A coupled remote sensing and modeling method for delineating groundwater discharge zones in eskers

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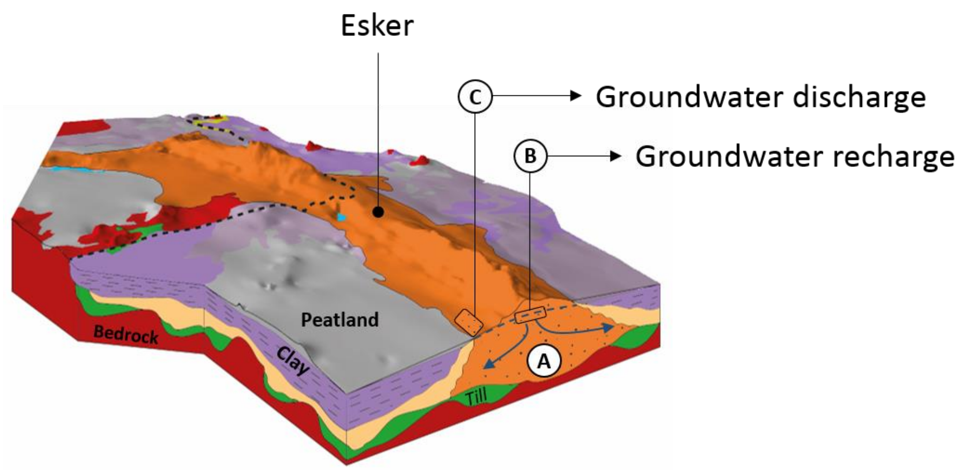
Summary

This study focuses on the development of thermal remote sensing and modeling approaches for delineating groundwater discharge areas near eskers in a boreal region of the Canadian Shield, in north-western Quebec. The working hypothesis is that groundwater partly controls soil surface temperatures in groundwater discharge areas. Low-resolution (30 m x 30 m) satellite images are first used for identifying thermal anomalies at the regional scale. High-resolution (0,1 m x 0,1 m) thermal images are subsequently acquired locally in areas associated with thermal anomalies identified from satellite images. Coupled simulations of water and heat fluxes are then conducted using SEEP/W and TEMP/W in order to provide a quantitative interpretation of the influence of groundwater depth on soils surface temperatures in groundwater discharge areas. The approaches developed here provide tools for identifying the potential localization of groundwater dependent ecosystems where increased environmental protection could be relevant.

Context

Eskers are widespread glaciofluvial formations in the northern hemisphere. They are known to host highly valuable aquifers in many areas, including Canada (Nadeau et al., 2015; 2017) and Finland (Okkonen et al., 2010). Depending on the prevailing hydrogeological conditions, these formations can constitute shallow unconfined aquifers (Figure 1A) where local-scale recharge-discharge groundwater flow systems develop (Figure 1B; 1C). The groundwater discharge areas located on the margin of eskers (Figure 1C), including springs and diffuse groundwater exfiltration zones, are likely to be associated with groundwater dependent ecosystems of high ecological value (Smerdon et al., 2012; Nadeau et al., 2015; Rosa et al., 2018). Considering their protection in the context of land-use planning is essential in order to protect biodiversity. However, the delineation of groundwater discharge areas represents a challenge, particularly in vast regions where the access to groundwater monitoring infrastructures such as wells and soil moisture probes is limited. In such regions, the use of broadly applicable non-invasive approaches for studying groundwater stands as a potential solution. Fitting in this context, this study aims at developing coupled thermal remote sensing and modeling approaches for delineating groundwater discharge areas at the margin of eskers. The focus is set on the glaciofluvial formations (eskers and moraines) of a boreal region of the Canadian Shield, in Abitibi-Témiscamingue, Quebec, Canada. The results obtained in this region are further discussed for developing an approach aimed at delineating groundwater discharge areas in glaciofluvial formations of northern Quebec, a vast region where remote sensing approaches seem much needed given the limited access to *in situ* groundwater monitoring data.

Figure 1. Conceptual model of a local groundwater flow system in an esker (Adapted from Nadeau et al., 2015)



Methods

This study uses thermal remote sensing approaches coupled with numerical modeling (Figure 2). LANDSAT TIRS/OLI satellite images (collected in June and September 2017/2018) with a spatial resolution of 30 x 30 m were first use to identify thermal gradients at the margin of eskers over a 9184 km^2 region (Figure 2A). Land surface temperature (LST) were retrieved from calculations using the Plank's law, based on the QGIS plugin developed by Isaya Ndossi and Avdan (2016). It allows for the production of datasets such as radiation, brightness and emissivity and for the application of atmospheric corrections. The plank's function used here is given by:

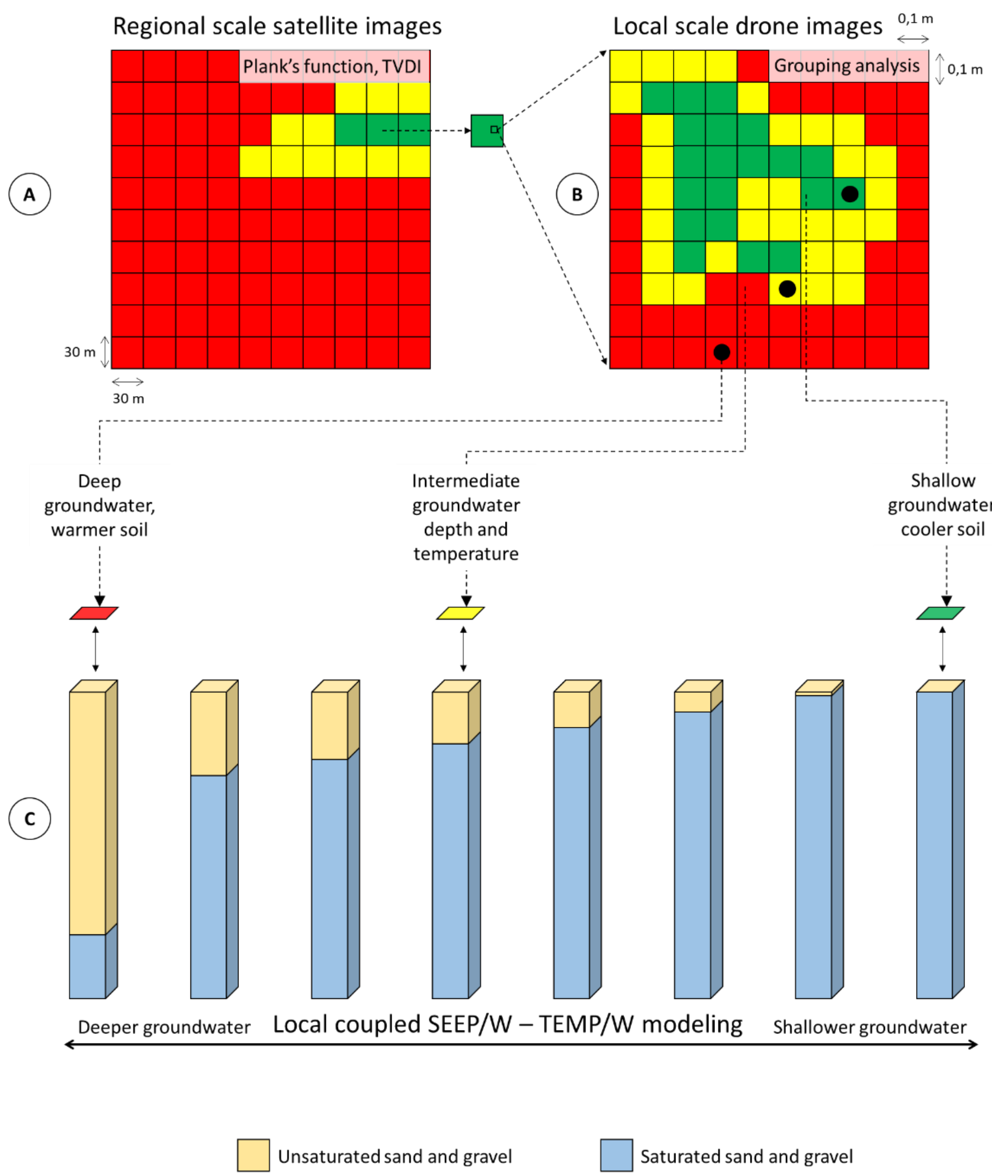
$$Ts = \frac{BT}{\left(1+\frac{\lambda * BT}{\rho}\right) * \ln(\varepsilon)} \quad \textbf{Equation 1}$$

where λ is the wave length, $\rho = h * \frac{c}{\sigma} = 1.438\ 10^{-2} mK$; h is the Plank's constant and c is the velocity of light, σ is the Boltzmann's constant, ε is the emissivity. The surface brightness (BT) is given by:

$$BT = \frac{K_2}{ln(\frac{K_1}{L_\lambda}+1)} \quad \textbf{Equation 2}$$

where K_1 and K_2 are constants from metadata file and L_λ is the spectral radiance at the top of the atmosphere. The areas that are likely to be associated with groundwater exfiltration zones were identified using temperature-vegetation and dryness indices (TVDI) calculated based on LST (Chen et al., 2015). Statistical tests were conducted on the data in order to delineate low temperature anomalies, based on the hypothesis that during the summer, humid soils found in groundwater discharge areas are colder than dry soils.

Figure 2. Conceptual scheme of the methodological workflow used in this study



High-resolution optical and thermal images (10 x 10 cm) were subsequently acquired using a *DJI Zenmuse XT2* camera mounted on *a DJI Matrice 200* drone, with a focus on zones where thermal anomalies were identified from the satellite images (Figure 2B). The DJI GS PRO application was used to automate 42 flights allowing the acquisition of 4 000 thermal images during 5 days in September 2019. Mosaics of georeferenced images were created using the *Pix4Dmapper* software.

Field experiments consisting of repeated flights (between 6h00 and 21h00) conducted over a single site characterized by marked thermal gradients were realized in order to identify the optimal time of the day for data acquisition. Drone flights were then conducted in areas of thermal anomalies identified from satellite images. Following the acquisition of high resolution thermal images, the pixels from raster images were converted to points in ArcGIS and grouping analyses were conducted to identify points sharing similar temperatures that are spatially associated. This method allows for a quantitative identification of thermal anomalies, thus minimizing the subjectivity that could be associated with a qualitative visual analysis of the thermal images. It also provides a broadly applicable method for a systematic identification of thermal anomalies.

Numerical simulations using SEEP/W and TEMP/W were subsequently developed in order to provide a quantitative analyses of water and heat fluxes in discharge areas (Figure 2C). Eight different two-dimensional models were used to evaluate the influence of groundwater depth on surface water temperatures, as illustrated in Figure 2C. Different sets of model boundary conditions are being tested to document the effect of meteorological conditions, infiltration, groundwater recharge and groundwater flow on soil surface temperatures for groundwater depths ranging between 8 m and 0,05 m. All models assume a constant groundwater temperature of 6°C, consistent with measurements conducted in eskers of the region. The first simulations were applied to the Saint-Mathieu / Berry esker, where *in situ* monitoring data are available for comparison.

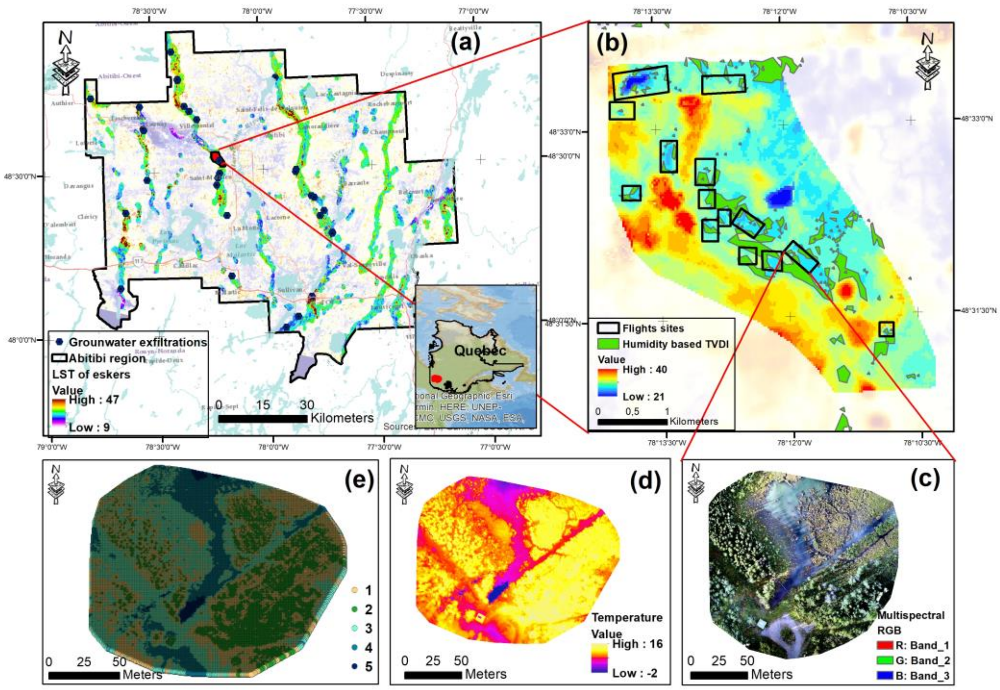
Preliminary results and discussion

The repeated drone flights conducted over a zone characterized by marked thermal gradients revealed that data collected in the afternoon, between 15h00 and 19h00, were optimal for delineating thermal anomalies in the local hydrogeological environment. Figure 3b shows the cold thermal anomalies identified from satellite images near the Saint-Mathieu / Berry esker. The 14 zones of thermal gradients identified therein were used as target for the acquisition of drone-based high-resolution thermal images. The high-resolution thermal images acquired using a drone over one of the 14 aforementioned zones are showed in Figure 3d, whereas the grouping analyses conducted on the data are presented in Figure 3e. Overall, these preliminary results suggest the approach developed here has a significant potential for the delineation of groundwater discharge areas at the margin of eskers. Coupled SEEP/W-TEMP/W simulations are currently being developed in order to provide a quantitative interpretation of the thermal anomalies identified by remote sensing.

Opening remarks

Ultimately, the approaches developed in this study will allow for a better identification of groundwater discharge areas associated with eskers. This information is critical for better identifying the potential location of groundwater dependent ecosystems where greater environmental protection could be required. It also provides tools for better understanding the complex shallow groundwater flow systems associated with eskers.

Figure 3. Mapping on différent scale of study area. (a) LST of Abtitbi region and groundwater exfiltration from PACES-AT1; (b) Flights sites using LST and TVDI; (c) Hyperspectral hight resolution mosaicing images of a specific groundwater exfiltration; (d) Hight resolution thermal mosaicing of the same specific groundwater exfiltration; (e) Result of function "Grouping Analysis" using ArcMap software.



Acknowledgements

This project was possible due to funding from the *Ministère des Affaires municipales et de l'Habitation du Québec* (MAMH) and from the *Ministère de l'Environnement et de la Lutte contre les changements climatiques du Québec* (MELCC).

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