DERIVING QUANTITATIVE MONITORING DATA RELATED TO ACID DRAINAGE USING MULTI-TEMPORAL HYPERSPECTRAL DATA

Cindy Ong[1] and Thomas Cudahy[2]

Acid drainage (AD) has been recognized as one of the major problems facing the Australian mining industry. Much of Australia has a semi-arid to arid climate and is sparsely populated. The impact of AD is therefore less here than in many other countries. Nevertheless, community and shareholder expectations, and the globalization of Australian mining company activities, have ensured the industry is committed to best practice and due diligence in managing AD.

Mapping the spatial extent of the AD affected areas, let alone monitoring the effectiveness of remediation programs has been difficult because of the cost and limitations of current methods. Therefore, low cost, accurate, spatially comprehensive methods for assessing the extent of affected areas, as well as the effectiveness of any subsequent containment and remediation programs is clearly necessary. Swayze et al. (1998) have shown the great potential of AVIRIS imaging spectrometer data for locating acid-generating minerals. However, no such account has been recorded in Australia and the accurate quantification of AD using hyperspectral techniques, such as measurement of surface pH level and the amounts of associated heavy metals, has not yet been demonstrated.

This study aimed to develop and demonstrate operational methods for deriving critical environmental parameters related to AD using hyperspectral data. The study site is the Brukunga abandoned pyrite mine in South Australia where a multi-temporal dataset has been acquired from 1998 to 2001.

1 Introduction

The abandoned Brukunga Pyrite Mine is located in the Mount Lofty Ranges and is 50 kilometers east-south-east of Adelaide, the capital of South Australia. It was developed in the early 1950s to produce pyrite as a source of sulphur for the manufacturing of superphosphate fertilizer. The richest pyrite zones were mined and a concentrate was produced for processing into sulphuric acid at Port Adelaide. The acid was used to convert insoluble rock phosphate into a soluble fertilizer. About 300 000 tons of ore were mined annually, and the pyrite concentrate railed to the Sulphuric Acid Pty Ltd plant at Birkenhead, a northwestern suburb of Adelaide.

Closure of the open pit mining operations in 1972 left large exposed quarry faces and benches, waste rock dumps and tailings from the flotation treatment plant. These, along with natural rock outcrops in the area, contain remnant pyrite that will potentially oxidize and leach high levels of dissolved metals and acids.

A study conducted by Agnew (1994) found that there is potential for 300 000 tons of sulfuric acid to form. The potential health and environmental impact is considered to be one of the largest in Australia as the mine is surrounded by a town site and the nearby Dawesley Creek is used for agricultural and recreational purposes.

2 Methods

2.1 Field and Laboratory Study

The laboratory study was conducted to develop an understanding for the relationships between spectral data and physicochemistry (mineralogy, chemistry, pH). Concurrent with the 1999 airborne acquisition, field samples were collected from 43 locations across the mine environment. These were characterized in the laboratory using an ASD-Field Spec, collecting spectral data in the 350-2500 nm range, and a PIMA-SP, collecting higher resolution spectral data in the 1300-2500 nm SWIR range. Independent measurements of chemistry and mineralogy were made using XRD and chemical analysis from a commercial laboratory to measure heavy metals, pH and electrical conductivity. The pH was measured on the soil samples using a 1:5 ratio sample to water to an accuracy of 0.01.

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[1] CSIRO Exploration and Mining (Cindy.Ong@csiro.au)
[2] CSIRO Exploration and Mining (Thomas.Cudahy@csiro.au)

2.2 Airborne data

Airborne hyperspectral data (HyMap (*http://www.intspec.com*) were acquired over the Brukunga Mine in April 1998. The 128 channel HyMap4 data (450-2500 nm) were acquired at 5 meter pixel resolution. Three additional datasets were acquired over the next three years at approximately the same time each year but at 3.5 meter pixel resolution.

Atmospheric correction, bi-directional reflectance distribution functions (BRDF), calibration and cross-calibration are essential issues to be considered when using airborne hyperspectral data for multi-temporal monitoring. The successful implementation of the laboratory results to the airborne data depended on successful cross-calibration of all the datasets. To achieve this, the airborne data were first processed to remove instrument, atmospheric and bi-directional reflectance distribution function (BRDF) effects. The HyMap datasets were reduced to apparent surface reflectances using Atmospheric Correction Now (ACORN) (http://www.aigllc.com). Ground validation data from three man-made invariant sites were collected proximal to the mine site. These targets consist of three homogenous large areas (>15 by 15 m each) of concrete paving bricks, concreted pavement and bitumen. These data were used to remove artifacts associated with incorrectly modeled atmospheric conditions including systematic errors in estimating the water vapor bands at 1400 and 1900 nm, the 760 nm O_2 and the 2050 nm CO_2 features, as well as residual instrument effects.

Instrument wavelength calibration was performed on each year's dataset, hence waveband centers and widths differ for each acquisition. Thus, spectral resampling was performed on the 1998, 1999 and 2000 data to produce comparable results between the four dates. After spectral resampling, each pixel's spectrum was normalized with respect to its own mean reflectance of all wavelengths. The normalization was applied to all the datasets to remove differences seen in the overlaps between adjacent flight lines. These differences are related to residual radiative transfer correction differences, topographic shading and wavelength-independent and multiplicative BRDF effects.

3 Results

3.1 Laboratory Analysis

Partial least squares (PLS) (Haaland et al., 1988) explores for linear correlations between multivariate data and a parameter of interest. In this study, PLS analysis was performed on the VNIR-SWIR spectral data and and pH measurements of the field samples. If a significant linear correlation is found, then the resultant linear comibination of bands that provides this correlation can be used to assess which wavelengths are critical. This linear combination of bands is called the final regression coefficient (FRC), which is a linear combination of weighted spectral bands that transforms each input spectrum to a predicted value of the parameter of interest. The spectral bands showing high FRC weightings, positive or negative, can be interpreted as bands that are important for the related correlation.

Figure 1 shows the results of the partial least squares analysis. To assist in the interpretation of the FRC, typical secondary minerals related to AD, namely ferrihydrite, hematite, goethite and jarosite (plotted in navy, blue, green and cyan, respectively) are also plotted. In this analysis, the wavelength regions with large weightings are centered at 437, 582, 910, 1917 and 2267 nm (black arrows show their location). Relating these high FRCs to spectral attributes of the AD-related secondary minerals, the highest contribution is attributed to the ferric iron absorption band centered at 582 nm caused by a charge transfer absorption (Curtis, 1985). Superimposed on this broad feature is a sharper and smaller excursion of the FRC related to a small feature at 437 nm attributed to jarosite. Equally important is the 910 nm ferrous iron crystal field absorption (Curtis, 1985). It is interesting to note the comparison of the contribution of the combined 910 nm and 437 nm features relative to the 2267 nm jarositefeature, which although has significant weightings, is nonetheless much smaller. Taken altogether, this result implies that pH predictions are related primarily to ferric iron mineralogy. Given that much of the correlation is driven by the wavelengths less than 550 nm, it is important that additive atmospheric effects are properly corrected when applying these FRCs to remotely sensed data. Note that the high FRC weightings at 1917 nm, related to water, would not be detectable in airborne data because of strong atmospheric absorption.

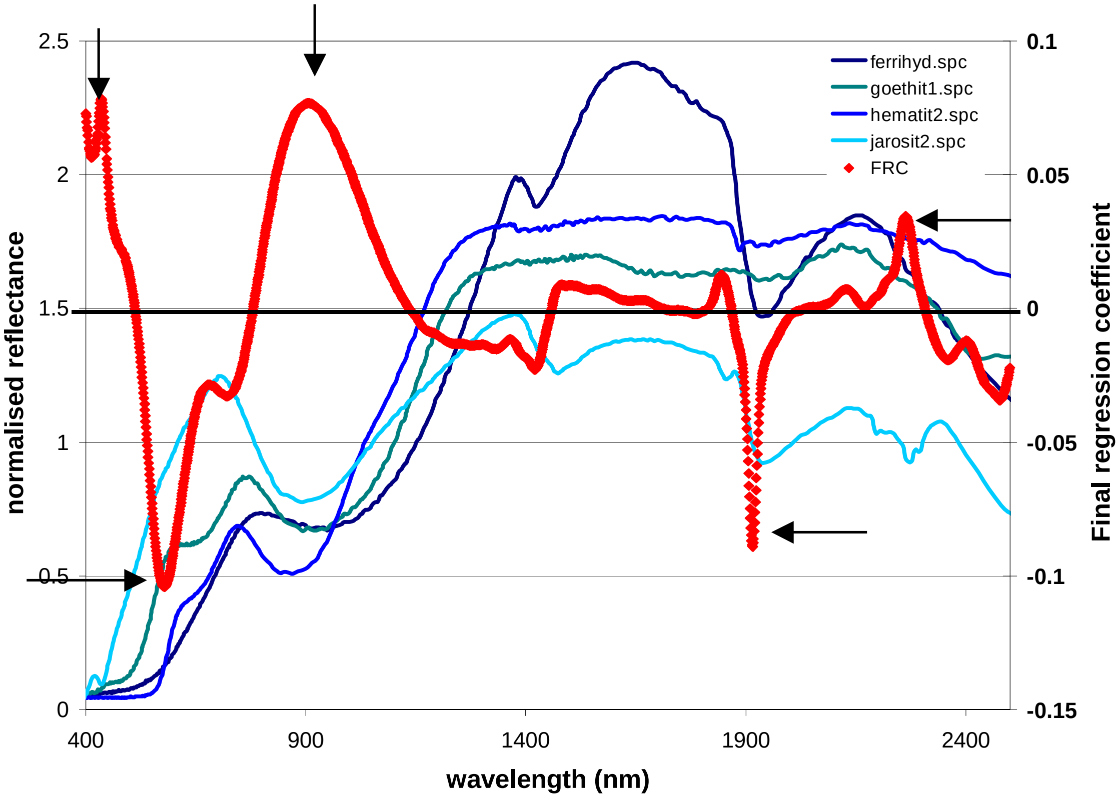
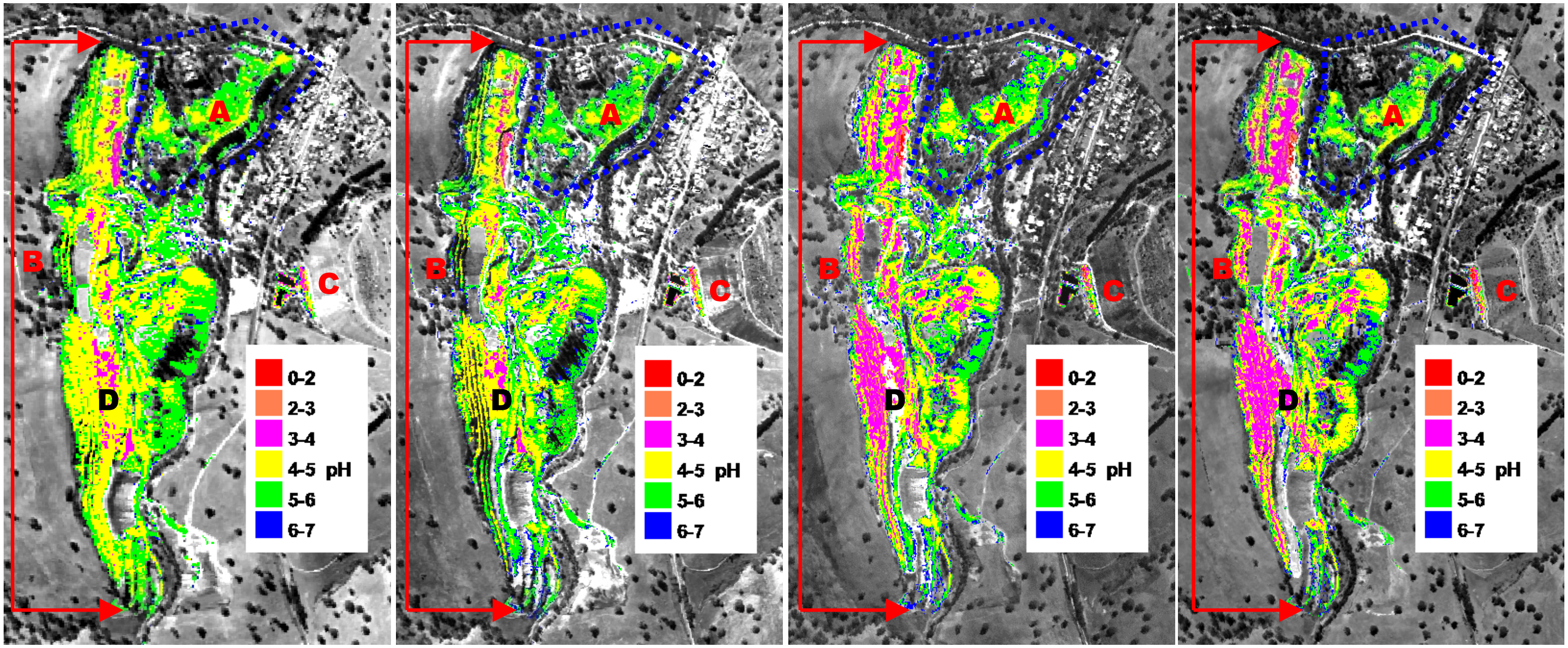


Figure 1: Final regression coefficient results from partial least squares analysis of pH (red) and spectra plotted in conjunction with typical AD related secondary minerals (blue, dark blue, cyan and dark green). The arrows illustrate high coefficients.

3.2 Airborne data

The result from the laboratory analysis was used to enable predictions of pH from the fully corrected and calibrated airborne hyperspectral imagery. The resultant pH maps are shown on Figure 2. Spectral-based masking was applied to the derived products in order to remove small commission problems, including man made materials in the township and areas of standing water. All pixels with pH >7 were also masked. These relate essentially to pixels with a significant vegetation component. The four dates of predicted pH maps are presented over gray-scale albedo image backgrounds in Figure 2. These are color coded for the range of pH values from <2 to 7 from red through to blue.

These predicted maps of surface pH effectively demonstrate the capabilities of airborne hyperspectral data for spatially mapping of critical AD information over a multi-temporal sequence. This series of maps can then be used to assess the success of rehabilitation and/or remediation procedures used as part of the mine environment management practices over the four years. For example, they may be used to assess the remediation efforts at the North-Eastern waste rock dump (marked A on Figure 2) identified previously to potentially be acid generating materials. The multi-temporal sequence shows this area to contain pH of 4-6 and this value remains constant over the monitoring period possibly showing this area to be of a fairly stable nature. Conversely, another example is the mine benches that span the Western extent of the mine and marked B on Figure 2. Major changes are mapped in this area over the four years evolving from an average pH value of 4-6 to pH of 4 and below. This sequence of pH maps is able to map the spatial extent of the areas that may need further attention or evaluation of remediation strategies as well as determine the acid generating potential of these affected areas. .



1998 1999 2000 2001

Figure 2: Time series pH predictions derived from hyperspectral data collected between 1998 to 2001. A marks the North Western waste rock dump and B marks the mine benches.

3.3 Validation of pH maps

The accuracy of the 1999 map was checked with laboratory pH measurements of field samples collected also in 1999. The first validation site consists of samples collected along a wall of a filled tailings dam at the site of the acid treatment facility (Site C in Figure 2). The pH mean and STD of samples is pH 2.31 +/- 0.44 which is consistent with the mean airborne prediction for this site of pH 2.4. The airborne and field spectra of this site also compares well, with both showing jarosite-related ferric iron absorption at 930 nm and jarosite-related hydroxyl absorption at 2265 nm. The second validation site was a transect along a mine bench (Site D in Figure 2). A total of 10 samples were collected along this transect. Comparing the transect data and the pH map, there is good correlation between the airborne predicted (pH 4.50 +/- 0.45) and field sample (pH 4.05 +/- 0.51) pH values.

4 Discussion and conclusion

The results from the laboratory study showed that pH is related to iron mineralogy. From this information, a model was developed to predict pH from hyperspectral data. It was shown that it is possible to use this laboratory-derived model to produce pH maps from a multi-temporal airborne hyperspectral dataset. However, for predictions of pH to be accurately derived from the airborne spectral data or other ground spectral data, apart from those that formed the calibration set, it is important that proper calibration of the dataset to accurate ground reflectances be obtained. Cross-calibration between airborne and laboratory sensors are also important considerations.

It was shown that is it possible to derived maps of pH from a multi-temporal dataset using the pH model developed in the laboratory. However, to be able to use the data in a quantitative manner, further work has to be undertaken. This include for the laboratory investigations: (1) the collection of a comprehensive set of calibration and validation data to build a robust model for the predictions of pH from these data; (2) understanding the secondary minerals produced from AD; and (3) the changes related to environmental conditions; and for the airborne processing: (4) methods for proper correction of the airborne dataset to accurate ground reflectances especially in view of the stability of the VIS region for mapping iron mineralogy.

5 References

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