 m a.g.l. Furthermore, flying experience is needed to pilot UAVs, as well as knowledge of the Trafi regulations specific to aviation and other applicable regulations. Helicopter-based TIR surveys cover considerably larger areas and are highly applicable in first-phase mapping of large areas. However, the georeferenced thermal data produced by UAV-TIR increase the application possibilities of TIR data. According to the TIR surveys and stable isotopic composition of water samples, a notable groundwater discharge into the main river channel as well as its tributaries was observed The River Valkeajoki and Kivivuopionoja brook, in particular, are dominantly fed by groundwater (fig. 2). The option (1A, fig. 5) for locating the TMF will be challenging from the perspective of sustainable management of the mine and natural waters. The planned mining activities could have significant effects on the surrounding rivers and brooks, especially the River Valkeajoki and Kivivuopionoja brook, due to the exceptionally thick and permeable Quaternary sediments, the large groundwater reserves and their direct connection to surface water bodies.

There are general limitations concerning TIR as a method. TIR imagery receives thermal radiation emitted from the “skin” layer (<0.1 mm), and only groundwater contributions reaching the surface of the soil or water bodies can therefore be detected (Torgersen *et al.*. 2001). TIR imagery can be biased by thermal stratification in water bodies if the stratified conditions are not recognized (Torgersen *et al.*. 2001, Rautio *et al.*. 2015). Moreover, TIR imagery is sensitive to the prevailing weather conditions and variability in these conditions during the TIR imagery. Clear cloudless weather conditions develop strong shadows that increase the time needed in post-processing, as shadow-induced anomalies need to be removed from groundwater-induced anomalies.

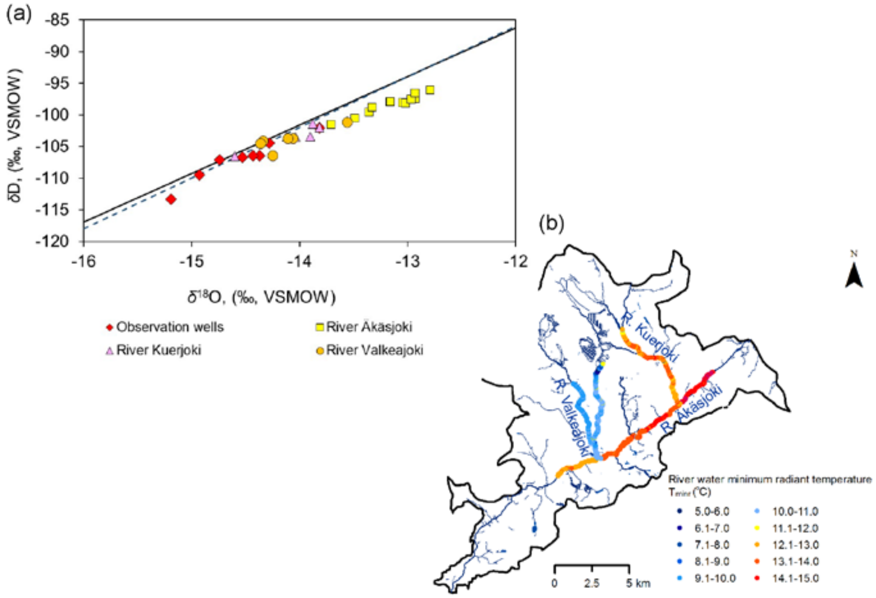

Figure 2 *a) The $\delta^{18}O$ and δD values in groundwater and the Rivers Kuerjoki, Äkäsjoki and Valkeajoki. The data are shown against the local meteoric water line (LMWL) ($\delta D = 7.67\ \delta 18O + 5.79‰$) defined by Kortelainen (2007). (b) Longitudinal profiles of T_{minr} of the studied river sections in 2012 (Topographic Database © NLS 2016; Watershed Database © SYKE 2010).*

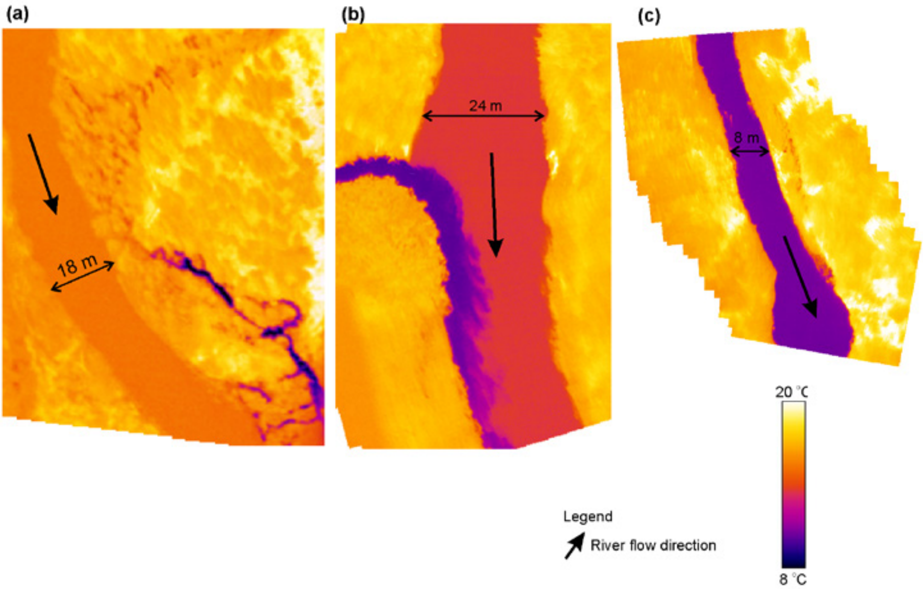

Figure 3 *Categories of discrete and diffuse thermal anomalies in thermal mosaic images; (a), seepage, (b) a cold tributary (R. Valkeajoki discharging into R. Äkäsjoki) and (c) diffuse discharge. The black arrows indicate river flow directions.*

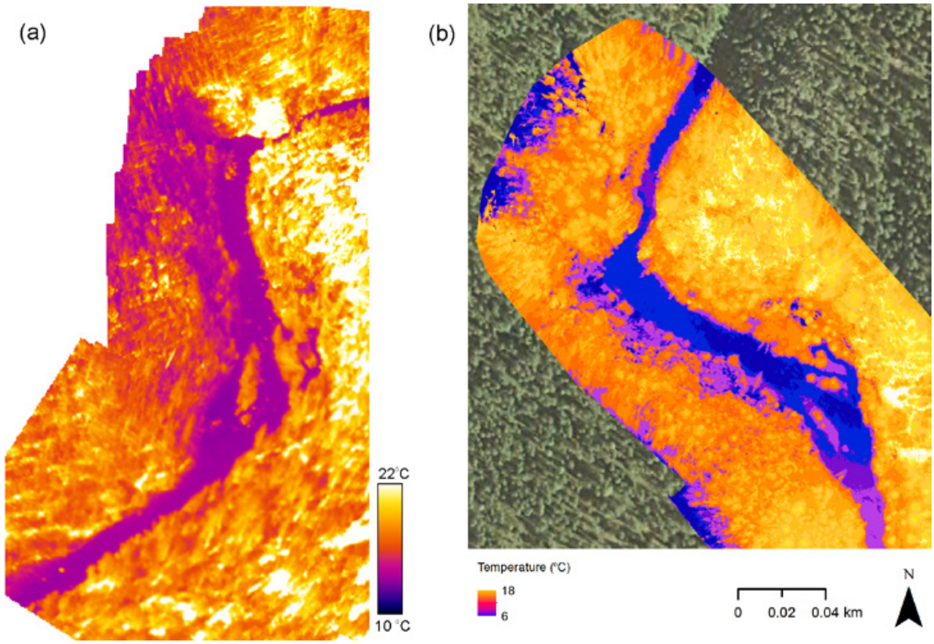

Figure 4 *TIR images with two acquisition methods: (a) helicopter and (b) UAV.*

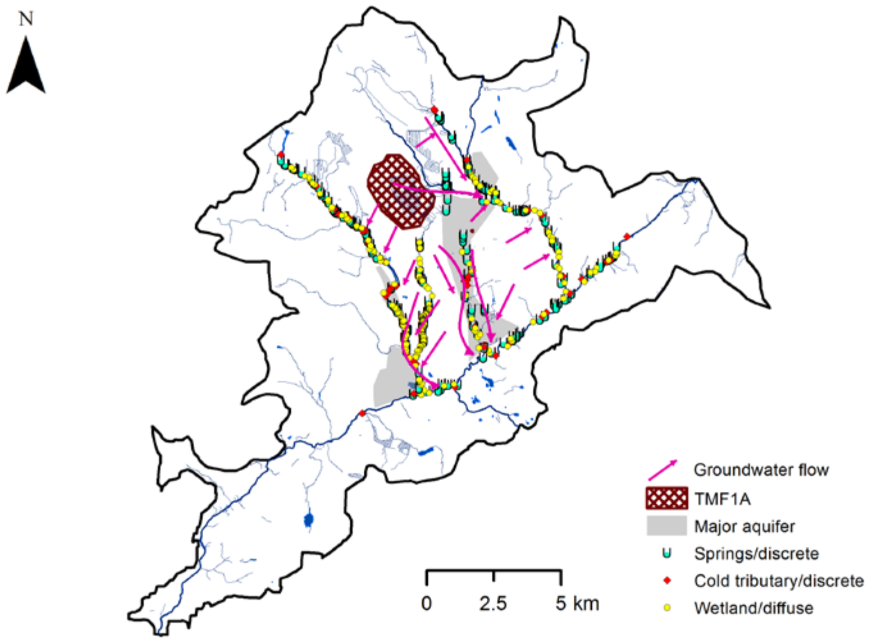

Figure 5 *A synthesis map including the observed thermal anomalies, the TMF 1A option and major aquifers. Modified after Salonen et al.. 2014b. (Topographic Database © NLS 2016; Watershed Database © SYKE 2010).*

Conclusions

The applied methods (TIR surveys and stable isotopic compositions of waters) supported each other and confirmed that groundwater–surface water interactions are far more common in the study area than has thus far been acknowledged. These interactions should be taken into account in planning and siting essential mining facilities such as tailings areas in order to prevent any undesirable environmental load into water bodies. TIR was found to be a highly applicable method to identify thermal anomalies indicating active groundwater–surface water connections. UAVs provide an excellent addition to research by enabling aerial surveys with different imagery devices for a larger number of researchers. Moreover, UAV-TIR provides georectified data with a better resolution that is more usable in detailed planning compared to helicopter TIR data.

Acknowledgements

This research was funded by the K.H. Renlund Foundation. We would like to thank Jukka Jokela and Joanna Kuntonen van't-Riet for their valuable support and cooperation in Northland Mines Oy in 2011–2013, making the first phase of the research possible.

References

Dugdale S, Bergeron N, St-Hilaire A (2013) Temporal variability of thermal refuges and water temperature patterns in an Atlantic salmon river, Remote Sens. Environ. 136:358—373, doi 10.1016/j.rse.2013.05.018

Howett P, Salonen V-P, Hyttinen O, Korkka-Niemi K, Moreau J (2015) A hydrostratigraphical approach to support environmentally safe siting of a mining waste facility at Rautuvaara, Finland, Bulletin of the Geological Society of Finland 87:51—66

Korkka-Niemi K, Kivimäki A-L, Lahti K, Nygård M, Rautio A, Salonen V-P, Pellikka P (2012) Observations on groundwater–surface water interaction at River Vantaa, Finland, Management of Env. Quality. 23(2): 222—231, doi 10.1108/14777831211204958

Kortelainen NM (2007) Isotopic fingerprints in surficial waters: stable isotope methods applied in hydrogeological studies. PhD Thesis, University of Helsinki, Finland

Rautio A, Korkka-Niemi K (2015) Chemical and isotopic tracers indicating groundwater/surface-water interaction within a boreal lake catchment in Finland, Hydrogeol. J. 23(4):687—705, doi 10.1007/s10040-015-1234-5

Rautio A, Kivimäki A-L, Korkka-Niemi K, Nygård M, Salonen V-P, Lahti K, Vahtera H (2015) Vulnerability of groundwater resources to interaction with river water in a boreal catchment, Hydrol. Earth Syst. Sci. 19(7):3015—3032, doi 10.5194/hess-19-3015-2015

Salonen V-P, Korkka-Niemi K, Moreau J, Rautio, A (2014a) Kaivokset ja vesi – esimerkkinä Hannukaisen hanke [Mines and water – an example from the Hannukainen project], Geologi 66:8—19

Salonen V-P, Moreau J, Hyttinen O, Eskola KO (2014b) Mid-Weichselian interstadial in Kolari, western Finnish Lapland, Boreas 43(3):627—638, doi 10.1111/bor.12060

SRK Consulting (U.K.) Limited (2014) Technical report on the Hannukainen iron-copper-gold project, Kolari district, Finland. SRK Consulting (U.K.) Limited. 408 p. Avaliable at http://tupa.gtk.fi/valokuva/mineraalivara/References/462_Hannukainen/462_SRK_Hannukainen Technical-Report_2014.pdf.

Torgersen CE, Faux RN, McIntosh BA, Poage NJ, Norton DJ (2001) Airborne thermal remote sensing for water temperature assessment in rivers and streams, Remote Sens. Environ. 76(3):386—398, doi 10.1016/S0034-4257(01)00186-9