Spectral Reflectance and Detection of Iron-Oxide Precipitates Associated with Acidic Mine Drainage

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Abstract

The objective of this study is to develop a repeatable technique to spectrally discriminate between acid and neutral streams based on the reflectance characteristics of acid and neutral iron precipitates. Field spectral measurements were conducted in situ *on iron-oxide precipitates coating bottom substrates of an acidified stream (pH $<$ 4) in the Virginia Gold-Pyrite Belt. Spectra of two neutral (pH 6 and 7) streams, one with iron precipitates present, were also measured. Acid precipitates were found to have higher spectral reflectance than neutral precipitates in the 650- to 750-nm region. With regard to water quality, the acid stream possessed low pH and high specific conductance.*

Guided by the field spectral data, a remote sensing technique using bandpass interference filters and a digital multispectral video system was used to detect mine drainage in two Virginia streams. Where acidic discharge was present, false-color composites showed precipitates having high reflectance in both the 650-nm and 750-nm wavebands. In contrast, neutral iron-rich streams were low in reflectance, and streams unimpaired by mine drainage had virtually no detectable reflectance.

Introduction

Acidic mine drainage (AMD) from both active and abandoned mines is a water quality concern for many areas in the United States and is ranked fifth as a major cause of surface water degradation (U.S. Bureau of Mines, 1994; U.S. EPA, 1990; Waters, 1995). Where iron oxide precipitate is present, the impact is highly visual — colors of yellow, orange, and red line affected creeks and river bottoms (Lackey, 1938). Using the Munsell color chart system for classifying value, hue, and chroma, these precipitates can range from 5 YR 3/4 (yellow-red) to 2.5 YR 5/3 (yellow-reddish brown) (Tarutis and Unz, 1994). Landa and Gast (1973), Towe and Bradley (1967), and Chukhrov *et al.* (1974) have explained the various spectral changes of iron oxide precipitates as being the result of iron mineral transformations caused by fluctuating pH/Eh conditions and biological (microbial) metabolism. Similar precipitates also form naturally in places where iron-bearing, anoxic ground water discharges into streams. In these circum-neutral settings, the precipitates have red and red-orange hues (Robbins and Norden, 1994).

The microbes that assist in the production of these net acidic (acidity$>$alkalinity) and net alkaline (alkalinity$>$acidity) ferric-hydroxide precipitates are quite different. In acid waters (pH $<$ 4), iron precipitates are produced by the bacteria *Thiobacillus* which derive energy from directly oxidizing the Fe or S in pyrite (Erlich, 1990; Singer and Stumm, 1970). Oxidation produces sulfuric acid and FeOH precipitates that appear bright yellow-orange. In contrast, neutral (pH 7) iron-bearing water contains a different group of bacteria. The iron-depositing "iron bacteria" predominate where anoxic, neutral ground water transports ferrous iron and discharges it into oxygen-rich surface waters (Erlich, 1990). These FeOH precipitates appear dark red to red-orange. Among this group, *Gallionella* is known to directly derive energy from iron oxidation (Erlich, 1990; Ballows *et al.*, 1992). The amorphous ferric hydroxide mineral ferrihydrite has also been identified in precipitates from both acid and neutral environments and plays a role in the spectral attributes of streams affected by AMD (Chukhrov *et al.*, 1974; Ferris *et al.*, 1989).

The use of spectral data and remote sensing for mineral detection and analysis of mining impacts is well documented. Early studies by Alexander *et al.* (1973) described the use of ERTS-1 (later called Landsat) multispectral scanner (MSS) data to evaluate the damage caused by strip mining in Pennsylvania. Other studies involving the application of multispectral data for monitoring AMD impacts have been described by Chase and Pettyjohn (1973) and Schubert and MacLeod (1973). Using multispectral image data with spectroradiometric data was described by Peters (1983) for the detection of the iron minerals goethite and hematite in the Powder River Basin in Wyoming. In this case a technique was used to separate the mineral types based upon unique spectral reflectance and absorption characteristics occurring at visible and near-infrared wavelengths. The successful application of visible and near infrared (500 to 800 nm) airborne videography to detect mine drainage in Indiana mine pools has also recently been reported by Repic *et al.* (1991).

While useful over wide, higher-order streams, satellite sensors do not yet possess the combined spatial and spectral resolution necessary to detect and evaluate AMD impacts occurring on smaller headwater streams. Under the 305b reporting provisions of the Clean Water Act, states are required to account for impacted streams; however, due to the remoteness of these surface waters and the difficulty in assessing their condition, many impacted headwater streams are not accounted for under the guidelines (Riordan, personal communication, 1994). Evolving digital multispectral video technology may offer a solution to the evaluation of these small

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affected surface waters. Remote differentiation of AMD impacted headwater streams could benefit resource and regulatory agencies charged with management of water quality as well as provide a tool to check the effectiveness of the mediation efforts. The objective of this study is to spectrally characterize acid and neutral iron oxide precipitates and use remote sensing to effectively detect headwater streams impacted by acid discharges.

Study Sites

Three sites in Virginia were chosen to represent the conditions that often characterize eastern metal and coal mining regions. The Virginia sites included the highly acidified Contrary Creek and an unnamed circum-neutral tributary of Contrary Creek, Quantico Creek, a lesser-impacted stream adjacent to an abandoned pyrite mine site, and Cedar Run, a stream unaffected by mining (Figure 1).

Contrary Creek in southeastern Virginia (Mineral, Virginia, 7.5-minute quadrangle) is an acidified stream containing yellow iron precipitates that accumulate on bottom substrates. The site is 9.6 km north of the town of Mineral on U.S. Route 522. The creek flows into Lake Anna, an impoundment on the North Anna River. For 100 years pyrite and gossan ores were mined in-stream and adjacent to the flood plain from rich veins in the Chopawamsic Formation (Adams, 1883; Poole, 1973). Neutral tributaries containing red iron precipitates, originating as neutral ground water seeps, also drain into Contrary Creek.

Quantico Creek, located approximately 120 km northeast of Contrary Creek in Prince William County, Virginia (Triangle, Virginia 7.5-minute quadrangle) is an acidified stream that has recently undergone extensive reclamation by the National Park Service. This area was selected as a test site for conducting trial aerial and field surveys to detect acid mine seeps resulting from the Cabin Branch Pyrite Mine tailings adjacent to Quantico Creek. Where the upper reaches of Quantico Creek cross the Piedmont Province, Lonsdale (1927) characterized the geology as the northern continuation of the Chopawamsic (Chlorite-Biotite Schist) Formation. This is the same pyrite-rich country rock that occurs at Contrary Creek.

Cedar Run, near Airlie, Virginia, was selected to provide a control site representing an unimpaired Piedmont stream. Cedar Run is approximately 145 km northeast of Contrary Creek and drains approximately 125 square kilometres of the northern Piedmont. There is no record of mining having occurred in the watershed. Above the sampling site at Airlie, the drainage area is approximately 15 square kilometres. This is comparable in area to the Contrary Creek drainage area. Cedar Run s drainage pattern is largely dendritic in the lower portion of the watershed and trellis (following the strike of the bedrock) in the upper portion of the watershed where the control site was located. Geologically, this portion of the Piedmont is underlain by the Catoctin Formation, which is lower in readily transportable iron than the Chopawamsic Formation at Contrary Creek (Sweet, 1995).

Methods

Water quality, spectral reflectance, and imagery were collected and compared for 21 months at Contrary Creek, the neutral tributary at Contrary Creek, and Cedar Run. Water quality measurements (pH and specific conductance) and spectral reflectance data were recorded monthly from March 1994 through November 1995 using a Cole-Parmer DS/pH-3 meter. Laboratory analysis of stream water followed standard U.S. Geological Survey methods (Fishman and Friedman, 1989; Wood, 1976). Iron bacteria also were sampled from Contrary Creek iron precipitates and the neutral tributary during the same collection period to characterize acid versus neutral conditions. Digital multispectral imagery was acquired by the U.S. Army Corps of Engineers Topographic Engineering Center in three separate missions flown between the March 1994 and November 1995 sampling periods.

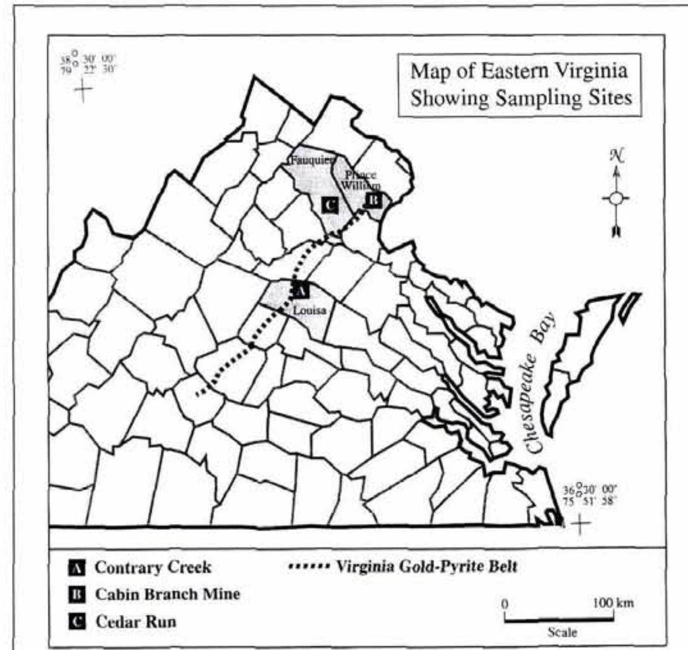

Figure 1. Map of eastern Virginia showing locations of sampling sites.

Monthly Water Quality Data Sampling

The pH/conductivity meter was calibrated prior to use following standard methods and the manufacturer's (Cole-Parmer) suggested procedures. The instrument was also checked against laboratory instruments to maintain measurement consistency and accuracy. The sampling sites at Contrary Creek, the unnamed neutral tributary, and Cedar Run averaged 6 to 8 cm in water depth. Probes were placed into the three shallow streams at an average depth of 4 cm, which was approximately the mid-point between the water surface and the bottom substrate. Three readings were collected from the pH/conductivity meter and averaged. Measurements also established the water quality characteristics of the unimpaired control site at Cedar Run. All measurements were taken at the same time and at the same locations used for collecting the stream spectral reflectance data.

Readings were taken in standard pH units and in µS/cm for specific conductivity. Specific conductance provided a measure of electrical conductivity providing information on ion content. Typically, acidic waters possess high specific conductance values. The water quality data collected at Contrary Creek were compared for consistency to data recorded at the USGS gaging station adjacent to the Route 522 (Prugh, USGS, personal communication, 1994).

Monthly Bacterial Precipitate Collection

Bacterial precipitates were collected to monitor the seasonal presence (or absence) of acidophilic and neutral iron bacteria that facilitate the production of the amorphous iron oxide precipitates. Microscope slides were fixed to stainless steel or aluminum rods that were driven into the stream bed of Contrary Creek and the neutral tributary stream and left for 30 days, allowing for the colonization of attached iron bacteria. Mineral precipitates and bacteria samples were collected monthly and studied using microbial ecology methods. All samples were analyzed using transmitted light microscopy. Microscopic observations of bacteria morphology were supplemented with standard microbial testing techniques for thiobacilli using NO_3 and Fe utilization by Mark Stanton (microbial ecologist) of the USGS, Denver, Colorado (Stanton, personal communication, 1994).

Monthly Spectroradiometric Data Collection

Monthly spectral reflectance measurements using an Analytical Spectral Devices PS II spectroradiometer (350 nm to 1100 nm full range) were made through the water column on acid and neutral bacterial stream precipitates covering the bottom substrates of Contrary Creek and the neutral tributary sites. Spectral measurements were also made on bottom substrates lacking iron precipitates at Cedar Run. It is important to note here that the spectral data are being used principally to measure the reflectance characteristics associated with acid and neutral FeOH precipitates. These data are not being used to discriminate mineral species or water quality. The 400- to 850-nm spectral region was selected for three reasons. First, this region covers the visible as well as part of the near-infrared portion of the electromagnetic spectrum affected by ferric iron (Podwysocki, USGS, personal communication, 1994). Second, this region covers the spectral sensitivity range of the aerial multispectral camera's silicon detectors. Finally, the region represents the spectrum of water (400 nm to 750 nm) where light is readily transmitted and within which most biotic and abiotic processes involving light occur (Wetzel, 1983; Bukata *et al.*, 1995). Spectral reflectance data of acid and neutral reaches were measured *in situ* along transects crossing each stream channel using the spectroradiometer. Three measurements were collected at 12 randomly chosen sampling locations for each stream. Data collection and analysis followed the procedures outlined by Satterwhite and Henley (1990) and Kruse (1992). A five-degree field-of-view (FOV), in an 8-cm sampling spot at a distance of 1 metre above the shallow water surface, was used to gather reflected light. All spectra were collected at a nadir viewing angle in direct sunlight and referenced to a white Spectralon (halon) standard. The nadir angle was maintained by adapting a small bubble level to the optical head of the radiometer.

Spectral reflectance was measured during cloud-free periods and as close to local solar noon as possible in order to take advantage of a solar zenith that more closely approaches zero ($\theta = 0°$). According to studies by Plass and Kattawar (1972), water subsurface irradiance is greater at $\theta = 0°$ than at angles approaching 90°. To help achieve this, the (monthly) hour angle of the sun was obtained for each site using an ephemeris (solar elevation and azimuth) generated by the National Observatory at Glen Echo, Maryland. Maintaining a high sun angle limited specular reflectance and scattering brought about by the motion of the water's surface.

Digital Multispectral Imagery Collection

The remote sensing of acid-mine drainage was tested using a Specterra Systems digital multispectral video system (DMSV). The DMSV is a portable, four-channel digital imaging system capable of acquiring both single frame and stereo four-channel images along a line-of-flight recorded directly on computer hard disk. The optics of the DMSV incorporate four charged couple device (CCD), 24-mm focal length cameras capable of continuously recording narrow-band wavelengths from approximately 350 to 900 nm. All functions, including image acquisition and iris adjustments, are controlled through a laptop computer. Integration times (shutter speed) for each camera are preset independently depending on the filters used and the available light conditions.

Narrow (25 nm wide) blue (450 nm), green (550 nm), red (650 nm), and near-infrared (750 nm) bandpass interference filters were incorporated into the fore-optics of the digital multispectral video system. These spectral bands were selected based upon the field spectral reflectance measurements for iron precipitates forming under acid and neutral conditions. Wavelengths in the blue-green region (450 nm and 550 nm) have been used in studies requiring optical penetration into the water column (Harding *et al.*, 1995; Liedtke *et al.*, 1995). The 650-nm bandpass was used for detecting iron oxide-based mine drainage precipitates appearing dark red in color, based on the findings of Anderson (1995) and Tarutis and Unz (1994). The selection of the 750-nm wavelength was based upon the spectral data collected on Contrary Creek acid mine drainage precipitates during the course of this study (Anderson, 1995; Robbins *et al.*, 1995; Anderson and Satterwhite, 1995; Podwysocki, unpublished data, 1994).

The following method described by Jensen (1986), statistical transformed divergence (Equation 1), also was used to validate the spectral band selection logic based on statistical separability of the ASD field spectral reflectance data: i.e.,

$$Diverg^{T}_{cd} = 2000\ (1 - exp\ \frac{(-Diverg_{cd})}{8}) \qquad (1)$$

where c and d are all possible pairs of classes and *exp* is an expotentially decreasing weight assigned to increasing class distances.

Using a program developed by Fischer (1996), transformed divergence was applied to the field spectral data to generate the best three-band combinations for the (classes) acid, neutral, and unimpaired (control) streams. The input data represented 200 bands at 5-nm bandwidths between 400 and 900 nm. Following the algorithm, band combinations in which the value of $Diverg^{T}_{cd} = 2000$ achieve the best statistical separation between classes for optimal detection / separation of acid and neutral precipitates.

The DMSV cameras were calibrated prior to each mission using a Spectralon reflectance target (Anderson and Satterwhite, 1995). Histograms generated for each camera allowed pre-mission aperture settings and integration times to be set so that an imagery DN value of 255 approximated 100 percent reflectance without saturation of the camera detectors. Correction for the instrument's noise contribution to the signal, or dark current, was subtracted from the imagery DN values for the cameras after obtaining histograms with the lens caps fixed. All image data were collected under clear sky conditions between 1030 and 1200 hours local solar time to afford a relatively high sun angle.

To acquire the necessary coverage, imagery over Contrary Creek and the Cabin Branch Mine was acquired in one and two flight lines, respectively. Imagery was acquired for the Cabin Branch Mine in March of 1995 at an altitude of 1600 m above mean sea level (AMSL). Imagery for Cedar Run was acquired in one flight line. Imagery was collected at Contrary Creek and Cedar Run during March, July, and October, 1995, at altitudes of 1526 m and 2247 m AMSL, respectively.

Because Cedar Run is located near the approach to Washington Dulles International Airport, these missions were flown at a higher altitude. At the altitudes flown, a ground sample distance (GSD) of approximately 0.5 m per pixel was achieved for Contrary Creek and the Cabin Branch Mine. A GSD of 0.75 m per pixel was achieved for Cedar Run. These resolutions were adequate to observe the imagery reflectance characteristics of the three streams.

t-test for 750-nm Reflectance of Acid and Neutral Stream Water

A Student's *t*-test was used in statistical comparisons of the field reflectance data to establish whether significant differences in reflectance occurred between the Virginia streams

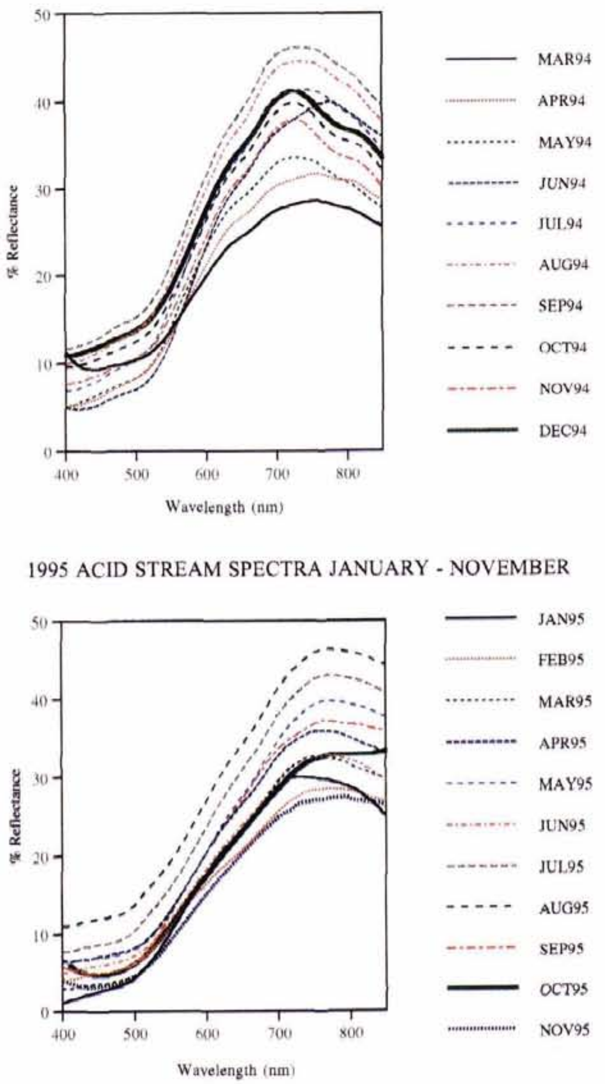

Plate 1. Field spectral reflectance measurements for Contrary Creek (pH < 4) acid iron-oxide precipitates.

(Horler *et al.*, 1980; Milton *et al.*, 1991). The test was first used to compare the acid precipitate reflectance data recorded at Contrary Creek to the neutral tributary reflectance. The test was then used to compare the Contrary Creek reflectance to the control at Cedar Run.

Results

Water Quality and Spectral Reflectance for Virginia Stream Sites

For the sampling period, Contrary Creek had an average pH of 3.5 and consistently high specific conductance (400 µS/cm). Bacteria present in acid iron oxide precipitates were dominated by *Thiobacillus*-type rods. Microbial cultures were positive for NO_3 and Fe utilization, also characteristic of acidophilic thiobacilli. The streambed of Contrary Creek was composed of a yellow-brown carpet of 2-mm-thick precipitates that also accumulated on exposed bedrock extending up the creek banks. Due to these acid precipitates, Contrary Creek exhibited the highest reflectance of all the stream spectral data examined. The spectra are characterized by a reflectance maximum at about 750 nm, with a steep falloff towards shorter wavelengths and a shallow falloff towards longer wavelengths (Plate 1). The falloffs are characteristic of Fe(III) electronic absorption features. The shallow falloff towards longer wavelengths suggests rather poor structure in the Fe-O bonds, characteristic of a ferrihydrite-like mineral rather than hematite or goethite (Robbins *et al.*, 1996).

Data collected for the neutral tributary resulted in an average pH of 6.2 and low specific conductance (200 µS/cm). This stream, which originates as a groundwater discharge from a hillside, is characterized by both floating and settled red-orange precipitates. Chukhrov *et al.* (1974) indicate that studies from these types of iron deposits reveal a close association between iron minerals and the neutral iron bacteria, including *Leptothrix ochracea*, *Gallionella ferruginea*, and *Toxothrix trichogenes*. *Leptothrix ochracea* was found to dominate the iron depositing bacteria in this tributary. Although limited, diatoms and green algae dominated by *Ultrothrix sp.* also added carotenoid and chlorophyll pigments to the precipitates (Krishnaswamy, 1996). The spectral measurements (Plate 2) exhibit a 10 to 15 percent lower reflec-

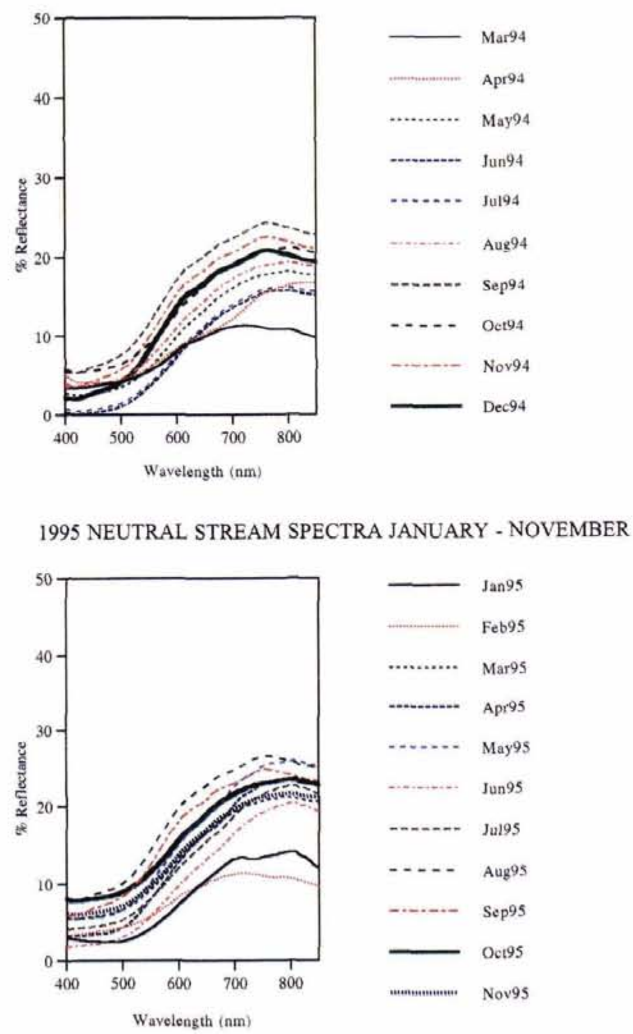

Plate 2. Field spectral reflectance measurements for neutral unnamed tributary of Contrary Creek (pH 7).

November 1995 for Contrary Creek, the neutral tributary, and the Cedar Run control site. Using the monthly spectral data, the peak reflectance of the FeOH precipitates was extracted and the mean calculated (Table 2). The mean position of the reflectance peak provided a basis for using the 750-nm reflectance signature in the red/near IR region as compared to the acid spectra. Falloffs in reflectance towards longer and shorter wavelengths also are less precipitous than those of the acid spectra; the Fe(III) absorption feature at longer wavelengths is nearly non-existent, suggesting that the ferric iron-oxygen bonds of the ferrihydrite-like mineral are weaker than that precipitating in the acid environment (Robbins *et al.*, 1996). The mineral transformation of ferrihydrite to the iron minerals goethite and hematite has been linked to fluctuations in water quality conditions such as pH and specific conductance (Chukhrov *et al.*, 1974). These fluctuations could explain the seasonal variations in reflectance of both the acid and neutral precipitates observed in the spectral data.

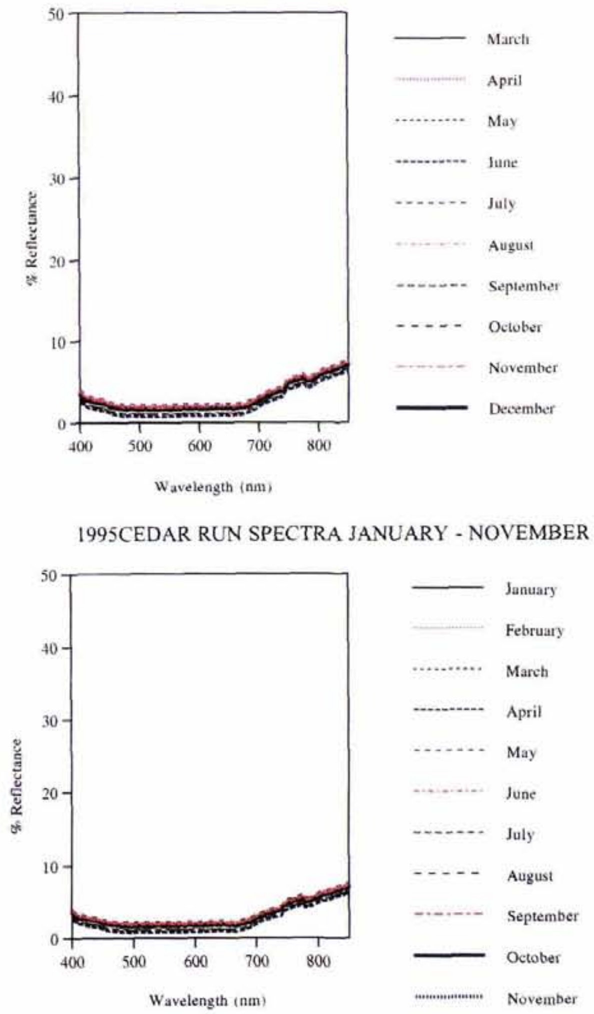

Plate 3. Field spectral reflectance measurements for Cedar Run (pH 7).

The water chemistry at the Cedar Run site was consistently neutral at pH 7 with an average specific conductance of 150μS/cm. The stream was clear and bottom substrates (quartz cobbles and gravels) were free of sediments and precipitates. Algae was also less abundant in this stream. Spectrally, this stream was consistently low in reflectance across all bands (Plate 3).

Table 1 provides the percent spectral reflectance recorded at the 750-nm wavelength between March 1994 and

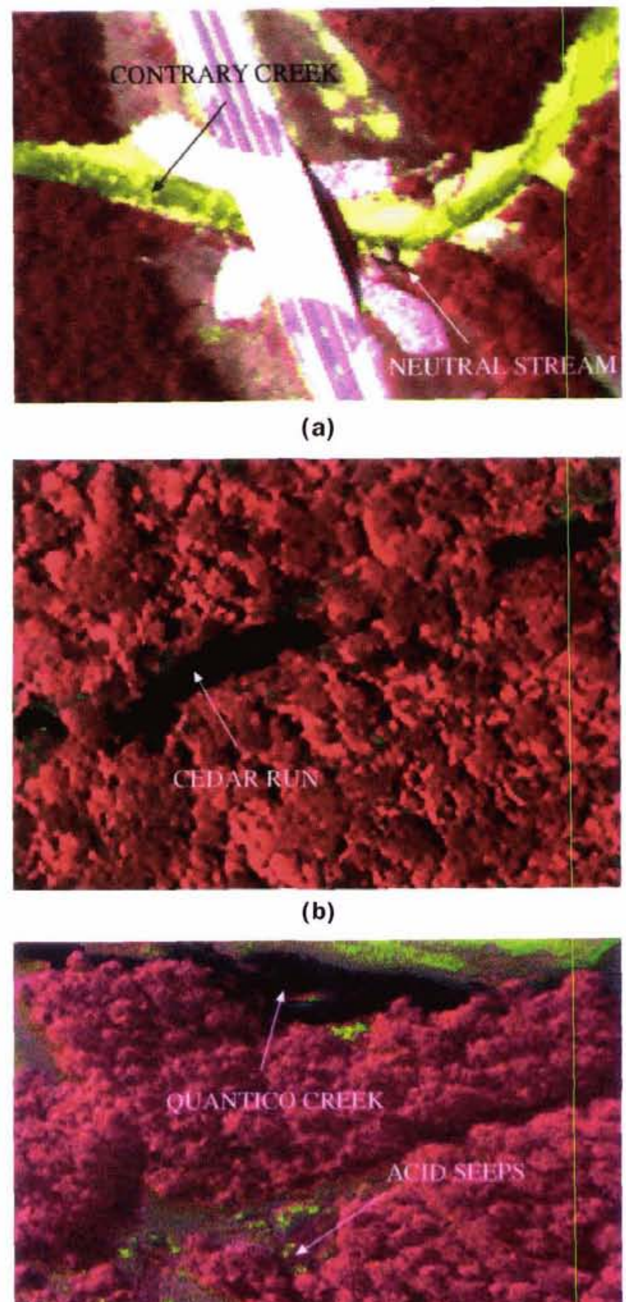

Plate 4 (a). Digital multispectral image of Contrary Creek showing acid precipitates (yellow) as a function of the 650-nm (green) and 750-nm (red) wavebands. (b) Digital multispectral image of Cedar Run showing uniformly dark signature of the unimpaired stream. (c) Digital multispectral image of Quantico Creek (Cabin Branch Mine) showing acid precipitates (yellow) emerging from seepage zones as a function of the 650-nm (green) and 750-nm (red) wavebands.

TABLE 1. STREAM PERCENT REFLECTANCES RECORDED AT 750 NM USING AN ASD SPECTRORADIOMETER

Month	1994 Contrary	1994 Neutral	1994 Cedar	1995 Contrary	1995 Neutral	1995 Cedar
Jan				29.8	13.5	4.6
Feb				28.4	11.0	5.1
Mar	28.6	11.1	4.6	32.6	20.7	4.0
Apr	31.8	15.1	5.1	35.8	23.0	3.8
May	33.3	17.6	4.0	39.3	25.3	5.3
Jun	39.2	15.3	3.8	32.5	19.2	5.0
Jul	41.3	15.7	5.3	42.5	21.5	4.2
Aug	44.5	18.8	5.0	45.8	26.6	4.1
Sep	46.1	24.1	4.2	36.8	24.8	5.1
Oct	38.7	20.6	4.1	32.3	23.0	4.8
Nov	36.8	22.3	5.0	27.1	21.3	4.9
Dec	31.9	20.7	4.8			

tance in comparing the reflectance data for all three streams over the course of the sampling period. The stream acid precipitates were higher in reflectance at 750 nm than either the neutral tributary iron oxides or the unaffected control and, therefore, could be separated where they occurred based on reflectance contrasts.

t-test for 750-nm Reflectance of Acid and Neutral Stream Water

Prior to applying the test, the reflectance data were tested for a normal distribution. Tests for kurtosis and skewness indicated that both the 1994 and 1995 data sets were normally distributed, with kurtosis and skewness both approaching zero (Clarke, 1994). An F test was also performed following Triola (1992) and Sokal and Rohlf (1981) to determine the equality of variances between samples. Comparisons of the reflectance between Contrary Creek and the neutral tributary for the 1994 samples indicated that, at $\alpha = 0.05$, statistically significant differences for the two streams occur with $p < 0.00000001$ at 18 d.f. The differences for the 1994 Contrary Creek and Cedar Run control reflectance were also statistically significant ($p < 0.00000001$ at 9 d.f., $\alpha = 0.05$). The 1995 data exhibited statistically significant differences, similar to those which occurred for the 1994 data. Results showed that the Contrary Creek and its neutral tributary reflectance was different ($p < 0.000001$ for 20 d.f., $\alpha = 0.05$). The *t*-test also showed a difference in the reflectance between Contrary Creek and the Cedar Run control site at the 95 percent confidence level ($p < 0.00000001$ at 10 d.f.).

Detection of Acid Mine Drainage Using Multispectral Imagery

Multiband composites of the DMSV spectral imagery were generated to present the detectable AMD as changes in color. The wavelengths and their R-G-B color assignments are 750 nm (red), 650 nm (green), and 550 nm (blue). This band combination presented the best statistical separability ($Diverg^{T}_{cd} = 2000$) between the acid, neutral, and unimpaired spectral classes as calculated using transformed divergence of the field spectral data. The 750-nm band provides information on the occurrence (or absence) of iron oxide precipitates associated with acid conditions. The 650-nm band provides information on red reflective features in the scene; these appear green in color. The 550-nm band is used because of its ability for water penetration. In this band, features reflecting green will appear as blue in the images.

Plate 4a shows the Contrary Creek acid mine drainage precipitates as bright yellow. This color represents a contribution by both the 750-nm band (red) and the 650-nm band (green), both of which, according to field spectral measurements, record high reflectance for the acid mine drainage precipitates (see Plate 1). The precipitates associated with the neutral tributary adjacent to Contrary Creek appear dark red when viewed as multispectral false-color composites of the selected filters 550 nm, 650 nm, and 750 nm.

In contrast to Contrary Creek, the composite image of Cedar Run (Plate 4b) presents a uniformly dark-colored stream, indicating the absence of any detectable iron-based minerals. Bukata *et al.* (1995) describe this low reflectance as consistent with clear waters. The use of the 750-nm band contributes significantly to this in the image because, as the near-infrared region of the electromagnetic spectrum is approached, clear water absorbs energy at longer wavelengths. The Contrary Creek and Cedar Run images present graphical evidence of the spectral disparity that occurs between a stream having acid-mediated iron precipitates and an unimpaired stream.

Plate 4c shows the March 1995 multispectral image of the seepage areas at the Cabin Branch Mine, detected as bright yellow areas using the 650- and 750-nm channels. The high resolution DMSV imagery (0.5 m/pixel GSD) allowed for detailed interpretation of the site and enabled the detected seeps to be field checked for specific conductivity based on photo-identifiable landmarks. The false-color composite generated for the Cabin Branch Mine also shows iron oxide precipitates present along both banks of Quantico Creek; however, the precipitates having the highest reflectance occur on the north side of the creek. The image indicates very little impact from the mine effluent on the waters of Quantico Creek. Quantico Creek exhibits a lower reflectance similar to Cedar Run, suggesting the absence of detectable iron oxide precipitates associated with the mine drainage. Post-mission water quality samples obtained for Quantico Creek showed low pH readings for the detected seepage areas (≤ pH 3.5) and specific conductance ranging from 300 to 600 μS/cm. The water chemistry of the creek maintained a pH of 6 at the time of sampling, and specific conductance averaged 200 μS/cm.

Summary

Field spectral measurements found iron oxides forming under severely acid conditions ($pH < 4$) to be highly reflective from the far red into the near-infrared. The remote sensing of AMD-affected streams using visible (650-nm) and near infrared (750-nm) reflectance properties of the iron minerals proved highly sensitive to iron oxides forming under acid conditions. Our use of the bands in the red and near-infrared region to detect iron oxide precipitates associated with AMD contrasts with the findings of Repic *et al.* (1991) for AMD detection in Indiana mine pools. Their findings correlated high concentrations of iron precipitates and low pH (6) with the yellow-green spectral region. This difference may, in part, be

TABLE 2. MEAN PEAK WAVELENGTH FOR REFLECTANCE FROM ACID PRECIPITATES

Month	1994 Peak λ (n = 36)	1995 Peak λ (n = 36)
Jan		753
Feb		747
Mar	747	741
Apr	745	755
May	745	770
Jun	750	750
Jul	755	748
Aug	745	755
Sep	741	755
Oct	750	753
Nov	755	750
Dec	750	
Mean Peak λ = 750.4 nm		

due to the contrast in pH regimes (pH$<$4 versus pH $\pm$ 6) and lotic versus lentic waters and perhaps prove to be very important in remote assessment of AMD.

At each sampling site, reflectance differences were associated with the presence or absence of iron oxide precipitates occurring within each stream. Furthermore, these spectral differences were the result of iron oxides precipitated under acid versus neutral conditions. Microscopic analysis of acid iron precipitates indicated that they were found to be enmeshed with rod-shaped acidophilic bacteria typical of *Thiobacillus*, whereas iron-depositing bacteria were dominated by dark red neutral precipitates. Water quality measurements served to characterize the conditions under which the oxidation of iron minerals was occurring. In acid streams, where precipitates showed high spectral reflectance, high specific conductance and low pH readings were consistently measured. This finding is consistent with observations reported by Repic *et al.* (1991) who showed higher reflectance values were inversely correlated with pH levels in AMD environments having iron precipitates.

The bright yellow color represented in the false color composites (650 nm mapped to green and 750 nm mapped to red) of Contrary Creek and the seepage area near Quantico Creek are consistent with findings by Nordstrom *et al.* (1978) for the presence of acid-mediated iron precipitates. The reflectance changes in the stream precipitates recorded by the 650- and 750-nm wavebands suggest a dynamic state-of-flux where the iron oxide precipitates undergo mineral transformations due to changing in-stream chemistry as suggested by Landa and Gast (1973) and Towe and Bradley (1967). In contrast, iron precipitates detected by Repic *et al.* (1991) in pH 6.2 to 6.7 waters may tend to represent transition mineral precipitates forming under less acidic conditions than those associated with Contrary Creek. These more neutral conditions may favor the development of algae and associated pigments that contribute to the overall spectral signature. In concurrence, Robbins *et al.* (1996) reported a strong yellow-green component in spectral signatures associated with Pennsylvania acid mine drainage precipitates. Those spectra represented AMD discharge waters having an abundance of algal biomass. However, field spectra from this study indicates that, when algae are less abundant and algal pigment contributions to the spectral signature are negligible, both acid and neutral precipitates exhibit high red and near infrared reflectance. These findings suggest that a suite of detection strategies needs to be adapted for different types of AMD.

Mining is a major source of pollution to streams of North America. The most acute mining effects have originated from the chemical and toxic pollutants stemming from the release of acid wastes into the aquatic environment (Waters, 1995). Facing the monumental task of reclaiming and mitigating abandoned and active mines, local, state, and federal resource agencies are turning to technological solutions to help detect and quantify degradation of rivers and tributary streams affected by mining. Although more work is needed at other localities to refine the technique presented, these data suggest that digital multispectral video can be effectively used as an objective tool by resource and regulatory agencies that manage water quality and mining reclamation.

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