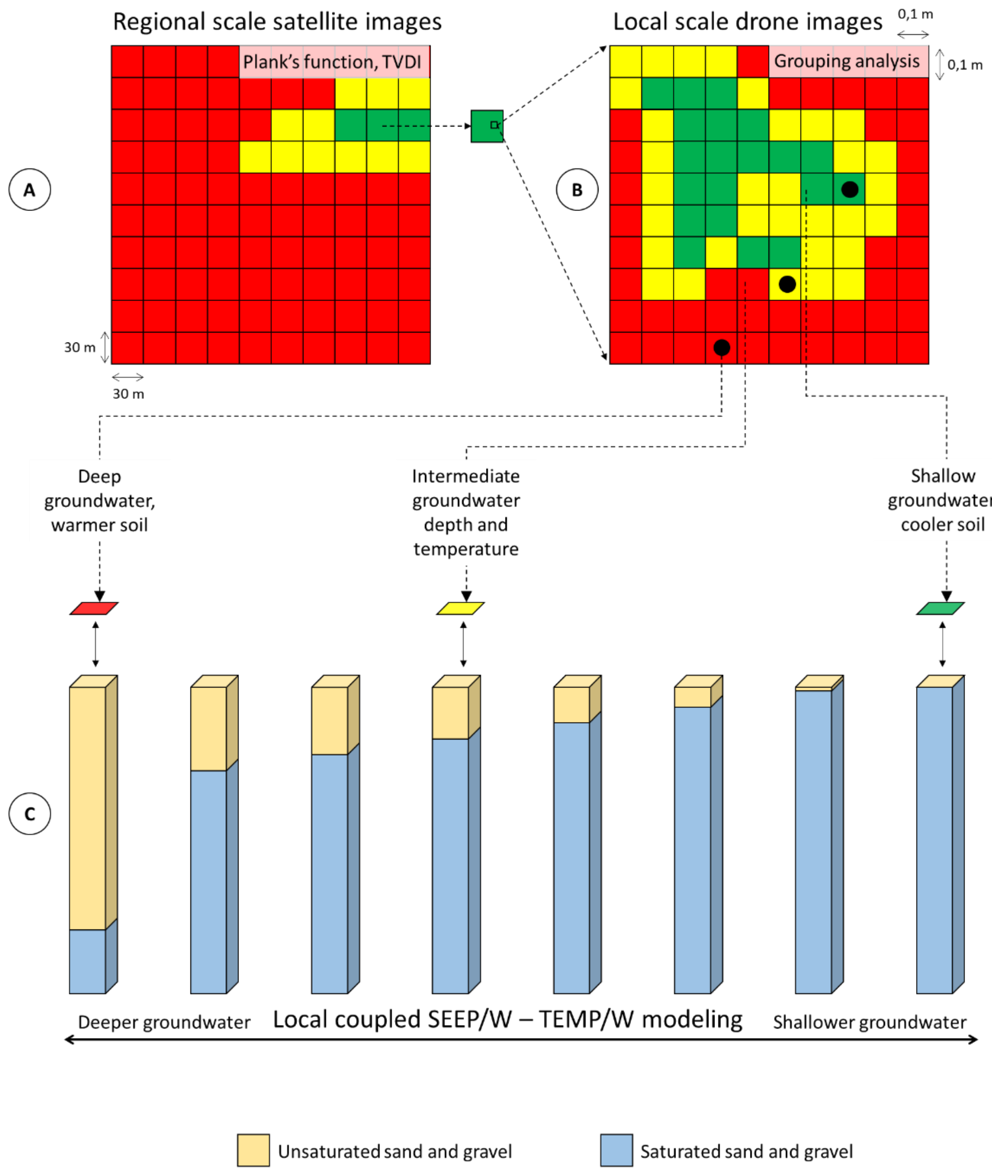
**Figure 2**. Conceptual scheme of the methodological workflow used in this study




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.

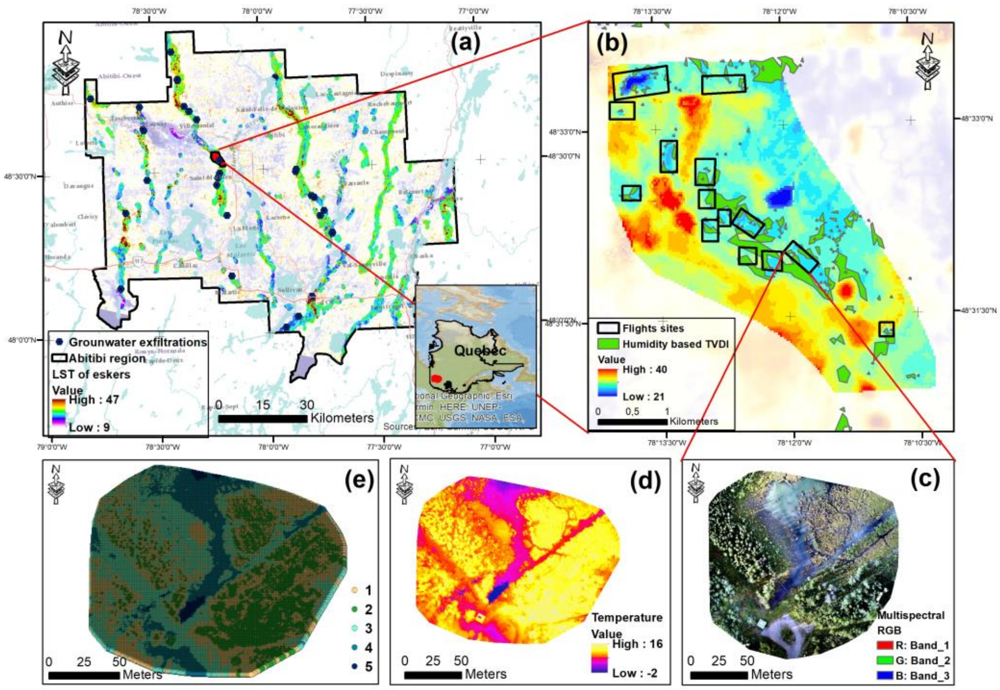
## Preliminary results and discussion

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.

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