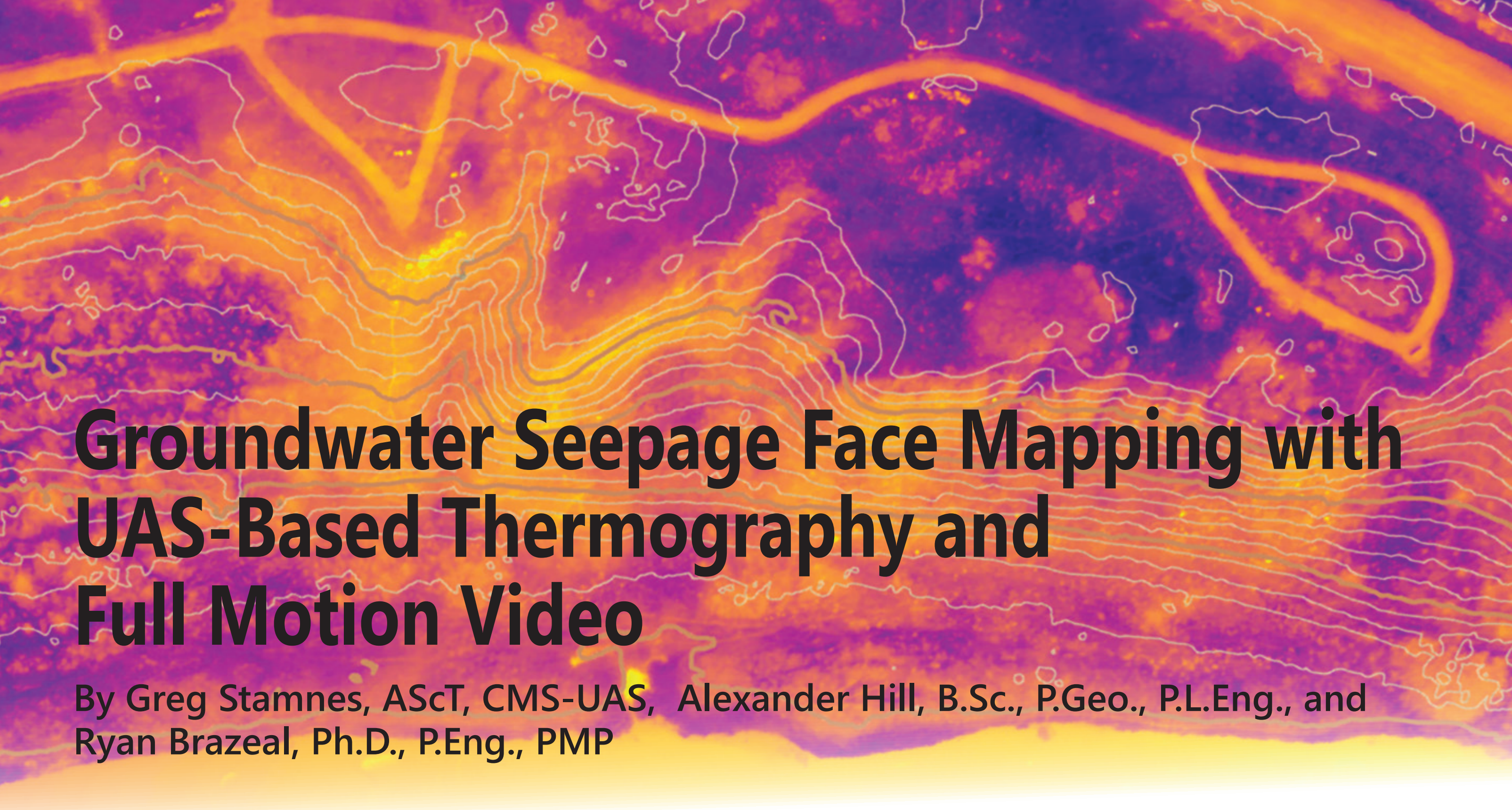

Groundwater Seepage Face Mapping with UAS-Based Thermography and Full Motion Video

By Greg Stamnes, AScT, CMS-UAS, Alexander Hill, B.Sc., P.Geo., P.L.Eng., and Ryan Brazeal, Ph.D., P.Eng., PMP

Introduction

Groundwater seepage is a geohazard which can be difficult to detect visually that contributes to terrain instability and possibly catastrophic failure (Budhu & Gobin, 1996; Alberta Environment, 2022). When terrain instability occurs near dams, highways, and other critical infrastructure, groundwater seepage can have immense economic, environmental, and public safety implications.

Groundwater seepage can be found by identifying the seepage face; the boundary where the flowing groundwater meets the atmosphere (Scudeler, et al., 2017). Identification is often achieved using remote sensing techniques and/or visual assessment via boots-on-the-ground survey. A variety of remote sensing techniques including image interpretation of stereo aerial images (e.g., terrain analysis of current and historical aerial photos), digital orthoimages, and more recently via thermography are utilized by hydrologists, geomorphologists, and geotechnical engineers to locate groundwater seepage faces (USGS, n.d.).

The use of thermographic sensors carried by Unoccupied Aerial Systems (UAS) can be an efficient alternative for identifying groundwater seepage faces. However, the method does have some limitations if the common practice of using a Structure from Motion (SfM) software package to produce a single orthorectified thermal index map from UAS-collected imagery is all that is utilized. This article highlights using Full Motion Video (FMV) to visually identify and georeference groundwater seepage locations using thermography.

There are also limitations of visual interpretation for groundwater seepage identification. Terrain analysis begins with the identification and distinguishing of elements of the landscape. These elements can typically be categorized as; topography or landform, drainage and erosion, vegetation and land-use (Mollard & Janes, 1984). This process requires the skills and knowledge of an analyst to determine the importance and significance of the identifiable features and elements of an observed landscape within the imagery, such as stereoscopic aerial photography.

A common approach is to conduct aerial photography analysis using softcopy photogrammetry. One of the many advantages to this approach is the ability to incorporate and overlay different sources of data and imagery including high-resolution digital aerial photography, orthorectified imagery, and Digital Elevation Models (DEM) to aid in the identification and interpretation of the landscape. This allows the analyst to navigate digitally in 3-Dimensional (3D) space without nominal scale constraints, which is especially important for viewing possible seepage faces. In the identification of groundwater seepage and drainage patterns using this method, the analyst is still reliant on visual cues, especially recognizing tone, shape, vegetation type and terrain relief.

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Analysts must acknowledge that site conditions may differ significantly when comparing conditions at the time of capture of the aerial photography to those currently being assessed. The occurrence of groundwater seepage at a particular area or site may be a function of other variables such as geology, ground stability, vegetation cover, human activity or be seasonal in nature. It is therefore possible that seasonal seepage issues may not be recognized by the analyst when conducting image interpretation of aerial photography alone. In Figure 1 this is illustrated by overlaying seepage identified from 1991 dated aerial photography interpretation (pink hatch), with more recent aerial photography interpretation (green hatch).

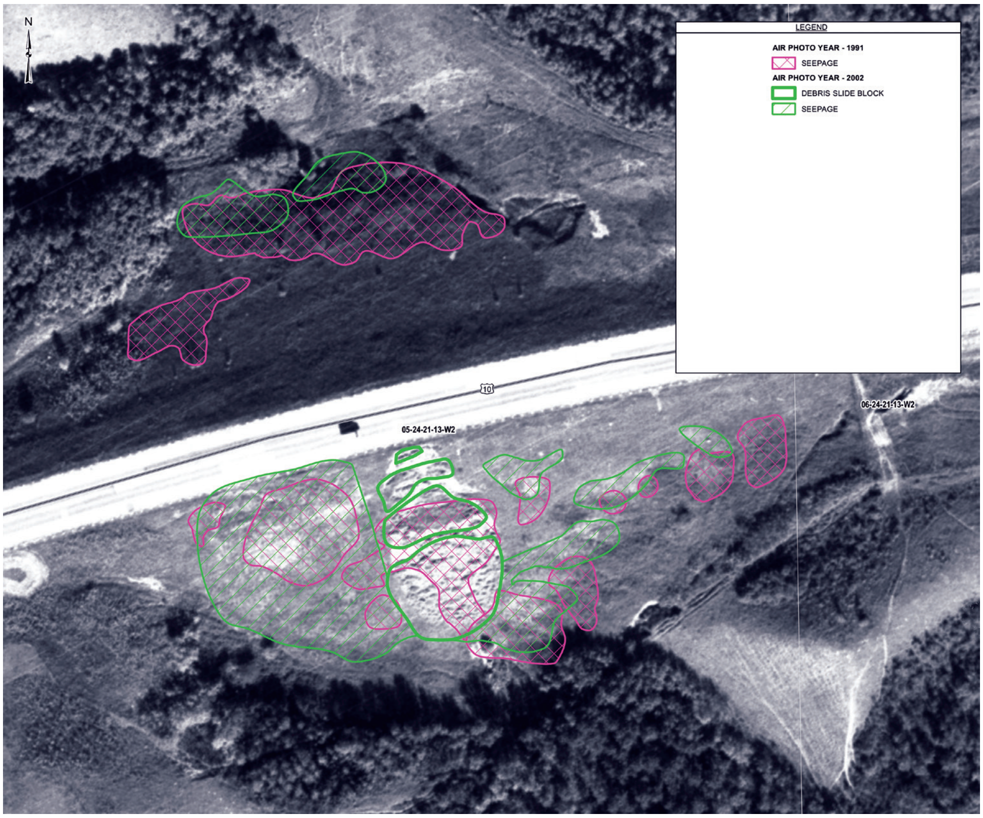

Figure 1: Typical black and white aerial photography used for terrain analysis and identification of potential seepage locations.

Analysis should include on-site ground truthing to validate the findings of the image interpretation phase and order to check the accuracy and relevancy of the mapped terrain features as shown in Figure 1. This is especially important when theorizing what relationships exist between landforms. Answering this question may also provide clues to where groundwater seepage may occur if not obvious from the aerial photography interpretation alone.

Aerial thermography can be used in the context of groundwater seepage to answer two questions: firstly, are there radiometric indications when seepage is occurring within an area of interest, and secondly, where (geographically) is the seepage occurring?

Aerial Thermography for Groundwater Seepage

Aerial thermography can be used in the context of groundwater seepage to answer two questions: firstly, are there radiometric indications when seepage is occurring within an area of interest, and secondly, where (geographically) is the seepage occurring?

Aerial thermal data acquisition for identifying seepage faces should be timed to commence when the greatest temperature difference occurs between the groundwater flow and the surrounding ground (Ozotta, 2021). This could be during late summer when the flowing groundwater is cooler than the surrounding warmer soil, or in the spring and autumn when the flowing groundwater is warmer than the cooler ground. However, there should not be snow cover on the ground, and the ground should not be deeply frozen during the acquisition of the thermal data (Harvey, et al., 2019). Data collection should occur at night with optimum meteorological conditions, including low wind speeds of less than 24 km/hr, humidity less than 50%, and no precipitation within the previous 24 hours (Infrared Training Center, 2019). Thermal sensors are a passive type of sensor and therefore suffer from environmental factors such as the effects of vegetation occlusion when mapping the ground surface (Ozotta, 2021; Infrared Training Center, 2019). As a result, it is recommended to conduct thermal imaging missions for groundwater seepage detection and mapping during the spring months before seasonal vegetation growth.

Our research was conducted on the riverbanks of the South Saskatchewan River near Saskatoon, SK, Canada in May, July, and October of 2020, and April, July, and November of 2021 in an area with known groundwater seepage.

Figure 2: Location of the research at the South Saskatchewan River. The study area along the river is about 650m long and 100m wide.

The surficial geology of the test site comprises alluvial floodplain deposits and glaciofluvial kame terrace deposits (Christiansen, 1992). However, no forms of intrusive or non-invasive geotechnical/geological investigations were undertaken prior to thermal imaging of the test site.

Thermal imagery datasets were collected using a DJI M200 UAS with a DJI Zenmuse XT2 payload with 13mm lens. The XT2 is a long-wave infrared (LWIR) camera with an uncooled VOx microbolometer, 640 x 512 resolution, and 30 Hz full frame rate. The total project area was approx. 65,000m². During an additional flight, UAS-based lidar data was also collected for orthorectification of the thermal images with Pix4DMapper and to create a DEM of the area for higher accuracy video frame reprojection. Our research concluded that the ideal time to collect data in this region was shortly after spring snow melt when the ground was thawing, and groundwater flow levels were above average.

SfM for Thermal Index Maps

Completing SfM mapping from thermal imagery has the advantage that the produced orthorectified thermal index map can be used in Geographic Information System (GIS) software to correlate areas of increased thermal index (i.e., temperature) with slope, as seepage typically occurs where groundwater zones intersect the faces of slopes (Winter, et al., 1998).

Figure 3 shows contour lines of the ground surface overlaid on an SfM-generated thermal index map created from the data collected on May 7, 2020, shortly after snow melt. The thermal imagery was collected over the course of multiple UAS flights totaling 4 hours in duration from an altitude of 121m above ground level (AGL) resulting in an average Ground Sample Distance (GSD) of 16.9 cm/pixel.

There is a distinct temperature increase noticeable near the top of the riverbank as identified in Figure 3, but it is difficult to confidently delineate where the seepage exists using only the thermal index map and contours. This is primarily due to the lower resolution of the input thermal imagery and the color blending applied to each pixel as part of the SfM orthorectification process. Because of the color blending, other objects with elevated temperatures in relation to the ground, such as trees, contribute to the elevated index values surrounding them and falsely represent the elevated ground temperatures.

Our experience reveals that thermal mapping using SfM has several limitations. Groundwater seepage faces are commonly composed of homogeneous earth with similar geological properties and/or permeability characteristics that heats and cools at similar rates resulting in low thermal contrast. This low thermal contrast in turn results in featureless imagery which can lead to SfM key point generation failure. SfM software developers have thermal data collection recommendations including 90% front and side overlap, low flight speeds of 2-3 m/s, using a gimballed camera, and flying higher to assist key point matching (Pix4D, 2019; Pix4D, 2018a; Pix4D, 2018b). However, by following these guidelines challenges arise due to the volume of image data from acquiring imagery with high overlap. To reduce data volume the solution is to fly higher, but this reduces the image resolution. Flying at higher altitudes increases the volume of atmosphere between the ground and the sensor, resulting in thermal energy loss due to atmospheric attenuation (Infrared Training Center, 2019). Flying at very slow speeds increases image quality by reducing motion blur but contributes to the impractical data acquisition and processing limitations of UAS mapping.

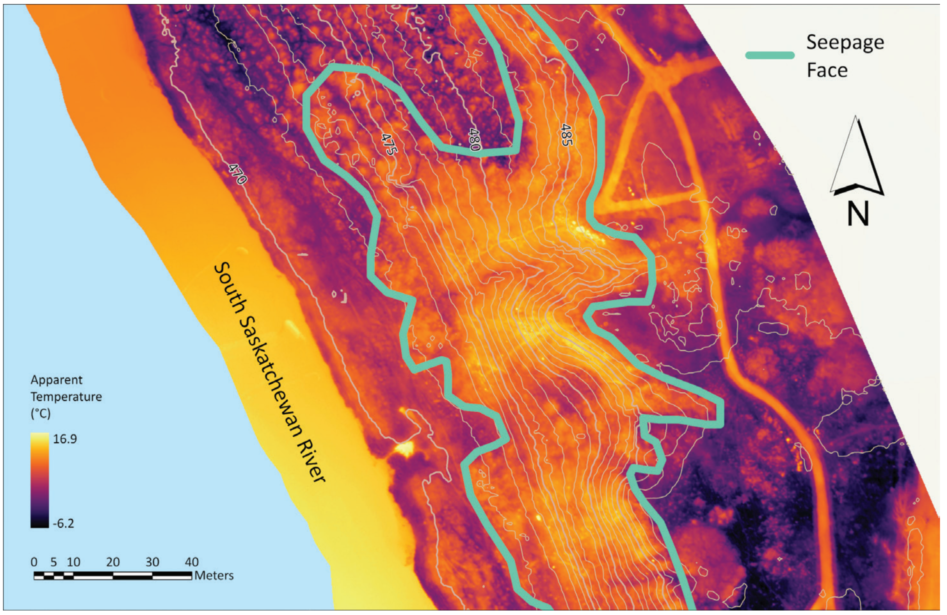

Figure 3: Thermal index map with elevated temperature on riverbank slopes. The contour interval is 1m. Date of data collection: May 7, 2020.

Another issue with SfM-based thermal mapping is the inconsistency of input data due to the loss of thermal energy over time. On larger projects that require multiple UAS flights and span several hours in duration, the data collected at the beginning of the acquisition period may have different thermal energy than the data collected near the end of the period over the same geographical area. In addition to all the above noted problems, thermal cameras onboard UAS will typically automatically adjust their measurable temperature range throughout the flight depending on the thermal energy that reaches the sensor. This is synonymous with collecting color imagery while adjusting the ISO light sensitivity setting significantly throughout acquisition. The resultant imagery can be difficult to process within SfM software in order to produce meaningful mapping products.

> *FMV is similar to Augmented Reality in that it combines real-world video data with georeferenced digital data such as point, polyline, and area features. Contour lines can be used to assist with the visualization of elevation change during FMV video review to identify temperature changes in areas of slope change.*

FMV for Identifying Groundwater Seepage

In addition to the high-altitude UAS flights, a single lower-altitude flight (45m AGL) was performed over the known seepage locations in order to investigate the practicality of using close-range thermal video for identifying groundwater seepage. This reduction in altitude subsequently increased the image resolution and reduced the volume of atmosphere between the thermal camera and the ground. This in turn resulted in an improved level of discernable temperature difference between the seepage faces and the surrounding ground. In order to georeference the features of interest identified within the thermal video, tests were conducted using FMV. FMV refers to a video file which has been combined with geospatial metadata to make the video file geospatially aware (Esri, n.d.). FMV is similar to Augmented Reality in that it combines real-world video data with georeferenced digital data such as point, polyline, and area features. Contour lines can be used to assist with the visualization of elevation change during FMV video review to identify temperature changes in areas of slope change.

To create a thermal index map with accurate absolute temperature values for each pixel, thermographic imagery collected with a radiometric camera needs to be corrected for emissivity and bias (Abdullah & Turek, 2021). This procedure presents challenges for FMV. However, in the case of locating seepage faces, apparent temperature differences are sufficient due to its qualitative nature (Harvey, et al., 2019). The non-disruptive nature of low-altitude UAS flights in comparison to using occupied aircraft, along with the suitability of using apparent temperature differences, favors the use of FMV from UAS for identifying and mapping groundwater seepage faces.

Site specific variables such as (but not limited to) geology, terrain, thermal characteristics, and slope aspect may dictate that FMV for groundwater seepage mapping be used in conjunction or at least supported by more conventional forms of terrain analysis (such as aerial photography analysis). Possible correlation between these variables and the findings of the FMV mapping and thermal imaging data may be drawn such that analysis can reliably map potential groundwater seepage areas.

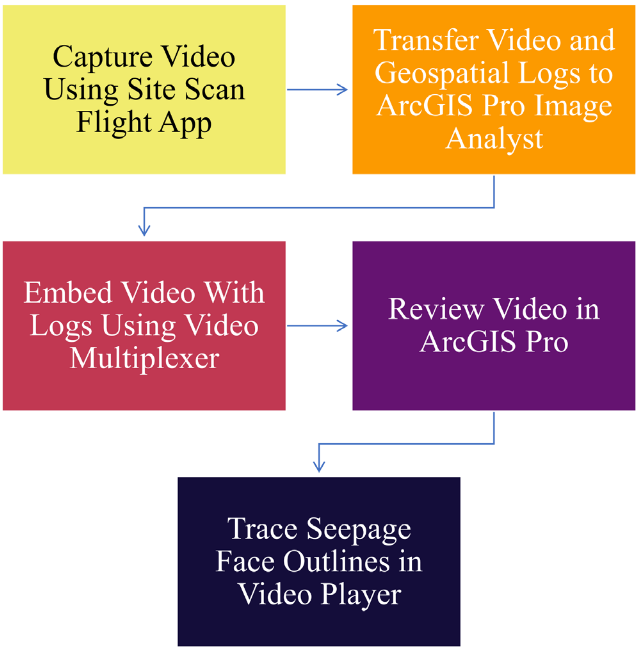

Figure 4: FMV Flow Chart (ArcGIS, 2020).

To create FMV, video data, along with position and orientation metadata of the UAS and gimbal orientation stored in geospatial flight logs created by Esri's Site Scan Flight app software, is combined using the Video Multiplexer tool within ArcGIS Pro. Areas of temperature change representing seepage can then be manually digitized to create vector feature classes, directly from the video frame within the Video Player similarly to how the area was manually digitized using the thermal index map as shown in Figures 3 and 5. The area of traced groundwater seepage in Figure 5 appears to coincide with the outcropping of more permeable soil deposits which may promote groundwater flow.

Another useful tool is the Frame Export tool which projects a single video frame onto the Esri map. Figure 5 shows an FMV frame that was overlaid onto the ArcGIS map view with the Frame Export tool.

Using ArcGIS Pro, the FMV can be displayed and a line feature displaying the UAS position during the flight will be shown in the map view (red parallel lines in Figure 6), as well as the position of where the video frame was recorded and the projected outline of the video frame on the ground. Feature classes that appear in the map or scene view can be displayed in the video frame, such as contours, cadastral boundaries, or manually digitized features by enabling the "Display Features" function. Such ability to view contours in the video frame assists reviewers in visually correlating changes in slope to the seepage faces. It also functions to ensure that all identified areas of interest within the video have been delineated. Once the FMV review has been completed, the feature classes can be easily exported as vector features for downstream GIS and CAD visualization and analysis.

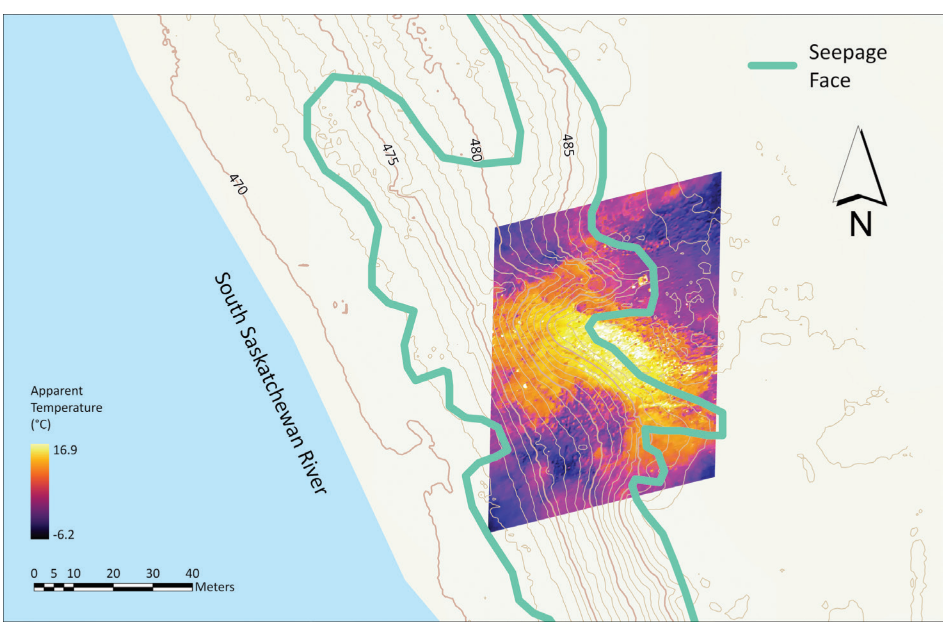

Figure 5: FMV Frame Export showing seepage face locations overlaid with contours – see the comments for Figure 3. Date of data collection: April 24, 2021.

In summary, there are many benefits to using FMV. It allows for reduced UAS flying height and distance from the sensor to the ground, reducing the effects of wind and other atmospheric conditions (e.g., humidity) within the thermal data. As a result, the FMV data are of more detail and higher resolution, and there is less thermal energy loss between the sensor and the ground. Parallel flight lines can be flown further apart as the high overlap for successful SfM processing is not required. The camera can be pointed in a nadir direction to reduce oblique distortion, and linear corridors can be mapped in a single pass, which is not successful when using SfM-based thermal mapping.

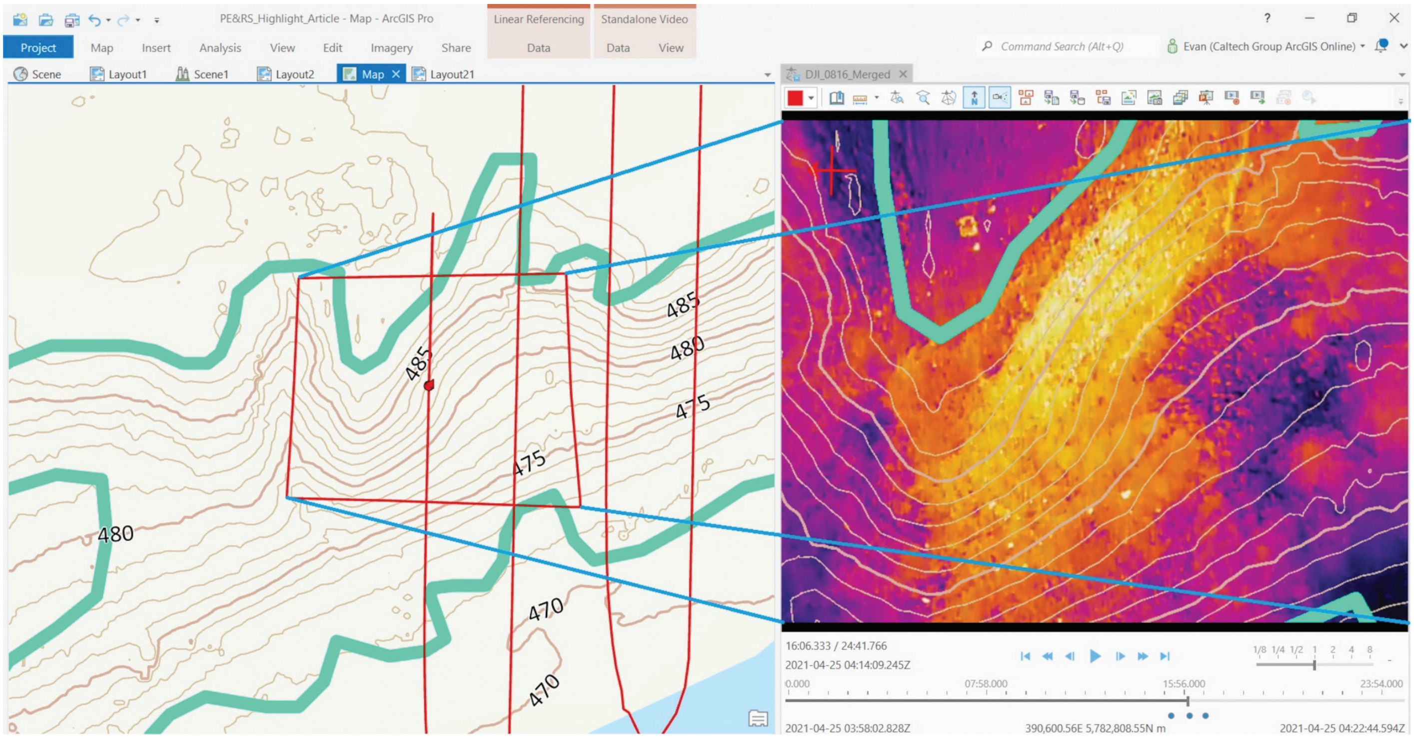

Figure 6: FMV Review in Esri's ArcGIS Pro Identifying Groundwater Seepage Face.

Although video files are typically large in size, the thermal video data collected over the research area was only 25% of the total size of the still thermal imagery collected. The total data collection time for the thermal video data was 40 mins, compared to 4 hours for still thermal imagery. Because the thermal data is collected faster, there will be less temperature variation from the beginning to the end of data collection. FMV data collection using UAS can be completed with high temporal frequency and in conjunction with aerial photography during sunlight to identify correlations. Lastly, groundwater seepage faces can still be identified in areas with reduced thermal contrast using FMV.

Similar to image interpretation of aerial photography (i.e., stereoscopic images), interpretation of FMV videos is required in order to identify and evaluate possible groundwater seepage areas. Misinterpretation of groundwater seepage due to vegetation cover and other land-use issues while using FMV increases without a fundamental understanding of the terrain.

> *"In summary, there are many benefits to using FMV."*

Future studies are to incorporate geology as a variable as it relates to thermographic mapping of potential groundwater seepage areas. Geology, specifically the physical characteristics of a soil or rock have influence over the thermal characteristics that will develop within a particular soil or rock. Heat transfer within a soil (other than conduction) may only be a factor in more permeable soils where groundwater flow is apparent (The Canadian Geotechnical Society, 2006).

The Future of FMV for Groundwater Seepage

One of the current trends in UAS industry is the integration of network connectivity for near real-time data transfer of imagery and video. Presently, some systems, such as the Freefly Systems Astro UAS, offer real-time viewing of data from several sensors including the Workswell WIRIS Pro or Flir Duo Pro R radiometric thermal cameras via the Auterion Suite. This allows for analysts to remotely view the thermal imagery from a live video dashboard and identify potential areas of interest to be further investigated while the UAS pilots are still in the field. The real-time data is not FMV, as it is not multiplexed with the position and orientation data streaming from the UAS and gimbal sensors. With the present ability to stream high-resolution video data to a remote viewer in real-time, it is perceivable that in the future it may be possible to perform the multiplexing of the video data and the position and orientation data for real-time FMV.

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