Use of Remotely Sensed Imagery and Methods for Mapping and Planning of Mine Waste Facilities

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Abstract
In mine environmental management, it is a truism that what is not measured, cannot be managed. Often, data collection systems on mines are set up to measure changes in parameters over short time periods and small areas. While this is necessary, and is effective in managing environmental liabilities, such systems should be coupled with input from a larger scale. Another truism is that fact that mine waste storage facilities can be one of the most significant areas of liability for an operation if not managed carefully. Remote sensing does not replace traditional monitoring techniques, but provides a valuable long-term, synoptic view. This paper demonstrates the value of conventional, well-tested remote sensing techniques by providing examples of mining applications from across Southern Africa.

1. Introduction

Managing the environmental impacts of mines, both during production and after closure, requires comprehensive monitoring and assessment of changes in environmental variables over both time and space. This facilitates control over those activities that are potentially damaging to the environment, and rehabilitating land that has been degraded by earlier activities. For environmental management to be effective, data collection and analysis must be timely, accurate and sufficient, but collection of a suitably comprehensive data set can be prohibitively expensive. One way of optimising data collection, is to augment surface sampling with remotely sensed (RS) data. RS data, especially that acquired using satellite platforms, enable a synoptic view and provide global coverage, as well as having the advantage of relatively good consistency and repeatability (Limpitlaw & Woldai, 2000; Mather, 1988).

This paper discusses the application of various types of RS data to the management of mine waste deposits in Southern Africa.

2. Types of Remotely Sensed Data

There are two principle types of commonly used sensors: passive and active. The former rely on reflected energy from the surface of the earth, while the latter emit energy and record the reflection (i.e. radar). Radar systems have many applications in mine waste monitoring, but are not discussed further in this paper.

Passive systems can be divided into three categories according to their spatial resolution:

- low spatial resolution, such as MODIS – ground cell of 1 km x 1 km,
- medium spatial resolution, such as Landsat, SPOT and ASTER – ground cell area of between 10 m x 10 m to 80 x 80 m, and
- high spatial resolution, such as IKONOS: 1 m x 1 m.

Sensors can also be classified according to their spectral resolution. For example, the original Landsat thematic mapper (TM) sensor is a multi-spectral sensor. This instrument recorded data in 6 bands in the visual part of the spectrum, ranging in wavelength from 0.45 μm to 2.35 μm and one band (10.40-12.50 μm) in the thermal part of the spectrum. Hyper-spectral sensors commonly record data in more than 100 bands, narrowly spaced over a portion of the spectrum similar to multi-spectral sensors. Weiersbye *et al*. (2006) report that a hyper-spectral instrument, known as the AISA-ES, consists of two sensors, one recording reflectance in the very near infrared (VNIR – 0.400-0.963 μm) and the other in the short wave infrared (SWIR – 0.968-0.2372 μm). Reflectances in each range are recorded in 180 bands at 0.010 μm intervals. This means that hyper-spectral images contain substantially more data than an equivalent multi-spectral image and that, assuming the ground cell (a measure of spatial resolution) is small enough, specific materials can be distinguished. This is useful when mapping salts associated with acid seepage at the toe of dumps, for example.

3. Applications for Medium Resolution, Multi-spectral Imagery

Satellite RS began in earnest in the 1970s with the launching of NASA's Landsat programme, which provided repetitive, inexpensive and synoptic monitoring of the earth's surface. This improved our ability to map changes in the environment over time and to infer a decrease or increase in environmental quality. Coupled with developments in the computational power of computers, this data created:

- the possibility of detailed and complex analyses within a broad range of analytical and manipulative capabilities,
- rapid, accurate provision of analytical results,
- scenario simulation via linked models,
- uniform, repeatable procedures, and,
- efficient analysis of large data volumes,

(Peuquet *et al*., 1993).

Several image processing techniques can be used to improve mapping of dumps. Vegetation index images are especially useful for tracking the progress of dump rehabilitation. Commonly used vegetation index images include the normalised difference vegetation index[1] (NDVI) and the Tasselled Cap (TC).

The (NDVI) is one of the indices most commonly used to measure the presence and condition of green vegetation. It is a combination of reflectance in the red and near infrared (NIR) wavelengths received by a sensor.

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[1] for a full discussion see Lillesand & Kiefer, 1994, Jensen, 1996, and Lyon *et al*., 1998.

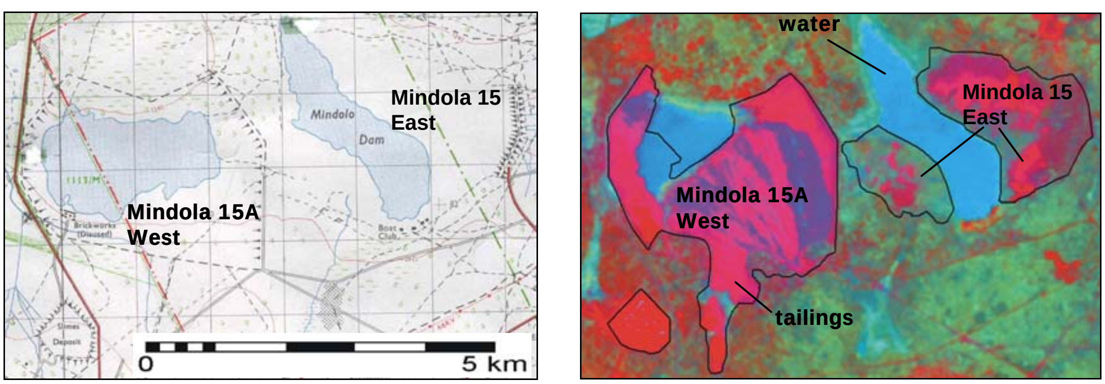
$$NDVI = \frac{NIR - red}{NIR + red}$$

Using this combination of bands, an image can be generated where vegetation has a strong signal and appears bright. Soil, rocks and hard man-made surfaces appear dark. Consequently, water bodies, dumps and roads appear black, as they are free of vegetation

The TC transform is based on the principle that combining multiple bands into a lesser number of features reduces the overall data volume and enhances the processor's ability to extract particular types of scene class information (Crist *et al*., 1986). In calculating TCs, an orthogonal transformation of Landsat data is undertaken to transform it to a new four-dimensional space (Perry & Lautenschlager, 1984). This transform provides linear combinations of the original sensor bands, which respond to particular physical scene class characteristics. Using half of the original number of channels, 95 percent or more of the total data variability is captured in scenes dominated by vegetation and soils.

3.1 Case Study 1: Updating Mine plans and Topographic maps in the Zambian Copperbelt

TC transforms yielded good land cover classification results for detection and monitoring of tailings storage facilities (TSFs) in the Zambian Copperbelt. This transformation is particularly useful as it facilitates comparison between data from different sensors, such as the old multi-spectral scanner (MSS) and the TM instruments on the Landsat series of satellites. Colour composite (CC) images can then be created using the three TC components. The benefits of this approach are shown in the updating of topographic maps in Figure 1.



Scanned topocadastral map (published in 1986)

Georeferenced TC image generated from the Enhanced Thematic Mapper (acquired in 2000)

Figure 1 Comparison between map data published 1986 and RS data acquired in 2000 (Limpitlaw, 2003).

The different areas of the TSFs, as measured on the 1:50,000 topographical map, as reported in mine inventories and as measured using RS techniques, are shown in Table 1.

Table 1. Reported and measured areas of mine waste deposits in the former Nkana Division of ZCCM (Limpitlaw, 2003).

Mine Waste Deposit	*Area Reported in Mine Plans* (ha)*	*Area Digitised from Topocadastral Map (ha)*	*Area Measured using ETM image (ha)*
Mindola West 15A	7,091.9	659.5	674.3
Mindola 15 East	1,300.0	not shown	411.6

* Mineral Resource Inventory, Nkana Division, ZCCM (unpublished).

3.2 Case Study 2: monitoring of long-term rehabilitation trajectories at old, closed collieries in KwaZulu-Natal.

In the Vryheid area of KwaZulu-Natal, old coal mines that closed in the late 1990s are located in hill terrain and not easily accessible. Traditional methods of monitoring these sites includes physical site inspections and the use of high resolution aerial photography – the latter providing useful information, but at substantial cost, especially when used to monitor a number of old sites spread over a large area.

Medium resolution satellite imagery was used to assess rehabilitation on small dumps and pits at the Vryheid Coronation Colliery (VCC) of Anglo Coal and was reported by Limpitlaw *et al.* in 2000.

To assess progress in rehabilitation, three Landsat images, acquired in 1989, 1995 and 1999 were used (Limpitlaw *et al*., 2000). Applying various common techniques, such the generation of colour composite images, ratio images and vegetation index images, these researchers showed that a significant increase in spectral response associated with vegetation was present on old coal discard dumps the VCC site. This improvement in response is directly correlated with rehabilitation success on these dumps (see Figure 2). For these sites, medium resolution satellite data was effective in monitoring the progress of rehabilitation, even when the areas being rehabilitated are small and surrounded by many different types of land cover. Simple, inexpensive image processing techniques can be applied to yield information on the progress of rehabilitation. Landsat, is, however too coarse to identify small changes on rehabilitated dumps, such as the early stages of gulley development – it should therefore be used in conjunction with conventional monitoring techniques, but does allow the frequency with which traditional techniques are used to be lower.

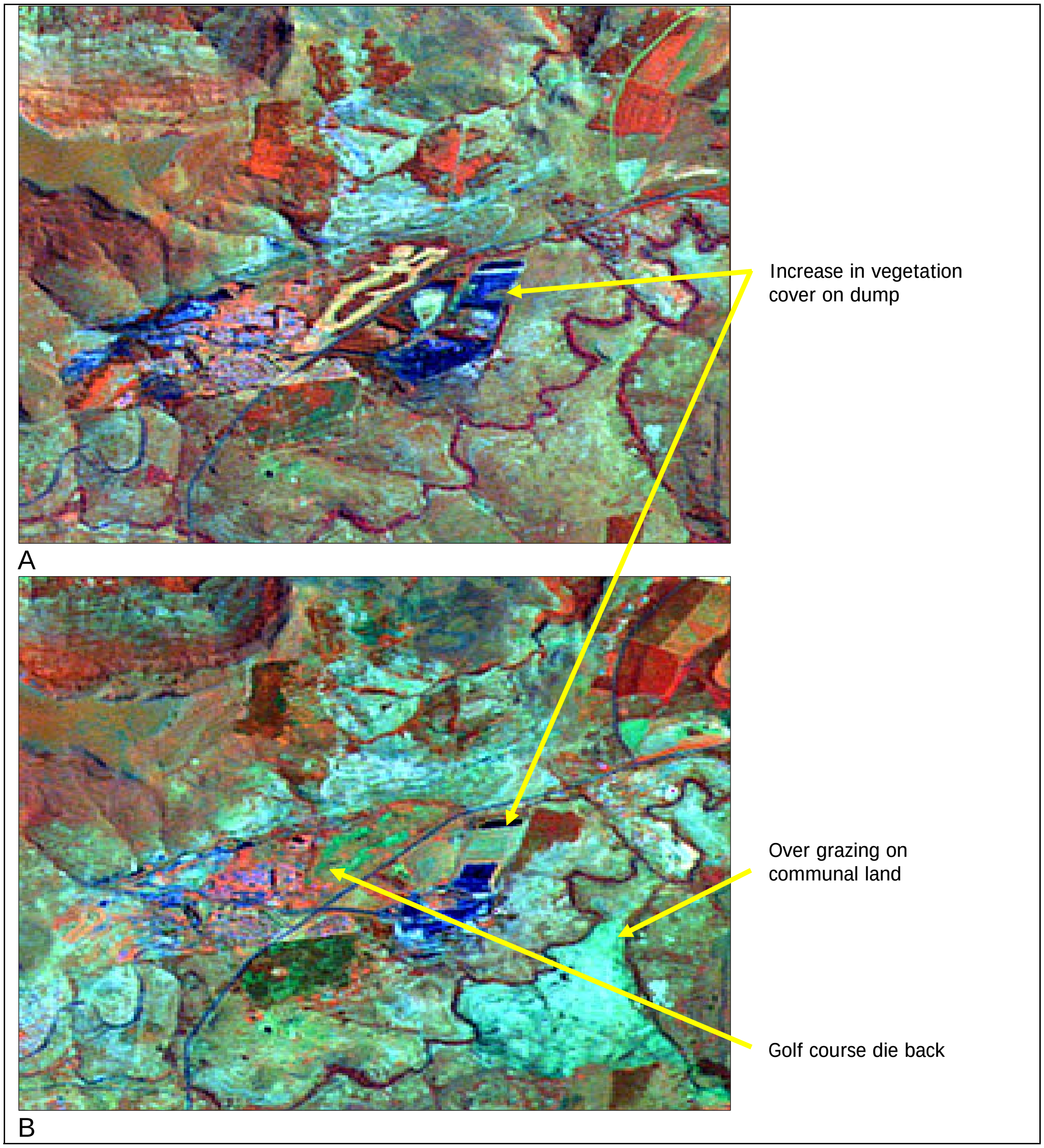


Figure 2 Changes in vegetation cover during operations at VCC (A) and post closure (B).

3.3 Case Study 3: Monitoring of operating coal fines storage facilities

Landsat images were used to monitor the environmental condition of fine coal storage facilities at a mine in Mpumalanga. The NDVI approach was applied to these images, and the changes in the vegetation cover at these impoundments is shown in Figure 3. An effective rehabilitation programme can be inferred from the images. Certain areas, undergoing rehabilitation, show a consistent improvement in vegetation cover while other, active dump areas, show no change at all.

In Figure 3 A, the impoundments walls have significantly higher vegetation signature (indicated by bright areas), showing effective grassing. The surfaces of the dumps have a lower vegetation signature (dark areas), especially the right-hand dump, which is in use. The dark triangle in the lower right corner of Figure 3 A is a pollution retention dam. In Figure 3 B, both dumps are in operation and the area covered by coal fines in the left hand dump is much larger than in the previous year. The strong signature shown on the retaining walls the previous year has diminished, possibly indicating the need to reassess the efficacy of the rehabilitation approach. By the end of the assessment period, in Figure 3 C, (8 years), the right hand dump had been decommissioned and revegetated. While the vegetation signature on the top of the dump is lower than the surrounding areas, it does not show large patches.

Figure 3 A time series of vegetation index images over coal dumps: 1994 (image A), 1995 (B) and 2001 (C).

The Landsat images were also used to map the extent to which slurry had propagated through the landscape after a wall breach at a third storage facility in the early 1990s. A stretched NDVI of the dumps in question is shown in Figure 4. The extent of spilt material is indicated by a magenta segment. The 1994 data set was used to produce a tasselled cap colour composite, a ratio colour composite and a NDVI image. Material with spectral characteristics similar to coal slimes, located adjacent to the waste storage facility and covering an estimated 7 hectares, was detected in the 1994 data set. Remediation has been carried out, and the material cannot be confidently identified in the 1995 data and is absent from the 2001 data set.

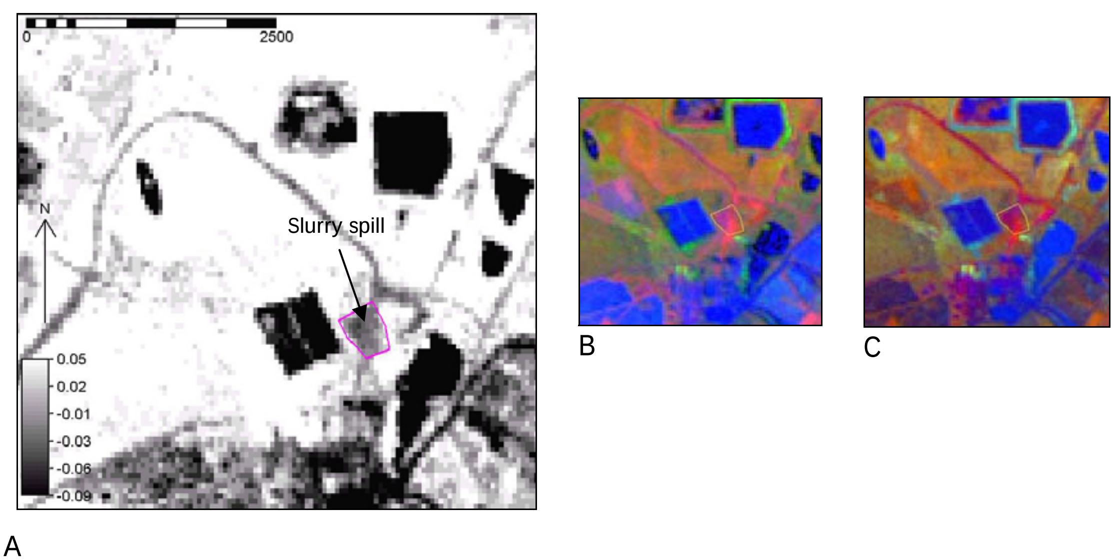


Figure 4 Stretched NDVI of the Mpumalanga colliery, showing the possible extent of spilt material (magenta segment) (A). Image B shows a ratio colour composite and image C shows a Tasselled Cap colour composite.

Thermal images, for 2001, derived from the two thermal bands of the Enhanced Thematic Mapper[2] (ETM), the instrument replacing TM on the last satellite in the Landsat series, Landsat 7, were used to detect heatings in the waste storage facilities. These images showed significant sunlight-heating effects. The sunny slopes of haul ramps exhibited high temperatures while the shadowed slopes had low temperatures. These differential sunlight-heating effects were reduced by applying an illumination intensity correction. The results were satisfactory and allowed identification of potential hot spots, as shown by the bright areas associated with the coal dumps in Figure 5.

$$\frac{ETMthermal - \sum ETMoptical}{ETMthermal + \sum ETMoptical}$$

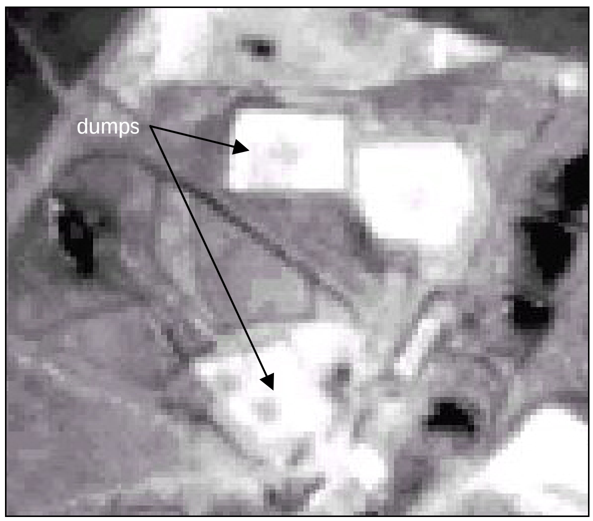


Figure 5 Illumination-corrected thermal image of the Mpumalanga colliery. Light shades indicate higher ground temperatures.

4. Applications for High Resolution, Hyper-spectral Imagery

Old TSFs experience erosion, failure and seepage. Cost effective methods for mapping contamination over large areas facilitates the identification of zones of potential risk. This approach also helps to focus resources for strategic remediation. In a study of TSFs in the Witwatersrand, Weiersbye *et al*., (2006) undertook accurate mapping of contaminant baselines before and after remediation efforts to determine success rates. This type of mapping requires high spectral and spatial resolution data, such as that provided by airborne hyper-spectral sensors.

[2] Landsat 7 was launched in 1999. ETM recorded reflected radiation in the same bands as TM, but has an additional 15 m panchromatic band and two 60 m thermal bands. Unfortunately, ETM has become practically unusable due to sensor malfunction.

These researchers validated RS data though chemical analysis of field samples and ground based collection of spectral data with a hand-held spectra-radiometer. Airborne data were collected with a hyper-spectral imager with 2 scanners (VNIR, SWIR) and a ground cell size of 3.3 m and 1.6 m, depending on the altitude of the aircraft (Weiersbye *et al*., 2006). They mapped 9 indicators of plant productivity and stress, as well as plant water content.

Weiersbye *et al*., (2006) used two observations to identify the mechanism of pollution dispersal:

- the fact that pyrophyllite, chlorite and some U-bearing minerals are the primary minerals associated with TSFs and the distribution of these minerals in the landscape occurs through physical transport processes, and
- jarosite, copiapite, gypsum and uranyl sulphate compounds are secondary minerals, characteristic of AMD.

Hyper-spectral RS is able to discriminate these compounds and map the spatial scale over which these processes operate in the landscape. Small areas of seepage were consistently detected. Accumulations of gypsum and other sulphates on surface soils from evaporation from acid drainage could be mapped, and was useful in the identification of risks areas such as leaking waste disposal facilities and irrigation with contaminated water

While this type of data is considerably more expensive than medium resolution imagery, it provides more information on the type of process resulting in the environmental disturbance, rather than just mapping the disturbance.

5. Conclusion

RS data is invaluable for long term environmental monitoring of mining waste dumps. This approach is especially useful when coupled with conventional monitoring. Medium resolution images can be used to monitor gradual changes over large areas. Where anomalies are detected, high resolution images can be used to identify and map the processes through which impacts occur in the landscape.

Old images are lower resolution, but provide a historical context for environmental impacts experienced today. With each year, the capabilities of imaging devices improve, and in the future RS data will play an increasingly important role in managing and monitoring the environmental impacts of mining waste.

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