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Using Drone Based Hyperspectral Analysis to Characterize the Geochemistry of Soil and Water

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Abstract: Geochemical analysis through field samples and laboratory testing is a well-trodden method for understanding the composition of soil and water. The limitation of this approach is in the spatial extrapolation of these diagnostic point-location samples. Over large areas such as operational and closed mine sites, sampling can be labor intensive and present potential health, safety and environment protection issues associated with the sampling. Hyperspectral image analysis has been shown to identify an object's spectral composition and discretize it from its surroundings. SLR Consulting Limited has been developing a methodology to assess the chemistry of soil and surface water using mounted hyperspectral sensors, and to combine these to provide greater accuracy and precision insights across sites with known mine water contamination issues. Through the use of case studies in the Ireland and US, SLR presents the application of drone based hyperspectral analysis. The studies have shown that the use of drone based hyperspectral sensors provide an excellent potential for the surveying of mining land-use and mining legacy sites. The surveys provide benefits in supporting soil and water geochemical investigation at active and historic mining sites both in data acquisition and also area coverage.

Key words: Hyperspectral, geochemistry, mining, heavy metals, hydrochemistry, innovation.

1. Introduction

The assessment of mining sites using geochemical and hydrochemical assessment is well established and can involve a variety of different analytical techniques. Similarly the use of multispectral and hyperspectral analysis of soil/rock has been undertaken over a number of years through the use of satellite and fixed wing aircraft to aid mineral exploration [1, 3, 5, 7] and in the interpretation of dominant geochemical regimes, such as acidic and metalliferous mine drainage [4, 6] and land contamination issues [2]. It is a passive non-intrusive analytical technique that can reveal alteration patterns that the human eye cannot see.

SLR Consulting Limited examined the information relating to the area of multi spectral and hyperspectral analysis and concluded that the use of drone technology could be a viable alternative when investigating mining sites. In particular it was seen as a useful method for assessing old and abandoned mine sites where acidic mine drainage was present. Furthermore, time variant studies were seen as a valuable addition to existing mine closure monitoring schemes. It is not the purpose of this paper to review the existing techniques for aerial hyperspectral analysis of soil and water, but rather to present the value-added application of using drone technology. This includes:

- Development of the approach;
- Brief presentation of the visible and near infrared (VNIR) and short wave infrared (SWIR) technology and its use;
- Typical issues with using aerial assessment tools;
- Presentation of preliminary studies in the Ireland and US which demonstrate successful use of the technology and value-added application; and
- Next stages of assessment.

2. Study Hypothesis

There were two hypotheses addressed in the study.

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These involved considering hyperspectral surveys of areas where:

- The formation of minerals associated with pyrite oxidation is dominant. This presents opportunities to understand wider scale geochemical environments at areas of the mine; and
- Non sulfidic mine areas such as lead zinc mines in carbonate host rock.

The objective has been to establish if the drone survey approach can integrate the geochemistry successfully such that informed decisions regarding long termed sampling, monitoring and management plans which can be put in place.

3. Geochemical Environment

Recent studies have shown that by understanding certain mineral assemblages using the hyperspectral analysis, the likely dominant geochemical environment controlling the solubility of the metals can be theorized. This is exemplified below where other authors have successfully used hyperspectral imaging to understand the geochemical environment.

For example review of such hyperspectral imaging demonstrates how identification of the different iron mineral assemblages can give an indication of acidity generation in an area which has implications. Zabic et al. [6] presented predicted pH maps for mining impacted areas based on the iron mineral assemblage which showed a strong correlation to the measured soil pH.

The second consideration was those mine sites typically not involving sulfide ores such as lead zinc ores in carbonate host rocks. In Ireland it was possible for the authors to assess preliminary metalloid concentrations in tailings and these results are presented in Fig. 5. This included consideration of a range of lead and zinc minerals, some of which are described in Table 1.

In addition the risk posed from metalloids such as arsenic can be more fully appreciated by understanding the areal distribution in the soil over a wider area than that determined from soils sampling. An example of this is presented below.

A review of the Table 1 and literature shows:

- There are a number of lead and zinc compounds which might be presented at such mine sites;
- Some of these may not be visible with the naked eye but do have a spectral reflectance;
- Knowledge of the likely dominant metal form from the local geology and potential weathering assemblage is very important; and
- A number of the reflectance spectra overlap and emphasize the importance of ground truthing the surveys with relevant geochemical analysis (XRD, XRF etc.).

Fig. 1 Examples of field sampling to support hyperspectral analysis.

Table 1 Zinc minerals with associated spectral reflections [3].

Name	Formula	Colour	Spectral reflectance
Common minerals			
Smithsonite	$ZnCO_3$	White	Red peak, broad depression at 800-1,200 nm
Hydrozincite	$Zn_5(CO_3)_2(OH)_6$	White, grey, yellow	Peak at 600 nm
Cerusite	$PbCO_3$	White	Peak at 800 nm
Rare minerals			
Adamite	$Zn_2(AsO_4)(OH)$	Clear-yellow if iron present	Peak at 650 nm (red)
Linarite	$PbCu(SO_4)(OH)_2$	Azure blue	Sharp peak at 450 nm (blue); broad depression at 550-1,050nm
Zinc melanterite	$(Zn, Cu, Fe)SO_4 \cdot 7H_2O$	Yellow green	Peak at 515 nm; broad depression at 700-1,100 nm with minimum at 790 nm
Tsumehite	$Pb_2Cu(PO_4)(SO_4)(OH)$	Green	Peak at 580 nm (green)

Notwithstanding the above, a hyperspectral survey can, depending on the mine site in question:

- Aid the understanding of the metal concentration across mine site areas;
- Potentially give information concerning the dominant geochemical environment; and
- Consequently enhanced interpretation of the risk posed by the metal presence can be theorized and applied though a source-pathway-target relationship.

The added benefit is that a drone mounted hyperspectral sensor can cover a large area of the mine site thereby accessing areas which might not be safe or accessible to sample by ground based sampling teams.

4. Hyperspectral Imaging

Hyperspectral sensors collect hundreds of contiguous bands of reflected and emitted energy. Unique signatures or finger prints are created by the collected wave lengths where the reflectance is related to the composition of different materials in the ground. In the case of mine sites, the molecular structure of a minerals' surface generates the distribution of its reflectance and associated absorption; the resulting spectral signature serves as a unique fingerprint in the identification its composition [9].

The infrared region of light is considered a good mineral detection wavelength range because of the associated wide range of minerals that can be identified. The infrared extends from (as shown in Table 2):

- The visible and near-infrared (VNIR, 0.4-1 μm);
- Through the short-wave infrared (SWIR, 1-2.5 μm); and
- Mid-wave infrared (MWIR, 3-5 μm) to the long-wave infrared (LWIR, 7-13 μm).

The value of each infrared wavelength range to any application is determined by its detection capabilities of the targeted minerals. Electronic and vibrational ("exciting" of the elements) processes associated with bonded elements within minerals cause characteristic wavelengths in the infrared ranges, which enable identification of mineral species and in certain instances mineral chemistries. This results in the ability to identify mineral composition being significantly enhanced [8].

The detection capabilities of the VNIR, SWIR and long wave infrared (LWIR) are illustrated in the summary table of mineral classification—refer to Table 3. These are the wavelength ranges where the most mineral detection capabilities are achieved.

Case Study #1

Alaska Tundra Water Bodies.

On behalf of our client, SLR supported collection of hyperspectral data using airborne hyperspectral cameras and ground based spectrometers to evaluate metals concentrations in tundra water bodies in Alaska.

The characteristics of the hyperspectral sensor acquiring the data greatly influence the amount and quality of information available within each pixel. Consideration of the required scale of assessment determines the resolution of the sensor used, for a large

Table 2 Hyperspectral ranges source: "Airborne Hyperspectral and Ground Truth Technologies" [9].

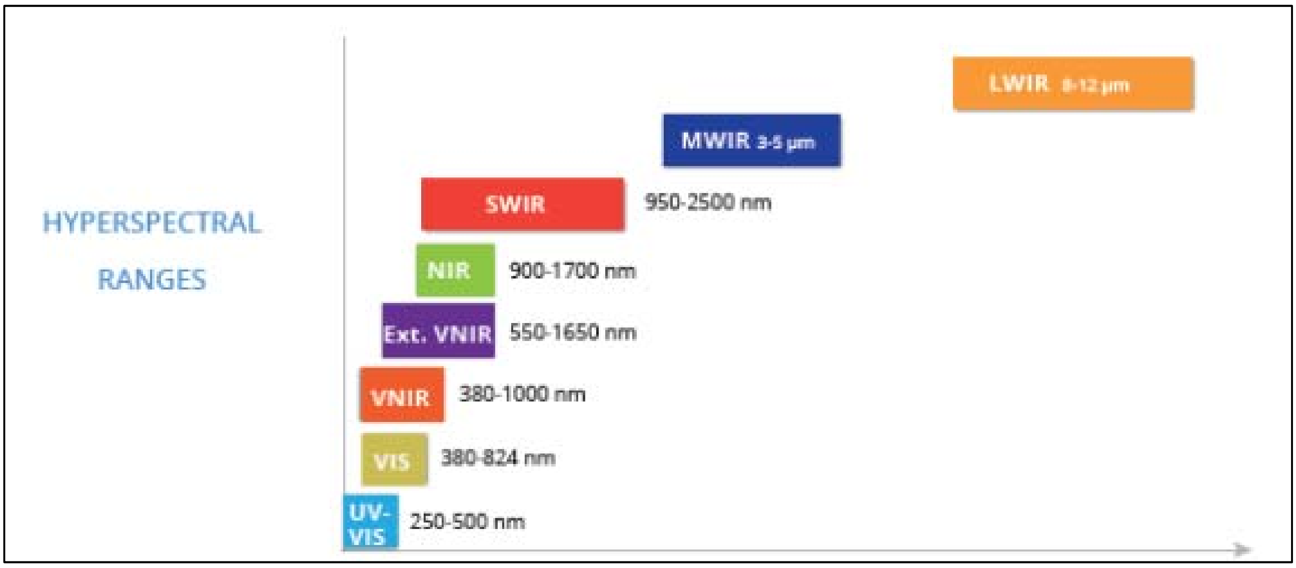

Table 3 Detection capabilities of VNIR, SWIR and LWIR for minerals [8].

	Structure	Mineral Group	Example	VNIR Response	SWIR Response	LWIR Response
Silicates	Inosilicates	Amphibole	Actinolite	Non-Diagnostic	Good	Moderate
		Pvroxene	Diopside	Good	Moderate	Good
	Cvclosilicates	Tourmaline	Elbaite	Non-Diagnostic	Good	Moderate
	Nesosilicates	Garnet	Grossular	Moderate	Non-Diagnostic	Good
		Olivine	Forsterite	Good	Non-Diagnostic	Good
	Sorosilicates	Epidote	Epidote	Non-Diagnostic	Good	Moderate
	Phyllosilicates	Mica	Muscovite	Non-Diagnostic	Good	Moderate
		Chlorite	Clinochlore	Non-Diagnostic	Good	Moderate
		Clay Minerals	Illite	Non-Diagnostic	Good	Moderate
			Kaolinite	Non-Diagnostic	Good	Moderate
	Tectosilicates	Feldspar	Orthoclase	Non-Diagnostic	Non-Diagnostic	Good
			Albite	Non-Diagnostic	Non-Diagnostic	Good
		Silica	Quartz	Non-Diagnostic	Non-Diagnostic	Good
Non-Silicates	Carbonates	Calcite	Calcite	Non-Diagnostic	Moderate	Good
		Dolomite	Dolomite	Non-Diagnostic	Moderate	Good
	Hvdroxides		Gibbsite	Non-Diagnostic	Good	Moderate
	Sulphates	Alunite	Alunite	Moderate	Good	Moderate
			Gvpsum	Non-Diagnostic	Good	Good
	Borates		Borax	Non-Diagnostic	Moderate	Uncertain
	Halides	Chlorides	Halite	Non-Diagnostic	Uncertain	Uncertain
	Phosphates	Apatite	Apatite	Moderate	Non-Diagnostic	Good
	Hvdrocarbons		Bitumen	IUncertain	Moderate	Uncertain
	Oxides	Hematite	Hematite	Good	Non-Diagnostic	Non-Diagnostic
		Spinel	Chromite	Non-Diagnostic	Non-Diagnostic	Non-Diagnostic
	Sulphides		Pvrite	Non-Diagnostic	Non-Diagnostic	Non-Diagnostic

scale assessment (over a large area) a resolution of 30-meters, such as what can be acquired from Landsat satellite data are adequate; however, when a finer resolution is preferred, a more accurate near ground assessment is needed. For the Alaska project, where some water bodies in the project area were significantly smaller than 30 meters in diameter, a finer resolution was required. To achieve the project objectives, a hyperspectral camera was flown across the area, at a flight height of c. 1,500 meters, by fixed wing manned aircraft at an elevation designed to achieve 2-meter pixel resolution. Concurrently, a ground based crew was deployed to collect surface water samples and spectral reading from selected tundra water bodies along the flight lines. The SLR team in Anchorage designed an innovative method for simultaneously collecting water samples and spectral data safely from the shore. The lake sampling device (LSD), designed by SLR, eliminated the need to transport a boat across sensitive tundra and mitigated the risk of collecting samples from a boat in cold and windy conditions—see Fig. 1.

Using the water analytical results and ground based spectral data, Satalytics, SLR project team partner, developed algorithms for estimating dissolved phase metal concentrations. The algorithms were then used to process the airborne hyperspectral data and develop metal concentration maps (2-meter resolution) for hundreds of tundra water bodies across the project area.

Traditional data collection methods involve sensors mounted on satellites (20-30 meters resolution) and manned aircraft (2-10 meters spatial: 10-20 nm spectral resolution). Sensors with medium to low resolution provide data adequate for regional and large-scale assessment such the tundra water body study in Alaska.

However, large pixels produce spectral signatures that represent a mixing of many independent variables, rendering the image unreliable for most detailed land use or other thematic classification requirements. Sub-meter resolution is preferred when more accurate ground assessment is needed. An example of the results for iron and barium is presented in Figs. 2 and 3.

Case Study #2

UAV mounted Hyperspectral Survey—Irish Mine Investigation.

Due to advances in technology, smaller and lighter hyperspectral sensors are being mounted on unmanned aircraft systems allowing hyperspectral data to be collected at a higher temporal and spatial resolution. Following the Alaskan case study described above and the limitations identified, SLR decided to explore the use of unmanned aircraft vehicles (UAVs) for improving the data collection method to complement the use of more traditional methods.

Following a review of available systems at the time (Summer 2016) it was decided to use this system:

1 X Aibot X6 V2 and hyperspectral sensor (VNIR only) sensor specification: Headwall (VNIR). (Spectral bands: 272, spectral range: 400-1,000 nm, spatial resolution (GSD): 5 cm, spectral resolution: 2 nm.)

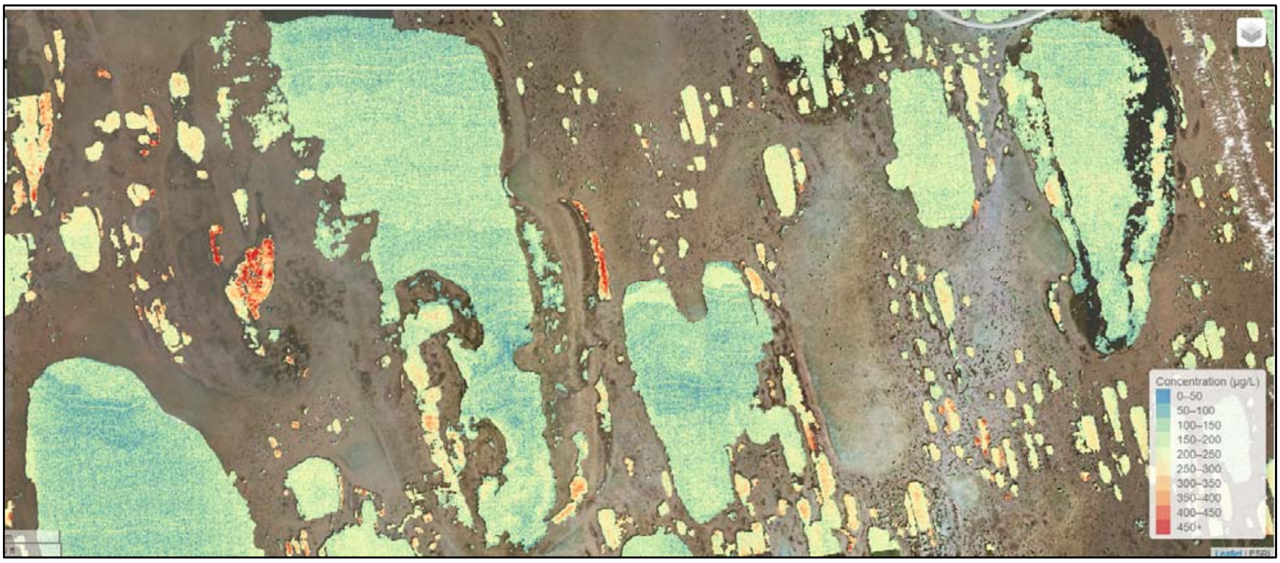

Fig. 2 Barium concentration in lakes across tundra survey area.

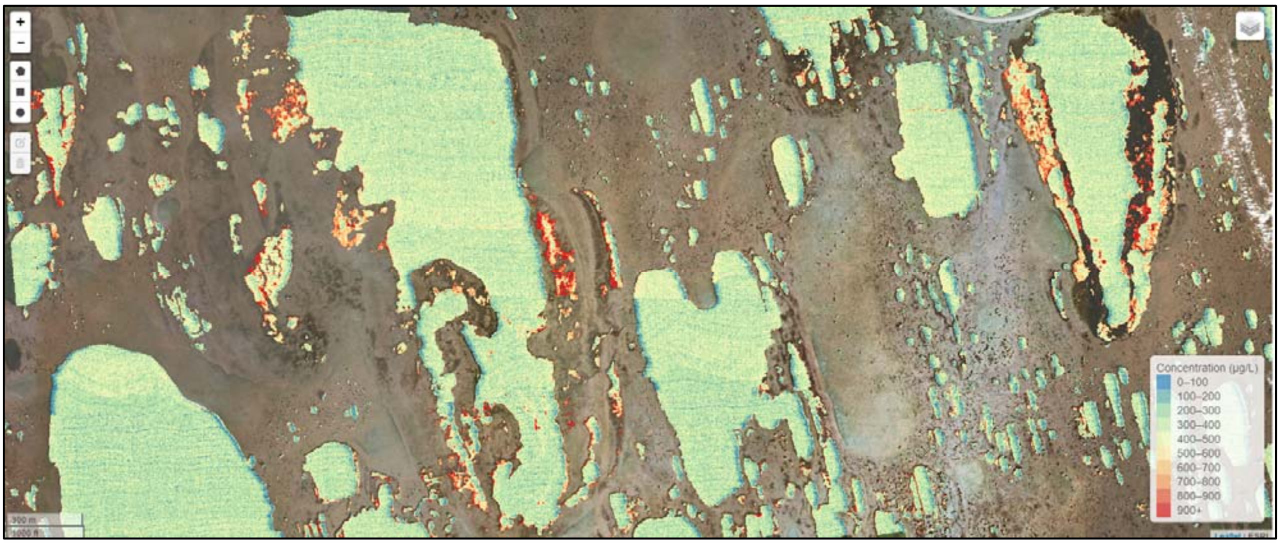

Fig. 3 Iron concentration in lakes across tundra survey area.

Fig. 4 Drones used in the study.

The field work, consisting of the UAV mounted sensor only (no ground truthing) was carried out in November 2016 at an active mine site in Europe (see Fig. 4).

An area of c. 2 Hectares was covered at a flight height of 50 meters producing data of 5 centimeters resolution, with 1 battery. This 10 minutes flight produced c. 10 gigabytes of hyperspectral data as we collected data across the full spectral range. The case study above (Alaska Tundra Water Bodies) produces data at c. 2 meter resolution using a manned aircraft and was flown at c. 1,500 meters flight height.

Interpretation of hyperspectral remote sensing requires specific algorithms able to manage high dimensional data in comparison to multispectral data. The collected data were processed by Harris Geospatial using ENVI image analysis software and by Satelytics using their proprietary algorithms. Results were processed to allow feature extraction for thematic purposes, using standard algorithms, leading to a spatial pattern and spectral identification pixels within the scene displayed as a map—refer to Fig. 5 that shows the processed hyperspectral data compared to RGB imagery (i.e. visible to the human eye).

The area was a tailings dam which is approximately 5,000 m^2 in area. The information presented demonstrates that the hyperspectral survey picked up more than the naked eye and with further preliminary interrogation; some elements in the soil are delineated. For example the distribution of relative concentrations of arsenic is present in Fig. 6.

The study indicates that the use of drone based hyperspectral survey exhibited excellent potential to increase the understanding of elemental distribution at former mine sites in soil and water, in particular:

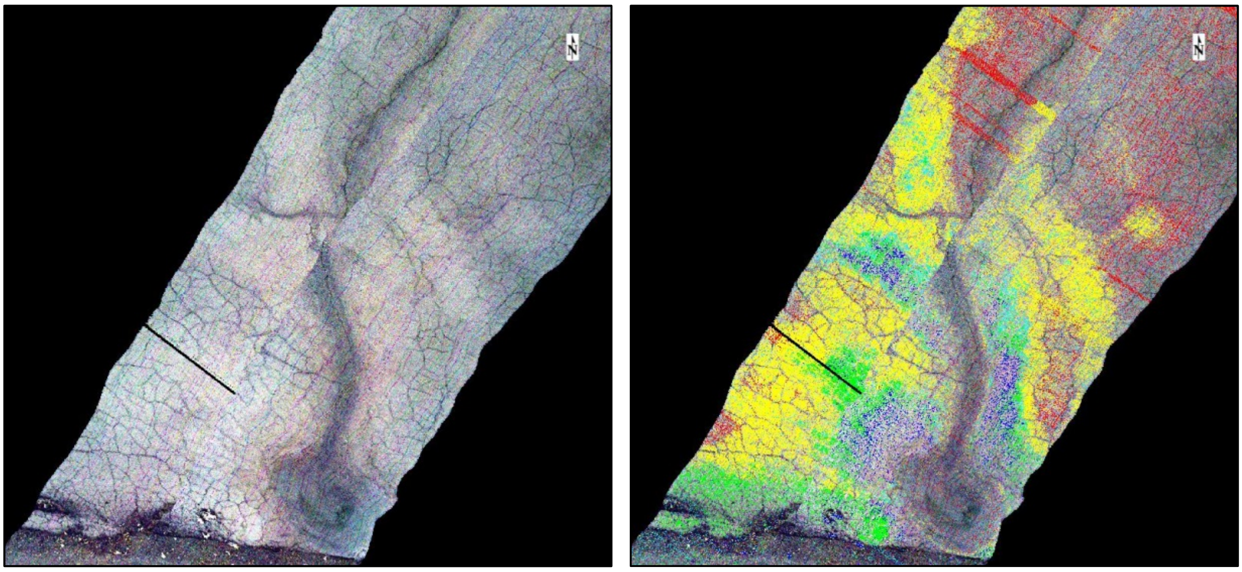

Fig. 5 RGB imagery compared to processed hyperspectral data.

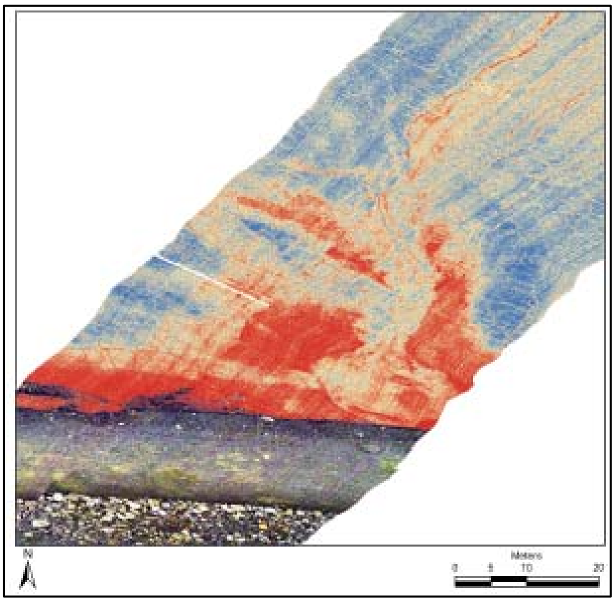

Fig. 6 Relative concentration for arsenic in tailings dam (red—high concentration, blue—low).

(1) It provides a real distribution of metals and metalloids which led to the interrogation of the conceptual site model for potential contamination migration at the site;

(2) It allows relatively rapid assessments of areas to be undertaken (compared to field sampling and lab testing), albeit with a requirement to collect relatively large files of data;

(3) Knowledge of the host geology is required such that key determinants can be optimized using the hyperspectral analyzer; and

(4) By understanding the factors controlling metal and metalloid mobility at the site, informed decisions regarding optimum and appropriate restoration can be made.

Learnings identified during the data collection stage included the usual issues with UAV's including, limited battery life allowing a limited flight time, variable wind speeds, and inconsistent lighting conditions. The data size of the captured spectrum was also a limitation factor due to the gigabyte size and associated transfer of data and associated storage. A number of challenges of working with the UAV collected hyperspectral data were identified by Harris when processing the data. These included, systematic noise in the direction of acquisition, variable speed of acquisitions and poor ortho-rectification. Awareness of these issues from the outset will dramatically improve the success of future surveys.

5. Next Stages of Assessment

The VNIR has limited mineral detection capabilities on its own, but provides valuable undetected identification of minerals when measured across other wavelength ranges. The VNIR is especially important for iron compound identification, which can be a useful area of study at sites producing acid mine drainage.

UAV systems are now available with VNIR and SWIR sensors and SLR are currently developing methodologies to use these systems on a number of active and legacy mine sites in Europe. The combination of these sensors will improve the detection capabilities of the system for the required minerals/contaminants. The next field study will include additional ground based sampling to enable calibration of the UAV collected data such that they make sense from a geochemical perspective. An example of this is field spectral measurements, X-ray diffraction (XRD), X-ray fluorescence (XRF) and supported by laboratory mineralogical analysis.

6. Conclusions

There are benefits of using UAV mounted hyperspectral sensors for monitoring a range of environments e.g. active and legacy mine sites, contaminated land etc. In the mining sector there are particular benefits in using this technology for mine closure monitoring and management (providing an invaluable tool for environmental evaluation and temporal/spatial change analysis). Hyperspectral data when used in combination with other monitoring methodologies and calibrated correctly, can assist in optimizing the time and cost required for long term management and monitoring programme. Experience in data collection, complementary analysis methodologies, hyperspectral data processing and geochemical interpretation are key to producing accurate and usable results.

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