Combining unmanned aerial vehicle-based remote sensing and stable water isotope
analysis to monitor treatment peatlands of mining areas

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22 Abstract

23

24 Treatment peatlands are water purification systems located on existing mires. They are commonly
25 used to treat different types of waters, ranging from municipal wastewaters to mine effluent. This
26 study evaluated the capacity of unmanned aerial vehicle (UAV)-based thermal infrared (TIR)
27 imaging, color infrared imaging, and stable water isotopes as a combined method for monitoring the
28 functioning of a treatment peatland purifying mine process effluent water under boreal conditions in
29 northern Finland. The results showed that TIR was an efficient tool for pinpointing cold groundwater
30 seepage points in the peatland area that were not otherwise visible. Color infrared imaging was used
31 to define Normalized Difference Vegetation Index (NDVI), as an indicator of plant health in the
32 treatment area. A NDVI map of the area, measured on a day representing the main growing season
33 (summer, +12 °C day temperature), revealed areas with stressed coniferous trees. This was probably
34 due to excess water in these areas, resulting from successful spread of the process effluent water to
35 the treatment peatland. Stable water isotopes were able to spatially differentiate the treated process
36 effluent water, surface waters, and groundwater in different parts of the treatment peatland. This first
37 attempt at combining these methods in monitoring of treatment peatlands was promising, as the
38 results obtained with different methods complemented each other. While they produce only a
39 snapshot of prevailing conditions, all three methods, singly and in combination, could be valuable
40 tools in treatment peatland management.

41

42 Keywords: constructed wetland, groundwater-surface water interaction, thermal infrared, color-
43 infrared, Normalized Difference Vegetation Index, treatment peatland management, UAV

44

45 1. Introduction

46 Treatment peatlands are a type of constructed wetland (CW) established on pristine mires. Treatment
47 peatlands are efficient in purifying different process effluents, including treated municipal
48 wastewaters (Nichols, 1983; Ronkanen and Kløve, 2007), mining process waters (Humphries et al.,
49 2016; Kwong et al., 1994), and runoff waters from peat extraction areas (Karjalainen et al., 2016),
50 forestry (Nieminen et al., 2014; Silvan et al., 2004) and agricultural areas (Kleimeier et al., 2014). As
51 peatlands are abundant, especially in the boreal climate zone, they can serve as a cost-efficient and
52 low-maintenance method to treat large amounts of water, in order to reduce the environmental impact
53 of point and diffuse pollutant sources on recipient water bodies (e.g., Gazea et al., 1996; Szucs, 2006).
54 However, flow processes (such as flow paths, effective flow area, flow depth, and water residence
55 time) that control purification efficiency (Ronkanen and Kløve, 2008) are often complicated in
56 peatlands, causing challenges to achieving good performance of treatment peatlands (Heikkinen et
57 al., 2018).

58 Peatlands are often classified into rainwater-dominated, nutrient-poor bogs and groundwater-
59 dependent, nutrient-rich fens (Charman, 2002). As a location for a treatment peatland, bogs are
60 generally more suitable, since flow paths can be controlled to some extent and runoff from outside
61 the peatland can be excluded. In fen-type peatlands, potential groundwater discharge to the treatment
62 area can disturb the purification process, as groundwater typically differs in quality from the treated
63 water. Moreover, seepage of process water into the local aquifer is not desirable. However, the
64 groundwater dependence of peatland often varies spatially and temporarily (Isokangas et al., 2017),
65 making classification into fens and bogs less straightforward. Thus a detailed understanding of flow
66 processes in treatment peatlands or areas planned for use as treatment units is needed, in order to
67 achieve the best possible purification efficiency.

68 In Finland, treatment peatlands are widely used, as they are generally considered one of best available
69 techniques for purifying peat extraction runoff (Heikkinen et al., 2018) and are generally an efficient
70 method to enhance water treatment. Treatment peatlands have been used, or are in use, in mining
71 areas in Finland to treat mining-influenced waters (Palmer et al., 2015; Räisänen et al., 2001; Sunnari,
72 2008). In northern Finland, the performance of treatment peatlands is affected by cold climate
73 conditions, as mean annual temperature ranges from 0 to -2 °C and the seasonal snow cover generally
74 lasts from October to May (based on the reference period 1981-2010; Finnish Meteorological
75 Institute, 2018). In addition, the volume of mining-influenced waters to be treated varies during the
76 lifecycle of a mine, e.g., larger quantities of water will need to be treated as mining operations expand.
77 As the hydrological and biogeochemical conditions and the composition of the treated water are
78 constantly varying, cost-effective methods to monitor flow processes in treatment peatlands are
79 needed, in order to better understand the peatland dynamics involved in water purification.

80 There are several methods that can be used to study the hydrological dynamics of a peatland. A key
81 parameter that can provide information about hydrological processes is temperature. As groundwater
82 and surface waters can have distinctly different temperatures, temperature measurements can be used
83 to distinguish their relative contributions and locations where they interact (Anderson, 2005).
84 Temperature is commonly measured *in situ*, but this can be problematic in peatlands, where access
85 can be difficult or even near impossible due to wet conditions. This is an issue especially if the study
86 area is large. However, thermal infrared (TIR) imaging, either airborne or handheld, can be used to
87 estimate the temperature of various surfaces, which allows mapping of temperature patterns over
88 larger areas. Even though TIR only produces information on surface temperature variation, this
89 information is valuable in many regards. For example, TIR imagery has been used on different
90 hydrological scales and in different surroundings to assess groundwater seepage to lakes (e.g.,
91 Lewandowski et al., 2013), streams (e.g., Rautio et al., 2015) or oceans (e.g. Johnson et al., 2008).

92 TIR imaging has also been successfully used to detect groundwater seepage areas in peatlands (e.g.,
93 Hare et al., 2015). However, TIR has so far not been tested as a design tool in CW studies.

94 As water levels and water quality can have a strong influence on vegetation, monitoring and mapping
95 of vegetation type and vegetation health may also provide information on hydrological processes and
96 potential contamination. For example, groundwater discharge is often associated with higher plant
97 species richness (e.g., Kuglerova et al., 2016), while changes in groundwater level or heavy metal
98 concentration can affect vegetation health (e.g., Eamus et al., 2006). Color infrared (CIR) imaging
99 has been used for decades to estimate the relative amount of green biomass (e.g., Bannari et al., 1995;
100 Jordan, 1969; Rouse et al., 1973; Tucker, 1979). The use of CIR imaging is based on the principle
101 that vegetation absorbs most of the visible light, while it strongly reflects near infrared (NIR) radiation
102 (Jordan, 1969). A typical approach for using this variation in absorption and reflectance is to define
103 some form of vegetation index. One such index is the Normalized Difference Vegetation Index
104 (NDVI), which enhances the contrast between visible and NIR reflectance in order to highlight
105 aboveground green biomass (Rouse et al., 1973). As absorption and reflectance are determined by
106 the amount of leaf pigment (chlorophyll) and by leaf structure, NDVI values are influenced not only
107 by biomass, but also by plant type and health. Thus NDVI values derived from CIR remote sensing
108 can be used as a proxy for vegetation biomass and plant health status over large areas. Previous studies
109 using CIR imaging in the context of wetlands or northern peatlands have largely focused on land
110 cover mapping or estimation of carbon fluxes (e.g., Guo et al., 2017; Lees et al., 2018), while only a
111 few have assessed the effects of groundwater-surface water interactions or metal stress (e.g., Arkimaa
112 et al., 2009) or other effects that can be essential for treatment peatlands purifying mine waters.

113 Another commonly used method to examine the hydrological dynamics of water bodies and
114 catchments is the use of stable water isotopes. Different water sources, such as groundwater and
115 surface water, have their own distinct isotope signal, since e.g., evaporation fractionation processes

116 have a distinctive impact on their isotope signal. Therefore analysis of stable water isotopes is a
117 powerful tool for studying complex contaminant behavior and interactions in mining-influenced
118 environments (Larkins et al., 2018), as well as water flow paths and preferential flow areas in
119 wetlands (e.g., Carrer et al., 2015; Palmer et al., 2015; Ronkanen and Kløve, 2008; Sun et al., 2016).
120 Stable water isotopes have also been used to examine groundwater-surface water interactions in
121 complex peatland environments (Isokangas et al., 2017) and hydrological processes and the origin of
122 water in wetlands (e.g., Carol et al., 2013; Wilcox et al., 2004).

123 In this study, we used TIR and CIR imaging and normal photography from an unmanned aerial
124 vehicle (UAV) to map the variation in surface temperature and vegetation abundance and health. The
125 aim was to investigate whether and how this information can be used to monitor the performance of
126 a treatment peatland purifying mining-influenced waters in a boreal region. The remote sensing data
127 were combined with the results from analysis of spatial stable water isotope samples, which were
128 collected to indicate the hydrological dynamics of the treatment peatland. Specific objectives of the
129 study were to: i) evaluate the applicability of TIR and CIR imaging for studying treatment peatlands
130 in a boreal region, ii) combine stable water isotope monitoring with TIR and CIR to obtain
131 information on e.g., groundwater-surface water interactions, and iii) determine water flow routes in a
132 peatland treating mining waters in northern Finland.

133 2. Materials and methods

134 2.1. Site description

135 The studied treatment peatland is located adjacent to a metal mine in northern Finland and is operated
136 as a passive, secondary treatment step for pre-treated process waters (Figure 1). Mean annual
137 temperature in the region is approximately -0.5 °C and mean annual precipitation is 521 mm. The
138 treatment peatland has been in use since May 2013. Before process water enters the peatland,

139 chemical precipitation is used to purify it to the water quality standard specified in the environmental
140 permit for mining operations. This treated effluent water still has some residues of nickel (Ni), sulfur
141 (S), nitrogen (N), potassium (K), calcium (Ca), magnesium (Mg) and sodium (Na), and the treatment
142 peatland removes at least the nickel and nitrogen (Sandelin, 2015). As there are no specific guidelines
143 on designing treatment peatlands for mine waters, the treatment peatland was dimensioned based on
144 the guidelines for treatment peatlands for peat extraction areas (Savolainen et al., 1996), which set a
145 hydraulic load of $340 \text{ m}^3 \text{ ha}^{-1} \text{ d}^{-1}$. However, the amount of process effluent waters has increased since
146 the opening of the peatland, so the hydraulic load to the peatland was approximately $650 \text{ m}^3 \text{ ha}^{-1} \text{ d}^{-1}$
147 when water samples were taken for this study (in 2014).

148

149 Figure 1. a) The treatment peatland study site in northern Finland. b) Digital elevation model (DEM,
 150 2x2 m resolution) produced by National Land Survey of Finland (2017), showing the sites of
 151 piezometer and hydraulic conductivity measurements and the approximate treatment area within the
 152 peatland.

153

154 The total area of the peatland is approximately 35 ha, of which a 13-ha section in the eastern part is
155 considered the treatment area. Process effluent water is conducted by two distribution pipes (northern
156 and southern) to the peatland area from the eastern edge (Fig. 1a). The peatland area is separated from
157 the rest of the mining area by background ditches next to the distribution pipes and by southern and
158 northern cutoff ditches. The waters from northern and southern parts of the peatland drain to a natural
159 collecting ditch flowing from east to west approximately in the middle of the peatland. This ditch
160 carries the water to a pumping station located on the western side of the peatland area, from where it
161 is pumped to a nearby river (Fig. 1a).

162 2.2. Field measurements and water sampling

163 Samples of peatland surface water were taken from 79 sampling locations on 18 August 2014. These
164 samples were mainly taken from the effective treatment area (13 ha, determined based on visual field
165 observations) in the eastern part of the peatland (Fig. 1b). Sampling was carried out at 50-m intervals,
166 in surface water pools on top of the peat layer or in channels and ditches. In addition, the process
167 effluent water was sampled from the distribution pipe and groundwater was sampled from 13
168 piezometers located in the mine area (Fig. 1b). Six of the piezometers were situated in the treatment
169 peatland area. The depth of the piezometers (with 2-3 m screens) ranged from 2.9 to 8.7 m, with an
170 average depth of 4.1 m. All water samples were analyzed for stable water isotopes ($\delta^{18}\text{O}$ and $\delta^2\text{H}$)
171 using cavity-ring down spectroscopy (CRDS) technology with a Picarro L2120-i analyzer. Samples
172 with visible color or suspended matter were filtered (pore size 25 μm) prior to analysis. The measured
173 isotope ratios are reported as relative deviations from the Vienna Standard Mean Ocean Water
174 (VSMOW) using δ notation. The precision of measurements was ± 0.1 and $\pm 1.0\text{‰}$ for $\delta^{18}\text{O}$ and $\delta^2\text{H}$,
175 respectively.

176 Hydraulic conductivity of the peat was determined at eight locations in the eastern part of the peatland
177 (see Fig. 1b) in summer 2014, using a direct-push piezometer with a falling head (Hvorslev, 1951).
178 This method is described in detail in previous wetland studies (Mustamo et al., 2016; Postila et al.,
179 2015; Saarinen et al., 2013). Measurements were made at 10-cm intervals for 2 to 10 different depths,
180 depending on the thickness of the peat layer.

181 Maps of the stable water isotopes ($\delta^{18}\text{O}$ and $\delta^2\text{H}$) were created using the natural neighbor interpolation
182 method in an ArcGIS 10.2 environment. The interpolation method was chosen because the surface it
183 produces is smooth and passes through all the input points (ESRI, 2015). Furthermore, deuterium
184 excess ($d\text{-excess} = \delta^2\text{H} - 8 \delta^{18}\text{O}$, Dansgaard, 1964) was determined for the peatland surface water
185 samples, in order to study the effect of evaporative fractionation on the samples.

186 2.3. UAV imagery acquisition and processing

187 Aerial images of the peatland were acquired during two flights on 15 August 2016, using a custom-
188 built, fixed-wing UAV carrying three different sensors. Flight height was approximately 120 m and
189 flight speed ranged from 10 to 20 m s⁻¹. The three sensors used were: Flight 1: a modified Canon
190 Powershot SX260 HS NIR-Green-Blue (NIRGB) camera, with the red channel replaced with NIR
191 (customised by LDP LLC, Carlstadt, U.S.); Flight 2: i) a Canon Powershot S100 RGB (Red-Green-
192 Blue) camera (Canon Inc., Tokyo, Japan); and ii) a FLIR Tau 2 TC324 TIR camera (FLIR Systems
193 Inc., Wilsonville, U.S.) with 324 x 256 resolution (25 μm pixel size) and a 9 mm lens, in combination
194 with a ThermalCapture OEM (TeAx Technology UG, Wilnsdorf, Germany).

195 Measurements at the nearest Arctic Space Centre (ASC) of the Finnish Meteorological Institute
196 (67.37°N, 26.63°E, 35 km south of the study site) show an average air temperature of 11.0 °C on the
197 day of measurements. The air temperature is measured at 1-minute intervals at the ASC, and the
198 minimum temperature during the day was 9.4 °C and maximum 12.8 °C. The weather during the day

199 was cloudy, with light drizzle. The average groundwater temperature at the ASC was 4.0 °C on the
200 day, resulting in a temperature difference of 7.0 °C between air and groundwater.

201 AgiSoft PhotoScan Professional version 1.2.4 (AgiSoft LLC, St. Petersburg, Russia) was used to
202 process the NIRGB and RGB images and create 5 cm/pixel orthomosaics. The orthomosaics were
203 subsequently manually georeferenced to ETRS-TM35FIN based on imagery provided by the National
204 Land Survey of Finland. The channels in the NIR orthomosaic were calibrated and converted to
205 reflectance using ~50% reflectance panel. TIR images were captured at 1-s intervals during the flight,
206 with a total of 2200 images collected for the peatland. Prior to stitching, a flat field correction was
207 performed on all images to correct for lens distortion and artefacts. In addition, the images were
208 corrected for variations in sensor and air temperature during the flight, by normalization based on the
209 image average. The TIR images were then matched with the images from the RGB camera in order
210 to obtain initial Global Positioning System (GPS) positions, and Agisoft Photoscan Professional was
211 used, with additional manually created tiepoints, to create a 1 m/pixel TIR orthomosaic.

212 2.4. Analysis of UAV imagery

213 The TIR remote sensing method involves measuring the thermal radiation emitted by all objects with
214 temperatures above 0 °K. The intensity of the emitted radiation depends on the surface temperature
215 and emissivity of the object: the higher the temperature and emissivity, the higher the intensity of the
216 radiation. It is worth noting that TIR remote sensing does not measure the actual temperature of an
217 object in the same sense as a contact thermometer. Rather, when the intensity of radiation and
218 emissivity are known, the temperature of an object can be estimated. In this case, the TIR data were
219 not calibrated to reflect actual temperatures on the Celsius/Kelvin scale. As the main purpose of the
220 study was mapping and identification of temperature variations and anomalies, the apparent
221 temperature is given as a brightness value (BV) that does not take emissivity into account.

222 The use of low-cost, modified NIRGB cameras in CIR vegetation mapping is discussed for example
223 by Hunt et al. (2010, 2011). In these kinds of cameras, the red (R) channel is converted to be sensitive
224 to NIR radiation. However, because the camera lacks the red channel most commonly used in
225 combination with NIR in vegetation mapping (e.g., Tucker, 1979), the usual NDVI [$NDVI = (NIR -$
226 $R)/(NIR + R)$] cannot be calculated. However, it is still possible to calculate indices that rely on the
227 blue (B) and green (G) channels, such as Green NDVI [$GNDVI = (NIR - G)/(NIR + G)$] (Gitelson et
228 al., 1996) and Blue NDVI [$BNDVI = (NIR - B)/(NIR + B)$] (Wang et al., 2007). For this study, NDVI,
229 BNDVI, and GNDVI would provide very similar information, and BNDVI was chosen.

230 3. Results and discussion

231 3.1. Peatland conditions

232 The outflow from the treatment peatland (e.g., $8700 \text{ m}^3 \text{ d}^{-1}$ on average in 2014) is typically larger than
233 the effluent amount pumped from the mine basins (average $6400 \text{ m}^3 \text{ d}^{-1}$ in 2014), which indicates that
234 other waters are also discharging into the treatment area (Sandelin, 2015). Since the study site is
235 located in a region with seasonal snow cover generally lasting from October until May, snow melt
236 can be a main source of extra inflow water to the peatland in spring. However, at the time of the
237 measuring campaigns in this study (August), the snow melt pulse was not expected to be still affecting
238 the treatment peatland. Thus, the main contributors to surface water in the treatment peatland were
239 probably groundwater and process effluent water.

240 The slope of the peatland is low, varying between 0.3° and 0.7° . Soil under the peat layer is mainly
241 sand and silty sand, and the peat thickness varies between 0.2 and 1.7 m. Peat thickness is smallest in
242 the northern part of the peatland (close to measuring point 1 in Fig. 1b), where it can permit
243 interactions between groundwater and surface water. The vegetation cover consists mainly of mosses,
244 sedges, and trees (birch, spruce, and pine). The roots of trees and sedges can increase the possibility

245 of preferential flow channels, i.e., pipe flow channels in the peat through which water can more easily
 246 flow (Holden, 2005; Holden and Burt, 2002). Pipe flow channels have been found in Finnish
 247 peatlands in previous studies (Rossi et al., 2012). This, added porosity of the peatland might increase
 248 groundwater-surface water interactions in the area.

249 The hydraulic conductivity of the peat was highest in the top layer (0.1 m depth), where it was on
 250 average $7.4 \cdot 10^{-4} \text{ m s}^{-1}$ (Fig. 2). The hydraulic conductivity in the acrotelm (0-0.4 m) varied between
 251 $1.3 \cdot 10^{-7}$ and $9.6 \cdot 10^{-4} \text{ m s}^{-1}$ and that in the catotelm (0.5-1.0 m) between $3.0 \cdot 10^{-8}$ and $4.0 \cdot 10^{-4} \text{ m s}^{-1}$.
 252 These results indicate a decrease in hydraulic conductivity with depth and degree of humification,
 253 which is consistent with previous findings for Finnish peatlands (Huikari, 1959; Isokangas et al.,
 254 2017; Päivänen, 1973; Ronkanen and Kløve, 2005). The measured hydraulic conductivity values
 255 suggest that the structure of the peat promotes lateral water flow in the upper part of the peatland
 256 horizon.

258 Figure 2. Variation in hydraulic conductivity (measured August 2014) with depth in the peat at eight
 259 locations within the treatment peatland (for locations, see Fig. 1b).

260 3.2. UAV measurements

261 3.2.1 Thermal infrared imaging

262 The orthomosaics produced from the UAV measurements are presented in Figure 3. Although the
263 TIR data were not calibrated to represent actual temperature values, they still served their purpose in
264 detecting cold or warm anomalies that clearly deviated from the surroundings. Such anomalies can
265 arise due to cold groundwater upwelling, or elevated vegetation temperature due to e.g., vegetation
266 stress. *In situ* temperature measurements in the northern and southern background ditches and at the
267 pumping station indicated surface water temperatures between 10.4 and 12.4 °C. Assuming an
268 average groundwater temperature of 4 °C, the temperature difference between surface water and
269 groundwater (6.4-8.4 °C) was very similar to that between the air and groundwater temperature (5.4-
270 8.8 °C), giving a temperature gradient detectable in the TIR data.

271

Figure 3. Red-green-blue (RGB), near infrared-green-blue (NIRGB), thermal infrared radiation (TIR), and Blue Normalized Difference Vegetation Index (BNDVI) orthomosaics of the studied treatment peatland produced from the acquired unmanned aerial vehicle (UAV) imagery. Black and white boxes indicate the locations of details highlighted in Figures 4 and 5, respectively.

The weather on the day of measurement was sub-optimal as regards detecting groundwater upwelling: a warmer air temperature would have improved the temperature gradient and made cold anomalies more easily detectable. Furthermore, a slight drizzle during the later stage of the TIR surveillance might have affected the apparent temperature seen in the northern parts of the TIR mosaic. Nevertheless, some cold spots and regions that were interpreted as groundwater upwelling were clearly seen (Fig. 4). Similar groundwater upwelling has been detected in previous peatland TIR imaging studies (Hare et al., 2015; Isokangas et al., 2017). Fig. 4d shows a close-up of the eastern (upstream) end of the peatland, where a considerable amount of cold groundwater discharges to the

285 surface. The groundwater mixes with the warm process effluent water pumped into the peatland,
286 which is apparent due to the quickly dissipating colder signal. Fig. 4c highlights a detail further
287 downstream where the cold groundwater, or at least the cold signal, re-appears. It is evident that
288 enough groundwater discharges along the stream to cool the initially warmer water coming from
289 upstream. Similar stream-groundwater discharge dynamics affecting the stream temperature in
290 peatland streams have been reported previously, e.g., by Lowry et al. (2007). The TIR data also
291 showed very distinct cold spots alongside the stream that were not apparent in the RGB data (Fig.
292 4c).

294 Figure 4. A, B) Red-green-blue (RGB) images and (C, D) corresponding thermal infrared radiation
295 (TIR) images of likely groundwater upwelling areas appearing as cold spots in the peatland.

297 3.2.2. Color-infrared imaging

298 A BNDVI image based on the color-infrared data can be utilized in estimating vegetation biomass
299 and physiological status, or in other words, vegetation “greenness”. Low BNDVI values observed for
300 the roads, ditches and water surfaces are apparent in the BNDVI orthomosaic displayed in Fig. 3.
301 However, some vegetated areas also displayed low values, which may be indicative of stressed
302 vegetation, as was later confirmed with a site visit. Fig. 5d shows numerous individual, low BNDVI
303 spots that appear greyish in the corresponding RGB image (Fig. 5a). cursory site mapping indicated
304 that the low BNDVI spots in Fig. 5d are coniferous trees (especially spruce species) that are largely
305 needleless in these wetter portions of the peatland. The damage might relate to waterlogged soil or
306 metal stress caused by the process effluent water. Waterlogging usually decreases oxygen
307 transportation in the root system (Ernst, 1990; Philipson and Coutts, 1978) and coniferous species
308 typically have lower tolerance for flooded conditions (Wenger, 1984) than deciduous trees such as
309 birch species (Ranney and Bir, 1994). Figs. 5a and 5d also show a stand of green and largely healthy
310 looking trees with relatively high BNDVI values, which were identified as deciduous, which is
311 indicative of their higher tolerance for both excess water and possible metal stress. In order to get a
312 comprehensive understanding of the main reasons for stress in the trees, more detailed studies would
313 be needed.

314

315 Figure 5. A-C) Red-green-blue (RGB) images and (D-E) corresponding Blue Normalized Difference
 316 Vegetation Index (BNDVI) images of areas with stressed trees and ponded water.

317 Fig. 5e shows a slightly denser stand of trees with a large group of low BNDVI spots. The composition
 318 of the stand is more complex, with both deciduous and coniferous trees. In this case, the coniferous
 319 trees are clearly stressed and excess water was visible in this area during the visit, but some of the
 320 deciduous trees also seemed to have lower BNDVI values. However, the UAV flights were made in
 321 the middle of the August, when some deciduous trees might be showing early signs of normal autumn
 322 colors. Furthermore, that summer was particularly cold and rainy, and leaf rust (*Melampsoridium*
 323 *botulinum*) caused premature fall of leaves in many affected birches. Some lower BNDVI values,
 324 especially in the lower part of Fig. 5e, relate to ponded water. Thus, in the case of wetlands, care must
 325 be taken not to simply classify all low BNDVI values to stressed vegetation/low biomass. Figs. 5c
 326 and 5f provide clearer examples of ponded water typical in peatland settings.

327 The parts of the peatland with less distinct BNDVI variation were more difficult to analyze with
328 regard to vegetation status. A multilayer peatland structure with standing vascular plants and
329 underlying mosses can display different spectral properties depending on the species (Letendre et al.,
330 2008). Boreal forest and peat mosses exhibit different spectral characteristics in the visual and NIR
331 region than typical vascular plants, e.g., the reflectance in the NIR region is typically less than that of
332 vascular plants and mosses can have a 'green' peak in the visible portion reflecting the dominant
333 color (red, brown, or green) of the individual species (Bubier et al., 1997). In *Sphagnum* species, a
334 narrow NIR peak caused by a minor absorption feature at 0.85 μm (absent in brown mosses and
335 vascular plants), combined with narrow red absorption, reduces the efficiency of standard NDVI
336 methods in characterizing biomass or greenness (Bubier et al., 1997).

337 It can be concluded that autumn is the optimal time for analysis of the peatland in terms of species
338 detection (not conducted in our study), due to variations in fall senescence between species. However,
339 in the case of stress detection, senescence effects complicate the analysis. In any case, the full
340 potential of CIR imagery for determining the performance of treatment peatlands could be better
341 utilized in long-term monitoring and in time series of observations. However, the method showed
342 good capacity for analysis of large treatment peatlands (typically >10 ha), which can otherwise be
343 difficult to assess, and the single image provides information that there may be issues with the
344 vegetation in certain areas and reason to monitor these areas in detail.

345 3.3. Stable water isotopes

346 The stable isotope composition in surface waters in the treatment peatland was determined for (i)
347 estimation of the effective treatment area, (ii) identification of flow paths, and (iii) characterization
348 of possible groundwater-surface water interactions in the treatment peatland area.

349 3.3.1. Estimation of effective treatment area based on the isotopic composition of surface water

350 The stable isotopic composition in surface water in the treatment peatland varied widely, from -12.9
351 to -8.6 ‰ for $\delta^{18}\text{O}$ and from -90 to -64 ‰ for $\delta^2\text{H}$ (Figs. 6 and 7), indicating that different water
352 sources and different hydrological processes influence the surface water. Groundwater had a more
353 stable isotopic composition, with generally more negative δ -values than surface water (i.e., a range
354 of -13.5 to -12.6 ‰ for $\delta^{18}\text{O}$ and -99 to -92 ‰ for $\delta^2\text{H}$).

355

356 Figure 6. Stable isotope composition ($\delta^{18}\text{O}$ and $\delta^2\text{H}$ values) of samples from groundwater (GW)
 357 wells (triangles) and interpolated maps of $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values of surface water (SW) sampled from
 358 the treatment peatland area in 2014 (circles). The values were interpolated to the approximate area of
 359 the treatment peatland.

360

361 Figure 7. Relationship between $\delta^2\text{H}$ and $\delta^{18}\text{O}$ in treatment peatland surface water (SW), groundwater
 362 (GW) well water, and process effluent water, and spatial distribution of deuterium excess values,
 363 together with different water type symbols. The isotopic signal of precipitation was measured at
 364 Rovaniemi GNIP station and the local meteoric water line (LMWL) was determined based on three
 365 years of precipitation data from the region (Kyllönen, 2018) and compared against the global meteoric
 366 water line (GMWL) (Craig, 1961).

367 The isotopic composition of the process effluent water from the mine was -10.0 ‰ for $\delta^{18}\text{O}$ and -78
 368 ‰ for $\delta^2\text{H}$ and can be assumed to be stable, as the water is mixed and stored in large basins before it
 369 is pumped to the treatment peatland. The majority of the δ -values from surface water samples
 370 clustered with the δ -value of the process effluent water in the δ plot (Fig. 7). Moreover, 15 of these

371 samples had similar isotopic composition to the process effluent water (within the precision of the
372 isotope analysis), indicating that process effluent water was the main water source in these areas.
373 Isotopic composition can be used to identify areas in the treatment peatland where the water is
374 characterized by increased evaporation (Gat, 1996). During evaporation from open water surfaces,
375 the residual water is enriched in heavy isotopes, while transpiration by plants does not affect isotopic
376 composition (Gat, 1996). Enriched areas were identified based on the δ plot, where 'enriched mine
377 water' with slightly higher δ -values and smaller d-excess values indicated areas in which process
378 effluent water had undergone evaporative fractionation (Fig. 7). However, this fractionation was not
379 very pronounced, indicating that the water residence time in the treatment peatland is relatively short.

380 The isotopic composition of surface waters is also affected by precipitation (Gat, 1996). The isotopic
381 signal of precipitation measured at the Rovaniemi GNIP (Global Network of Isotopes in Precipitation)
382 station, located 140 km south of the mine, in August 2014 was -10.84 ‰ for $\delta^{18}\text{O}$ and -76.6 ‰ for
383 $\delta^2\text{H}$ (Fig. 7). Since precipitation in the area amounted to 37.5 mm between 1 August and 18 August
384 2014, an influence of precipitation on the measured isotopic composition in surface water cannot be
385 excluded and would have resulted in more negative $\delta^{18}\text{O}$. However, the $\delta^{18}\text{O}$ value in most surface
386 water samples was similar to, or more positive than, the value for process effluent water, indicating
387 that the influence of precipitation on the isotopic composition of surface water was minor. In contrast,
388 the isotopic composition at the majority of the sampling points in the western part of the peatland
389 (i.e., outside the area intended for water treatment) clustered near the local meteoric water line
390 (LMWL) determined for the region (Kyllönen, 2018) (Fig. 7). This indicates that these samples are
391 likely of meteoric origin and are not considerably affected by process effluent waters. Thus, the
392 effective treatment area of the treatment peatland can be delineated based on the surface water
393 samples that were isotopically similar to the process effluent water and the 'enriched mine water'
394 samples. The area obtained by this delineation was rather similar to the area intended for water
395 treatment, and is restricted to the eastern part of the treatment peatland.

396 3.3.2. Assessment of groundwater-surface water interactions in the treatment peatland

397 Groundwater-surface water interactions can be located based on the δ -values of hydrogen and oxygen
398 when those δ -values differ significantly between groundwater and surface water (Barth et al., 2005;
399 Engelhardt et al., 2014). In groundwater samples taken at the mine site, the heavy isotopes were more
400 depleted than in surface water. The difference in $\delta^2\text{H}$ and $\delta^{18}\text{O}$ between groundwater and the majority
401 of the surface water samples in the effective treatment area was 15-25‰ and 2.5-4‰, respectively
402 (Fig. 7). The isotopic signatures indicated groundwater-surface water interactions in the study area.
403 At several sampling points in the effective treatment area, $\delta^2\text{H}$ and $\delta^{18}\text{O}$ were more depleted than in
404 the surrounding surface waters, indicating discharge of groundwater (Fig. 6, Fig. 7). Groundwater
405 discharge was predicted for the eastern part of the treatment peatland (where the most negative δ -
406 values in surface water were measured), which is in good agreement with the TIR data. Additional
407 groundwater discharge spots were predicted in the northern part of the treatment peatland with
408 shallow peat (20 cm) and sparse tree cover, as well as near the natural stream collecting waters in the
409 middle of the treatment area. However, there were also indications that groundwater in some spots
410 was influenced by surface water. While most of the groundwater samples clustered relatively close
411 to each other in the δ plot, three groundwater samples deviated strongly from the general isotopic
412 composition of the groundwater in the area (Fig. 7). These samples had more positive $\delta^2\text{H}$ and $\delta^{18}\text{O}$
413 values, suggesting surface water influence. The influence was most pronounced at the piezometer
414 located next to a storm/drainage water basin south of the peatland, where δ -values deviated most from
415 the groundwater average ($\delta^2\text{H} = -68\text{‰}$, $\delta^{18}\text{O} = -9.1\text{‰}$; Fig. 6). This might be explained by recharge
416 from the drainage basin into the groundwater. However, the recharge from the drainage basin does
417 not seem to reach the treatment peatland, as the nearest groundwater sampling point within the
418 treatment area clustered with the average groundwater samples in the δ plot (Fig. 6, Fig. 7).

419 Complex groundwater-surface water interactions, as observed in the present study, are common in
420 natural peatlands (Hare et al., 2017; Isokangas et al., 2017; Levy et al., 2016). In many cases stable
421 water isotopes have shown potential in revealing these interactions (e.g., Clay et al., 2004; Hunt et
422 al., 1996; Isokangas et al., 2017; Ladouche and Weng, 2005; Sikdar and Sahu, 2009; Zurek et al.,
423 2015). If surface water in the peatland is taken to be a mixture of process effluent water and
424 groundwater, the contribution of groundwater to surface water in the treatment area can be estimated
425 based on the assumptions that: (i) The isotopic composition of the pumped process effluent water is
426 relatively constant, (ii) the process effluent water spreads in the treatment area mainly by surface flow
427 and the isotopic pulse of the process effluent water is thus similar in the whole area, (iii) the most
428 negative δ -values represent the unaltered isotopic composition of groundwater, and (iv) the influence
429 of precipitation and evaporation on isotopic composition is minor. According to this representation,
430 the maximum groundwater contribution in the treatment peatland area would be approximately 40%.
431 As groundwater discharge affects surface water quality in many ecosystems, including wetlands
432 (Johnston et al., 2011; Kornelsen and Coulibaly, 2014; Rozemeijer et al., 2010; van Belle et al., 1996),
433 the relatively high contribution of groundwater in the treatment peatland might influence surface
434 water quality. Thus, groundwater influx can be responsible for observed irregularities in the
435 performance of the treatment peatland (Sandelin, 2015).

436 3.4. Combining information from remote sensing methods and stable water isotopes

437 Remote sensing methods, TIR, and BNDVI were found to be efficient tools for spatial studies of
438 treatment wetland environments. However, they provided different kinds of information, e.g., about
439 groundwater-surface water interactions, from the stable water isotopes. The information gained from
440 different methods used in this study is combined in Figure 8. BNDVI was used to spot trees that show
441 potential stress in the treatment area. Stress in coniferous trees in the peatland was most probably due
442 to excess water from incoming mine process effluent water or from groundwater affecting tree

443 growth. If the excess water derives from the process effluent, these locations can be considered to
 444 indicate successful process effluent distribution to the treatment peatland. In general, the stressed
 445 trees in the treatment peatland indicate that the process effluent water is distributed over the area, as
 446 it should be to achieve a well-functioning treatment peatland (Heikkinen et al., 2018; Ronkanen and
 447 Klöve, 2007).

449 Figure 8. Conceptual model of the methods applied to monitor the treatment peatland in this study.

450 The TIR method was used to detect the cold anomalies in the peatland surface. These anomalies can
 451 be related to groundwater seepage locations with high probability. Stable water isotopes were able to
 452 differentiate different water types from the peatland surface water and also showed locations where
 453 evaporation had affected the peatland surface water.

454 The stable water isotope results verified the considerable groundwater seepage location on the eastern
 455 side of the peatland that was identified from the TIR images. In addition, an influence of groundwater

456 and process effluent was detected in the northern part of the peatland using stable isotopes. This
457 location was characterized by browner trees and lower BNDVI values than other forested areas in the
458 peatland. In addition, the groundwater in this area, with shallow peat, was influenced by surface
459 water. Based on these results, it can be concluded that this northern region of the treatment peatland
460 has interactions between groundwater and surface water, enabling mine process effluent to mix with
461 groundwater.

462 Comparison of the areal TIR/BNDVI with stable water isotope data is associated with uncertainties,
463 as the flights and water sampling were carried out in different years. They represent different temporal
464 snapshots of the situation, but there were no dramatic changes in operation of the mine or the
465 treatment peatland between the two campaigns. Average temperature in the area was 13.4 °C in
466 August 2014 and 11.7 °C in August 2016 (FMI), which could enhance the effect of evaporation on
467 isotope concentrations and diminish the temperature differences in TIR. Total precipitation in the area
468 was 62 mm in August 2014 and 85 mm in August 2016.

469 This first attempt to combine information from different surveillance methods in monitoring of a
470 treatment peatland produced promising results. The amount of information gained by combining
471 different methods was more valuable than the sum of the individual contributions, as different
472 methods complemented each other and thus provided a more complete picture of the situation. This
473 more complete picture could prove very valuable when constructing treatment peatlands on fen-type
474 natural peatlands, where groundwater-surface water interactions might pose a risk to treatment
475 performance.

476 4. Conclusions

477 Using remote sensing methods and stable water isotopes, this study assessed flow paths and possible
478 groundwater-surface water interactions in a peatland treating mining-influenced water. The results

479 obtained were promising, e.g. they showed that the methods tested were all well suited to measuring
480 different aspects of the hydrology and ecosystem functioning of the treatment peatland. Stable
481 isotopes were a good indicator of detailed hydrological flow systems, TIR pinpointed groundwater
482 influence in the peatland, and BNDVI revealed the effect of changes in hydrology of the treatment
483 peatland on vegetation. Thus, these methods can be useful for studying wetlands treating different
484 types of water, not only mining waters, and we recommend their combined use in performance
485 assessment of existing and planning of future treatment peatlands. Stable water isotopes and TIR
486 might be the most promising tools in the planning phase of treatment peatlands. For the treatment
487 peatland studied here, application of the methods prior to construction would have given valuable
488 information about groundwater seepage points and their possible influence on treatment performance,
489 and the plans (e.g., size and location of the treatment peatland) could have been adjusted accordingly.

490

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