Goldmine Tailings: A Remote Sensing Survey

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Abstract

Pollution originating from mine tailings is currently one of the environmental problems South Africa has to deal with. Because of the large number of tailings impoundments and their changing status, authorities are battling to keep their records and controls up to date. This project is aimed at investigating the use of remote sensing as a way of conducting surveys of mine tailings efficiently, regularly and at a low cost. Mine tailings impoundments of the Witwatersrand in Gauteng provide an ideal study area because of the large number of tailings dams of different sizes and conditions and the availability of satellite images and aerial photographs covering the area. Tailings impoundments conditions are analysed through satellite images, airborne multi-spectral data and aerial photographs captured during the Safari 2000 dry season campaign. Remote sensing interpretation of colour composites of multi-spectral bands, Principal Components and supervised and unsupervised classifications are the methods of analysis used. The overall goal of the project has been achieved through the production of a comprehensive database of tailings impoundments and their rehabilitation status, in an accessible format, containing identity, coordinates, area, rehabilitation status and owner of each tailings impoundment, map them and end up with a comprehensive database of tailings impoundment on the Witwatersrand.

Declaration

I declare that this research report is my own work. It is being submitted for the Degree of Master of Science in Environmental Science to the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination in any other University.



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Abbreviations

AMD	Acid Mine Drainage
ASTER	Advanced Thermal Emissions and Reflection Radiometer
DACEL	Department of Agriculture Conservation and Environment
DEAT	Department of Environmental Affairs and Tourism
DEM	Digital Elevation Model
DME	Department of Minerals and Energy
ECA	Environmental Conservation Act
EIA	Environmental Impact Assessment
EMPR	Environmental Management Programme
EMR	Electromagnetic Radiation
ERGO	East Rand Gold and Uranium Company
ERPM	East Rand Proprietary Mines
ESE	Earth Science Enterprise
GIS	Geographical Information Systems
GPS	Global positioning System
LRC	Legal Resources Centre
MAS	Modis Airborne Simulator
NEMA	National Environmental Management Act
SAFARI	Southern African Fire-Atmosphere Research Initiative
SWIR	Short Wave Infra Red
TDS	Total Dissolved Solids
TIR	Thermal Infra Red
VNIR	Visible Near Infra Red

Chapter 1
Introduction

Mine tailings are heaps of crushed solid waste matter that result from the extraction of commercially useful metals and minerals. In the Witwatersrand gold mining area that runs from Randfontein to Nigel there are two kinds of tailings, namely slimes dams and sand dumps. Slimes dams are structures where finely crushed siliceous rock (70 – 80 μm mean particle diameter) from mine workings is deposited as waste in the form of slurry. While sand dumps are also mine waste disposal structures, they differ from slimes dams in that they comprise granular material (>200 μm) that is deposited by mechanical tipping (Chenik, 1960). Most sand dumps in the area are older mining waste, pre 1950, while slimes are more recent waste. Currently many sand dumps and older slimes dams are being reclaimed i.e. reprocessed to extract residual gold. The resulting waste is being deposited either onto existing slimes dams of low residual gold content (<0.6 $\mu g\ g^{-1}$) or onto totally new slimes dams.

Environmental impacts of gold mining

Since the discovery of gold on the Witwatersrand in 1884, millions of tones of tailings material have been deposited in the area (Figure 1.1). Most of the tailings are gold mine tailings (Van As *et al.*, 1992). Many of them have been in existence for more than a century. With the evolution of the mining industry and the different mines changing ownership, some of the tailings have been left uncared for and therefore in a position to cause environmental problems.

Tailings dams are supposed to be areas where mine waste is kept safely away from interfering with the environment. However this is far from the truth especially considering the history of disasters surrounding tailings dams around the world. South African examples of tailings structural failure include the Merriespruit disaster caused by dam wall breach, which took place in 1994 and the Bafokeng embankment failure in 1974 (Wise Uranium Project, 2003). Failure is the most common cause of environmental problems surrounding tailings. The term failure does not only refer to physical structural failure, but it also refers to the inability of tailings dams to safely contain material in them. It follows that incidents such as leakage of chemicals onto streams and ground water, dust being blown off tailings and release of radiation to the environment would be called failure (ICOLD, 2003).

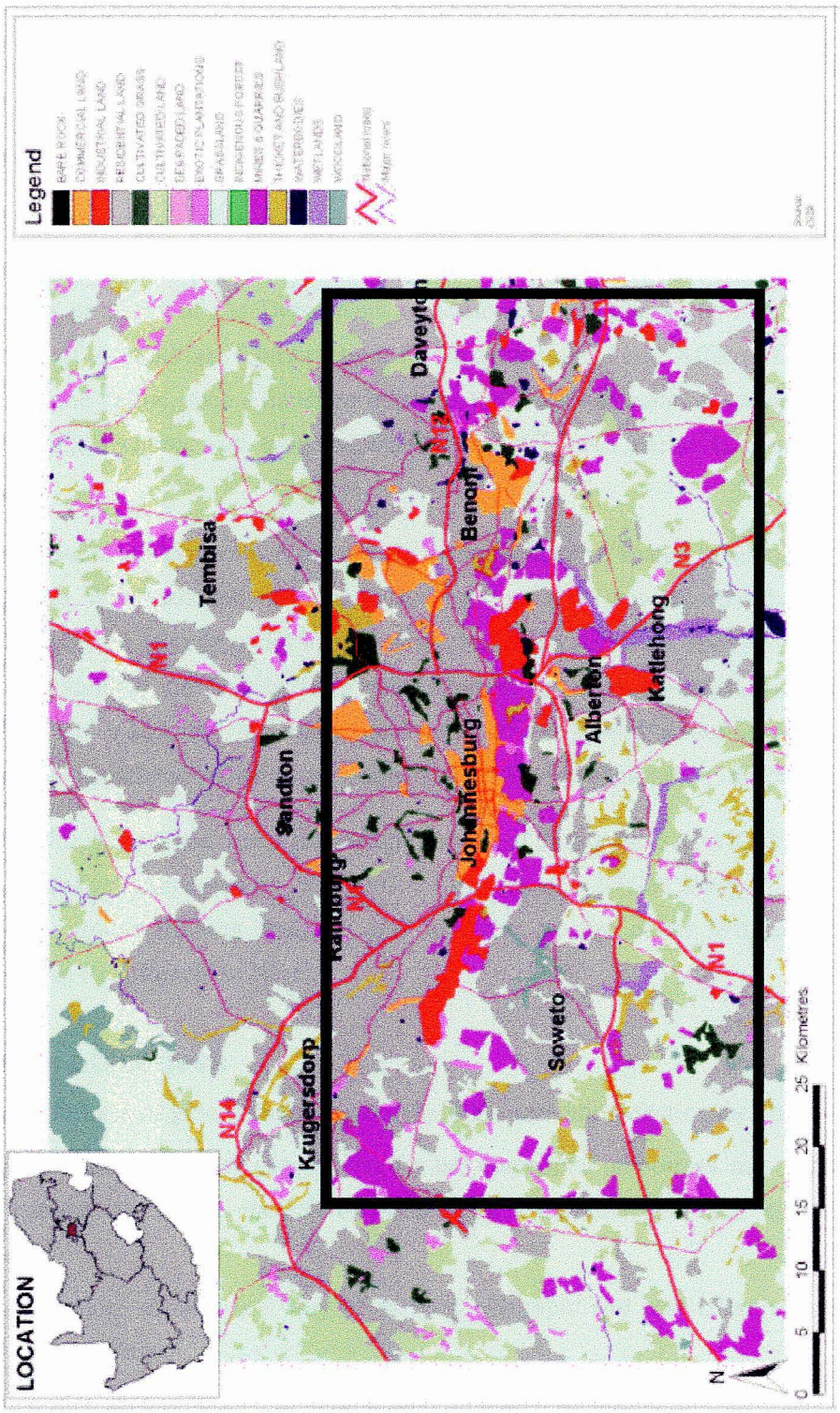


Figure 1.1 Study area, showing mine tailings (purple) embedded in the residential and urban structures of the Witwatersrand. The rectangle on the picture indicates the area covered by the Modis Airborne Simulator images. (Credit: Greater Johannesburg Metropolitan Council).

The results of tailings failure would lead to various undesirable effects on the environment. The overall effect of the presence of mine tailings renders the land unproductive in that normal vegetation growth ceases to take place, nor can the land be used for other productive purposes like agricultural or recreation.

The aim of this report is to create a spatial database of slimes dams and sand dumps of the Witwatersrand and the current rehabilitation status of these tailings. For environmental management purposes of the Department of Minerals and Energy (DME), the Gauteng Department of Agriculture, Conservation, Environment and Land Affairs (DACEL) and members of the public, such a database needs to contain information on tailing ownership or mining right, location, size, type and, status of rehabilitation, reclamation or subsequent land use.

As the purpose of the project was to compile a comprehensive spatial inventory of tailings dams on the Witwatersrand, a remote sensing approach was selected based on the availability of high altitude aerial images from the Modis Airborne Simulator (MAS). To support and validate information from these images, aerial photographs, databases from mining companies and the DME and ground truthing were used. For more accurate feature identification, visual and statistical techniques are utilized to achieve the objectives.

Use of satellite images and aerial photographs obtained during the SAFARI 2000 Regional Science Initiative (Annegarn *et al.*, 2002b; Swap *et al.*, 2002a; Swap *et al.*, 2002b), validated by ground truthing data, are used to assess an area of the Witwatersrand that stretches from Randfontein to Nigel.

Research objectives

- Identify failures of gold mine tailings in the Witwatersrand affecting the environment.
- Document the difficulties encountered by environmental authorities in compiling and maintaining up to date records of mine tailings deposits and their environmental impacts.
- Present remote sensing as a way of carrying out rapid and cost effective surveys of these mine tailings.
- Use satellite images and aerial photographs validated by ground truthing data to create a spatial (GIS) based inventory and a list of tailings dams found in the area.
- Generate a comprehensive database of tailings impoundments for the Witwatersrand, listing reprocessing and rehabilitation status.

Chapter 2
Literature Review

This work makes a contribution to the goals of the Gauteng Mining Pollution Forum to remedy environmental degradation caused by mining and mine residues. The forum's aims are to work together and share information with interested parties on the matter. The Forum created two working committees, one that looks at possible technologies for remediation of water and air pollution and the other, at the use of Geographical Information System (GIS) technology in collating available data on mining environmental impacts (Creamer, 2001). As this paper is a contemporary collation of available information it should constitute a large part of the latter committee's objectives.

Remote sensing image processing is the principal method used to survey the area in order to examine the status of goldmine tailings. Satellite imagery interpretation is used, supported by aerial photographs, databases and maps from mining houses and the Department of Minerals and Energy (DME). Ground truthing is also used to create training sets to facilitate classification.

While this work only focuses on the area that stretches from Randfontein to Nigel, the method should be able to be replicated on any part of the world where there are similar problems.

Pollution from wind blown dust

Some of the common complaints received by mine operators and the Government concern pollution that emanates from tailings in the form of dust and polluted water. Most affected by dust and polluted water are neighbouring settlements, formal and informal. Among the affected formal settlements are locations such as Kagiso, Davidsonville, Dobsonville, Meadowlands and Reigerpark (Nicol *et al.,* 2002). Some of these formal locations were established during the 1950s and 1960s in the neighbourhood of goldmine tailings on the

south of the Witwatersrand ridge despite the known adverse environment associated with wind blown dust. Newer settlements were driven by the national policy priority to make available land for housing. This process in some cases was carried out following proper Environmental Impact Assessments, or adhered to DME regulations that specified how much space to leave between houses and mine tailings. In other instances, DME regulations were ignored and consequently severe negative impacts of goldmine impoundments are experienced (Annegarn and Sithole, 2002a). The situation with informal settlements is different, in that most of them evolved out of individuals seizing land without any pre-consultation with housing or mining authorities. Some of this land is vulnerable with respect to the proximity of tailings impoundments or water that has been polluted by mining activities.

The *Aide Memoire* for Prospecting and Mining of the Department of Minerals and Energy (DME, 1992) specifies that impacts of wind blown dust may be significant within 3 km from source and that planning and monitoring of dust impacts should be considered within this zone. Many years of dust monitoring in the area have proved that under Highveld climatic conditions, dustfall becomes indistinguishable from background dustfall beyond 3 km from the source (Annegarn and Sithole, 2002a).

The main cause of dust in the Witwatersrand area is goldmine impoundments that are still being used, reclaimed and those that have not been properly rehabilitated. Where unacceptable dustfall levels have been experienced, for example in areas south and southwest of Johannesburg, it has been established that the cause has often been dump reclamation. An impoundment is said to be under reclamation when mining companies reprocess impoundment materials using newer, more efficient gold extraction processes. The resulting waste material is deposited in safer, better situated and controlled slimes dams. Elevated dust levels are often experienced in such cases when vegetation cover is removed, coupled with windy conditions.

Rehabilitation or mitigation involves laying a cover of some sort over an impoundment. There several kinds of mitigation techniques, of which vegetation is the most popular method, followed by many others that are often not long term measures. These include the use of chemicals, rocks and water sprays. In short, tailings with a potential to pollute persistently are those on which no attempt has been made to mitigate effects or where there

are poor mitigation techniques and no follow up maintenance. Pollution is expected from reclamation works, only for the duration of reclamation.

The Gauteng province has a semi-arid climate. This makes it easier for the wind to erode the powdery crushed rocks left over after gold-bearing ore is crushed and the gold extracted. High winds before the onset of spring rains are the cause of the wind erosion in the region. Studies have shown that most of the wind erosion takes place on the upper slopes of the windward side of the dams and less comes off the tops (Blight and Da Costa, 2001).

Dust from goldmine tailings commonly contains high levels of silica (SiO_2) and there have been fears that this causes silicosis. Silicosis (known as white death) is described as an incurable, often fatal disease caused by exposure to microscopic silica particles (Katz, 1994; Rosenman *et al.,* 1997). The other complaint that is commonly raised concerning dust is that of nuisance. During the 1960s and the 1970s, the chamber of mines and the major mining houses embarked on an extensive programme of vegetation of tailings impoundments. In the Randleases case, deposition of fresh slimes covered vegetation and allowed the nuisance dust problem to reappear, with serious impacts on the adjacent Meadowlands suburbs (Annegarn *et al,* 2000; Nicol *et al.,* 2002).

An illustration of how bad wind blown dust nuisance can be is shown by a case study. A comparison is made between two areas located close to the city centre of Johannesburg. One is an area located at a leafy suburb away from tailings impoundments (background area) (Figure 2.1) and with very minimal dustfall and the other is located close to reclamation works in Heriotdale. During the 1998 windy season, unauthorised activity on the dumps incident led to particularly heavy dustfalls (Figure2.2). These dustfall levels resulted in prolonged legal proceedings.

The amount of airborne dust is rated according to guidelines established by the Department of Environmental Affairs and Tourism (Table 2.1). A 17-year record of monitoring has revealed a seasonal trend to dust levels for most of the monitored sites around Johannesburg (heavy line in figure 2.1 and 2.2). Months with the least dust counted are normally the months of April, May and June and with the most are August to November (Annegarn *et al.,* 1990). Dust levels are normally within the acceptable level on the points that are being monitored (Annegarn *et al.,* 1990). As the monitoring is performed on behalf

of responsible tailings impoundment owners this cannot be extrapolated to the vicinity of the neglected impoundments. Dust fall-outs should be no more than 650 mg/m^2/day in residential areas (Mutume, 1998; Annegarn and Sithole, 2002a).

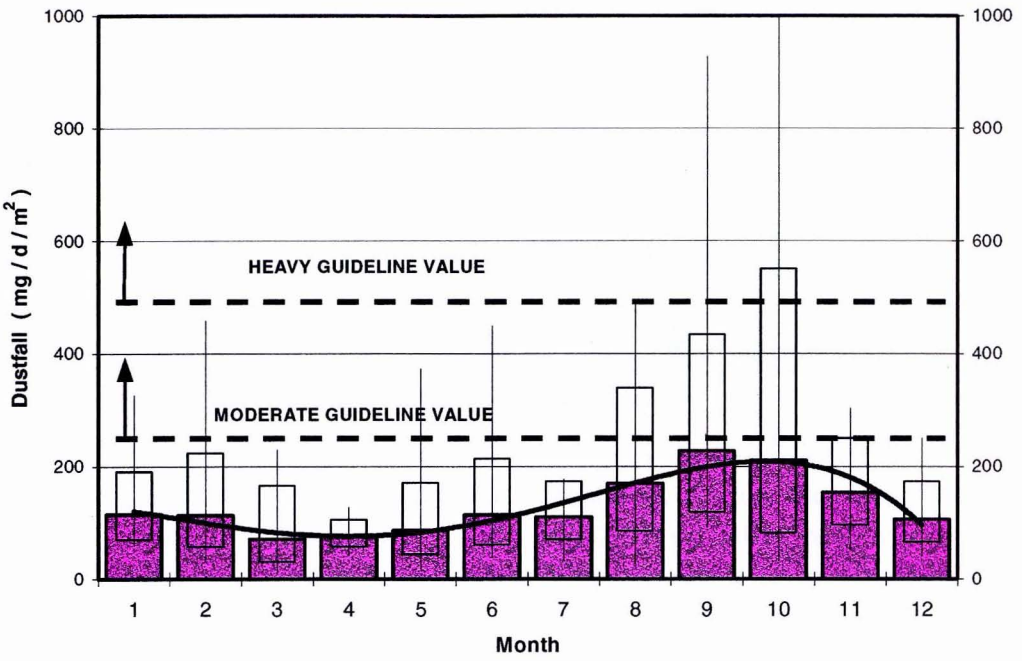


Figure 2.1 Monthly average dustfall rates, 17-year record, at Milner Park Johannesburg suburban control site. (Mean trend line is a 4-degree polynomial fit. Boxes indicate ± 1 standard deviation, whiskers the maxima and minima for each month.) (Annegarn and Sithole, 2002a)

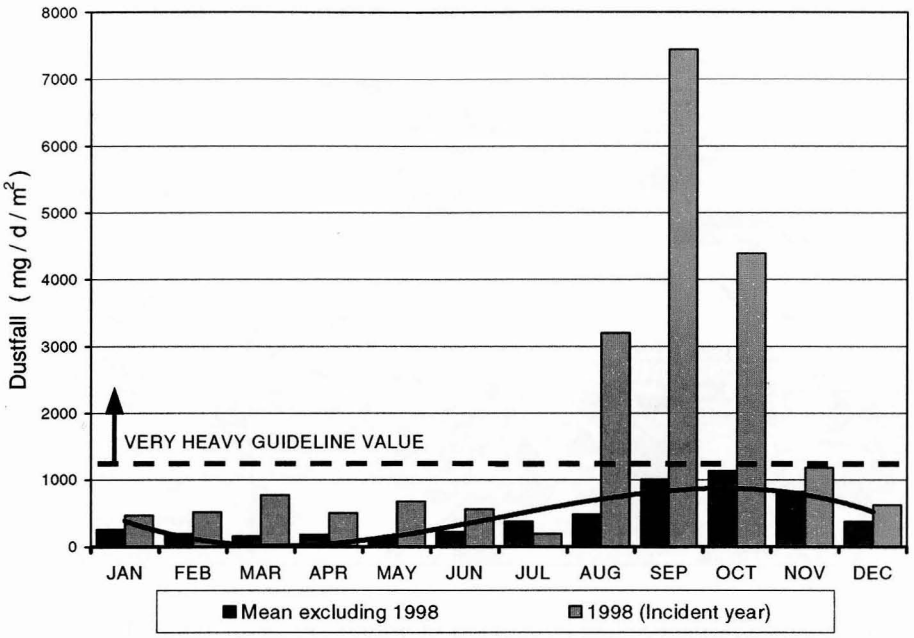


Figure 2.2 Monitoring site 50 m downwind of active reclamation site. Mean values of monthly dustfall for the period 1994 to 2001 excluding the year of the incident – 1998, contrasting dustfall from an active reclamation site with dust mitigation in operation and without mitigation (the incident) (Annegarn and Sithole, 2002a).

Table 2.1 Dustfall guideline values issued by the Department of Environmental Affairs and Tourism.

Classification	**Dustfall averaged over 30 days (mg / m^2 / day)**
Slight	< 250
Moderate	250 to 500
Heavy	500 to 1 200
Very Heavy	> 1 200

A model indicates dust levels and dust dispersion patterns on the central Witwatersrand between the 11 of September and the 11 of October 2001 (Figure 2.3). The model indicates that some residential areas south of Johannesburg were covered by dustfalls rated as high and very high.

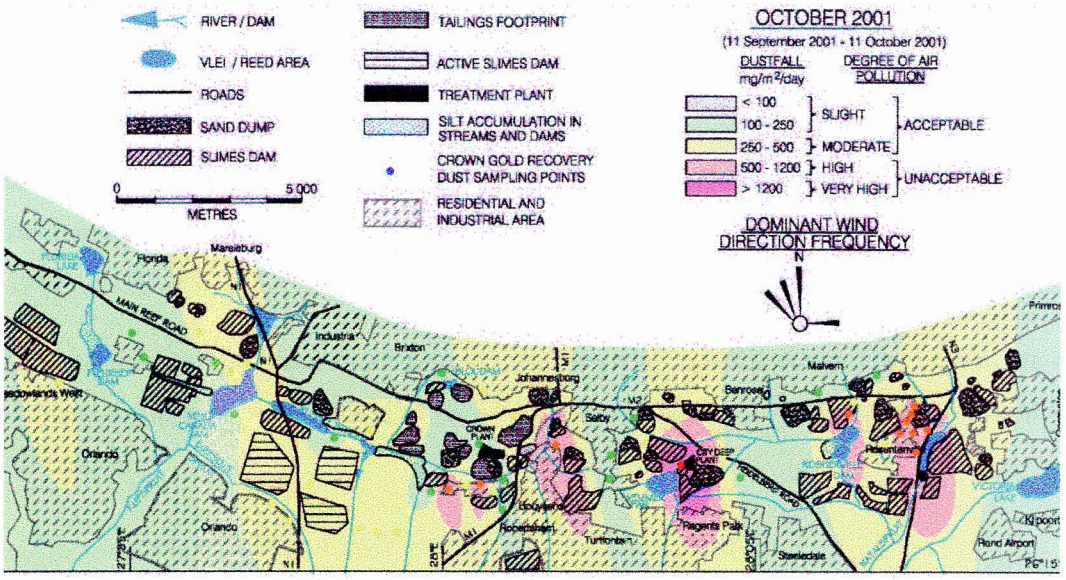


Figure 2.3 Tailings dams in relation to residential and industrial areas showing dust dispersion patterns. (Mphephu, 2003)

Water pollution and acid mine drainage

The Witwatersrand area is drained by rivers such as the Klipriver, the Natalspruit and Rietspruit. The Klipriver has its catchments around Soweto and the Natalspruit and the Rietspruit flow out of the East Rand to the Vaal River (Koch, 1998). Although all these rivers are classified as highly polluted by waste from the city of Johannesburg, the Klipriver is the most polluted by mining activities. Low pH values, high electrical conductivity and high sulphate values were recorded (Greater Johannesburg Metropolitan Council, 2003) (Figure 2.4). Siltation and colouration are some of the visual evidence of river pollution (Ogola *et al.,* 2001).

Ground water pollution is also a problem because of this legacy of past mining practices and current mining operations. The Witwatersrand Supergroup sediments contain varying levels of sulphide minerals the most predominant being pyrite (FeS_2). It is said that on some of the gold bearing reefs, pyrite can be up to three percent of the rock mass. Other minerals like pyrrhotite (FeS), arsenopyrite (FeAsS), chalcopyrite ($CuFeS_2$), galena (PbS), cobaltite ((FeCo)AsS), gersdorffite (NiAsS) are also present, in smaller traces. Water gets degraded when it comes into contact with sulphide minerals (Scott, 1995). Waste rock dumps, slimes dams, low-grade ore, overburden and run-off mill stockpiles are sources of acid drainage in mining related activities (Ogola *et al.,* 2001).

South African gold mines are described as the biggest producers of Acid Mine Drainage (AMD). AMD is a name describing polluted effluent from base metal, coal and gold mines (Robinson, 2003b). This is most commonly caused by the oxidation of FeS_2. Pyrite and marcasite generate the acidity of the mine waters, through the release of H^+ and simultaneously supply large quantities of Fe and sulphate by a reaction described by Scott (1995) as follows:

Atmospheric reaction initiates the reaction whereby the sulphidic component is in pyrite is oxidized to sulphate then the acidity (H^+) is generated and ferrous iron ions are released in this manner:

$$FeS_2 + (7/2)O_2 + H_2O \rightarrow Fe^{2+} + 2SO_4^{2-} + 2H^+$$

After the reaction is initiated, ferrous iron (Fe^{2+}) is oxidized to form ferrous iron (Fe^{3+})

$$Fe^{2+}_{(aq)} + ¼\ O_2 + H^+ \rightarrow Fe^{3+}_{(aq)} + ½\ H_2O$$

The ferric iron (Fe^{3+}) is then hydrolysed by water to form the insoluble precipitate ferrihydrite ($Fe(OH)_3$) and more acidity:

$$Fe3^+_{(aq)} + 3H_2O \rightarrow Fe(OH)_{3(s)} + 3H^+$$

Pyrite can also be oxidized by dissolved ferric iron to produce additional Fe^{2+} and acidity:

$$FeS_{2(s)} + 14Fe^{3+} + 8H_2O \rightarrow 15Fe^{2+}_{(aq)} + 2SO_4^{2-}{}_{(aq)} + 16H^+$$

As the water table rises or as recharge percolates through the unsaturated rock, dissolution of these minerals takes place and adversely affects water quality (James, 1965). The reactivity of water increases and as a result it reacts with other minerals to produce more acidic conditions or to neutralise the acid. The TDS (total dissolved solids) of the water is increased (Scott, 1995). Water degradation is usually diffuse because of the variable nature of the recharge sources and the places where acid formation can occur. As a result, surface degradation and subsurface degradation both contribute to ground water pollution (Scott, 1995; Funke, 1990).

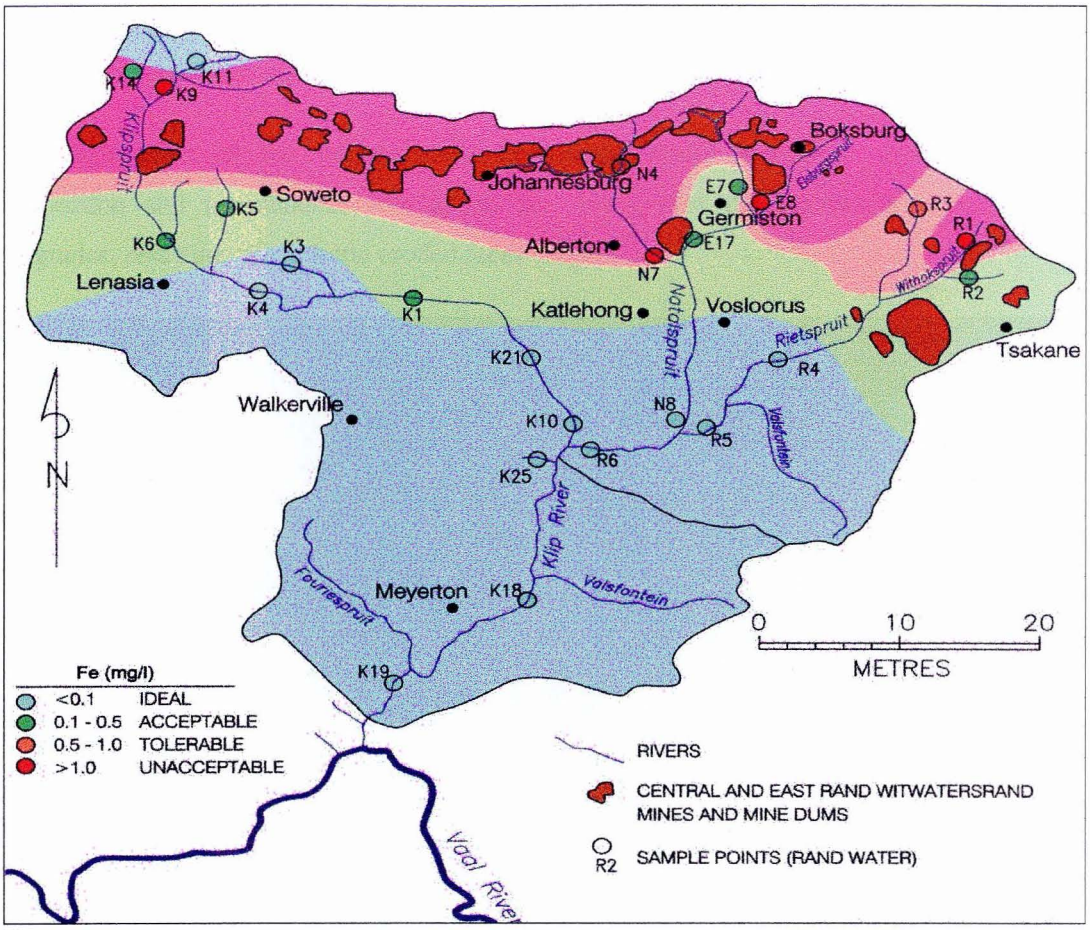


Figure 2.4 Pollution levels on the local river drainage system of the central Witwatersrand. (Davidson, 2003)

Loss of amenity

Mine tailings impact on the environment in many ways. Most obvious of all, the presence of tailings changes the original form of the landscape. These can be commonly seen on the skyline of Johannesburg. The landscape that is often described as damaged has been left with often sterile scars that have the potential to cause other environmental problems. Where tailings impoundments exist, the mostly blocky features that represent tailings dams create a landscape that is not aesthetically pleasing. There are on the other hand some people that are against the removal of tailings impoundments for reasons that some of them are used for sport and that they are a part of Johannesburg's heritage, a reminder of the city's origin. These people include sand boarders who take their mountain bikes through the slopes, motocross and quad bikers (The Mail Archive, 2003) and also some people who

think the city would not look nice without the slopes. One lady was quoted as saying that mine dumps are comparable to the table mountain of Cape Town! (Leithead, 2003)

Although some of the tailings have been successfully vegetated, without ongoing inspection and maintenance, the added soil layer over the impoundment eventually degrades, resulting in synthetic eroded faces (Figure 2.5).

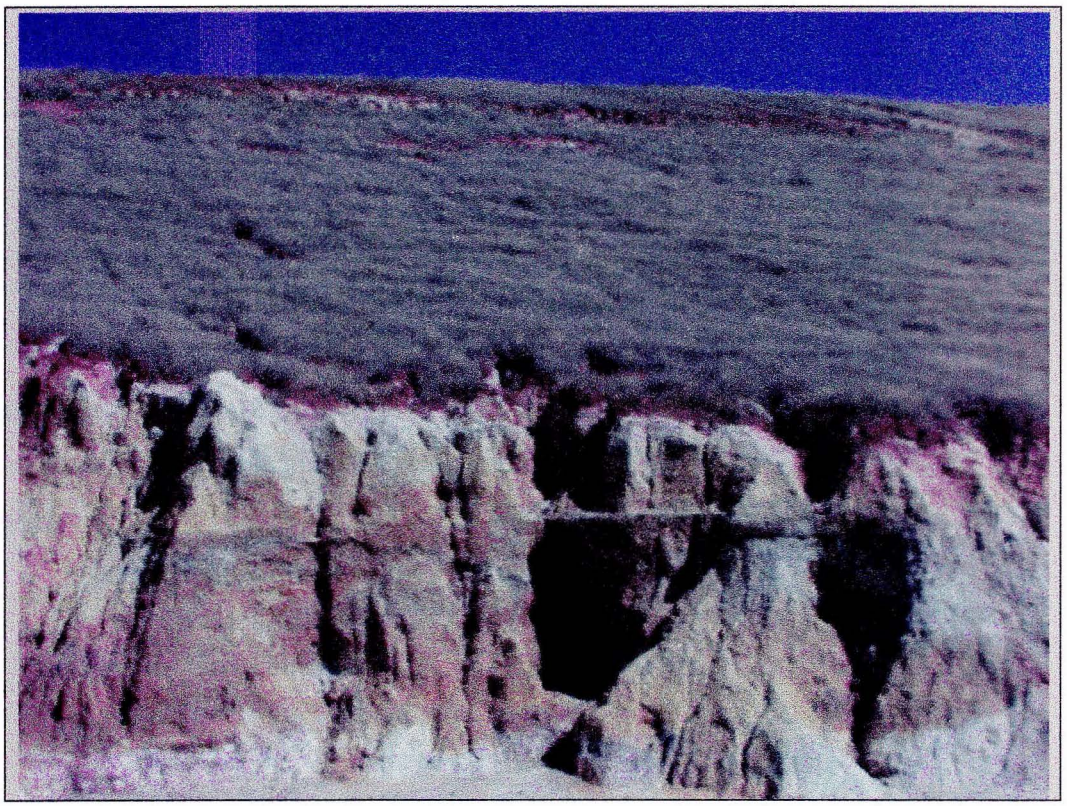


Figure 2.5 Erosion taking place on the side of a slimes dam, leaving it exposed for efflorescence to take place.

Environmental legislation

Generally the gold mining industry of South Africa is positive in ensuring that mining activities do not impact negatively on the environment. This can be seen in the Guidelines set by the Chamber of Mines and also the relevant legislation meant to ensure that controls are implemented at all stages of the mining cycle (Robb and Robb, 1998).

There are several Government departments that have legislation that has a bearing on protecting various aspects of the environment from mining related effects. These departments are Water Affairs & Forestry; Agriculture; Environmental Affairs and

Tourism; Finance and National Health & Population Development (Robb and Robb, 1998). The following legislation from these departments is relevant to mining pollution:

Environmental Assessment

- Environment Conservation Act 73 of 1989 and Regulations R 1182 to R 1184 in Government Gazette No. 18261 of 5 September 1997
- National Environmental Management Act 107 of 1998 (Chapter 5)
- The Minerals Act 50 of 1991

Land

- National Environment Management Act 107 of 1998
- Environment Conservation Act 73 of 1989
- Health Act 63 of 1977
- The Hazardous Substances Act 115 of 1973
- Minerals Act 50 of 1991

Air

- Atmospheric Pollution Prevention Act 45 of 1965

Water

- National Water Act 36 of 1998
- Water Services Act 108 of 1997
- National Environment Management Act 107 of 1998
- Environment Conservation Act 73 of 1989
- Health Act 63 of 1977 (Section 20 (1)(c))
- Minerals Act 50 of 1991 (Section 68(2))

Out of all legislation by different departments, the National Environment Management Act (NEMA) and Environmental Conservation Act (ECA) are regarded as the environmental framework legislation. While both NEMA and ECA have good intentions, some of the Acts conflict, which defeats the principle of cooperative government. For instance, some of the conflicts that exist are between the ECA 73 of 1989 and the Minerals Act 50 of 1991 concerning Environmental Impact Assessments (EIA). ECA says that EIAs have to be done for certain listed activities and the environmental impact regulations are not applicable to mining. The Minerals Act maintains that the Environmental Management Programme Reports (EMPRs) have to be carried out (Mabiletsa and du Plessis, 2003). Some of the confusion that often arises within mining companies is the belief that when

land has been declared a mining area, activities on that land fall under the scope of the Minerals Act (Mabiletsa and du Plessis, 2003, p. 155).

Mining companies no longer existing or ambiguous ownership of old dams remain major problems. It is not uncommon to find cases where the landowner is not the owner of the mining right. The problem is that some of these transactions that take place between mines are not reported to the DME, thereby culminating in information gaps. The legacies of some old mining companies that have gone into liquidation are being felt by new companies. In certain cases where assets have been bought, the new companies have inherited also accompanying environmental liabilities and problems. For instance letters of demand to rehabilitate the old ERPM gold mine tailings were sent by the Legal Resources Centre to the company that bought the assets of this liquidated company (Nicol, 2000).

Remote sensing

Mapping of features on the Earth's surface has been practiced for centuries. However the use of airborne and satellite imagery in remote sensing is relatively new and has seen an increase in recent years. This has eliminated the processes of carrying out detailed field surveys that require large human resources and extended time periods for the preparation of maps (Ragunathan, 1991). Use of images has mostly been favoured in mapping and monitoring natural and man made features on Earth's surface. Of interest is that organizations and departments that do environmental monitoring, especially for mine wastes are more and more taking an interest in the use of aerial photographs and high-resolution multi-spectral satellite images. For instance satellite imagery from Nasa's TERRA satellite has been used to monitor environmental hazards all over the world with notable examples like the SAFARI 2000 project images that are being used by many individuals in southern Africa (Swap *et al.*, 2002b).

Mapping and monitoring using remote sensing have the added advantage that accurate maps with precise relationships between mapped items and their true location on the ground are produced. Not only is accuracy achieved through geo-referenced remote sensing images, but also maps are created more quickly and cheaply (discounting the cost of the satellite!) (Congalton and Green, 1999). Satellite images are considered a flexible and fast way of obtaining digital data quickly and frequently. Sensors can be set to capture images covering large areas in one flight and also repeat flights can be made over an area

of interest. Aerial images can also be used for the same purposes as satellite imagery, but only often covering smaller areas and lacking in spectral range covered. Aerial images are often used also to validate satellite data. Sensors on board satellites or aircraft platforms offer the advantage of high resolution thus enabling the analyst to resolve small areas on the surface (Ragunathan, 1991).

The electromagnetic spectrum

The most important requirement in remote sensing is to have an energy source. Energy in the form of electromagnetic radiation (EMR) is provided by the sun (natural), generated by the sensor (active), or created by thermal emissions from the Earth's surface or atmosphere (Figure 2.6). For example, two sources of energy that contribute to the energy found in rocks are the solar energy absorbed during the daytime and the Earth's internal heat flow. All matter in the universe, even that in the nearly perfect vacuum between the galaxies is above absolute zero and emits some form of radiation. Remote sensing is therefore concerned with measuring EMR reflected or emitted by the Earth's natural and man made features, since every natural and synthetic object on the Earth surface and near surface reflects and emits EMR over a range of wavelengths in its own characteristic way according to its chemical composition and physical state. A diffraction grating can be used to spread visible radiation out onto its composite wavelengths. Intensities at discreet wavelengths are then used as indicators of the abundance of specific materials. In remote sensing, there are three kinds of spectra that can be measured for materials. These are absorption or transmission, reflection and emission (Drury, 1987).

The area between 10^{-1} μm and 10 μm, which is important for terrestrial remote sensing, is expanded in Table 2.2 to give more detail.

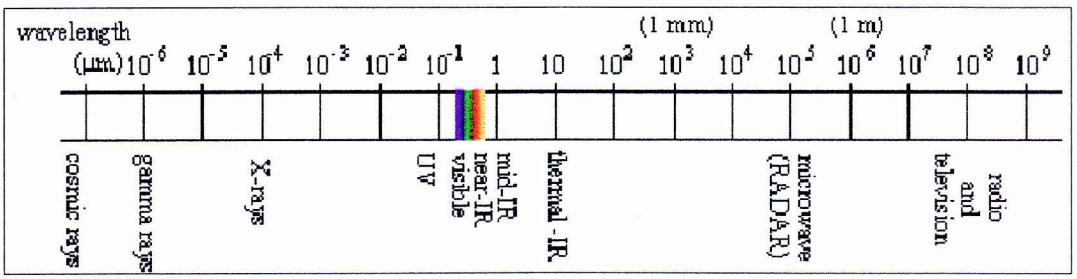


Figure 2.6 The Electromagnetic spectrum. (Lillesand and Keifer, 1994)

Table 2.2 The expanded region between 10^{-1} and 10 μm of the electromagnetic spectrum (University of Nottingham, 2003).

Region	Wavelength
Visible	0.4 - 0.7 μm
Near Infrared	0.7 - 1.3 μm
Mid-Infrared	1.3 - 3.0 μm
Thermal (far) Infrared	3.0 - 5.0 μm; and 8 - 14 μm

The Terra satellite

Sensors from many different satellites or remote sensing platforms can be and have been used for monitoring land features, common examples being Landsat and Spot sensors. However, most of the satellite and aerial images used in this paper and those that have been proposed for replication of results of this project are obtained from the Terra spacecraft. Terra spacecraft data are used because it is a component of the ESE (Earth Science Enterprise). ESE is a an international Earth science program aimed at providing observations, understanding and modelling capabilities needed to assess the impacts of natural events and human induced activities on the Earth's environment (Lillesand and Keifer, 2000). The other reason is that these images were freely available and also covered the area of interest. Two of the five Terra sensors found to be most suitable in terms of spatial resolution and spectral bands for detecting manmade features, like mine tailings, are Modis and Aster.

MODIS and MAS

While it is necessary to mention the Modis (Moderate-Resolution Imaging Spectroradiometer) sensor carried on board the Terra spacecraft, data from the airborne simulator (MAS) were used instead on this project. The Modis Airborne Simulator instrument is an engineering test version of Modis that is routinely flown on board Nasa's ER2 high altitude surveillance aircraft for development and validation purposes.

MAS is a scanning spectrometer that measures reflected solar and emitted thermal radiation in 50 narrowband channels between 0.55 and 14.2 μm (Table 2.3), as compared to the Modis sensor's 36 spectral bands. It is a modified Daedalus multi-spectral scanner configured to acquire digital imagery for the measurement of Earth biological and physical

processes and atmospheric properties (GSFC, 2004). Fifty 12-bit channels of multi-spectral data in the visible, near infrared, mid infrared and thermal parts of the spectrum are recorded (DFRC, 2003).

The ER2 (Figure 2.7) is a high altitude surveillance plane that normally operates at an altitude of 20 km in its mode as a remote sensing platform for testing or validating satellite sensors. The aircraft is adaptable to carry several instruments simultaneously, for flights of up to eight hours duration. The ER2 has been used for research on the photochemistry and dynamics of the lower stratosphere and upper troposphere (DFRC, 2003). Photographs captured at high altitudes on the ER-2s on long duration missions have been remarkable in high resolution imaging of large areas of the Earth's surface in a single flight.

Safari 2000 and MAS

The Modis Airborne Simulator was operated on board the ER2 as part of the of the SAFARI 2000 Regional Science Initiative dry season campaign (Swap *et al.*, 2002a). MAS images were acquired over extensive areas of southern Africa in August and September 2000, as part of a field campaign to validate the Terra Modis. In addition, the ER2 carried two RC-10 cameras, with panchromatic and false colour infrared film. Photographic images covering selected areas along the flight paths were acquired.

MAS and photographic images used in this report were obtained from ER2 Flight 149-09 on 22 August 2000. As part of the flight mission for this day, the ER2 made three parallel east-west passes over the Witwatersrand to acquire comprehensive coverage of the Witwatersrand gold fields, including mine tailings.



Figure 2.7 Nasa's ER2 high altitude surveillance aircraft taking off from Pietersburg International Airport, September 2000.

Table 2.3 MODIS Airborne Simulator (MAS) data channels and spectral ranges (DFRC, 2003).

Spectral Channel	**Spectral Range (μm)**		**Spectral Channel**	**Spectral Range (μm)**
1	0.4451 – 0.4848		26	3.0384 – 3.2000
2	0.5285 – 0.5703		27	3.2066 – 3.3552
3	0.6294 – 0.6805		28	3.3521 – 3.5138
4	0.6816 – 0.7231		29	3.5170 – 3.6709
5	0.7221 – 0.7641		30	3.6724 – 3.8174
6	0.8034 – 0.8461		31	3.8267 – 3.9870
7	0.8460 – 0.8874		32	4.1365 – 4.2034
8	0.8867 – 0.9276		33	4.1365 – 4.2034
9	0.9277 – 0.9674		34	4.3401 – 4.4656
10	1.6163 – 1.6682		35	4.4648 – 4.6160
11	1.6722 – 1.7228		36	4.6184 – 4.7775
12	1.7245 – 1.7752		37	4.7778 – 4.9294
13	1.7768 – 1.8259		38	4.9298 – 5.0767
14	1.8303 – 1.8792		39	5.0888 – 5.2288
15	1.8801 – 1.9288		40	5.2412 – 5.3738
16	1.9312 – 1.9794		41	5.3590 – 5.4365
17	1.9804 – 2.0291		42	8.3391 – 8.7341
18	2.0309 – 2.0793		43	9.4541 – 9.9906

Spectral Channel	Spectral Range		Spectral Channel	Spectral Range
19	2.0794 – 2.1280		44	10.278 – 10.736
20	2.1291 – 2.1774		45	10.776 – 11.247
21	2.1779 – 2.2259		46	11.777 – 12.196
22	2.2278 – 2.2765		47	12.713 – 13.089
23	2.2777 – 2.3265		48	13.041 – 13.500
24	2.3274 – 2.3750		49	13.540 – 14.075
25	2.3764 – 2.4246		50	14.051 – 14.428

ASTER

The Aster (Advanced Thermal Emissions and Reflection Radiometer) instrument consists of three separate scanners, operating in the Visible and Near Infrared (VNIR), the Short-wave Infrared (SWIR) and the Thermal Infrared (TIR) at 15 to 90m resolutions. It has a 60 km imaging swath and is capable of covering each point on the Earth surface every 16 days (Lillesand and Keifer, 2000). A summary of Aster instrument and channel characteristics is displayed in Table 2.4.

VNIR

The VNIR subsystem of Aster has 3 spectral bands operating at visible and near-IR wavelengths and that have a 15 m ground resolution (GSFC, 2003). There are 2 telescopes, one nadir three band detector and the other one a single band (band 3B) backward looking detector. This band set up facilitates for creation of Digital Elevation Models (DEMs) (Lillesand and Keifer, 2000).

SWIR

The SWIR subsystem operates in six spectral bands in the near-IR region through a single, nadir-pointing telescope that provides 30 m resolution (King and Greenstone, 1999).

TIR

The TIR subsystem operates in five bands in the Thermal Infrared region using a single, fixed-position nadir-looking telescope with a resolution of 90 m. It has a whiskbroom-scanning mirror (King and Greenstone, 1999).

Table 2.4 ASTER instrument characteristics. (King and Greenstone, 1999)

Characteristic	VNIR	SWIR	TIR
Spectral range (µm)	Band 1: 0.52 - 0.6 Nadir looking Band 2: 0.63 - 0.6 Nadir looking Band 3: 0.76 - 0.86 Nadir looking Band 3: 0.76 - 0.86 Backward looking	Band 4: 1.600 - 1.700 Band 5: 2.145 - 2.185 Band 6: 2.185 - 2.225 Band 7: 2.235 - 2.285 Band 8: 2.295 - 2.365 Band 9: 2.360 - 2.430	Band 10: 2.360 - 2.430 Band 11: 8.475 - 8.825 Band 12: 8.475 - 8.825 Band 13: 10.25 - 10.95 Band 14: 10.95 - 11.65
Ground resolution (m)	15	30	90
Swath width (km)	60	60	60

Aerial photographs

High-resolution aerial photographs of the Witwatersrand, taken during the same campaign, were used. These images are from two camera systems flown with a two different film types acquiring photography at different spectral ranges. These are the RC-10 Mapping Cameras, the Wild Heerbrugg RC-10 Mapping Cameras (Table 2.5). Films used were visible panchromatic and false-colour infrared.

Table 2.5 Summary of camera specifications. (DFRC, 2003)

Camera Type	Lens *	Film Format *	Ground Coverage	Nominal Resolution	Scale
RC-10	6"/f4	9" x 9"	30 x 30 km	3 – 8 m	1:130,000
RC-10	12"/f4	9" x 9"	15 x 15 km	1.5 – 4 m	1:65,000

** Non-SI units used as these values are manufacturer's designations.*

Chapter 3
Methodology

This chapter deals with sources and data parameters acquired for use in this project. The various techniques applied to bring these different data sources together are explained. The range of image processing techniques applied to the acquired MAS images is outlined. The main aim of this chapter is to develop techniques and procedures that would be most successful in selecting tailings from other features and materials in the area. These techniques are tested on validation sites.

The procedure to identify and determine the status of tailings impoundments involves:

- Finding a suitable sample that would represent tailings impoundments in the area
- Use of remote sensing techniques on satellite images to scan sample sites
- Assessing the entire study area using techniques developed on the sample sites and comparing the outcomes to sample sites.

Remote sensing techniques selected include:

- correlation plots of two selected MAS bands
- plotting of spectral signatures all the MAS bands against selected surface features found on the area, such as mine tailings, to assist in selecting which bands to use in other processes
- Visual analysis of RGB images of selected MAS-band composites
- Principal Components analysis to express the data in such a way as to highlight similarities and differences, in this case tailings against non-tailings.
- Application of classification techniques to distinguish tailings impoundments and status from other features found in the area.

For the creation of maps and databases, information from different organisations is used to construct a comprehensive map of the area through a GIS and determine the names, owners and status of tailings impoundments. The names and status of tailings impoundments are attached to the shape files created. The first stage of the database is then complete. The second stage is to use the developed remote sensing techniques to assess the whole area and then enter the new status of tailings impoundments on the database. The end result is to print the database onto an accessible format like MS Excel and also create a map of the status of tailings impoundments.

Site inspections, visual analysis and archive data

Ground survey

Mine tailing impoundments are classified in the following categories: active (deposition taking place), fully rehabilitated, un-rehabilitated, partly rehabilitated, partly reprocessed, or currently being reprocessed. A few selected mine tailings impoundments to be used as a training and validation set were visited and notes were made on the surface conditions and activity status (Figure 3.1). A hand-held GPS was used to capture the global coordinates of the visited areas, to be fed into the GIS. Visual inspection and photographic recordings of the conditions were obtained for use in validating the remote sensing images.

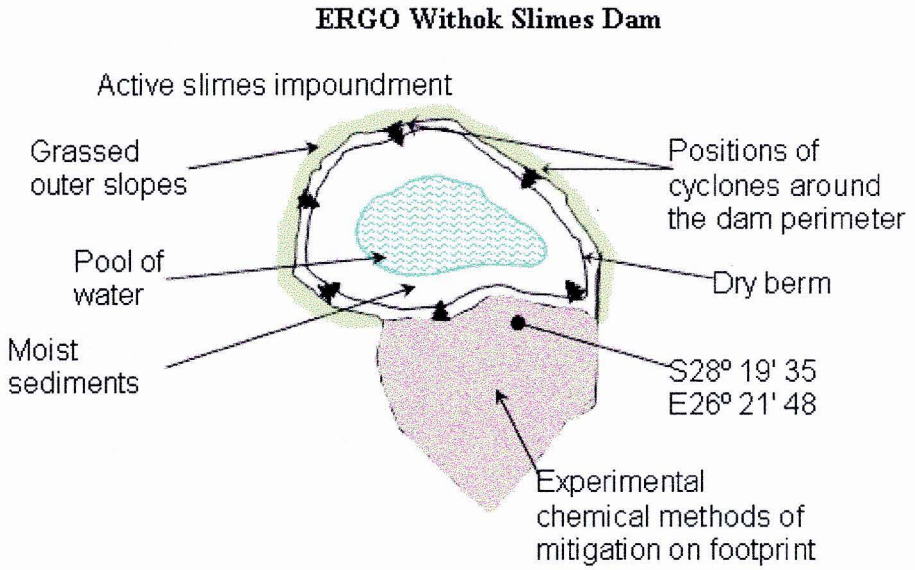


Figure 3.1 Notes and sketch from one of the tailings impoundments (ERGO Withok) showing the sort of detail captured while carrying out field work.

Aerial photographs

An analysis was carried out on geo-referenced aerial photographs captured using RC10 cameras (DFRC, 2003). These were used to source the impoundment areas and to locate positions of some of the impoundments that were not clearly indicated on the maps collected from mining companies. Aerial photographs were preferred for calculating areas because of their high spatial resolution that enabled visualisation of very fine details on tailings impoundments (Figure 3.2).

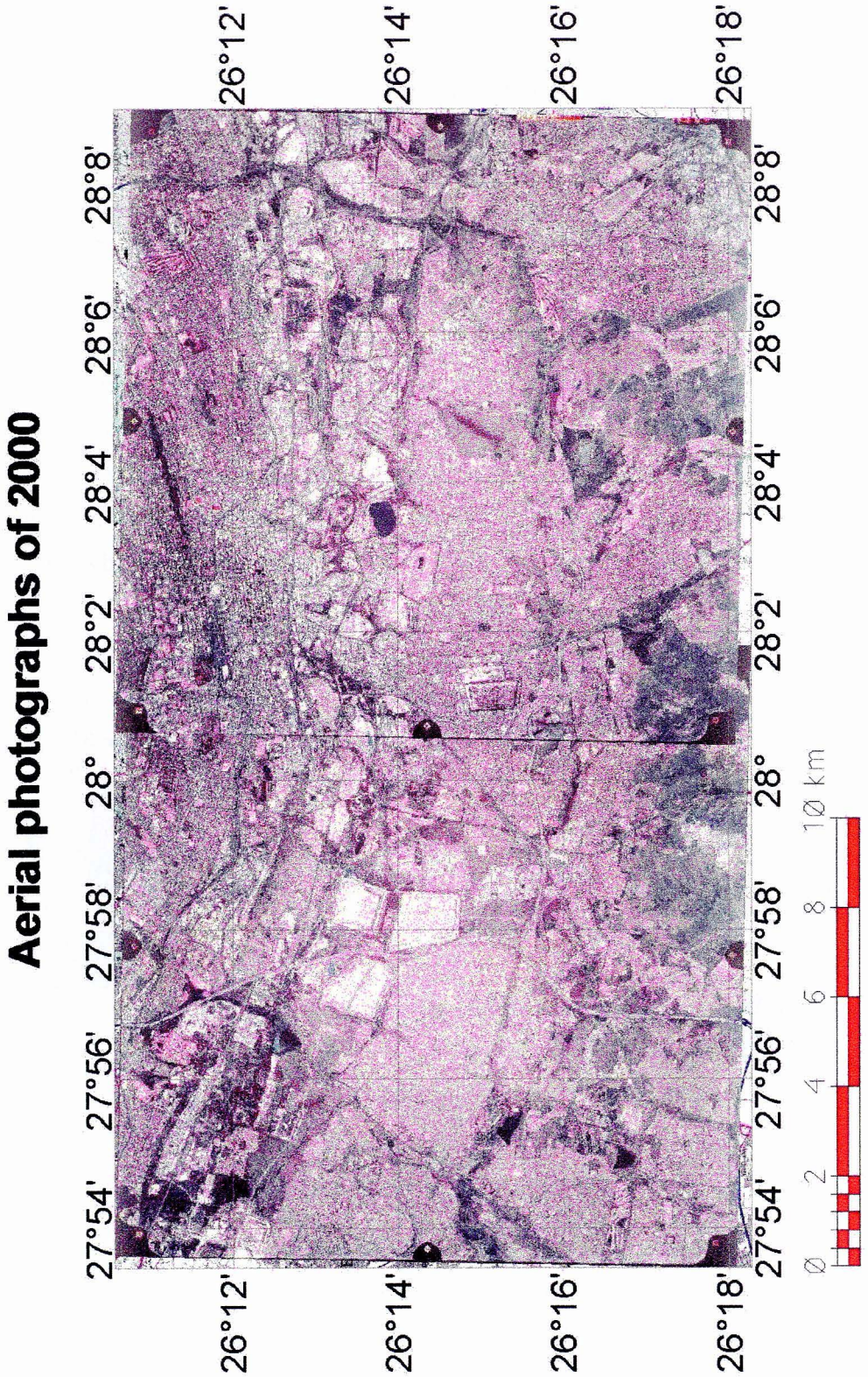


Figure 3.2 An aerial photograph of the Central Witwatersrand taken from the ER2 aircraft, 20 km altitude. (Data courtesy of Nasa Ames Research Centre.)

Archive data

Data in map and spreadsheet formats were obtained from ERGO, Crown Gold Recoveries and the Department of Minerals and Energy (Figure 3.3). These two companies represent some of the responsible mine owners and records for impoundments within their ambit are reliable. They are also the two largest operators of surface mining on the Witwatersrand and own or manage over 80% of the total impoundments. The DME data have been compiled from many diverse sources and are less reliable due to unspecified times at which data were acquired and absence of documentation as to completeness of the records.

The incomplete maps were scanned and saved as Tiff images. The Tiffs were imported into the GIS and image processing software package TNTmips® (Microimages, 2001). These maps were then geo-referenced using points collected using a GPS sensor and geo-referenced topography maps. A vector object covering the whole study area was created on TNTmips based on these maps.

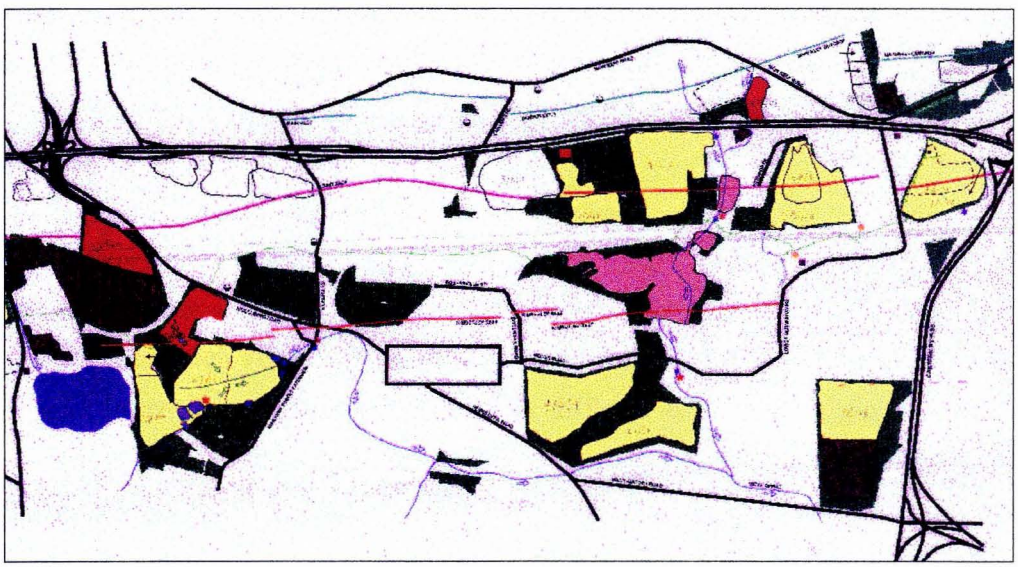


Figure 3.3 Example of the hardcopy maps that were imported into a TNTmips GIS software and geo-referenced. (Credit: Crown Gold Recoveries.)

A new list of tailings impoundments was put together from databases collected and entered into MS Excel. The databases were used to source the names and the reference numbers of the tailings impoundments (Table 3.1). Information from the database was also used to create the initial attribute maps on the GIS.

Table 3.1 Example of the Department of Minerals and Energy database of mine tailings.

Anglogold Mining Plan Link Data: June/July 2002 Pg 4				
Slimes		Permits		
Old Number	New Number	SRP Number	D/P Number	Status of Dump
7L8	2628 AD/L/18		17/75	Footprint, rehab
7L9	2628 AD/ L/19		14/75	Footprint, rehab
7L10	2628 AD/L/25		13/75	Footprint, rehab
7L15	2628 AD/L/13	168/91		Part footprint, part not reclaimed

(Printout obtained from Department of Minerals and Energy, Braamfontein Office.)

Remote sensing and statistical analysis

Specific wavelengths were selected for the creation of RGB band composites, inputs for statistical techniques and inputs for classification processes. These channels were chosen for their ability to select and differentiate mine tailings impoundments from the rest of the built up environment of the Witwatersrand (Table 3.2).

RGB colour composites

Image representations can be constructed in different forms in remote sensing. Colour images are one such representation that is commonly used. To create a RGB colour composite, three images have to be taken in different wavelength regions. These are combined additively red, green, and blue colour bars in the same chromatic order. Different colour combinations are used. Although these often have nothing to do with the real intrinsic colours of the shown object they are used to enhance the visible range of intensities in the image. Small differences in intensity are easily visible if they are presented with different colours (Smith, 2001).

Table 3.2 Selected MAS bands that were found to be appropriate for the study and were used on image processing (King *et al.*, 1996).

Spectral Channel	Spectral Range (μm)	Primary Use
1	0.4451 – 0.4848	Distinguish soils from vegetation
2	0.5285 – 0.5703	Plant vigour/ Water surfaces
3	0.6294 – 0.6805	Soils/ Suspended sediments
4	0.6816 – 0.7231	Vegetation types/ Clouds
5	0.7221 – 0.7641	Biomass content/ Mapping shorelines
6	0.8034 – 0.8461	
7	0.8460 – 0.8874	
8	0.8867 – 0.9276	
9	0.9277 – 0.9674	
10	1.6163 – 1.6682	Moisture content of soils & vegetation/ Clouds/ vegetation types
12	1.7245 – 1.7752	
14	1.8303 – 1.8792	Water vapour
17	1.9804 – 2.0291	Hydroxyl ions in minerals
18	2.0309 – 2.0793	
21	2.1779 – 2.2259	Quartz
42	8.3391 – 8.7341	SO_2/ Coal seams/ Fire detection/ Moisture patches
45	10.776 – 11.247	
46	11.777 – 12.196	

Raster correlation and band statistics

Raster Correlation calculates a correlation histogram between two raster objects. The results of this calculation give a visual sense of the level of similarity between geo-referenced pairs of multi-spectral and multi-temporal images. One of the advantages with carrying out this operation is that when a high degree of correlation is registered, one of the

two bands can be dropped from a set of processing raster objects (Richardson and Weigand, 1977; Motulsky, 1999).

The correlation histogram uses both position and colour to show the relation between two raster objects. For instance, a correlation histogram between two similarly geo-referenced channels of MAS image was calculated and plotted (Figure 3.4). The process counted how many instances there were of each possible coordinate pair, for example of the red value when the mid infrared is at a specific grid value (Richardson and Weigand, 1977).

The channels used on the histogram are MAS 3 (Red) and MAS 7 (Near Infrared). MAS 3 was selected because of its sensitivity to vegetation. Chlorophyll is strongly absorbed and green vegetation appears darker than in the other visible light bands. This absorption feature can be used to differentiate different vegetation types. This channel can also be used for soil colour (Smith, 2001). On MAS 7 green vegetation appears brighter than in any of the visible channels. This would be important in identifying different species of plants and grasses planted on and around tailings dams (Smith, 2001).

Figure 3.44 demonstrates a two dimensional comparison of the visible and the near infra red reflectance for varying materials that include water, roads, vegetation, tailings dam materials and other manmade materials. There are several distinct clusters of points (circled A through F), in addition to the main correlation zone (red and green colouration), possibly indicating extensive areas covered by materials of similar properties in the two wavelengths. Vegetation, which has a higher reflection in the infrared and a lower reflectance in the visible, would plot around areas indicated by **A** and **B**. The non-vegetative materials show an increased reflectance in both channels and they would plot around areas indicated by **C** and **D.**

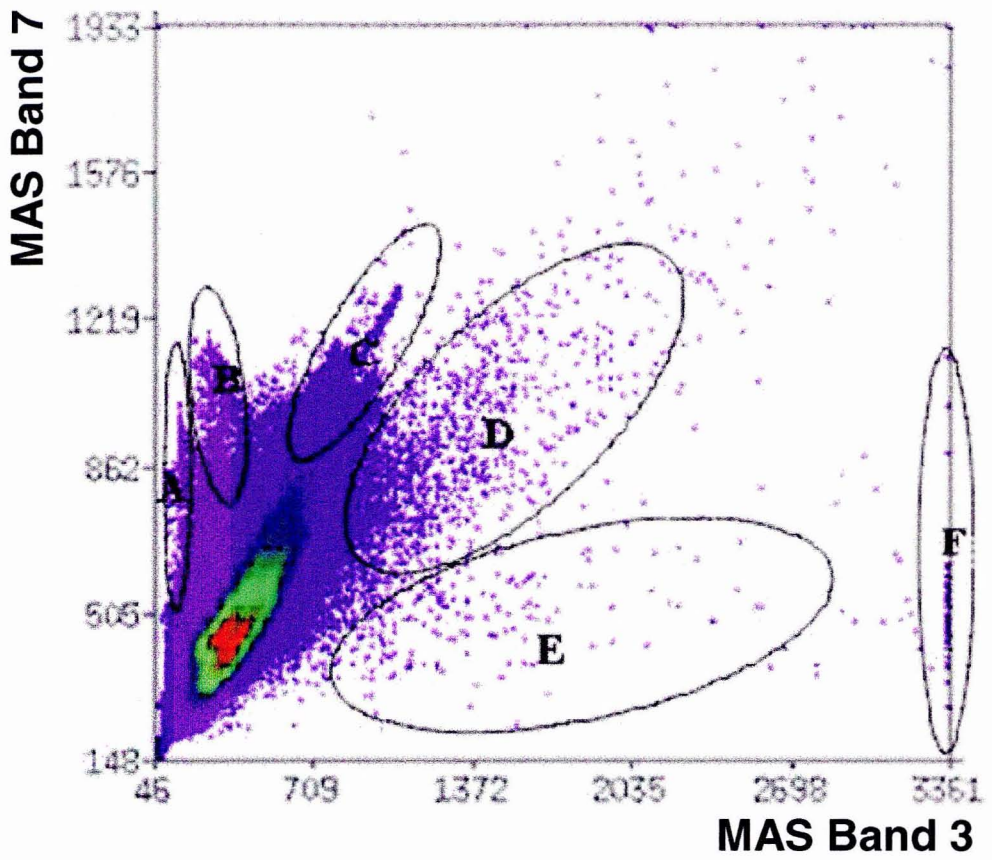


Figure 3.4 A scatter plot of channel 7 versus channel 3 of a MAS image, demonstrating multimodes in the distribution.

Vegetation has a very low reflectance in the visible part of the EM spectrum because of absorption by chlorophyll. In the near infrared part of the EM spectrum reflection is higher because of scattering by the leaves' internal spongy mesophyll layer. Compared to vegetation reflectance, other surfaces like soils, roads and buildings have similar reflectance in the visible and the near infrared wavelength (Figure 3.5). Healthy vegetation has a low reflectance in the blue and red and a slightly higher green reflectance (Harris, 1987). In the near infrared, reflectance of vegetation is higher. As vegetation gets older or leaves begin to die, the ability to absorb visible light through chlorophyll decreases and as a result reflectance is increased. Hence stressed vegetation has a higher reflectance than healthy vegetation in the visible. The mesophyll of leaves contracts in old age or stressed conditions, causing a reduction in the density of air spaces and therefore resulting in reduction also of reflectance in the near infra red (Harris, 1987).

Water almost has no reflectance at wavelengths higher than 0.7 μm unless there is a high sediment concentration and a high reflectance in the shorter wavelengths. The distinctive spectral signature of water is shown in Figure 3.5.

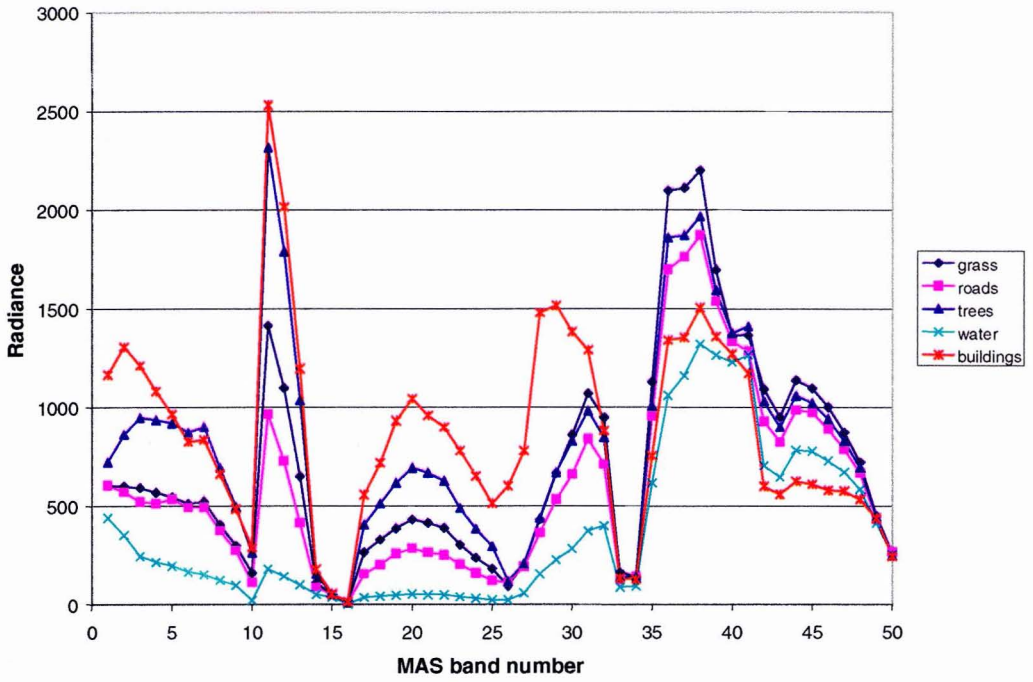


Figure 3.5 A plot of spectral signatures over the 50 MAS bands of the following common ground cover: trees, grass, water and buildings.

The soil reflectance curve varies according to chemical and physical properties. Some of the factors that have an effect on soil reflection are soil moisture, organic matter, iron concentration, texture and surface roughness. Reflectance of soil increases from the visible to the near infrared. However the degree of increase depends on whether soil is dry or wet (Figure 3.6). Generally dry soils have a higher reflection than wet soils at the same wavelength (Harris, 1987).

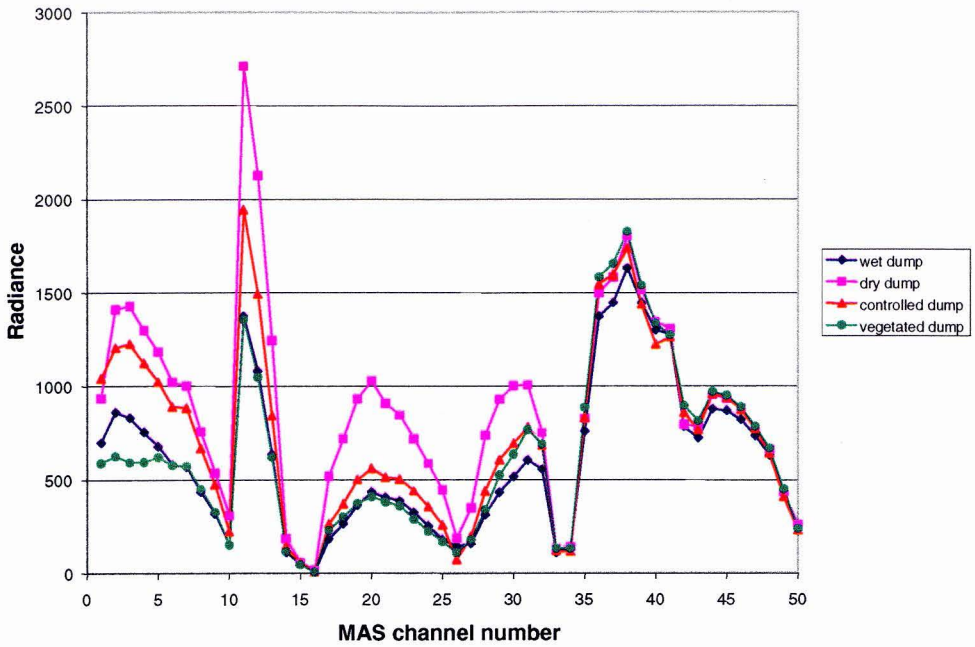


Figure 3.6 Spectral signatures of mine impoundments that are wet, dry, vegetated and controlled respectively.

Spectra from different features found in the Witwatersrand are displayed on Figure 3.7. These spectra can be used to pick out specific features on the land surface as each object has a unique curve. Where there are difficulties in separating tailings material and buildings visually, use of spectra is useful.

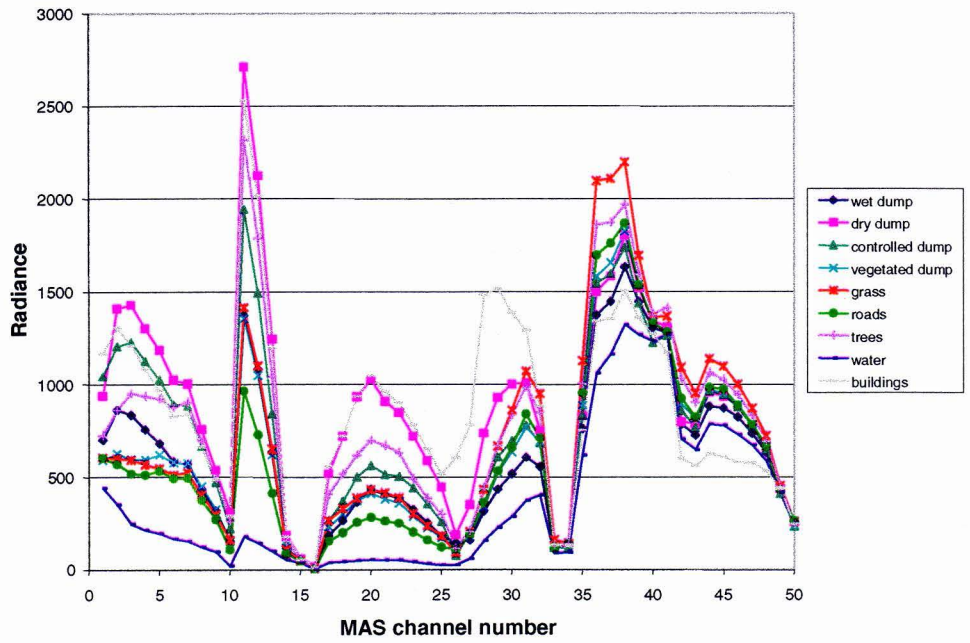


Figure 3.7 Spectra from tailings impoundments and other non-tailings materials.

Principal components

Principal Components analysis is a procedure for transforming a set of correlated variables into a new set of uncorrelated variables (Robinson, 2003a). It involves finding mathematically a new set of variables which describes variance of the original data set, but which are independent of each other (Harris, 1987, p. 89). The Principal Components statistical technique for reducing dimensionality of correlated multi-spectral data is used. The process can be used with many correlated rasters to create a smaller number of objects. For instance, information can be compressed from six Landsat (TM) bands to three transformed images that contain practically all of the variance from the set of input objects. An RGB display of the output can be created to form an image that is easier to interpret. Details that are unnoticed in raw data are often clearly seen through the transformation (Jensen, 1996). Figure 3.8 illustrates the concept of correlation scatter of new raster objects derived from principal component analysis of bands 1 and 2.

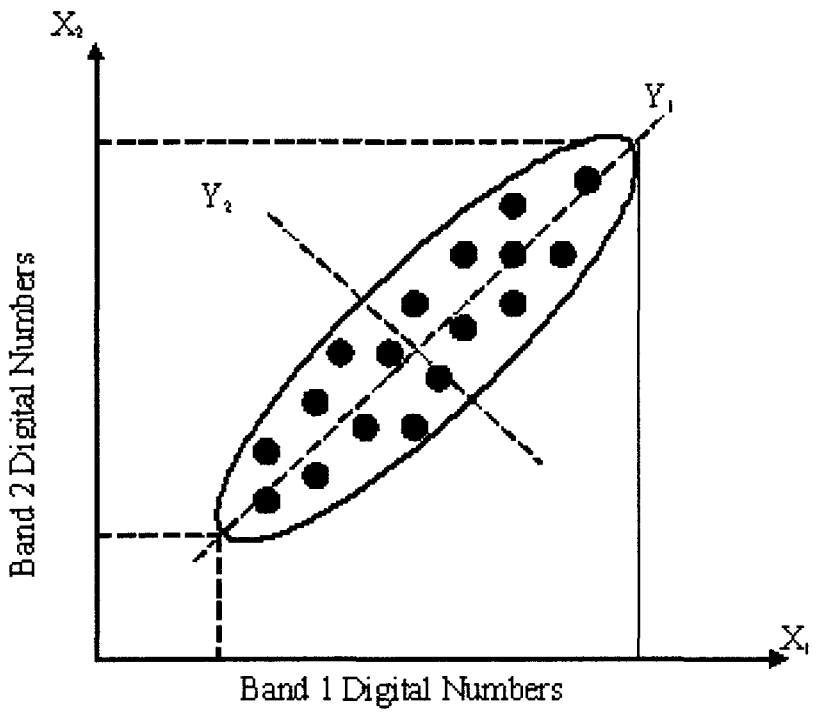


Figure 3.8 Scatter plot of band 1 (X_1 axis) and band 2 (X_1 axis) showing correlation between these bands. The principal components transformation was used to generate a new coordinate system (Y_1, Y_2).
(After Sabins, 1987, Figure 7.23)

One of the aims of the Principal Components analysis is to translate the origin and rotate data axes to better fit the brightness values of input objects. In the ideal case, after rotation there should be no correlation between the new variables defined by the rotation (Robinson, 2003a). For example, the first component accounts for most of the variance in the original data. The other input objects contain decreasing amounts of the variance in the information set (Jensen, 1996). A set of linear transformation coefficients are derived from a covariance matrix of the original data and applied to the input objects to generate a lesser number of output objects that encompass most of the variability of the information set.

A Principal Component analysis extends and automates the manual process adopted earlier, of examining the spectral signatures of various objects and identifying bands or spectral regions of maximum difference between features. While the Principal Component analysis reduces the full data set to smaller dimensionality, it does not assist in defining what the principal components represent. This remains a matter of interpretation and judgement on the part of the analyst.

Unsupervised classification

In unsupervised classification the algorithm uses a set of rules to automatically find the desired number of naturally occurring spectral classes from a set of input rasters (Skrdla, 1999). There are different classification methods with different rules. The result of the classification is kept in a class raster. This is a categorical raster on which numerical values in the rasters are a random class identifier that have been assigned to the cell by the process. One of the classification methods found in the software to be used is the *K-means*.

Classification via K-Means

The algorithm analyses the input raster set to determine the location of initial class centres. Cells are assigned to the nearest class and new class centres are calculated in each process. The new class centre minimises the sum of the squared distances between the points in the class and the class centre. Class centres shift with each process until the shift in class centres fall below a specific value.

Supervised classification

In contrast, analysis by supervised classification starts out with properties of a known sub-set of objects. In a supervised classification, training data from ground truthing is provided to define the initial axes. This training set raster identifies representative sample areas for

each of the desired output classes. The algorithm determines the statistical properties of each of the training classes and then uses them to classify the whole image. Some of the supervised classification methods found in TNTmips as standard tools include the *Minimum Distance to Mean* (also known as the Mahalanobis) and the *Maximum Likelihood* procedures.

Mahalanobis

Mahalanobis is a supervised classification method that is used for determining the similarity of a set of values from an unknown sample to a set of values measured from a collection of known samples. Mahalanobis is useful in that it is very sensitive to inter-variable changes in the training data. In addition, since the Mahalanobis is measured in terms of standard deviations from the mean of the training samples, the reported matching values give a statistical measure of how well the spectrum of the unknown sample matches or does not match the original training spectra (Smith, 2001).

Maximum Likelihood

Maximum Likelihood is a supervised classification method. It works out a class assignment for each cell on the basis of variance and correlation of cell values in the training set classes that are provided. The algorithm interprets the cell values in each training set class as having a Gaussian distribution. The resulting distribution can be described by the mean vector and the covariance matrix. It has no user-defined parameters (Skrdla, 1999). The Maximum Likelihood method works like the Minimum Distance to Mean method in the sense that they incorporate the variability of raster cell values within each training class (Skrdla, 1999).

Applications of these techniques to the acquired data sets are presented in the following chapter.

Chapter 4
Results

Results of the study are presented in this chapter, in the form of products of image processing. While going through the experimentation process, there are results that were successful, promising and those that were not so successful for reasons that the algorithm is not suited to the dataset, inappropriate bands are used or further tests are still needed with the input bands and the output parameters. Nevertheless all the results are presented as they all play a role in explaining what is feasible when dealing with satellite data on the Witwatersrand area as well as what challenges were encountered.

Image analysis was carried out through previously described methods that include band composites, RGB composites of principal components and unsupervised and supervised classifications. These were aided by information from known areas that were used as training sets. Each of the analysis procedures, for instance band composite MAS 3 MAS 2 and MAS 1, has a half a page description of what information can be extracted successfully from the image, or in what way the image does not successfully separate features of interest. On the following page is an image for the whole study area derived using this procedure, followed by expanded images of the four validation areas that had been selected for ground truthing, that is, the ERPM slimes dams (4/L/47, 4/L/48, 4/L/49 and 4/L/50) in Boksburg, the Ergo slimes dam (Withok) south of Springs, the Crown Gold Recoveries complex south west of Johannesburg (3/L/5, 3/L/7 and 3/L/8) and the Robinson Deep (3/L/32) slimes dams.

Three of the training sites were chosen because they are by far the three largest impoundments in the area, likely to provide the best statistical result for the training sets, and then a fourth known impoundment (Robinson Deep) was used because it was covered with vegetation. The ERPM (4/L/47, 4/L/48, 4/L/49 and 4/L/50) tailings dams were not being actively used in 2000. There was no vegetation or any kind of mitigation on it at the time of fieldwork. The surface had dry slimes that were susceptible to being blown by dust. On the sides there were signs of unchecked water erosion taking place.

The Ergo Withok tailings dams had two parts on it. One part of the impoundment (northern section, Figure 3.1) was being actively used. The structure of the dam was such that there was a large depression filled with water in the centre, with steep sides topped by cyclones for classifying the slimes aggregates pumped from the processing plant. As a result, this dam had a pool of water on the centre and high sidewalls, which dried rapidly. The southern part of the complex was a footprint where most of the material had been removed for gold reclamation, and where experimental chemical means of rehabilitation were being tested. This impoundment represented an active tailings dam and also a footprint with a different method of amelioration.

The three Crown Gold Recoveries (3/L/5, 3/L/7and 3/L/8) tailings dams were being deposited on at the time of the fieldwork. The lower sections of the sidewalls were covered with vegetation, while roadways and exposed areas had small water jets to keep the dust down. The top surfaces were mostly wet because of deposition of fresh slimes. This complex represented active slimes tailings with a different method of deposition to the Ergo impoundment.

Lastly, the Robinson deep (3/L/32) slimes dam represented a well-vegetated impoundment. It was thickly covered with vegetation on the tops and sides with slight areas being bare of vegetation.

Each of the images displayed is an aspect of the big picture of attempting to explain what is happening to tailings impoundments in the area. These all contribute to the information displayed on the last two images: the location of tailings impoundments, their condition, and the final classified status of each. The other important result is the database that contains information on the ownership, name, location, size and condition of all surveyed impoundments. The database is presented in Appendix Band as an electronic MS Excel spreadsheet on an enclosed CD Rom.

Ground data and aerial photograph results

Area by area analysis of the maps, sketches and fieldwork led to the development of the preliminary status column on the database (Appendix B) and the preliminary condition of the impoundments map (Figure 4.1).

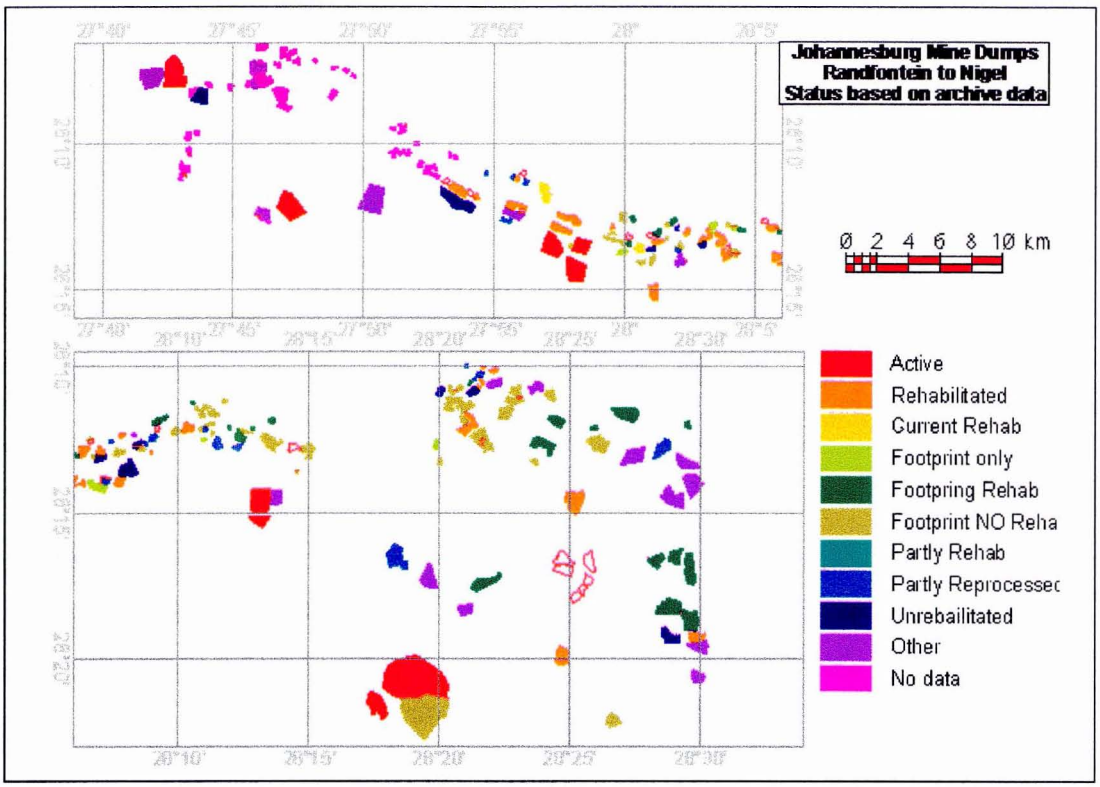


Figure 4.1 Preliminary classification of tailings dams based on maps and databases collected from mining houses and the DME.

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Remote sensing analysis and interpretation

Band composites analysis

On the band composite displays, the zoomed up image has arrows indicating aspects and condition of tailings impoundments. The arrows point at similar features on different images and the colours of these indicated features change with each composite. This illustrates the sensitivity of the bands on features of interest and how they are displayed on RGB additive colours. Some of these composites show many features clearly and some show only some.

Band composite MAS 3(R), MAS 2(G) and MAS 1(B)

A combination of the three visible channels in the blue, green and red part of the electromagnetic Spectrum MAS {3, 2 and 1} yields a colour composite illustrating natural colour. Also indicated on the image are the locations of the different groups of tailings dams that were used as sample sites (Figure 4.2a and 4.2 b).

Tailings dams can be identified using their unique size shape and also how they interact with the electromagnetic radiation. Dry impoundments appear white however there are other objects that reflect similarly in this band combination. Wet dams and footprints appear yellowish to brown in colour and water on tailings material appears a dark green. Tailings dams have a regular shape that is easy to identify even at the scale required to fit the whole area onto an A4 page.

The Crown Gold recoveries tailings dams offer an interesting comparison with the neighbouring Diepkloof suburb. These tailings are light grey coloured against the darker grey settlement. Known footprints have a more brownish grey colour as compared to tailings.

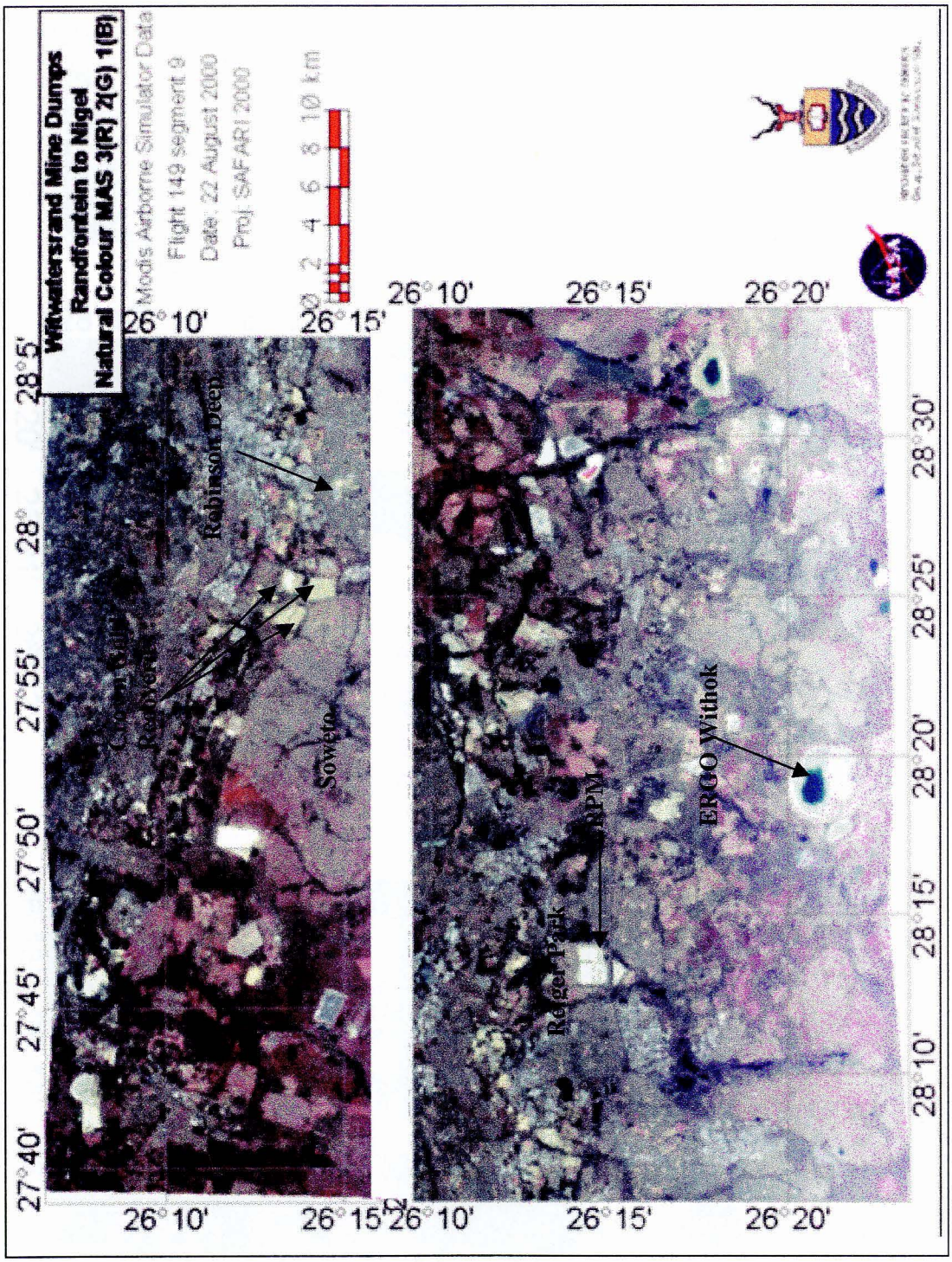


Figure 4.2a Colour composite of MAS {3(R), 2(G) and 1(B)} depicting natural colour. (Data courtesy of Nasa GSFC.)

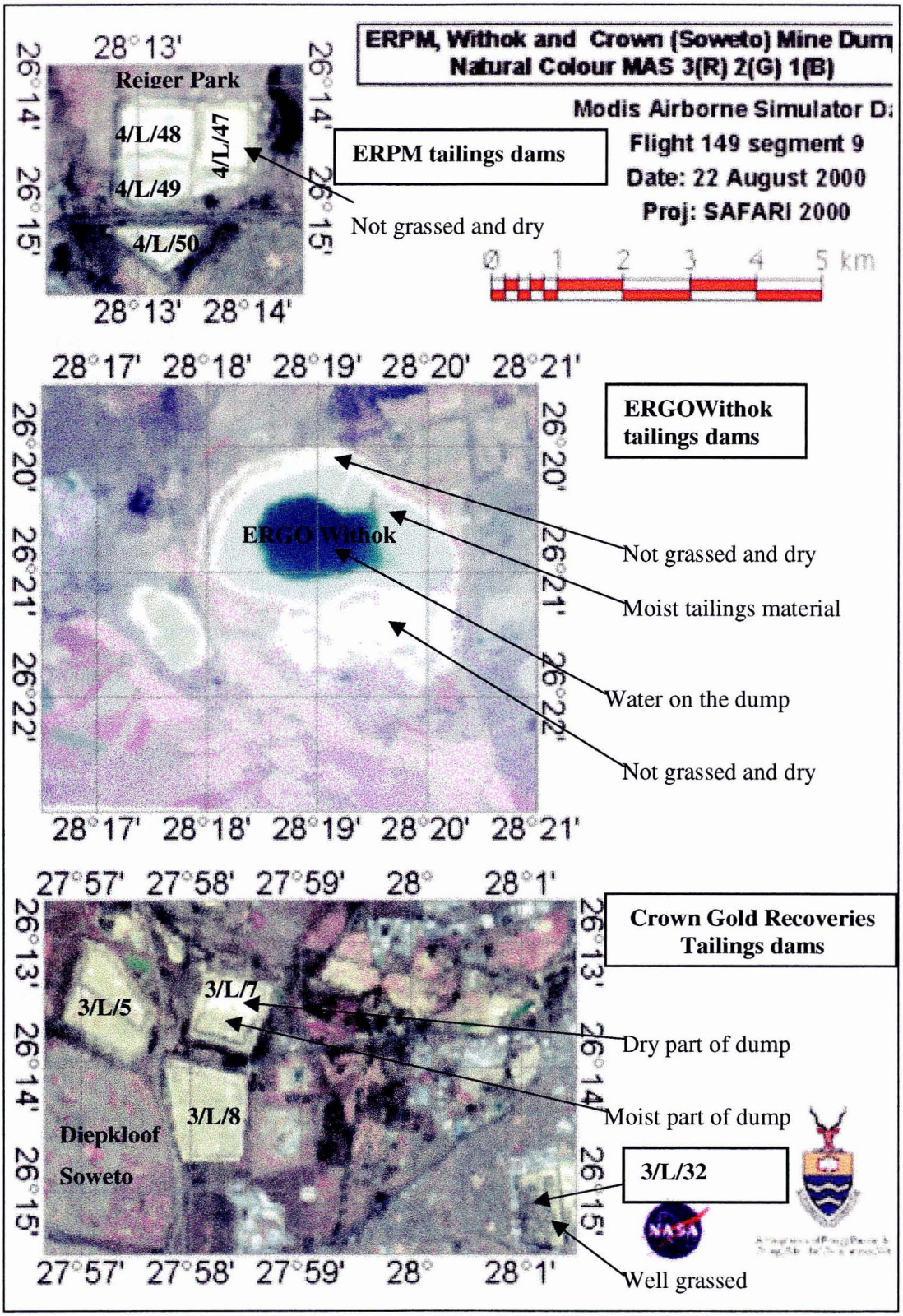


Figure 4.2b Selected sites of the Witwatersrand area, MAS {3 (R), 2 (G) and 1 (B)}. (Data courtesy of Nasa GSFC.)

Band composite MAS 21(R), MAS 7(G) and MAS 3(B)

On the RGB colour composite MAS {21, 7, 3} (Figure 4.3a) the ERPM tailings dam an, example of dry tailings, appears white to grey. The outline of the dam is clearly etched on the surrounding piece of land. There is very little vegetation observed around the perimeter of the tailings impoundments. The shack settlement surrounding this tailings impoundment can be distinguished from it and appears brown. There is a green area on the edges of the tailings that appears to be vegetation.

The Ergo tailings dam in the middle of the page (Figure 4.3b) can also be easily identified using the spatial characteristics. There is less green material around the dam. The edge appears as a white outline around the blue and dark blue spheres which make up the impoundment. From the satellite images, the white outline represents dry material in the same way as on the ERPM dams. From the white outline inwards, the blue material represents moist tailings material. There is no evidence of moisture on the ERPM dam. In the centre of the Ergo dam is a pool of water that appears to be black. There is no evidence of green colour around the Ergo dam, which indicates that the level of vegetation that they have planted on the impoundment has not reached detection threshold level. Next to it is a relatively smaller Rooikraal impoundment, which appears dry but with moisture indications on the surface.

Extrapolating this interpretation to the tailings impoundments spread on the area, it can be concluded that on this band composite, all tailings looking white are dry tailings impoundments. Those tailings that have a bluish colour on them can be classed as wet tailings and on these images the wetness is caused by active slimes deposition. There is a little vegetation around the impoundments. There are no clear difference between the vegetation around tailings impoundments and the anthropogenic forest in the northern suburbs of Johannesburg.

The MAS {21, 7 and 3} composite is fairly informative with respect to tailings impoundment information. Successful feature identification can be made on it.

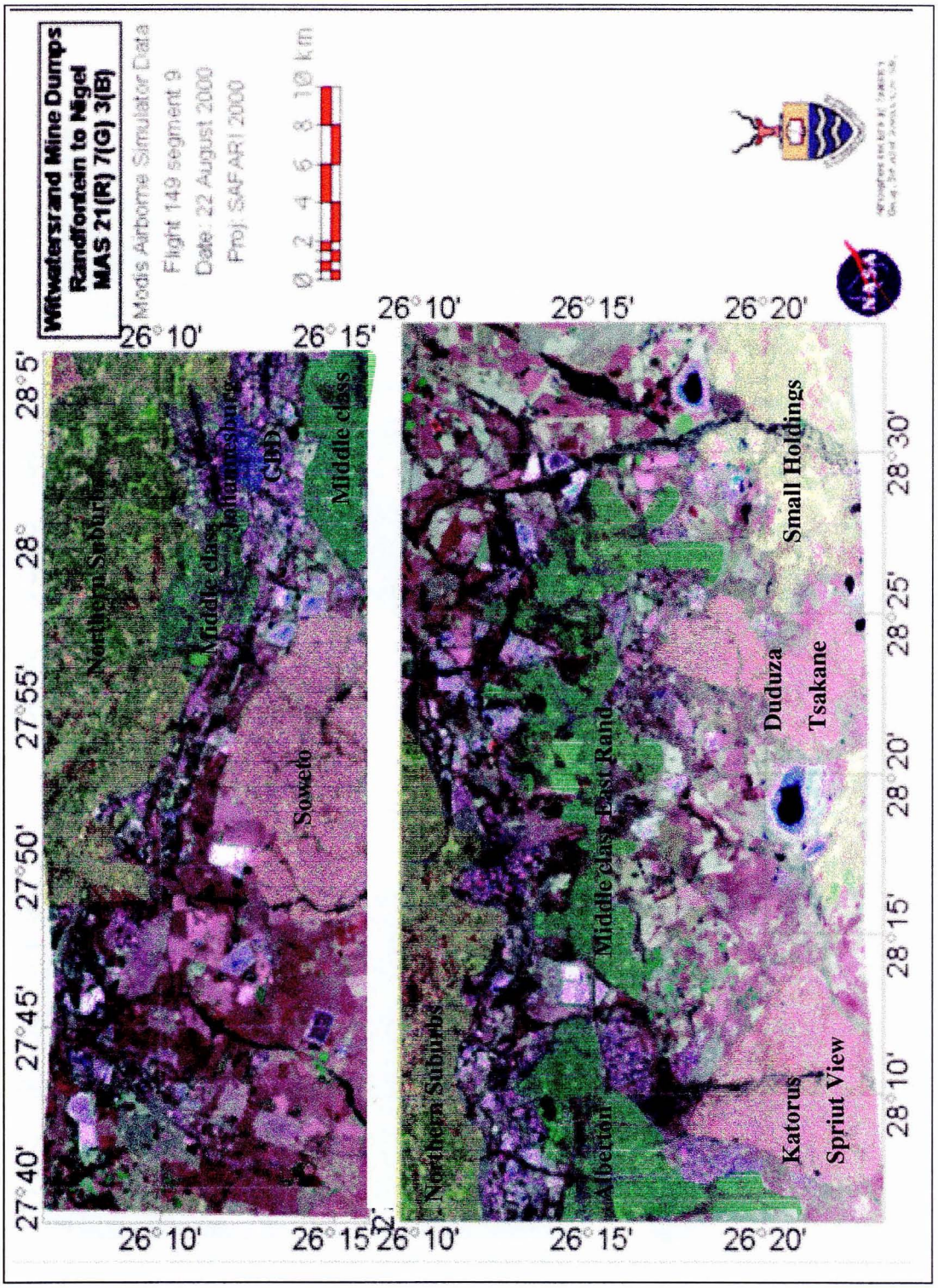


Figure 4.3a MAS {21(R), 7(G) and 3(B)} colour composite. (Data courtesy of Nasa GSFC.)

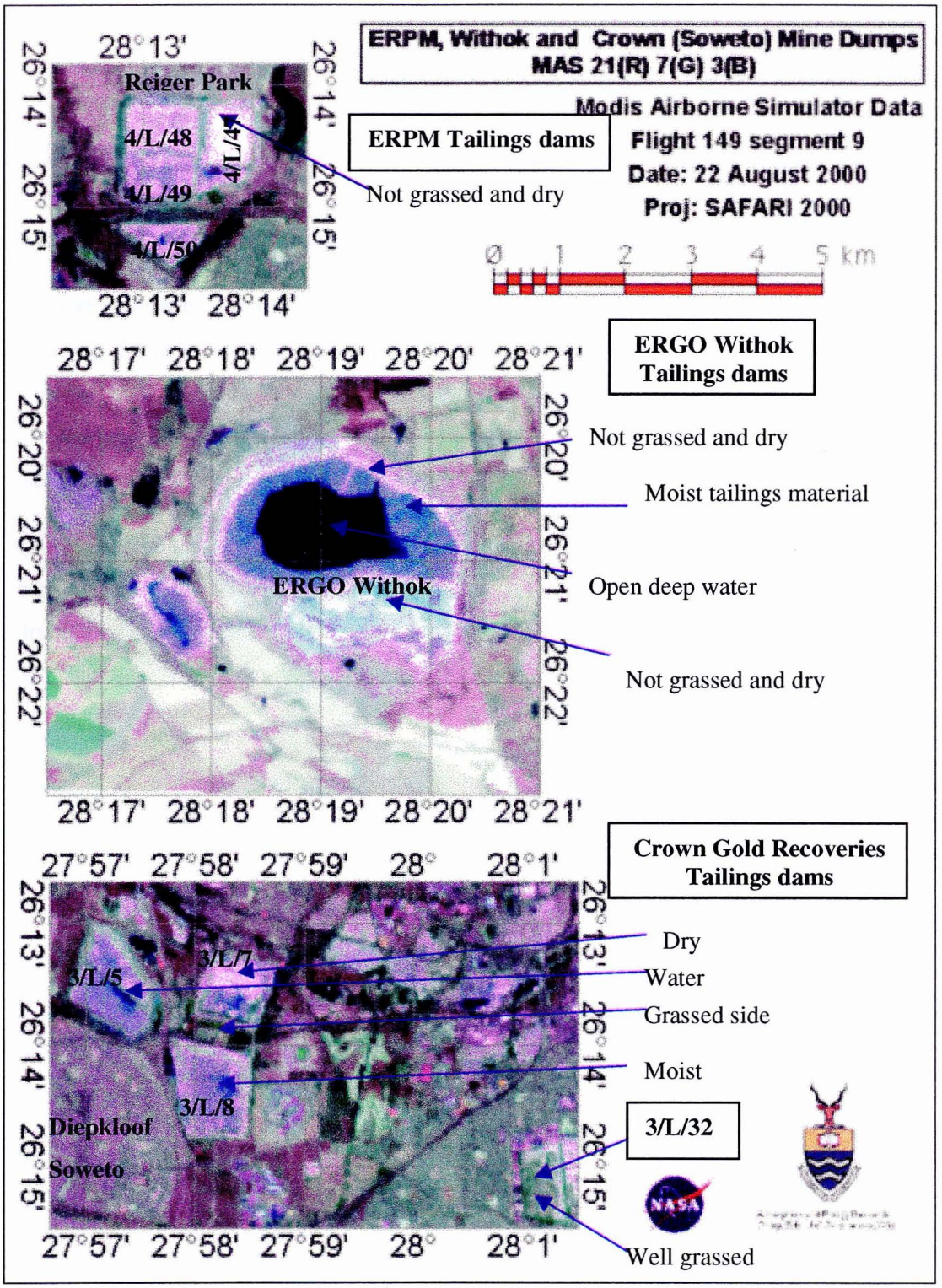


Figure 4.3b A Colour composite of selected sites in the area made up of MAS {21 (R), 7 (G), 3 (B)}. (Data courtesy of Nasa GSFC.)

Band composite MAS 18(R), MAS 12(G) and MAS 1(B)

The MAS {18, 12, 1} RGB false colour composite shows dry impoundments as white (Figure 4.4a). This composite seems to be more sensitive to moisture as some of the ERPM (4/L/49 and 4/L/50) dams appear to have areas with moist material. Here moisture takes several levels of blue. For example the same shades of blue can be seen on the Ergo Withok slimes dam showing different amounts of moisture.

Positive vegetation identification cannot be made on this composite as compared to figure 4.3a and figure 4.3b. Here vegetation has a greyish colour that other features have so it becomes inseparable to these. For instance a known vegetated impoundment on the south of Johannesburg has the same colour as the environment around it. Some of the areas in this environment are known to have no vegetation.

On this composite, dry tailings impoundments appear a bright white. Moisture and water take shades of blue to dark blue. This composite has been successful in mapping moist and dry tailings material, therefore it can be used to identify impoundments of active deposition and abandoned or impoundments that are being reprocessed.

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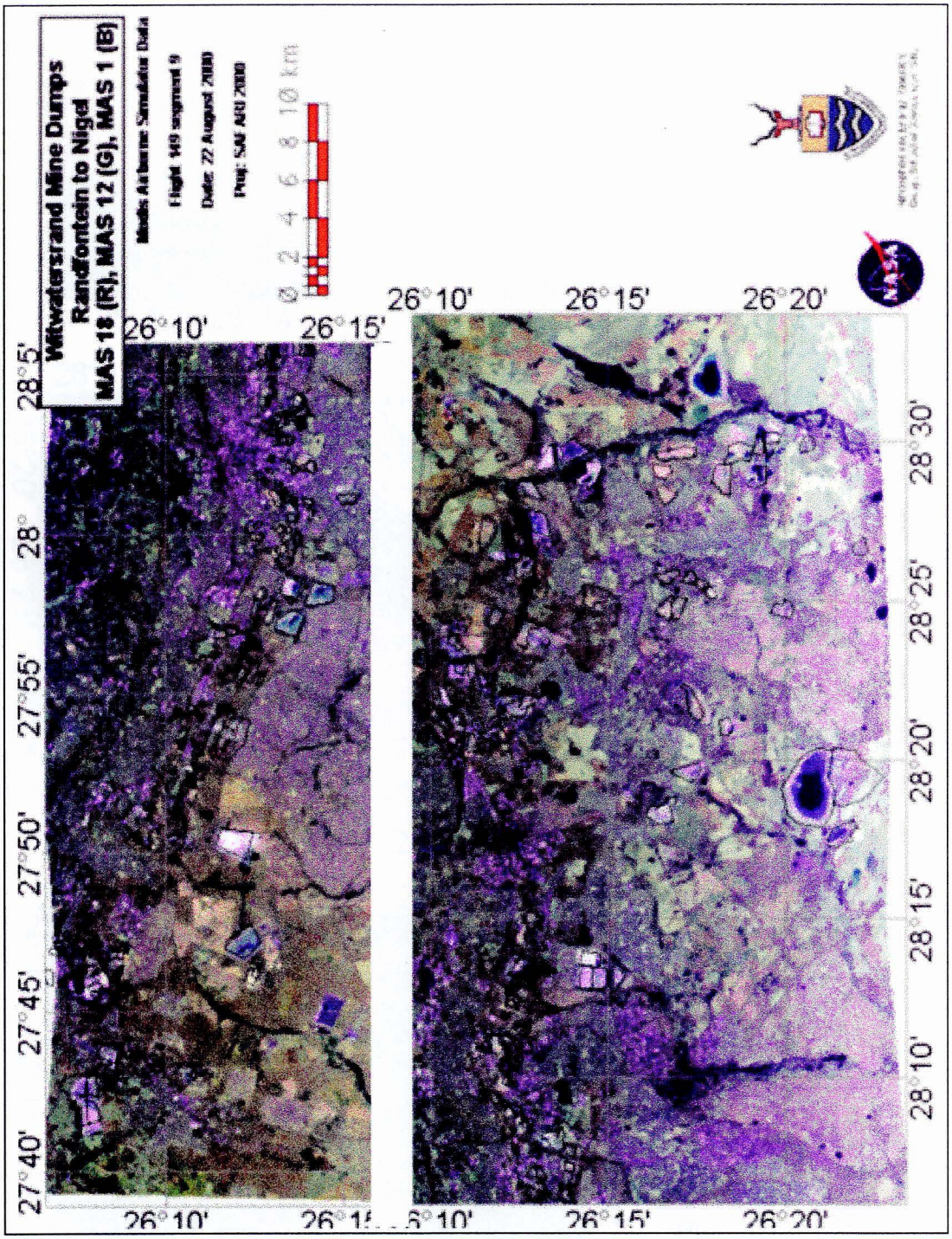


Figure 4.4a MAS {18(R), 12(G) and 1(B)} false colour composite. (Data courtesy of Nasa GSFC.)

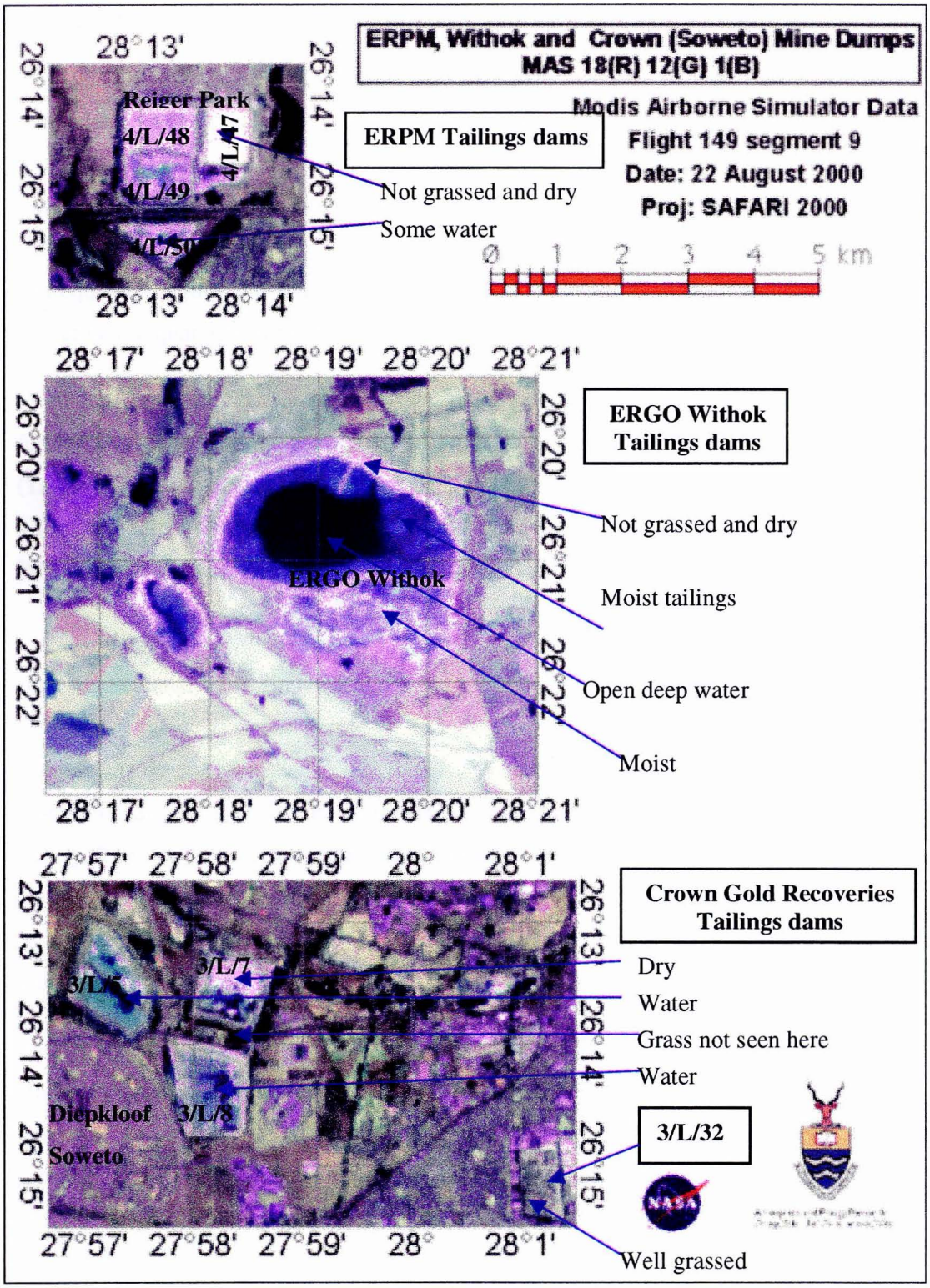


Figure 4.4b MAS {18(R), 12(G) and 1(B)}. (Data courtesy of Nasa GSFC.)

Remote sensing statistical techniques

Principal components

Ten selected MAS bands were fed into principal components process. These bands were selected, guided by the use classification provided by Nasa, table 3.2, and due to their minimal noise levels and to their sensitivity either to quartz, vegetation, and soils. A visual analysis was carried out on all the fifty MAS bands to screen out all the noisy ones and subsequently Figure 3.6 was used to pick out bands either with high absorption or reflectivity to quartz, vegetation and soils.

From the Principal Component Analysis, eight principal components were retained for further investigation. Principal components {1, 2, and 3} account for 98% of the variance (Table 4.1) Useful bands can be picked using the raster versus principle components (Table 4.2). Only values above 0.1 were considered as having any useful data. In each plot, the PCs listed {a, b, c} are plotted in the order Red, Green, Blue.

Principal Components 1, 2 and 3

An image created by retaining the first three principal components is presented in Figure 4.5a and b. This is meant to pick the most abundant material on the surface. These components do not represent features associated with the mine tailings, but represent the more abundant materials on the landscape. The sample sites image shows impoundments clearly. The dry impoundments are light coloured. Water shows as green, however there are many other areas that are not water that show up as green. In fact trees look green also. This could be a result of one of the bands being sensitive to moisture and picking up moisture from vegetation also.

This composite shows bigger impoundments clearly against other non-tailings material. However, smaller impoundments blend in with the surrounding, built up areas. Water becomes confused with vegetation, so that the well-treed areas of the northern suburbs of Johannesburg have a similar hue as for example the Natalspruit and Rietspruit wetlands (refer to figure 2.4 for names of streams).

Table 4.1 Eigenvalues and associated percentage variation accounted for.

Axis	Eigenvalues	Percentages	Cumulative %
1	199513	87.3	87
2	16809	7.4	95
3	6839	3.0	98
4	3046	1.3	99
5	1135	0.50	99
6	851	0.37	100
7	180	0.08	100
8	120	0.05	100
9	100	0.04	100
10	17	0.01	100

Table 4.2 Correlation between input rasters and Principal Components.

Axis	MAS46	MAS42	MAS21	MAS18	MAS17	MAS12	MAS7	MAS3	MAS2	MAS1
1	0.228	0.209	0.953	0.950	0.948	0.989	0.928	0.938	0.866	0.827
2	-0.767	-0.790	-0.185	-0.217	-0.242	-0.103	0.202	0.279	0.440	0.404
3	0.518	0.494	0.096	0.084	0.063	-0.099	-0.160	0.138	0.224	0.312
4	0.233	0.287	-0.187	-0.189	-0.173	0.018	0.227	-0.017	-0.009	0.055
5	-0.118	-0.002	0.020	-0.021	-0.014	0.016	-0.031	-0.137	-0.022	0.225
6	0.027	-0.008	-0.105	-0.057	-0.040	0.037	-0.145	0.043	0.013	0.009
7	-0.030	0.026	0.018	-0.029	-0.027	0.004	-0.008	-0.036	0.071	-0.049
8	0.147	-0.070	0.006	0.005	-0.033	0.001	0.002	-0.014	0.008	0.004
9	0.012	-0.006	-0.041	0.041	0.069	-0.001	0.007	-0.019	0.021	-0.003
10	0.012	-0.006	0.005	-0.027	0.034	0.000	0.000	0.001	-0.001	0.001

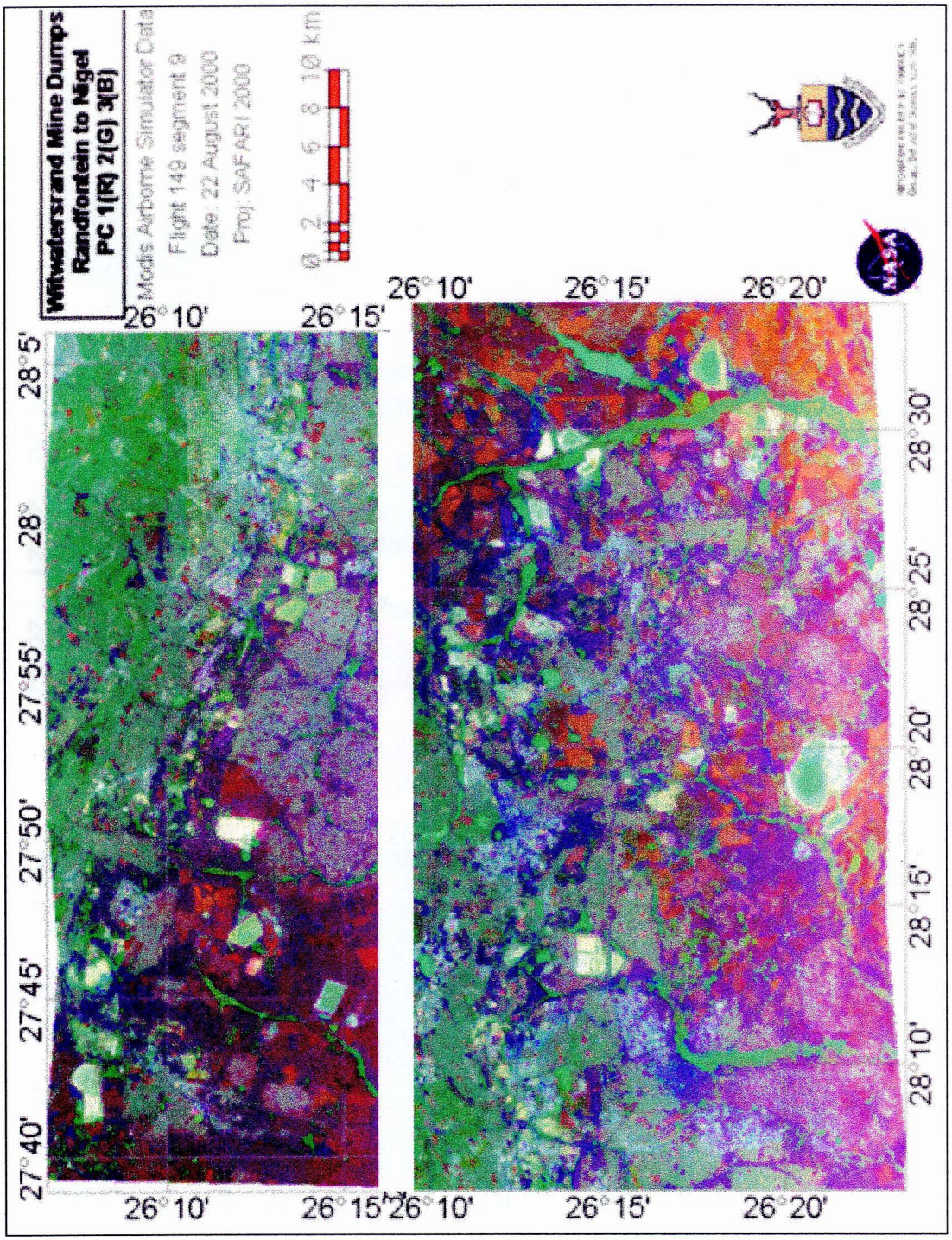


Figure 4.5a Principal component bands {1(R), 2(G) and 3(B)}. (Data courtesy of Nasa GSFC.)

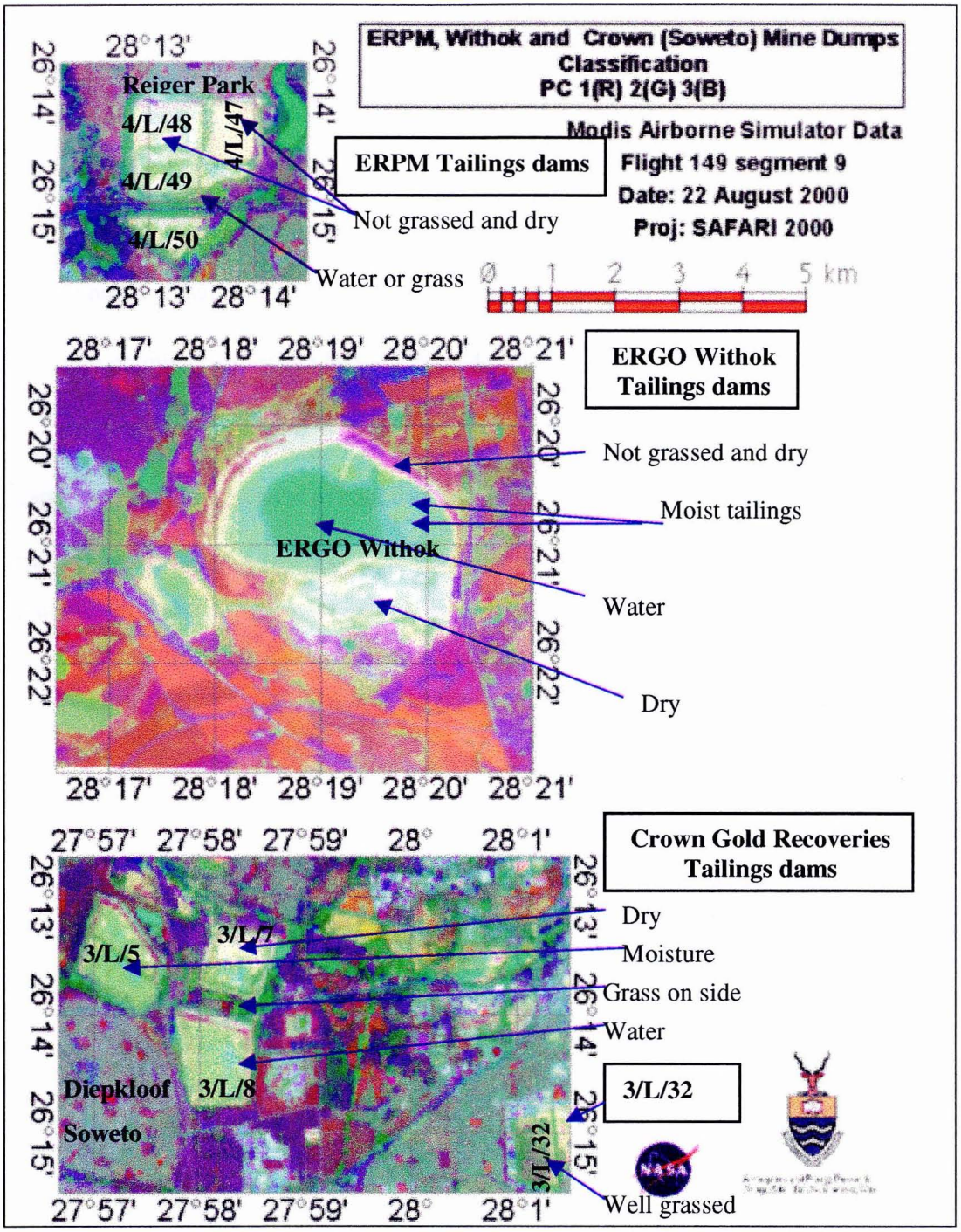


Figure 4.5b Principal component bands {1(R), 2(G) and 3(B)} at selected sites.

Principal Components {6, 5, 4}

Using Principal Components {6, 5 and 4} dry tailings dams have a red colour (Figure 4.6a), while the rest of the landscape is in shades of green and blue with little resolution of detail, other than water and wetlands, which are a distinct yellow. The Crown Gold Recoveries tailings dams stand out from city building and settlements. There is no confusion in the spectra of buildings and tailings. A known, well-vegetated tailings dam (3L32) on the image looks blue.

Moisture on mine tailings can be seen in shades of pink, best seen on the Ergo Withok dam (Figure 4.6b). Deep water appears yellow. However, there is not the discrimination of detail within the tailings areas witnessed on other composites (Figures 4.2 to 4.5), with respect to partially vegetated or slightly moist areas.

The PC {6, 5 and 4} image has been successful in identifying dry tailings material from non-tailings. This image cannot be used to successfully identify vegetated tailings, because vegetated tailings blend in with other vegetation. Moisture from dams and wetlands can also be identified here (yellow hues), but not as well as in some subsequent combinations.

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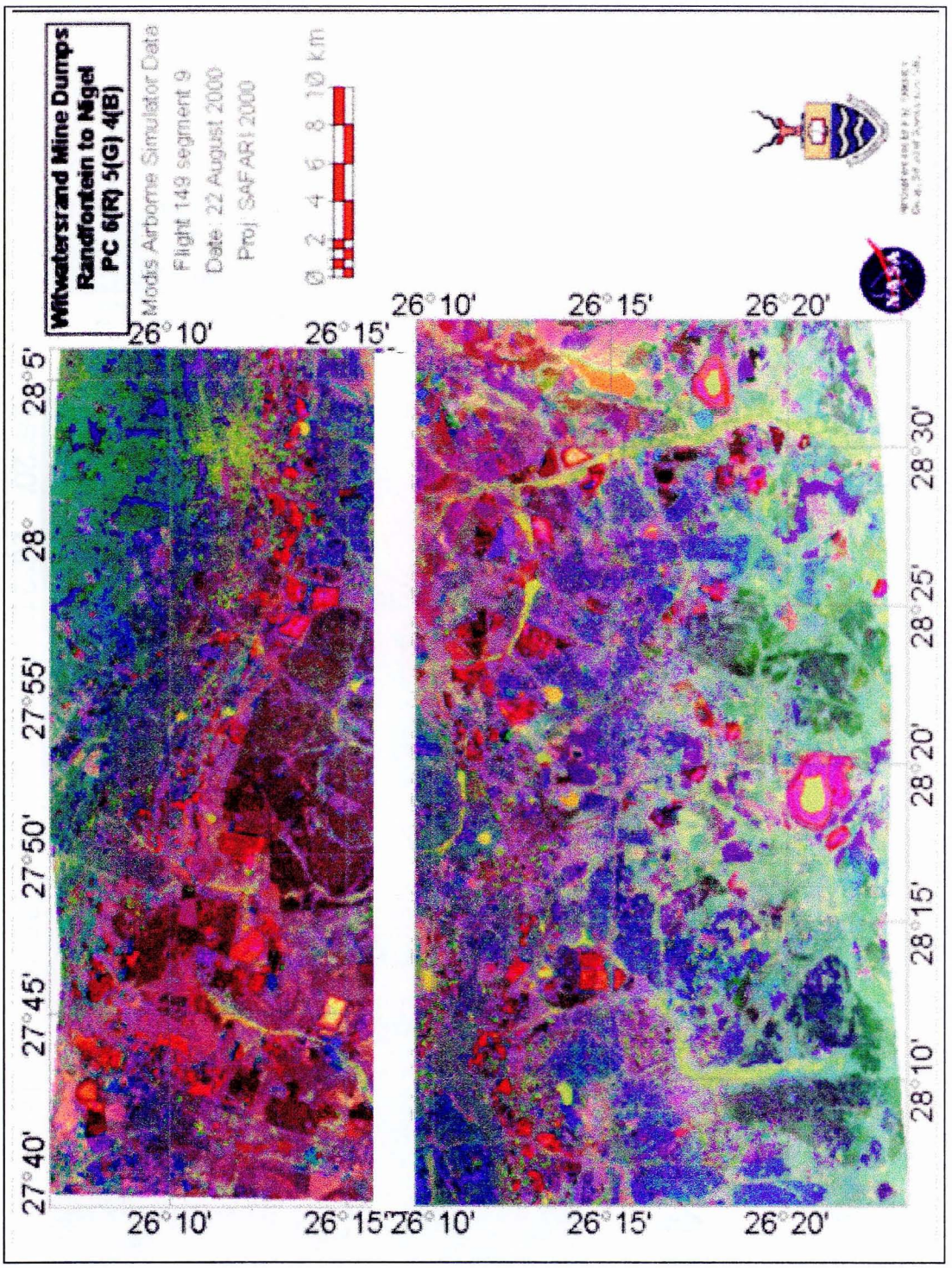


Figure 4.6a Principal components {6(R), 5(G) and 4(B)}. (Data courtesy of Nasa GSFC.)

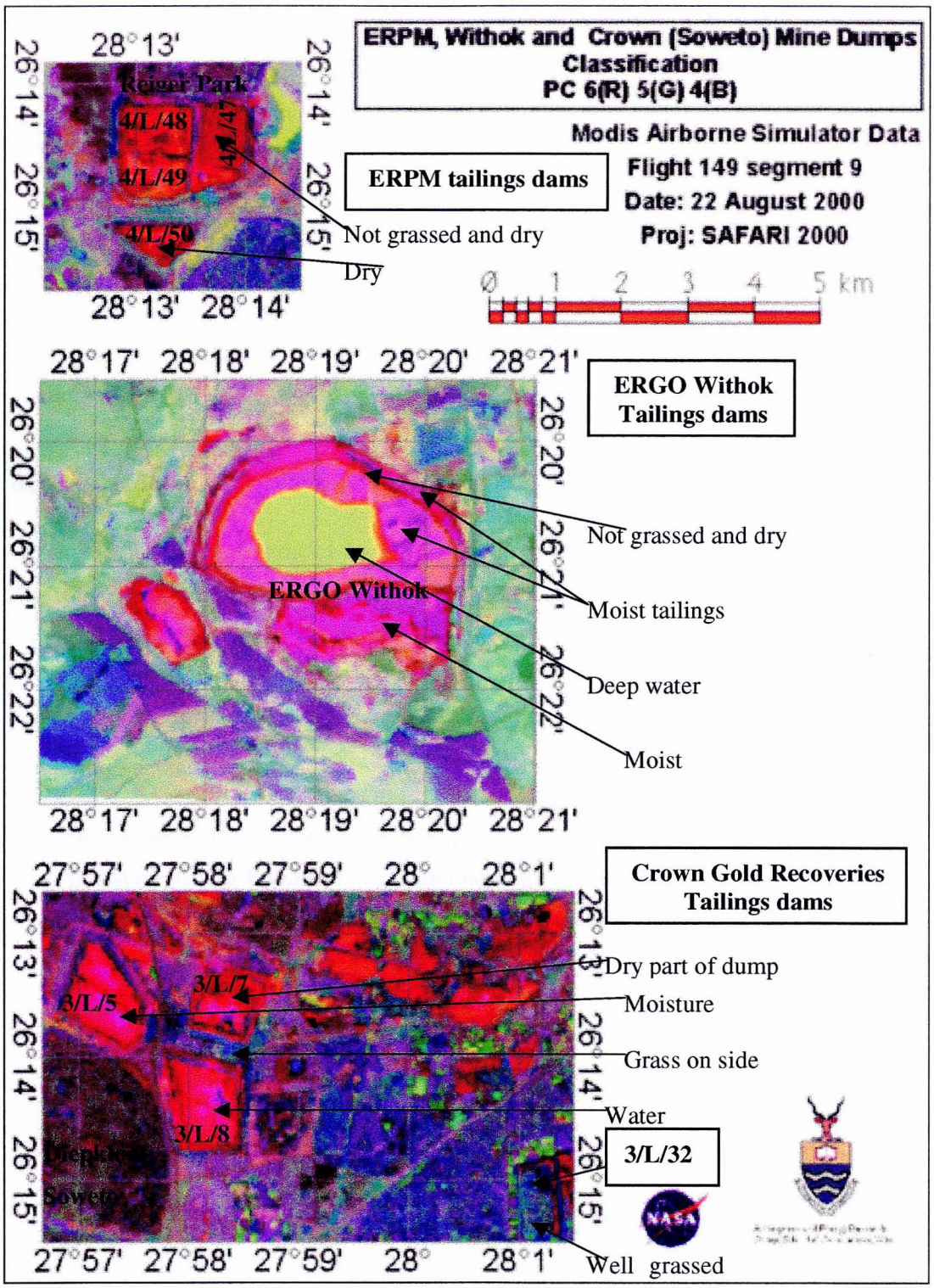


Figure 4.6b Principal components 6(R), 5(G) and 4(B) of selected sites. (Data courtesy of Nasa GSFC.)

Principal Components {8, 4, 1}

The principal components 4 and 8 account for 1.3% and 0.05% of the variability respectively. However, the correlation matrix between input rasters and principal components shows that PC4 and PC8 have moderate positive correlations with the far infrared channels, and negligible correlation with the visible channels, that is a strongly absorbing surface radiating only in the infrared.

The images derived from Principal Components {8, 4 and1} allow tailings material to be discriminated, with a pink colour representing dry tailings surfaces (Figure 4.7a and b). Deep water, such as on the Ergo dam, is almost black, indicating surfaces strongly absorbing of visible radiation. This combination selects with good discrimination minor dams and open waterways from the surrounding landscape.

Different surface characteristics can be distinguished on the Ergo tailings impoundment. The pink colour represents dry tailings material and the green colour represents wet tailings material. However, the finer gradations of moisture on top of the Crown tailings are not as well represented as in some of the simple composites such as MAS {21, 7 and 3} (figure 4.3b). Vegetation is poorly discriminated in density and from other material such as wet tailings and buildings.

Thus the PC {8, 4 and 1} image is a good process for identifying open water. It is not as good at discriminating between tailings and non-tailings material as was the PC {6, 5 and 4} image, nor does it give optimal gradations within a tailings area.

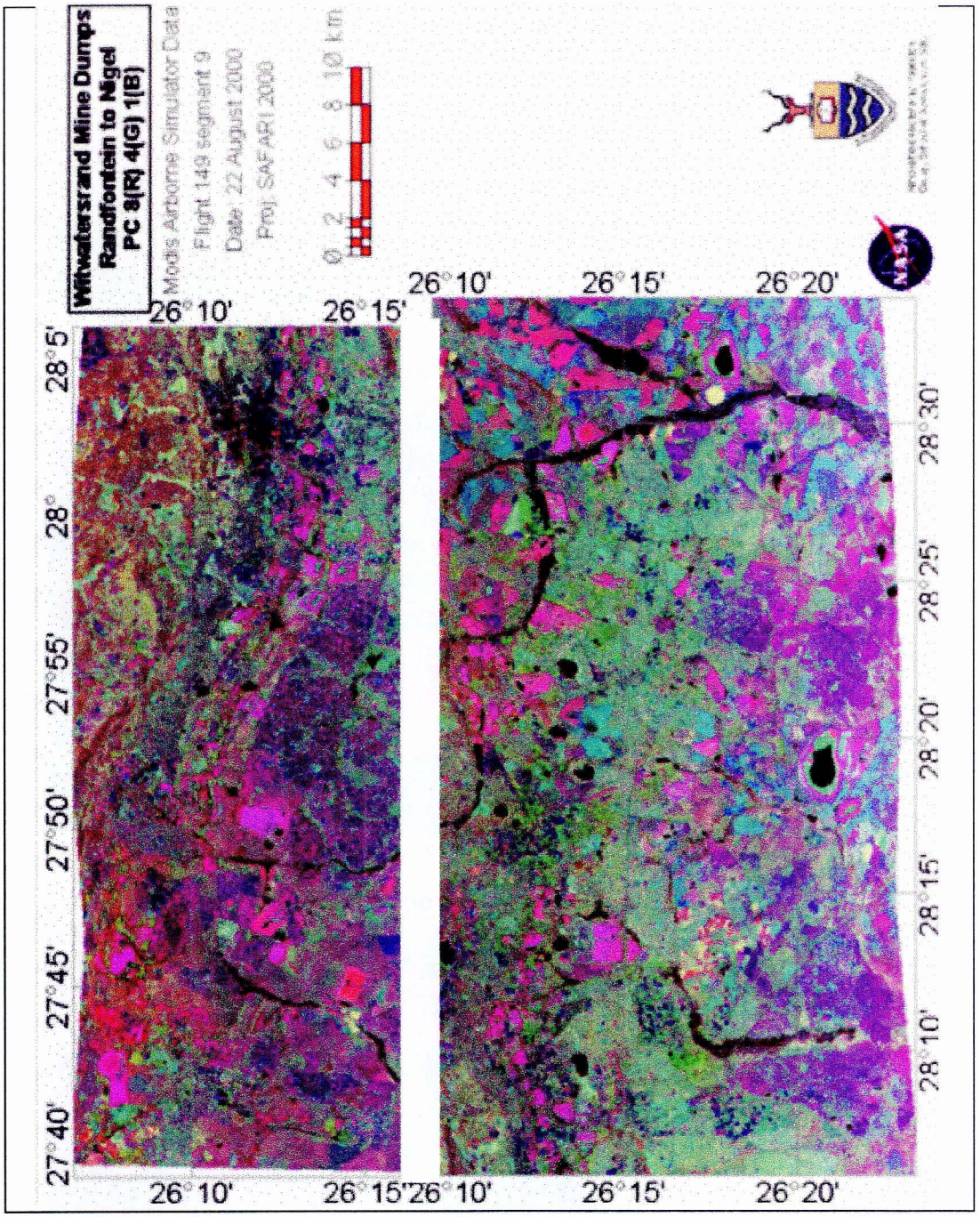


Figure 4.7a Principal components {8(R), 4(G) and 1(B)}. (Data courtesy of Nasa GSFC.)

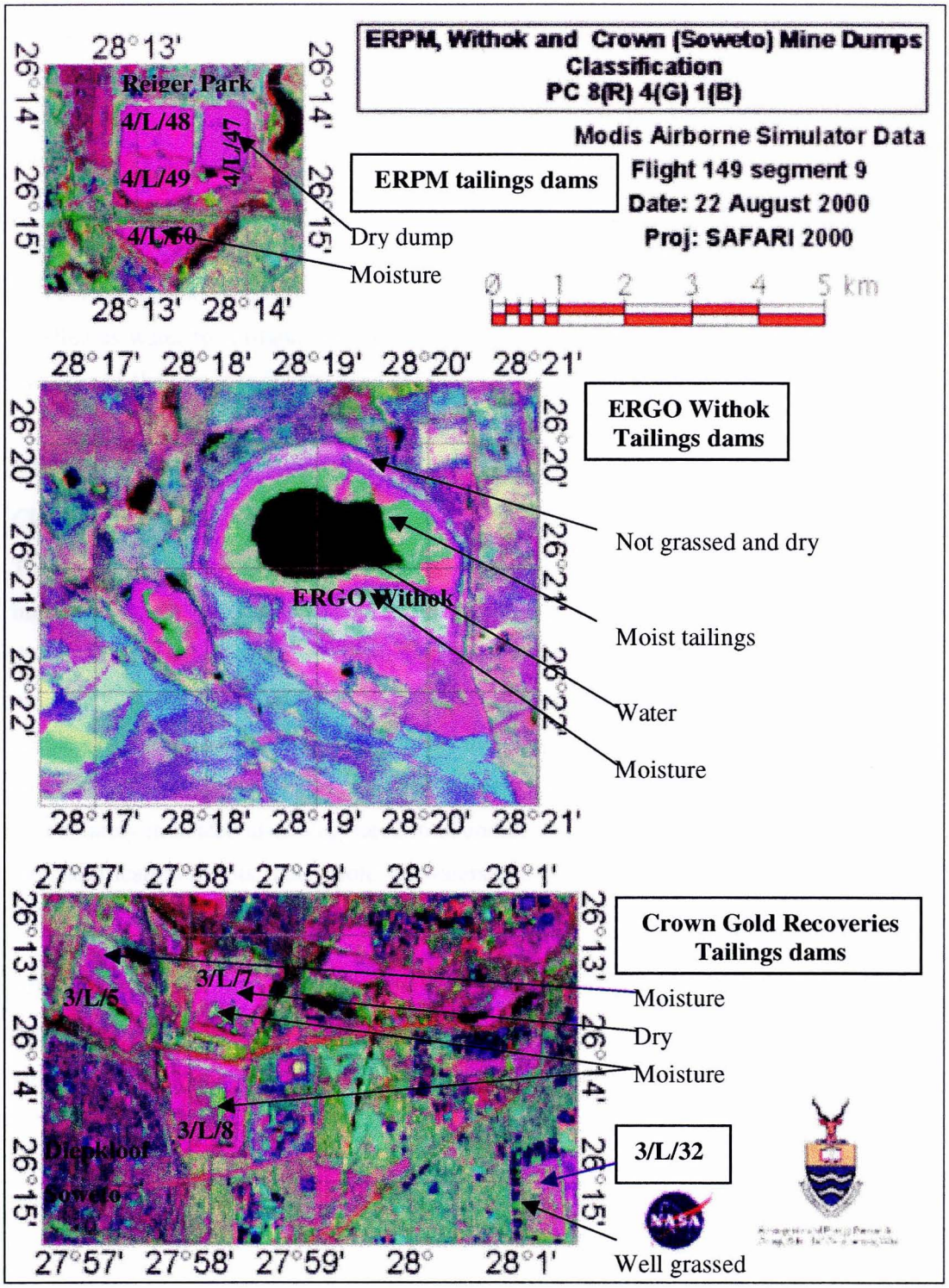


Figure 4.7b Principal components {8(R), 4(G) and 1(B)} of selected sites. (Data courtesy of Nasa GSFC.)

Examples of other techniques

Initial results on the following processes are less successful than those mentioned above. To begin with, it is important to clarify use of labelling arrows. With band composites and principal component composites, labelling arrows point at what can be identified on the image, but on the classification processes, labelling arrows are made to point at features even if the feature is incorrectly identified. This is to illustrate how the classification process colour coded the results on the image. What has to be noted is that some features labelled as water for instance are not water on the actual ground, but have been identified as water on the image to illustrate where the process did not accurately identify a feature.

Unsupervised Classification

Classification via K-means

The unsupervised classification via K-means is able to pick out differences in impoundment material within impoundments (Figure 4.8a and b). On the ERPM tailings dams, the dry area on the Ergo impoundment can be seen in green. Towards the inside, a bluish colour comes in, which indicates moist tailings material and the water within is a purple. The colour indicating moisture on the Ergo impoundment is consistent with the moist area on the Crown Gold recoveries tailings dams. The dry area of the impoundments is accurately indicated also. Vegetated impoundments are however not well represented on the classification results. The whole Witwatersrand area is a mixture of colours that appear illogical.

Although different materials can be differentiated within impoundments, there is a confusion of colours on the broader image and tailings cannot be selected from other objects on the environment.

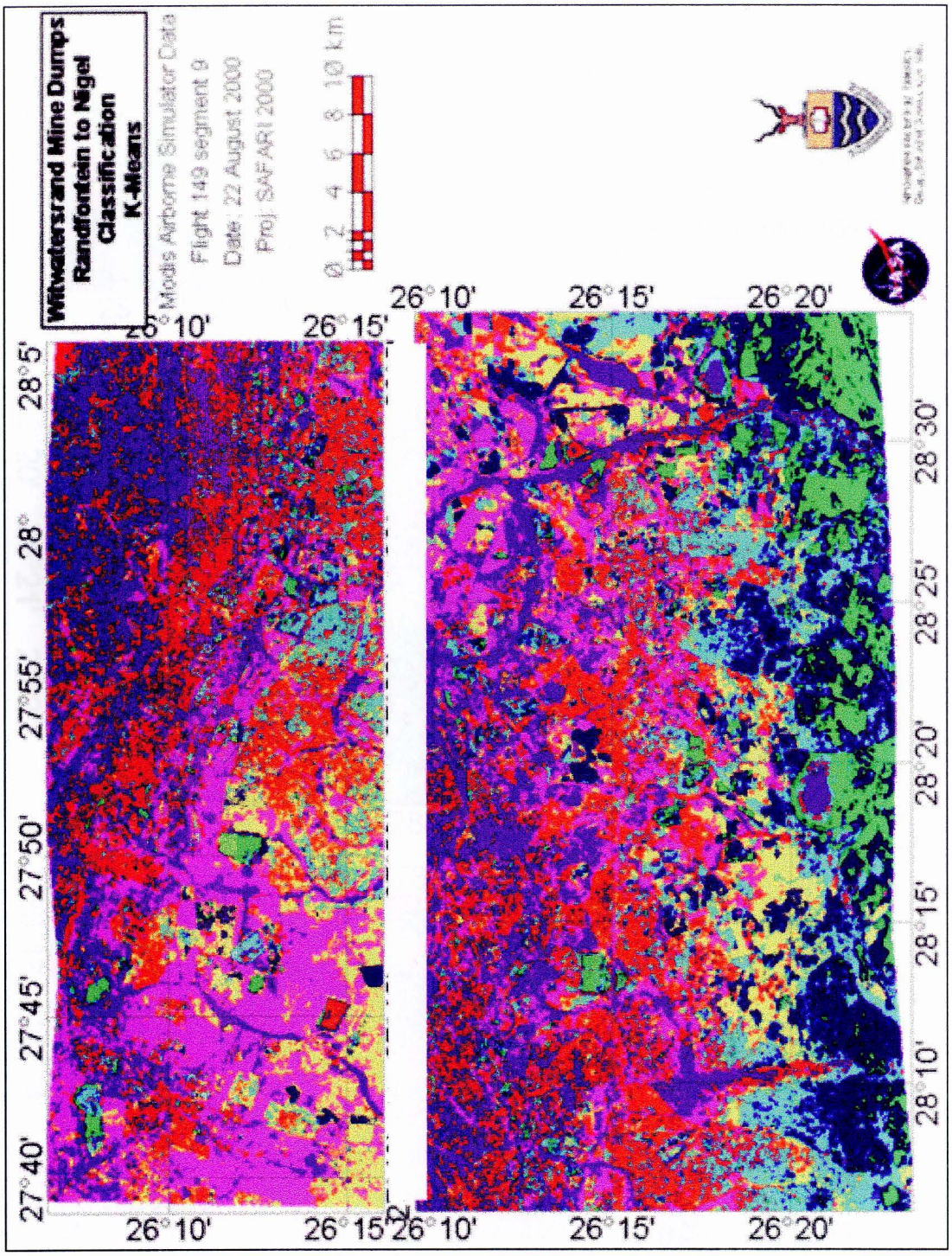


Figure 4.8a Classification via K-Means. (Data courtesy of Nasa GSFC.)

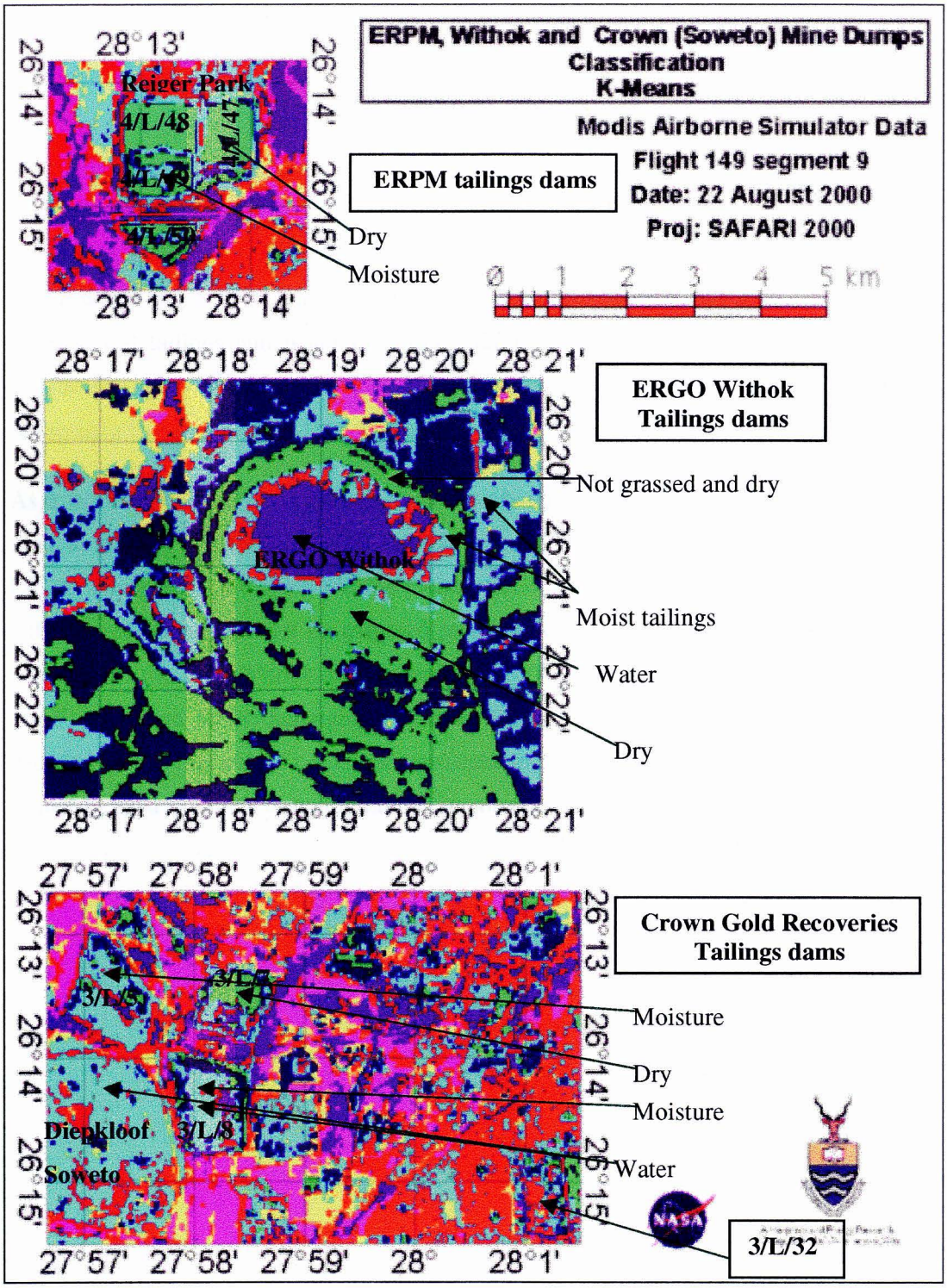


Figure 4.8b Classification via K-Means on selected sites. (Data courtesy of Nasa GSFC.)

Supervised classification

Mahalanobis

The first Mahalanobis attempt was assigned 10 input bands and 8 output classes (Figure 4.9a and b). Results show some of the mine tailings structures. However there is not much colour discrimination between tailings material and other features in the area as compared to colour composite images. Only some of the tailings impoundments can be selected out of the whole big area of features. Also there is no difference in the results between dry tailings, wet tailings and water on tailings dams. It was realized that the result is not satisfactory and therefore further alterations were made to the parameters of the algorithm. A second attempt was carried out with altered input parameters (Figure 4.10a and b).

As it is, this classification can be used to classify tailings to a limited extent. It cannot be used to display different status of tailings impoundments. For instance the mostly dry ERPM slimes dams looks red and the moist parts of the Ergo Withok slimes dam are also red (the red colour can not be assumed to represent dry tailings material). The pool of water inside the Ergo Withok dam appears white. The active wet surfaces of slimes dams (3/L5, 3/L/7 and 3/L/8) belonging to Crown Gold Recoveries appear yellow. The final decision here is that colour use is not consistent and is inaccurate; therefore this procedure cannot be used to form a basis for tailings impoundments classification.

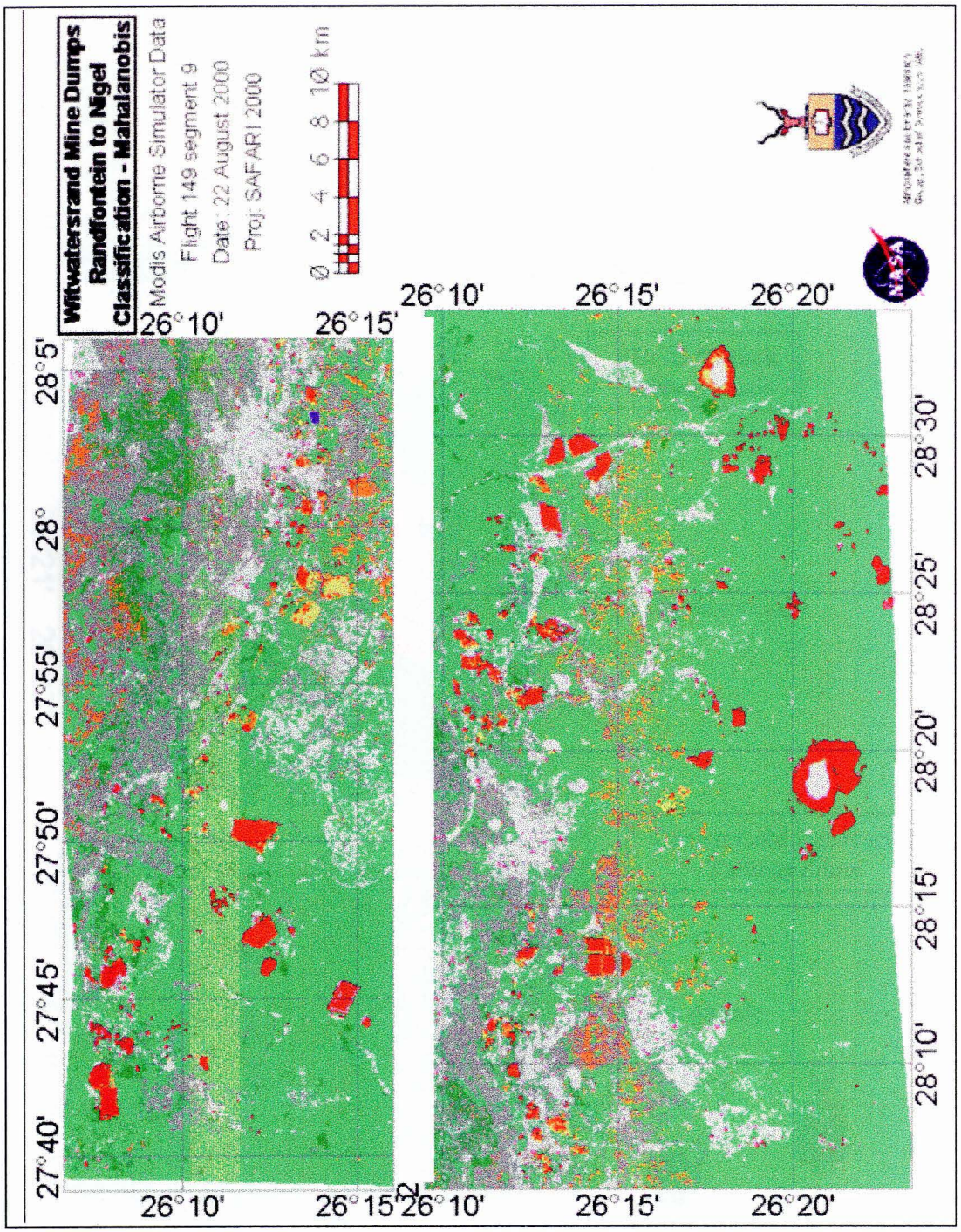


Figure 4.9a Classification via Mahalanobis. (Data courtesy of Nasa GSFC.)

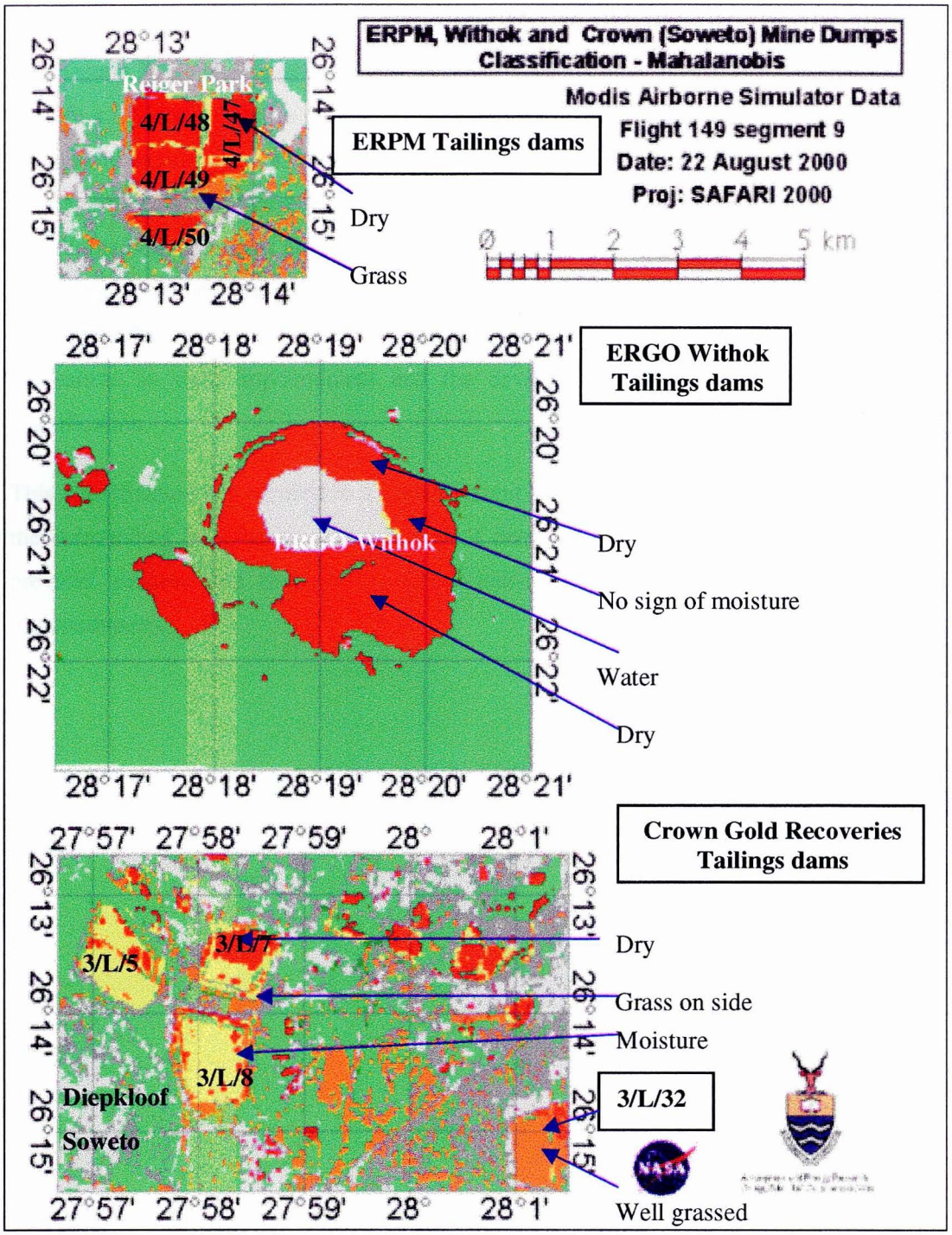


Figure 4.9b Classification via Mahalanobis on selected sites. (Data courtesy of Nasa GSFC.)

Mahalanobis

The second Mahalanobis attempt was assigned with 15 input bands and 8 output classes (Figure 4.10a and b). On the resulting image, tailings impoundments can be separated from the general environment and these can be identified in red and yellow colours. Wet and dry tailings cannot be differentiated easily as they seem to be coloured arbitrarily. Colours used on tailings impoundments are red and yellow. Grey seems represent water and the built up areas (e.g. Johannesburg city) and brown is for vegetation. This is not accurate however when these features are compared to ground truth information. There is so much variability of features in each impoundment and the environment that is not captured on this classification.

This classification can be used to a limited extent to pick out tailings impoundments from the surrounding built up environment, but it does not represent an improvement to the previous process and therefore is not suitable for mapping the status of tailings impoundments.

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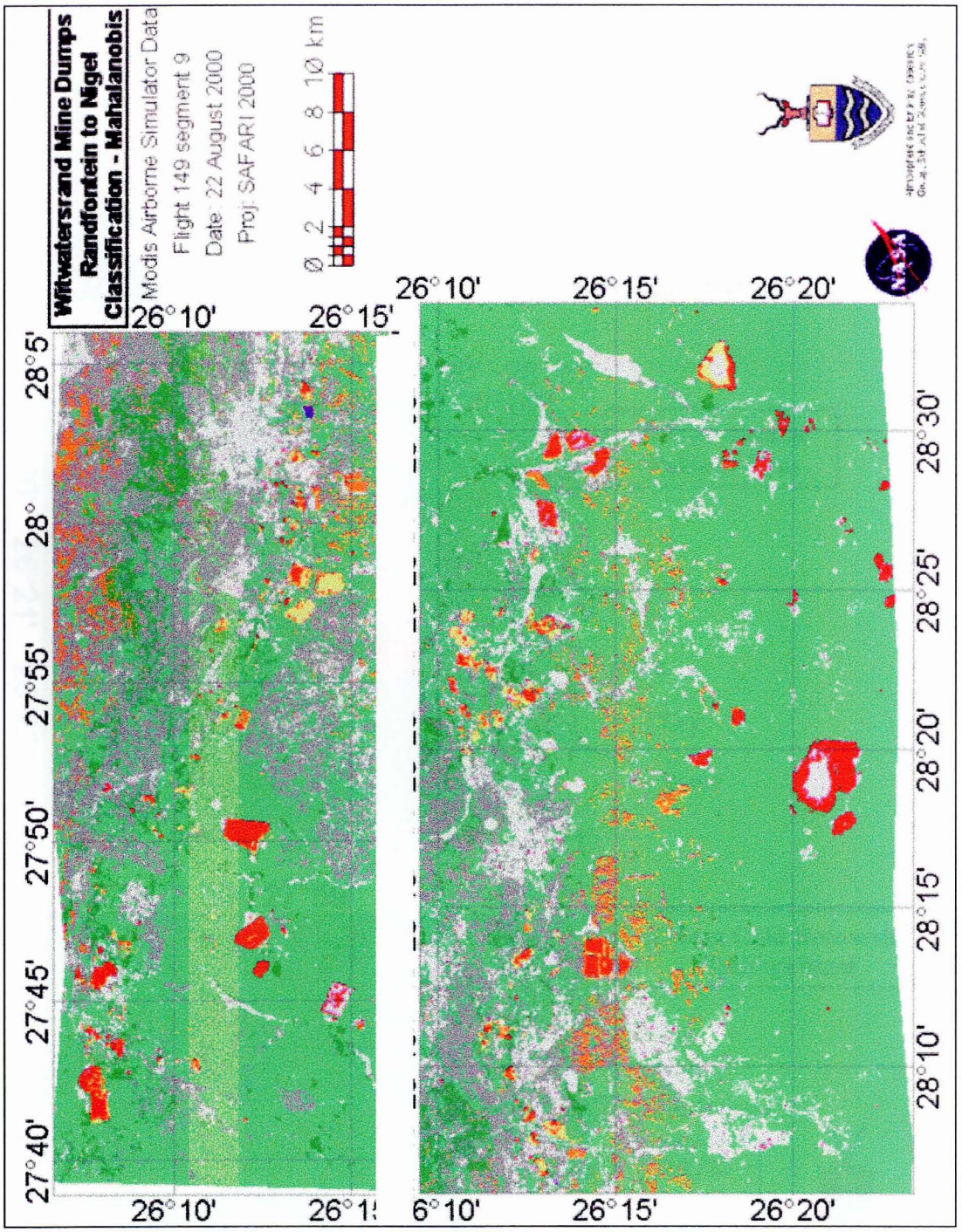


Figure 4.10a Classification via Mahalanobis. (Data courtesy of Nasa GSFC.)

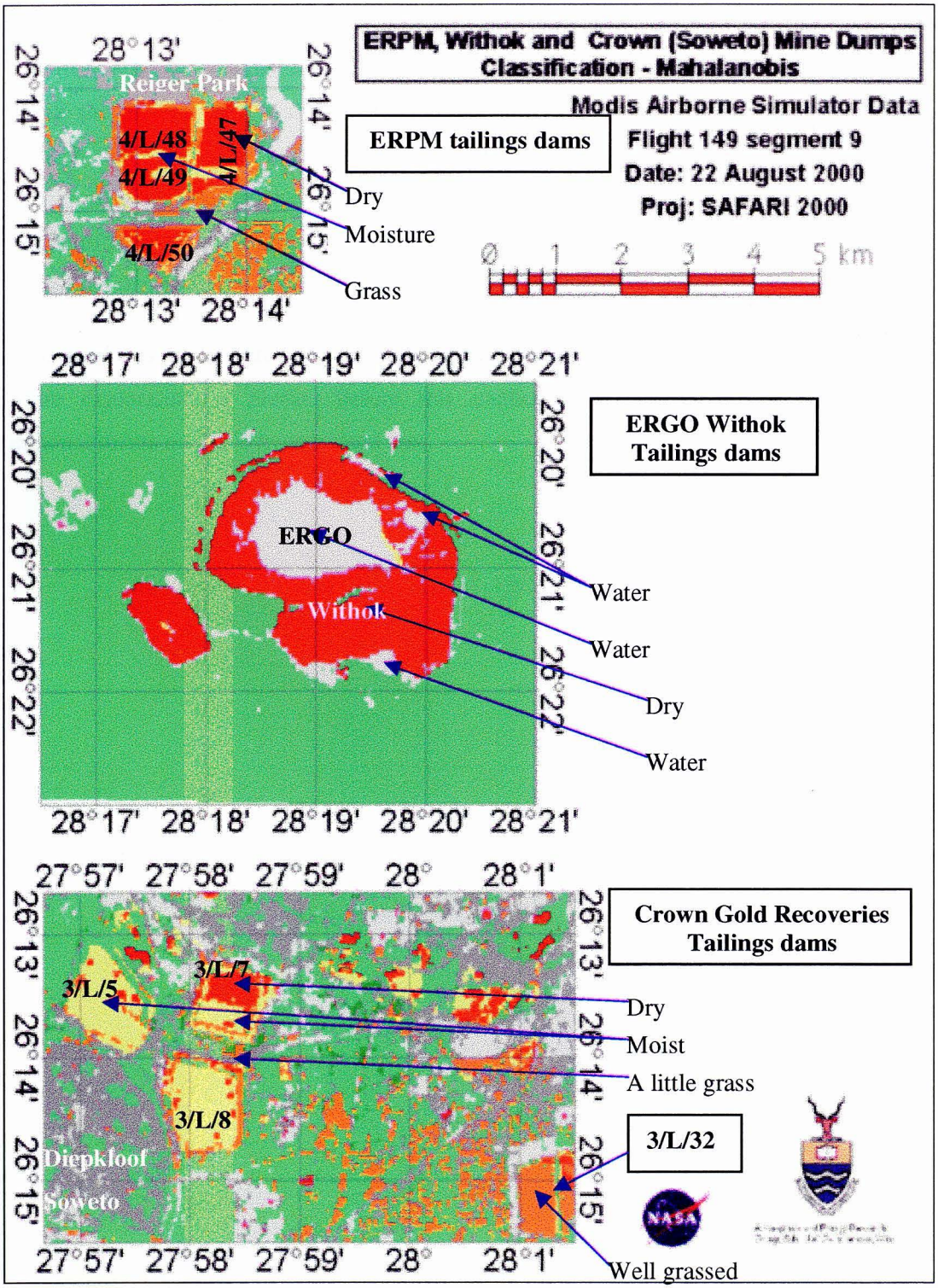


Figure 4.10b Classification via Mahalanobis on selected sites. (Data courtesy of Nasa GSFC.)

Mahalanobis

The third Mahalanobis calculation had 20 input bands and 8 output classes (Figure 4.11a). While the previous two Mahalanobis attempts could capture the spatial characteristics of some features including tailings impoundments, this one does not capture and represent shapes properly. The same colours are used as on the other Mahalanobis processes. There seems to be more grey and orange colours on the whole image. Also they are used and mixed illogically on the classification, producing a confused image.

Results of this process are not an improvement on the previous two Mahalanobis attempts. More exploration is needed before this method can be used to classify tailings impoundments on the Witwatersrand area.

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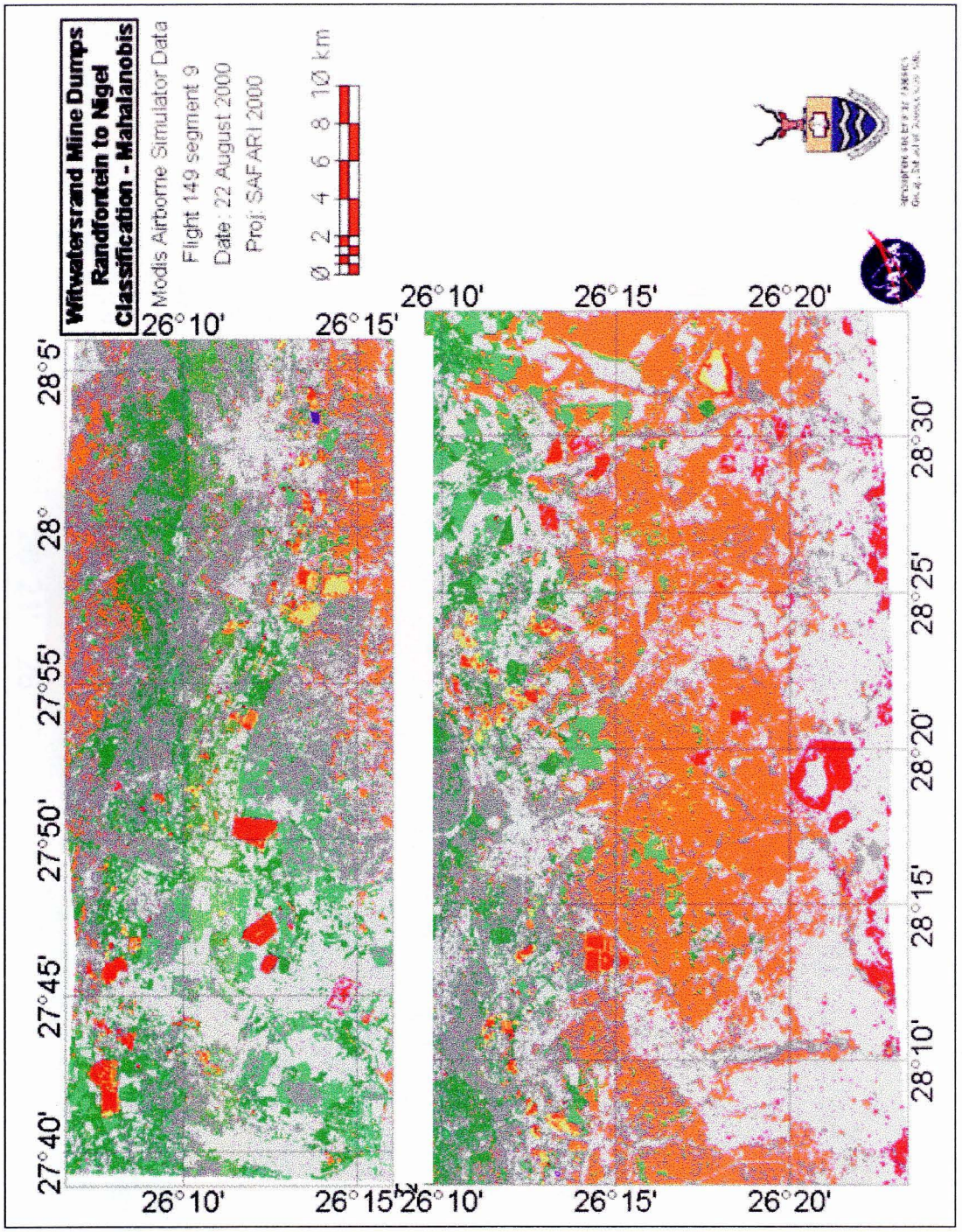


Figure 4.11a Classification via Mahalanobis. (Data courtesy of Nasa GSFC.)

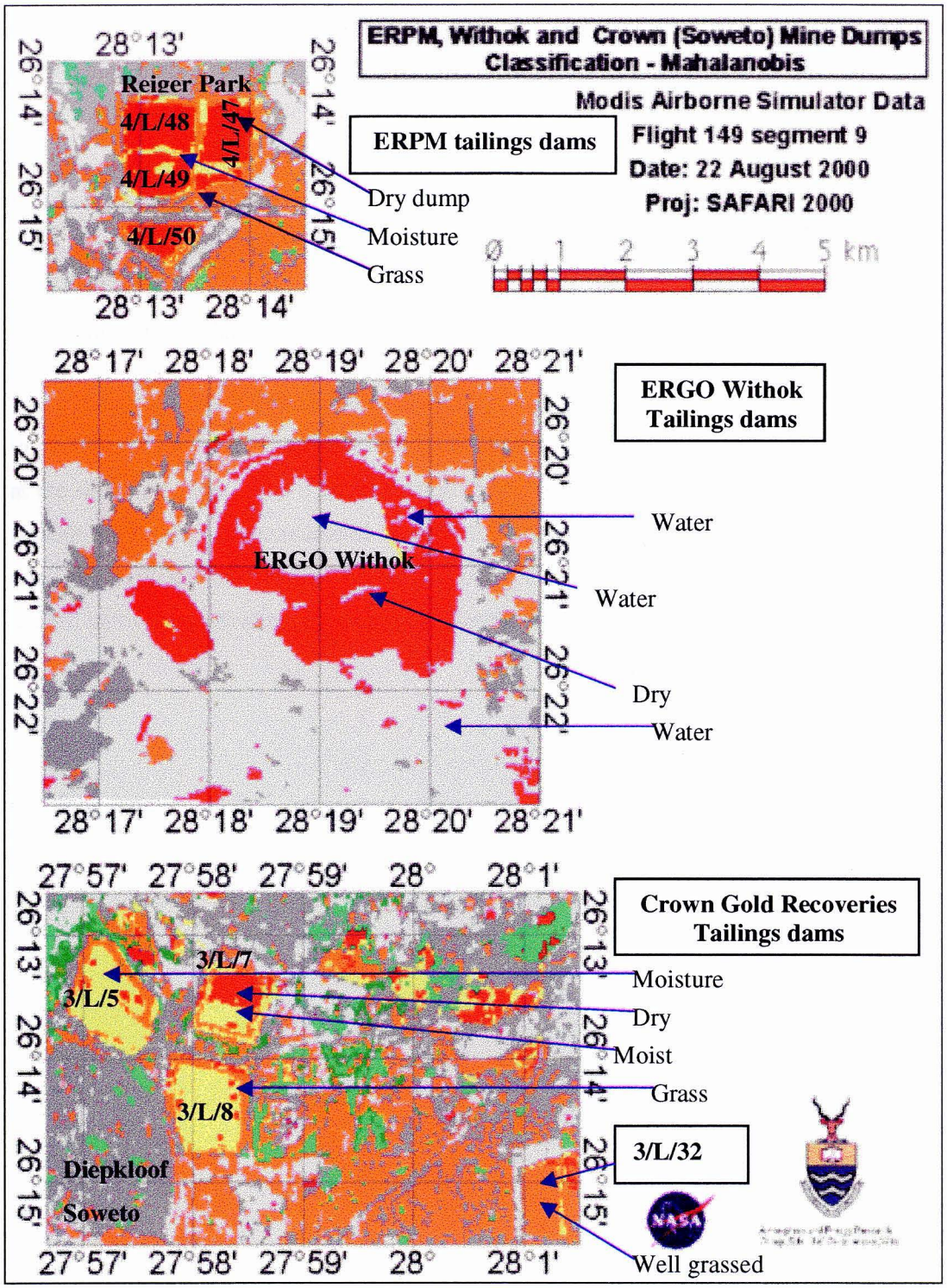


Figure 4.11b Classification via Mahalanobis on selected sites. (Data courtesy of Nasa GSFC.)

Maximum Likelihood

On the maximum likelihood classification, the ERPM dry impoundments have a red colour (Figure 4.12a and b). There is also slight yellow colouring on the tops and sides. This colour is not common with the Ergo impoundment, which has a large pool of water in the middle. However the Crown Gold Recoveries tailings have a more yellow colouring on them. The whole area is dominated by orange, green and grey. Similar to the Mahalanobis and the composites, this process can capture the spatial extents of the tailings impoundments, but has a problem with feature separation.

If it can be said that yellow indicates moisture, then it will not be true because the Ergo impoundment has water and the yellow is not showing. This could be a problem introduced at the sampling stage. Also it could be that the process is picking up a mineral that is not present on the Ergo impoundment. Overall, this classification with its present parameters does not separate the regions of the impoundments accurately. Further refinement is needed before classification via maximum likelihood can produce acceptable results.

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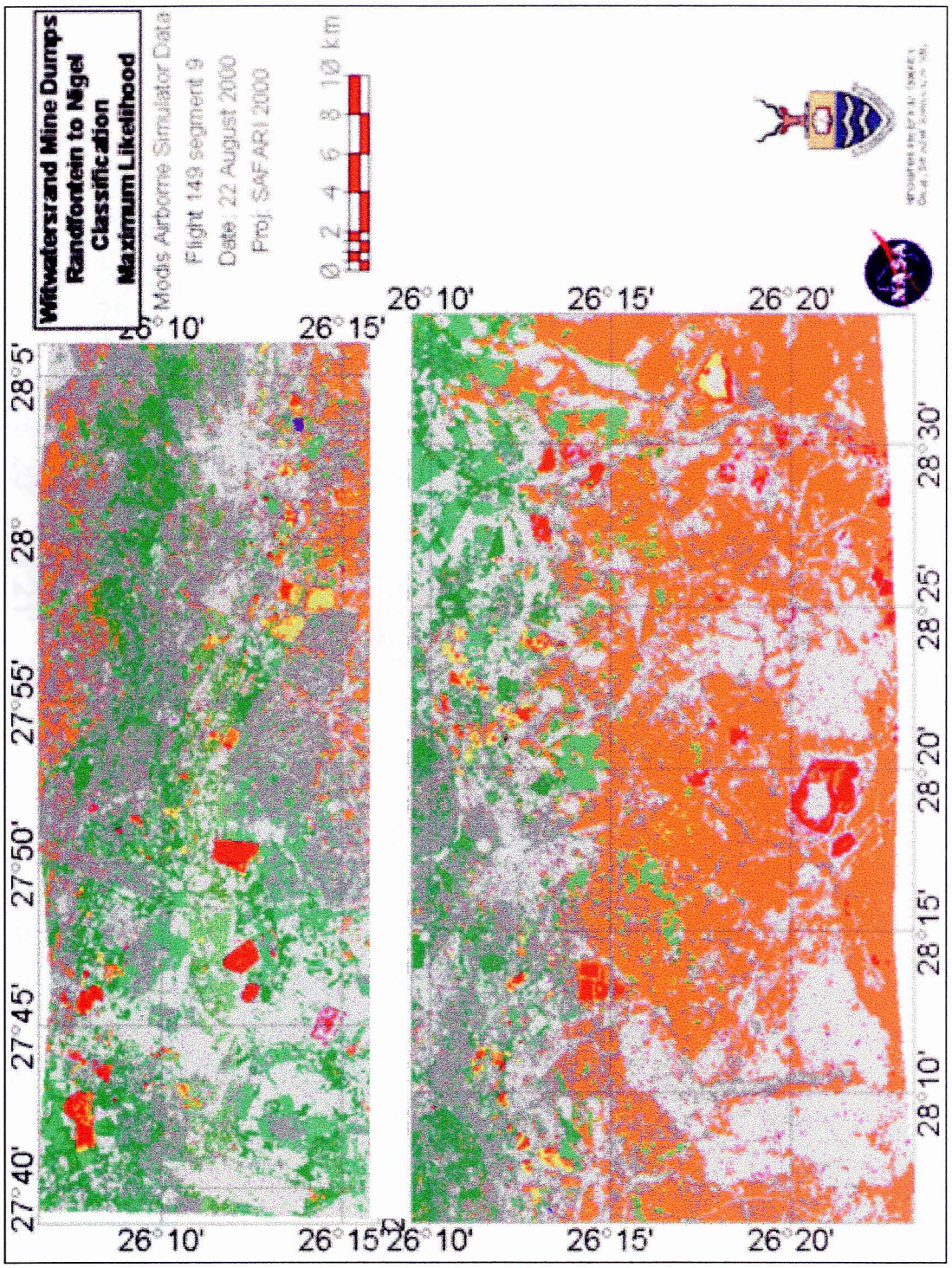


Figure 4.12a A classification carried out via Maximum Likelihood. (Data courtesy of Nasa GSFC.)

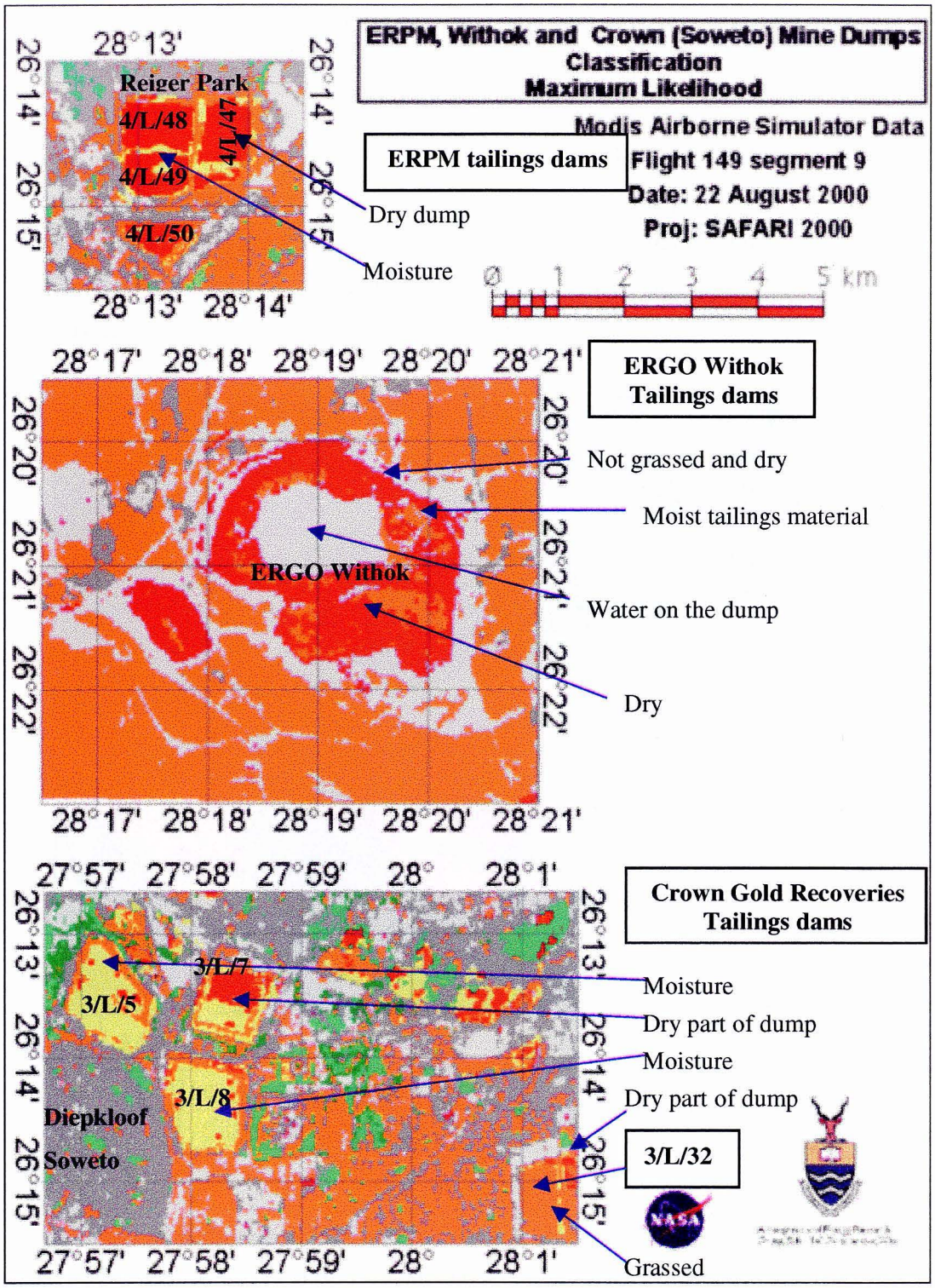


Figure 4.12b Classification on three known sites carried out via Maximum Likelihood. (Data courtesy of Nasa GSFC.)

Assigning new status categories

In this part of the project an attempt is made to use results from image analysis and classification to finally say what is taking place on the impoundments. To characterise tailings impoundments, each site was zoomed in (Figure 13) and manually scanned using each of the previously described processes on TNTmips and the product was compared to the sample sites. Comments were written on the status of each impoundment on a GIS and each comment was assigned a number. These numbers were later given colour codes for map display.

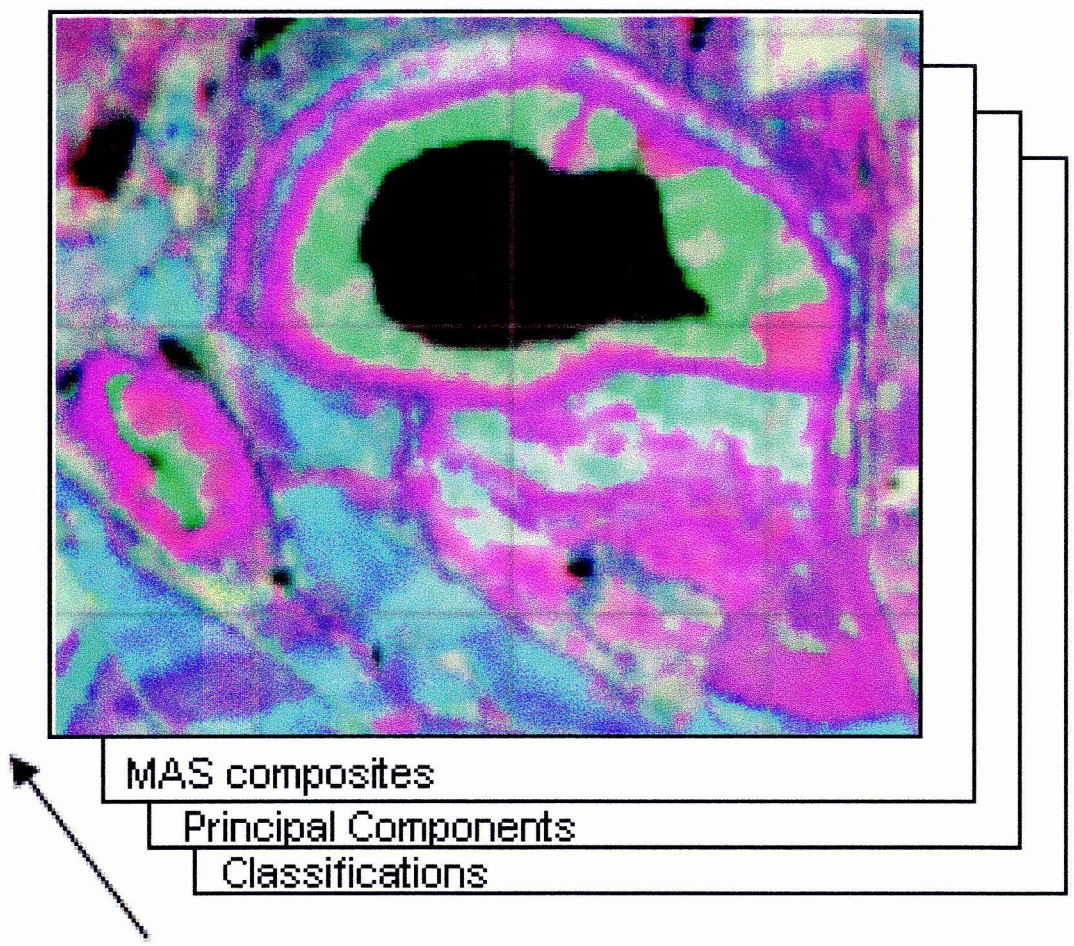


Figure 13 An illustration (of the Ergo tailings dam) showing how the final visual analysis was performed and the level of zoom during the tailings characterization process.

On the first image, four classes were created (Figure 4.14a and b). These would look at what sort of work is taking place and were identified as reclamation/reprocessing;

deposition; inactive and unknown. The group termed unknown in most cases refers to impoundments that were outside the area covered by the images.

Two of these classes, *active deposition* and *inactive,* relied extensively on image analysis. The active reclamation classification relied also on ground truthing data. Satellite imagery can be used to tell if an impoundment is active or not by using visual analysis on images developed for this project, but it is not easy to tell if active reclamation is taking place at the time. To be able to tell that kind of information, a series of images taken at regular intervals is needed to look at change.

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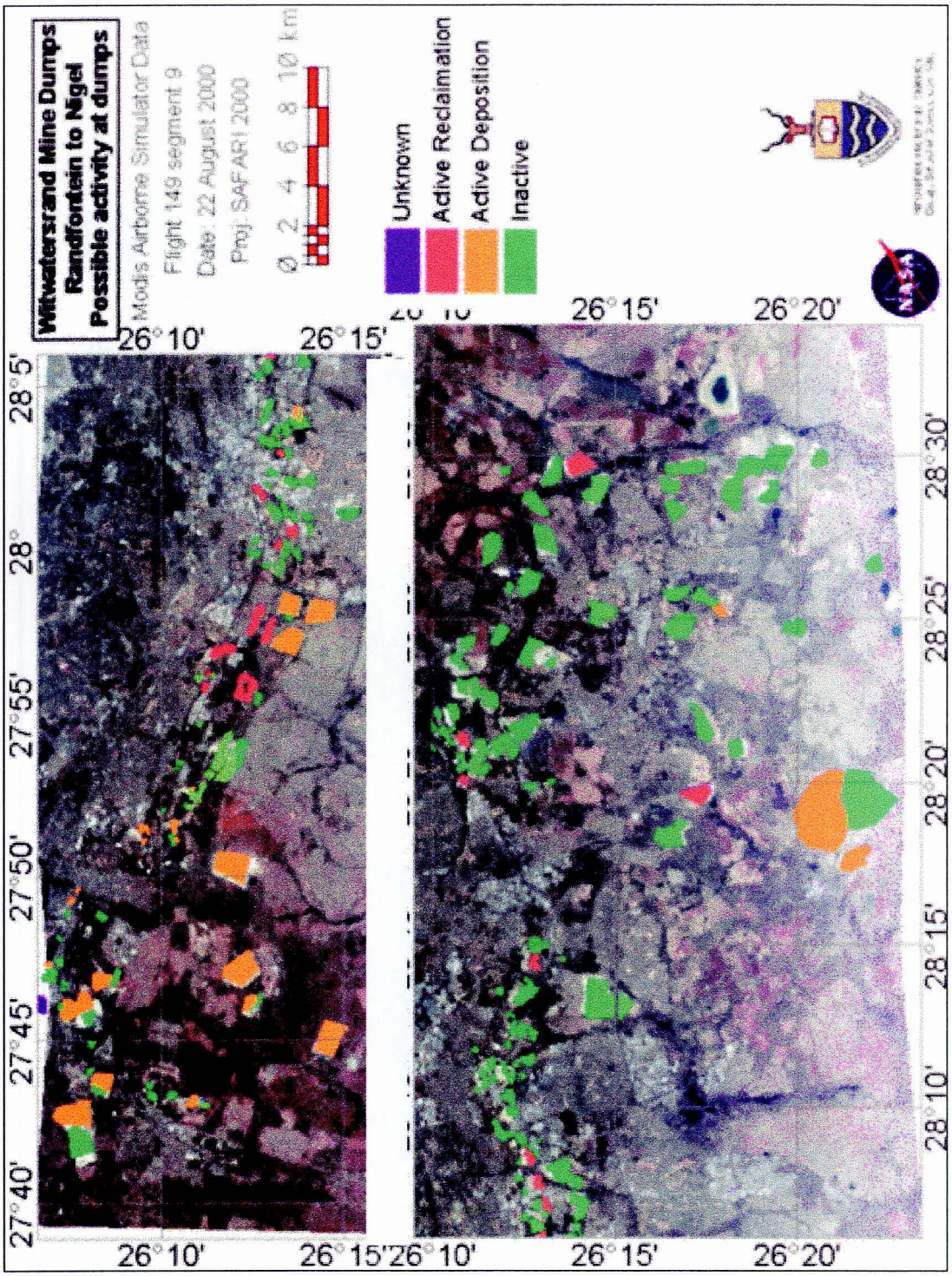


Figure 4.14a An estimation of possible activity on the tailings impoundments at the time the image was captured. (Data courtesy of Nasa GSFC.)

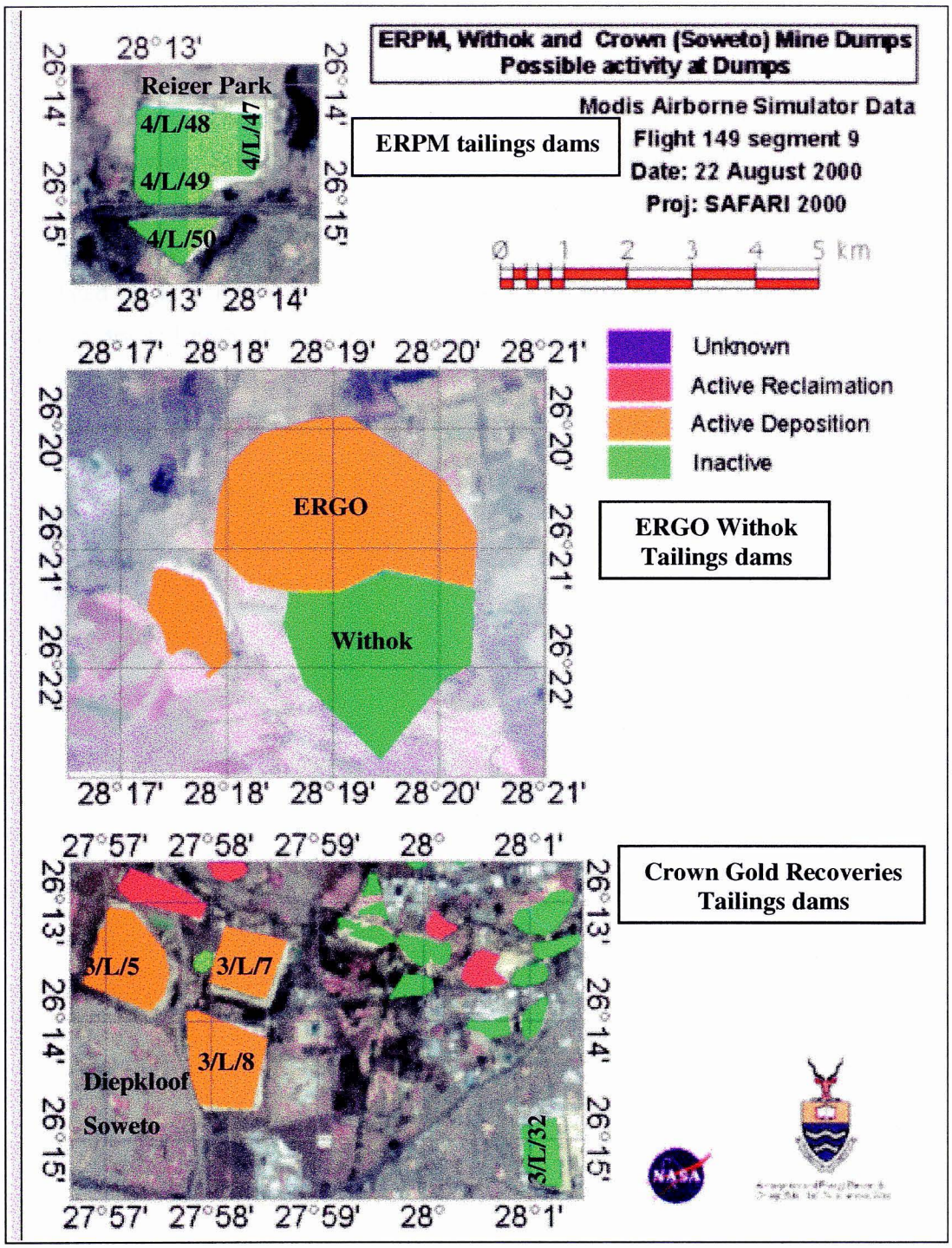


Figure 4.14b An overlay of a few selected mine tailings with known activity in the year 2000. (Data courtesy of Nasa GSFC.)

Condition of impoundments

The condition of impoundments is categorized on a five point scale *very good* to *very bad.* The class *very good* refers to well vegetated impoundments, impoundments that have been removed or where development has taken place replacing impoundments. The *good* class refers to those that are well vegetated but outlines can still be seen clearly. *Medium* are tailings that are partly vegetated, probably in the process of being vegetated or were vegetated but have been neglected. The *bad* and *very bad* classes refer to impoundments that are dry and probably a source of environmental problems (wind blown dust and or surface water contamination) (Figure 4.15a and b). For areas outside the range of the image analysis or where insufficient information is available, a sixth class, *unknown*, is assigned.

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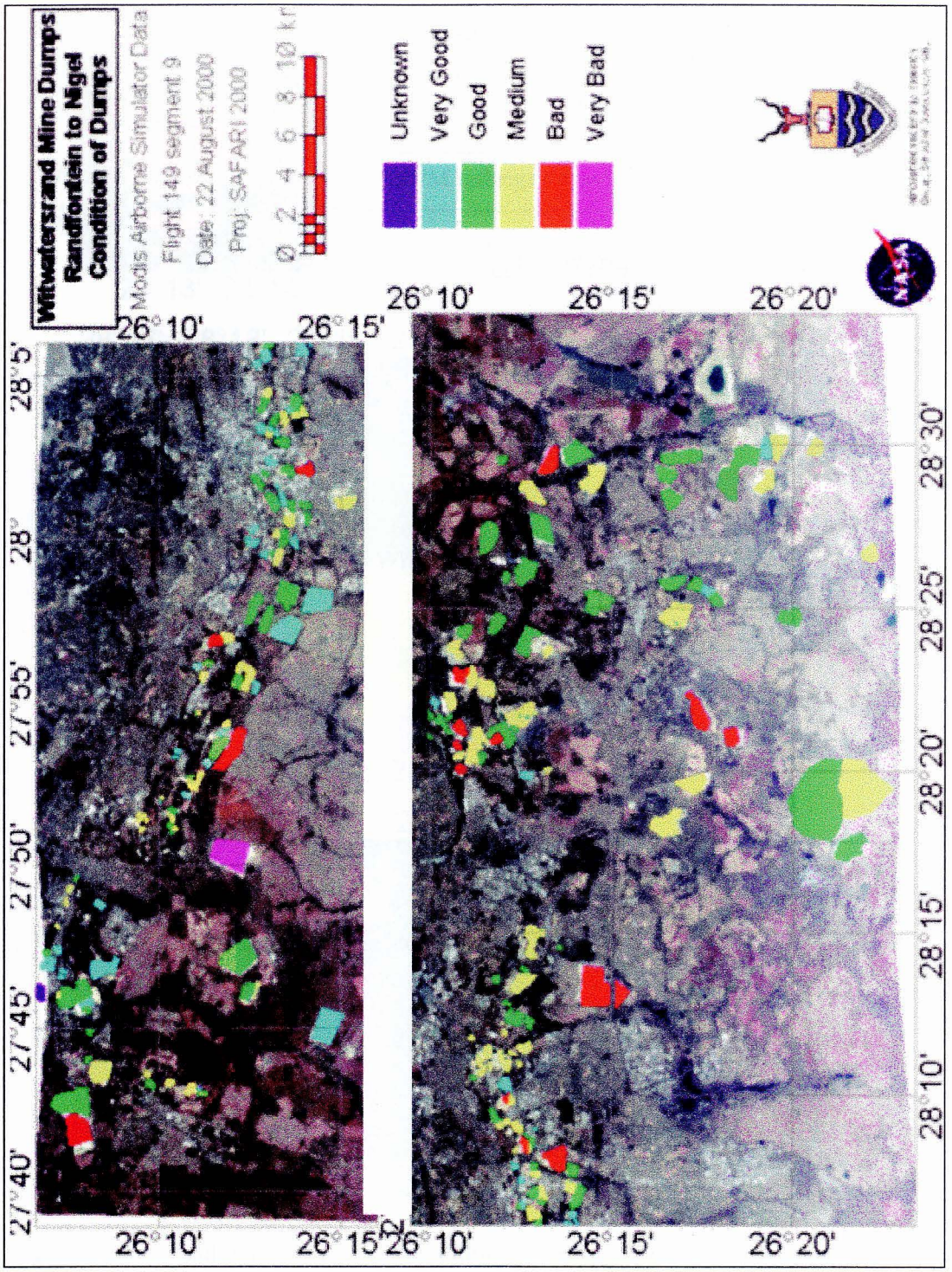


Figure 4.15a Conditions of tailings impoundments in August of the year 2000. (Data courtesy of Nasa GSFC.)

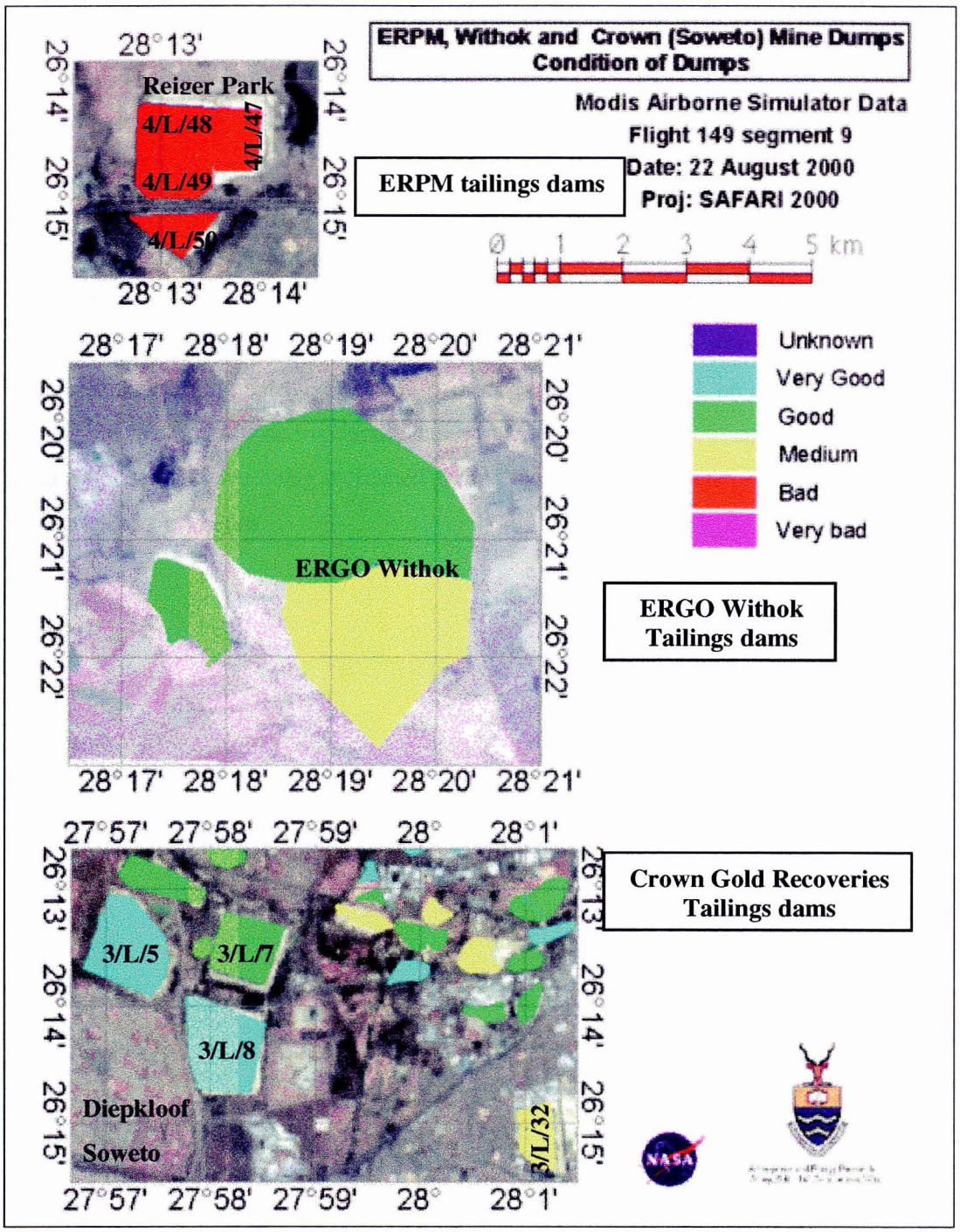


Figure 4.15b Conditions of three known tailings impoundment in the area for illustration. (Data courtesy of Nasa GSFC.)

Impoundments that require intervention map

The conditions map indicates how the tailings impoundments were in 2000. In labelling the impoundments good or bad, there are tailings impoundments that looked well kept and were labelled as good. Some of these had patches or small areas on them that were not looking so good on the images and looked as if the had the potential to cause problems. This class of impoundments and those that were obviously causing problems were marked with polygons (Figure 4.16). These are the impoundments that from satellite imagery seem as though they need intervention and remediation. This does not say that these impoundments were neglected or were causing problems, because on closer inspection it might turn out to be those impoundments on which chemical means of stabilisation were used or those that were being reclaimed at the time and responsibility was being exercised to prevent any problems.

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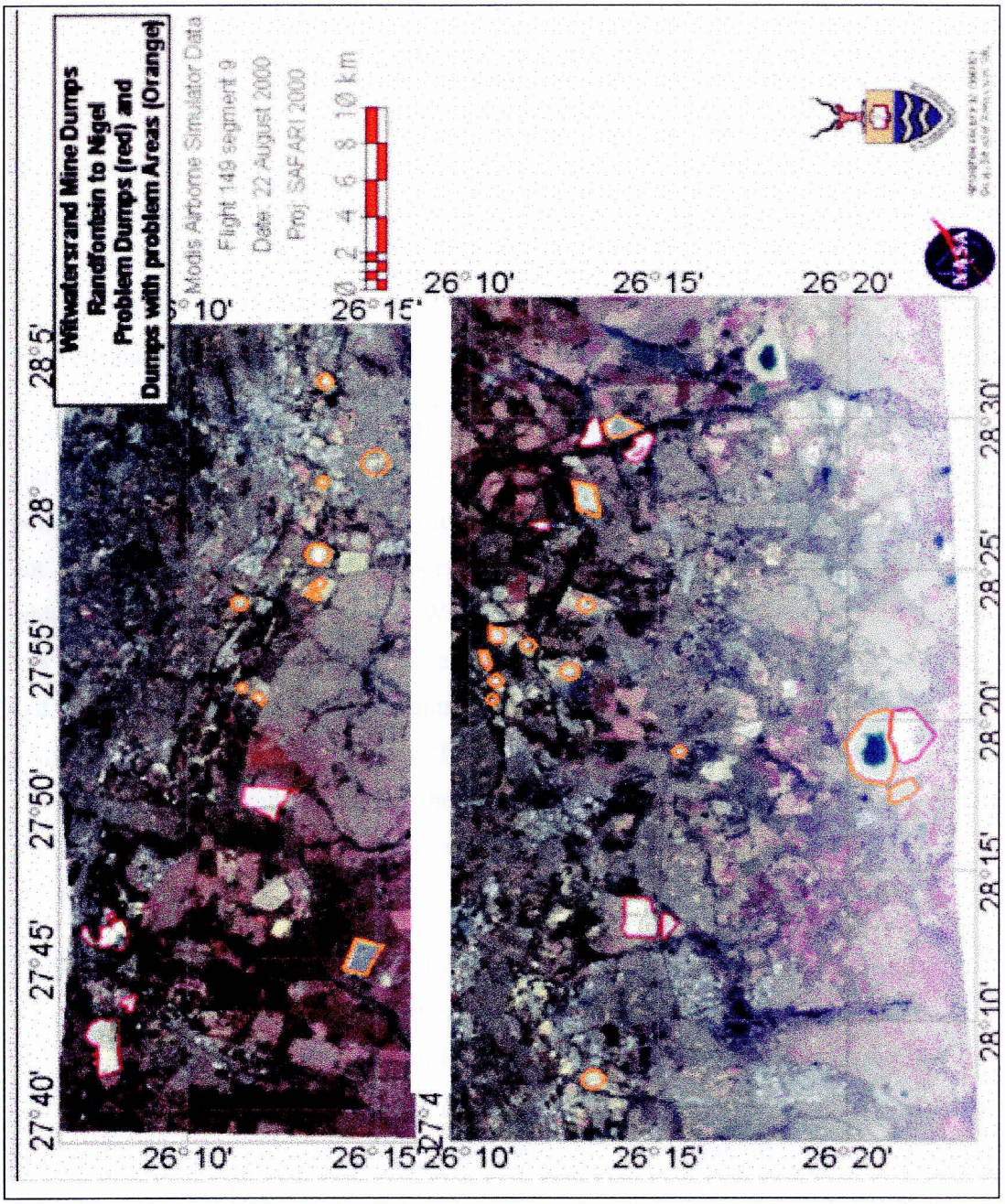


Figure 4.16 Tailings impoundments with problem areas that have the potential to cause pollution have been marked with polygons. In some cases where only part of the impoundment looks vulnerable, only that part was marked. (Data courtesy of Nasa GSFC.)

Final status map

The status map indicates part of the end result that this project set out to achieve (Figure 4.17a and b). It paints a different picture from the preliminary result presented earlier on in the experimental stage (Figure 4.1). The reason is that the preliminary map was based only on data from ground data and databases and the final status map is based on remote sensing data analysis, combined with ground truthing and initial databases. The legend indicates that six classes have been assigned. These classes are: dry, wet, vegetated, footprint, redeveloped or rehabilitated and other.

Tailings labelled as dry impoundments are assumed to have very little vegetation on them and there is no water on the surfaces. These are the impoundments that are potential polluters, unless chemicals have been used for stabilisation (surface sprays will generally not change the surface reflective properties of the dumps, other than lignon sulphonate, which turns the surface dark brown). Wet impoundments in many cases are those that are still active - water or moisture that is seen on these images is that coming from workings and transporting of slime. Impoundments can be seen as wet for other reasons, such as if an image was captured after heavy rains. These impoundments are not rehabilitated in many cases. Vegetated impoundments are those that have been rehabilitated using plants and grasses. To be classified as such from satellite imagery, grass or plants have to cover most of the surface.

Footprints (sites where tailings impoundments used to be) are not easy to identify from two-dimensional data because it is not easy to say if a surface is flat or not. Where the key says gone or removed, there is no sign from satellite images that an impoundment used to be on that site. This often happens where developments have taken place over the site. Finally the "other" class refers to instances where no positive identification can be made, an error in the classification system or where an impoundment is out of the study region.

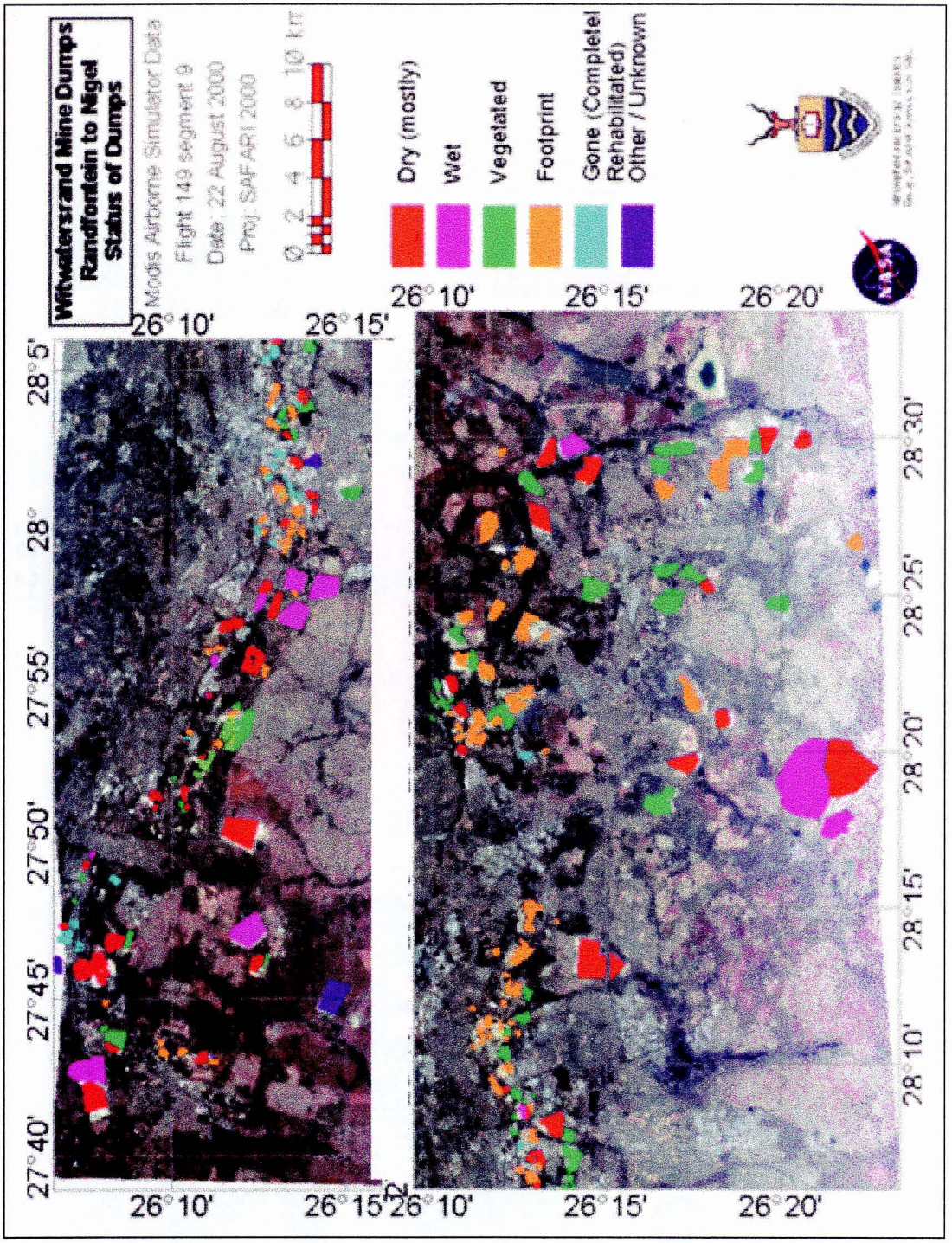


Figure 4.17a A sketch of the final status of tailings impoundments in the area of Witwatersrand in a natural colour background. (Data courtesy of Nasa GSFC.)

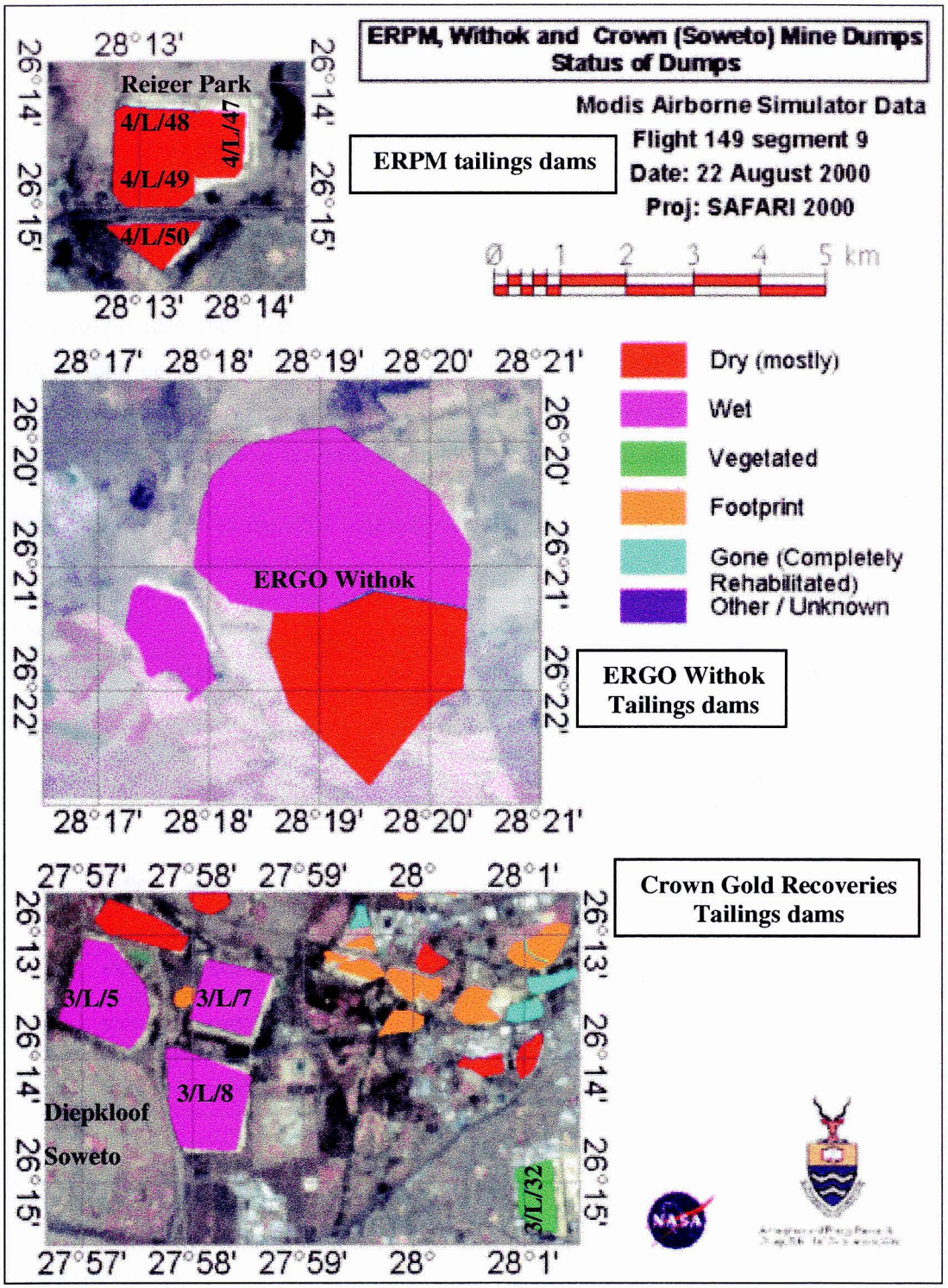


Figure 4.17b Tailings impoundments status maps of a few selected dams whose status is known and that were used as training sets. (Data courtesy of Nasa GSFC.)

Final status table

The final status table contains updated information on the status of mine tailings impoundments obtained through image analysis (Table 4.3). Also contained is preliminary status table created from the analysis of ground data and databases from mining companies and the DME. The table gives detail on the name and position of the impoundments as well as detail on what sort of activity was taking place during the ER2 flights over the area. What is also reflected on the table is numbers (status, condition and activity) that were used to produce the spatial maps on a GIS. The size column on the table contains information on the area of impoundments (km^2) in year 2000, measured from the aerial photographs using TNTmips. The new updated list can be viewed in Appendix B. A disk with an electronic copy of the database in MS Excel format is attached.

Table 4.3 Sample of the final database of tailings impoundments and status on the Witwatersrand.

Index	Dump No	Geog No	Size (km^2)	Type	Status	Mine	Type No	Cond No
1	3/L/31	"2628AA/L/16	0.67	slime	Waste disposal site	Robinson Deep	1	4
2	3/L/30	"2628AA/L/16	0.11	slime	Partly rehabilitate	Robinson Deep	1	2
3	3/A/11	"2628AA/A/9"	0.12	sand	Fully rehabilitated	Robinson Deep	2	2
4	3/L/23	"2628AA/L/20	0.12	slime	partly reprocessed	Robinson Deep	1	2
5	3/L/25	"2627BB/L/43	0.07	slime	Fully rehabilitated	City Deep	1	1

Index	Dump No	Lat	Lon	Final Anal	Status No	Activity No	Preliminary Status	Orig Index
1	3/L/31	28.03533	-26.23400	Landfill, Bad, Inactive	6	3	13	86
2	3/L/30	28.03394	-26.22710	Dry, Good, Inactive	1	3	7	90
3	3/A/11	28.04928	-26.22140	Dry, Good, Inactive	1	1	2	89
4	3/L/23	28.04976	-26.22400	Vegetated, Good, Inactive	3	3	8	83
5	3/L/25	28.05406	-26.22010	Vegetated, Very Good, Inactive	3	3	2	49

Sources of error and uncertainty

Geo-referencing

Geo-referencing problems were encountered while doing the experimental part of the project. What happened is that previously geo-referenced topography maps were used to geo-reference satellite images and aerial photographs. What came out in the end was that, the sample points that were picked up in the field were not in harmony with points on the

geo-referenced images. How ever this was not much of a handicap as precise geo-referencing was not essential here.

Time series images

Continuously changing features like tailings impoundments that are undergoing reprocessing could have been easily mapped using time series images, as this would show these tailings shrinking in size.

Topography

The difference between a tailings impoundments and footprints would have showed more clearly through the use of a DEM band. For this reason Aster imagery is recommended for its resolution and incorporation of bands 3N (nadir) and 3B (backward-viewing) from which DEM can be extracted.

Maps and databases

Some of the maps obtained were roughly drawn without any regard for relative location. This presented a challenge in that the vector object drawn from these did not fit squarely on satellite images. The databases obtained from the mining companies and the DME only had the *geog number* or the dump number for identification. It proved quite difficult to trace one or the other of the names in some cases; therefore some of the impoundments have either the dump number or the geog number.

Chapter 5
Conclusions and Recommendations

This research work has found that tailings failures are widespread in the Witwatersrand area. This information was gathered through documented complaints by communities affected by these failures and also through documents from NGOs like the Legal Resources Centre. It has been discovered that the types of tailings impoundment failure that takes place in the area and that cause a lot of concern are the pollution of water resources and air pollution.

Polluting tailings impoundments have been found to be those that were not rehabilitated, tailings impoundments that were rehabilitated, but no maintenance work carried out therefore resulting in a degraded cover and tailings impoundments that were being rehabilitated at the time.

Environmental authorities are finding it difficult to carry out their work of deciding where problems are and which tailings have been neglected and are a potential health hazard. This has been caused by the fact that no one has complete records of tailings location, ownership and present status of mine impoundments. For this reason the unit that is responsible for tracking and updating mine tailing information within the DME has to have GIS specialists who would be able to store and update data. The significance of a relationship between the environmental manager and information technology is illustrated on Figure 5.1.

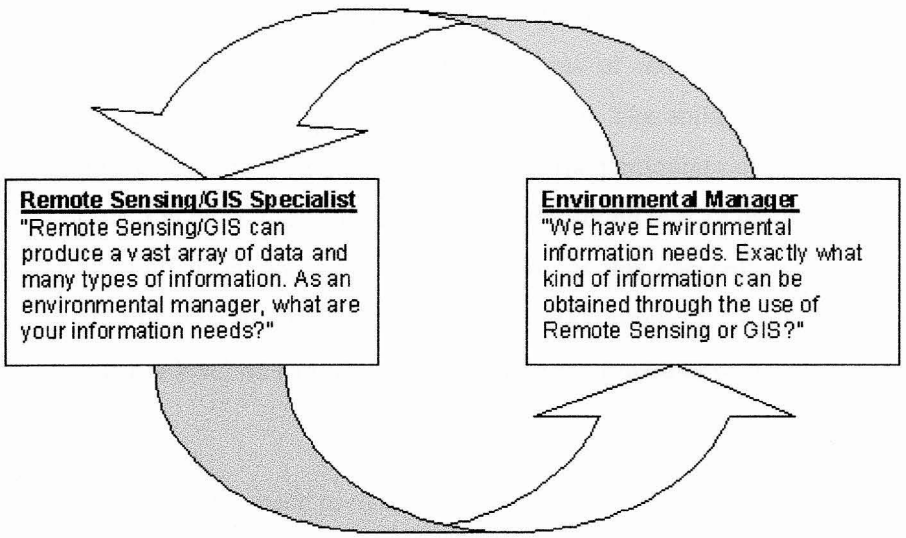


Figure 5.1 The "Information needs definition cycle." (after Hoffer, 1994)

The use of image interpretation in remote sensing has enabled operators to view the whole study area simultaneously, which is what environmental authorities have wanted to do. High-resolution satellite imagery can enable one to discern features on the ground surface. On this project, tailings dams were initially identified by their spatial characteristics, a task that involves using their shapes for identification. This was a straightforward feat when dealing with tailings dams, because they are often large and have characteristic shapes. When it comes to sand dumps and footprints, using spatial characteristics worked only to a certain extent. Smaller dumps could not be easily identified because they could not be separated from city buildings and excavations on the ground.

The use of high-resolution multi-spectral images solves the confusion that comes about when using spatial identification means, because terrestrial features have unique spectral signals. With appropriate image processing, spectral signatures are used as a way of picking out differences between features. Spectral signatures come in handy when it comes to differentiating city buildings, excavations and other features from mine tailings material in the Witwatersrand. Coupling the use of spatial and spectral recognition, a large percentage of tailings impoundments and footprints were identified, which was the first step of the project.

The larger part of image analysis went into dealing with conditions of impoundments as this was the driving motive for the project. Water can easily be identified in different images because of its ability to absorb in many channels of the spectrum. When it comes to

water on tailings impoundments, it was generally a quick process to identify in spite of the fact that water on tailings material has higher levels of minerals dissolved in it. The spectral absorption qualities are not altered significantly. The ability of having to identify water on tailings dams came with having to decide if the particular tailing is actively being dumped on or not. On dams used for validation, it was found that all dams with water were active impoundments. Caution has to be taken here, as this can only be true for images captured at the same time of the year that the Safari 2000 project took place. As a result, it could be said with a level of confidence that all tailings impoundments with water on top are active.

Use of satellite imagery has been used for a long time to assess the presence and conditions of vegetation on the land surface. On this project also, the presence of vegetation was an important issue because many tailings impoundments are rehabilitated using some kind of vegetation. While some tailings impoundments are well vegetated, it is possible in most cases to see the underlying impoundment. This is caused by the levels of minerals that these impoundments often contain and their effect on normal vegetation growth and the level of disturbance that mining activities do on the environment.

Another task that proved problematic was identifying impoundments that used rehabilitation methods other than vegetation. This is not to say that it can not be done, but means that the spectra of material used has to be identified and the proper algorithms employed to delineate the specific spectra when found on an impoundment. On this project, if impoundments looked bare and un-rehabilitated on satellite images, they were defined as so in spite of the fact that they might have been chemically treated.

What confounded the use of all image analysis that went into this project was identifying if a feature was a dump or a footprint. This is a problem that arises because the data set used is not equipped to deal with topography. That is the reason why Aster imagery is recommended for any follow up work or replication of results of this project. Aster images can be re-sampled to operate at a higher resolution than MAS images. The resolution of Aster Visible channels is at 15 m. What becomes useful also is that the Aster band 3B, which is a backward looking, channel is set to deal with topography. A positive identification can be made on whether a feature is a full impoundment or a footprint, a problem that this project did not resolve sufficiently.

Data from the DME and mining houses have helped in the compilation and mapping of what is hoped to be a complete record of goldmine tailings impoundments in the area as of the year 2000. This information was used to aid satellite images in decision-making regarding the status of tailings impoundments. Thorough the use of a GIS/remote sensing package, a complete goldmine tailings impoundments database was compiled and a tailings impoundment status map was drawn. It is hoped that this work will greatly aid the efforts of organisations and forums concerned with the environment, mining and sustainability especially the Gauteng Mining Pollution Forum.

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Appendix A: Requirements for maintaining and updating the Witwatersrand tailings impoundment database

Responsibility and required skills for processing

Future monitoring of the status of mine tailings can be carried out by either the DME or DACEL by introducing a GIS unit to track changes using GIS software. One skilled person would be capable of maintaining and updating the database. With the right software, the status of dumps can be checked and updated on a scheduled basis by this officer, through acquisition and processing of new remote sensing images.

Ordering Aster scenes - costs and contacts

Aster images can be downloaded via FTP through the EOS Data Gateway web site currently at the cost of US$55 per image. To download Aster images, registration on the EOS data gateway has to be done at http://edcimswww.cr.usgs.gov/pub/imswelcome. A registration form appears on entering the site. Here user details are filled out and on completion, the next stage appears on which the new user can log in immediately.

The site keeps the user selection parameters (e.g. latitude - longitude rectangle, time period etc.) and these are recalled when one logs on again. A frequent check of new and updated features on Earth Observing System Data Gateway main page is essential to monitor acquisition of new images and status of the instrument and satellite platform.

Selecting Aster Data

Aster sensors can be selected by either selecting the raw data or the level 1B images on the fields provided on the site. The area of interest can be selected by choosing the geographic region using the lat/lon option. Also the date-time range can be selected to restrict the choice to a specific year and time period. An automatic search takes place there after and this comes up with the options where a data granule has to be selected. Thumbnails of images can be viewed to check if the image is cloud-free. To order the desired data, an FTP pull option has to be selected and EOS will send two e-mails with the instructions on how to proceed with the download.

As ASTER is not a continuously recording instrument, it may be necessary to negotiate with Nasa if routine image acquisition is required, e.g. annual scans of a specific region such as the Witwatersrand.

Appendix B: Witwatersrand Tailings Impoundments

Index	Index of the final database created after Image analysis.
DumpNo	Old system of numbering.
GeogNo	Number given in relation to toposheet grid letters and lat/lon.
Mine	Name of Company.
Lat	Latitude of centre of dump.
Lon	Longitude of centre of dump.
FinalAnal	Condition and status of dump from (MAS) satelite images.
StatusNo	Number used to colour code the final status map in a GIS.
CondNo	Number used to colour code the final condition map in a GIS.
ActivityNo	Number used to colour code the final activity map in a GIS.
Size_km2	Area of Dump (Measured in TNTmpis).
Type	Description of whether it is a slimes or sand dump.
Plant	Abbreviated name of the company.
Status	Preliminary classification using maps and databases from mines and the DME.
TypeNo	Number used to identify type of dump and colour code the preliminary type map.
Prelim	Number used to identify status of dump and colour code the preliminary status map.
OrigInd	The original index (index of the first created database).
Comment	Condition and pupose of selected dumps.

Appendix B: Witwatersrand Tailings Impoundments

Index	Dump No	Geog No	Status	Cond No	Activity	Size	Type	Status	Type No	Prelim	OrigInd
211	"4/L/50"	"2628AA/L/71	1	4	3	0.59	slime	Deposition slimes dam	1	1	157
212	"3/L/20"	"2628AA/L/5"	1	2	3	0.15	slime	Footprint (unrehabilitated)	1	6	22
213	"3/L/17"	"2628AA/L/9"	5	1	3	0.91	slime	Fully rehabilitated	1	2	6
214	"2/L/24"	"2627BB/L/35	1	5	2	2.07	slime	Unrehabilitated	1	9	109
215	"7/L/7"	"2628BC/L/5"	1	3	3	0.50	slime	Unrehabilitated	1	9	281
216	Benoni Slimes	"2628AD/L/29	1	3	1	0.97	slime	Unrehabilitated	1	9	265
217	"3/L/34"	"2628AA/L/11	5	2	3	0.05	slime	Partly reprocessed	1	8	82
218	"3/L/14"	"2628AA/L/9"	4	2	3	0.18	slime	Footprint (rehabilitated)	1	5	16
219	"2/A/1"	"2627BB/A/29	4	2	1	0.07	sand	Partly rehabilitaed	2	7	62
220	"2/A/2 -"	"2627BB/A/28	2	3	1	0.04	sand	Rehabilitated	2	2	63
221	"2/A/3"	"2627BB/A/27	1	3	3	0.02	sand	Rehabilitated	2	7	93
222	"2/A/7"	"2627BB/A/22	1	2	2	0.08	sand	No data	2	99	110
223	"2/L/22"	"2627BB/L/47	3	1	3	0.02	slime	No data	1	99	111
224	"2/L/31"		1	3	2	0.04	slime	No data	1	99	114
225	"2/L/25"	"2627BB/L/43	1	3	2	0.04	slime	No data	1	99	100
226	"4/L/13"	"2628AA/L/59	3	2	3	0.07	slime	Partly rehabilitate	1	7	138
227	"4/A/9"	"2628AA/A/20	1	2	3	0.10	sand	Fully rehabilitated	2	2	28
228	"4/A/7"		4	2	3	0.03	sand	Footprint (unrehabilitated)	2	6	42
229	"4/A/18"	"2628AA/A/15	4	3	3	0.09	sand	Footprint (unrehabilitated)	2	6	178
230	"4/L/37"	"2628AA/L/70	3	3	3	0.73	sand	Partly rehabilitate	2	7	177
231	"4/L/23"	"2628AA/L/82	4	2	3	0.31	slime	Footprint (unrehabilitated)	1	6	169
232	"4/L/35"	"2628AA/L/75	4	3	3	0.15	slime	Footprint (unrehabilitated)	1	6	182
233	"4/L/47"	"2628AA/L/80	1	4	3	0.97	slime	Unrehabilitated	1	9	155
234	"4/L/48"	"2628AA/L/84	1	4	3	0.76	slime	Deposition slimes dam	1	1	154
235	"4/L/49"	"2628AA/L/85	1	4	3	0.97	slime	Deposition slimes dam	1	1	156
236	"4/L/40"	"2628AA/L/80	3	2	3	0.19	slime	Partly rehabilitate	1	7	172
237	WITHOK	"2628AD/L/3"	1	3	3	4.80	slime	Deposition slimes dam	1	6	267
238	"5/A/1"		5	1	3	0.17	sand	Footprint (developed)	2	4	243
239	"5/L/23"	"2628AB/L/23	1	3	3	0.37	slime	Unrehabilitated	1	9	222
240	"5/L/18"	"2628AB/L/12	3	2	3	0.05	slime	Partly rehabilitate	1	7	226

Index	Dump No	Geog No	Mine	Lat	Lon	Final Analysis
241	"7/L/1"	"2628AD/L/23	East Daggafontein/ Dagga	28.48061	-26.30370	Footprint, good, inactive
242	"6/L/18"	"2628AD/L/20	East Daggafontein/ Dagga	28.47197	-26.27710	Footprint, good,
243	"6/L/1"	"2628AB/L/34	Modderfontein B	28.45250	-26.19310	Footprint, good,
244	"2/L/35"		Randfontein	27.77020	-26.20840	Dry, good, deposition
245	"1/A/9"		Luipaardsvlei	27.77984	-26.12220	Removed / undetected
246	"1/L/15"	"2627BB/L/19	Luipaardsvlei	27.78189	-26.14550	Vegetated, very good, inactive
247	"1/L/29"	"2627BA/L/9"	Randfontein	27.71993	-26.18130	Dry, medium, deposition
248	"5/L/16"	"2628AB/L/9"	New Modderfontein	28.35071	-26.16610	Vegetated, good, inactive
249			Pan Vlak	-26.24320	27.75150	Unknown

Appendix B: Witwatersrand Tailings Impoundments

Index	Dump No	Geog No	Status	Cond No	Activity	Size	Type	Status	Type No	Prelim	OrigInd
241	"7/L/1"	"2628AD/L/23	4	2	3	0.58	slime	Footprint (rehabilitated)	1	5	274
242	"6/L/18"	"2628AD/L/20	4	2	3	0.88	slime	Footprint (rehabilitated)	1	5	271
243	"6/L/1"	"2628AB/L/34	4	2	3	1.59	slime	Footprint (rehabilitated)	1	5	252
244	"2/L/35"		1	2	2	0.14	slime	Unrehabilitated	1	9	210
245	"1/A/9"		5	1	3	0.04	sand	No data	2	99	127
246	"1/L/15"	"2627BB/L/19	3	1	3	0.27	slime	No data	1	99	122
247	"1/L/29"	"2627BA/L/9"	1	3	2	0.19	slime	No data	1	99	200
248	"5/L/16"	"2628AB/L/9"	3	2	3	0.50	slime	Partly rehabilitate	1	7	228
249			6	1	2	0.00	slime	Undefined	0	0	99

Appendix B: Witwatersrand Tailings Impoundments

Index	Dump No	Geog No	Mine	Lat	Lon	Final Analysis
1	"3/L/31"	"2628AA/L/16	Robinson Deep	28.03533	-26.23400	Landfill, bad, inactive
2	"3/L/30"	"2628AA/L/16	Robinson Deep	28.03394	-26.22710	Dry, good, inactive
3	"3/A/11"	"2628AA/A/9"	Robinson Deep	28.04928	-26.22140	Dry, good, inactive
4	"3/L/23"	"2628AA/L/20	Robinson Deep	28.04976	-26.22400	Vegetated, good, inactive
5	"3/L/25"	"2627BB/L/43	City Deep	28.05406	-26.22010	Vegetated, very good, inactive
6	"3/L/24"	"2628AA/L/23	City Deep	28.05340	-26.21680	Footprint, medium
7	"3/A/15"	"2628AA/A/33	City Deep	28.05626	-26.21730	Removed / undetected
8	"3/L/41"	"2628AA/L/26	City Deep	28.06063	-26.21920	Vegetated, good, inactive
9	"3/A/30"		Robinson Deep	28.03566	-26.22460	Dry, good, inactive
10	"3/L/42"	"2628AA/L/29	City Deep	28.06156	-26.22350	Footprint, medium
11	"3/A/15A"		City Deep	28.06605	-26.21280	Footprint, good
12	"3/L/36"	"2628AA/L/22	City Deep	28.05606	-26.21310	Footprint, very good
13	"3/L/38"	"2628AA/L/13	City Deep	28.07033	-26.21400	Footprint, good
14	"3/A/16"		City Deep	28.07018	-26.21520	Footprint, good
15	"3/L/39"	"2628AA/L/34	City Deep	28.07449	-26.21580	Footprint, medium
16	"3/A/13 A"	"2628AA/A/8"	Robinson Deep	28.04008	-26.21630	Removed / undetected
17	"3/L/35"	"2628AA/L/19	Robinson Deep	28.03912	-26.21850	Removed / undetected
18	"3/A/9 Selby		Crown Gold Recoveries	28.02718	-26.22020	Removed / undetected
19	"3/L/21"	"2628AA/A/6"	Crown Gold Recoveries	28.02671	-26.22080	Removed / undetected
20	"3/A/13 "		Robinson Deep	28.03077	-26.21080	Footprint, good
21	"3/L/33"	"2628AA/L/12	Robinson Deep	28.02666	-26.21290	Removed / undetected
22	"3/A/8 A Dump	"2628AA/A/4"	Crown Gold Recoveries	28.02023	-26.21780	Footprint, good
23	"3/A/4"	"2627BB/A/32	City Deep	28.00502	-26.20960	Footprint, very good
24	"3/A/3"	"2627AA/A/2"	Crown Gold Recoveries	27.99881	-26.21020	Footprint, very good
25	"3/L/49 "	"2627BB/L/8"	Crown Gold Recoveries	27.99863	-26.20710	Removed / undetected,
26	"3/L/9 North	"2627BB/L/79	Crown Gold Recoveries	27.99205	-26.21450	Removed / undetected
27	"3/L/10"	"2627BB/L/77	Crown Gold Recoveries	27.99269	-26.21760	Footprint, good
28	"3/L/12"	"2627BB/L/78	Crown Gold Recoveries	27.99206	-26.22130	Footprint, medium
29	"3/L/11"	"2627BB/L/76	Crown Gold Recoveries	27.98756	-26.21960	Footprint, medium
30	"3/A/6 "	"2627BB/A/33	Crown Gold Recoveries	27.99900	-26.22310	Footprint, good

Appendix B: Witwatersrand Tailings Impoundments

Index	Dump No	Geog No	Status	Cond No	Activity	Size	Type	Status	Type No	Prelim	OrigInd
1	"3/L/31"	"2628AA/L/16	6	4	3	0.67	slime	Waste disposal site	1	13	86
2	"3/L/30"	"2628AA/L/16	1	2	3	0.11	slime	Partly rehabilitated	1	7	90
3	"3/A/11"	"2628AA/A/9"	1	2	1	0.12	sand	Fully rehabilitated	2	2	89
4	"3/L/23"	"2628AA/L/20	3	2	3	0.12	slime	Partly reprocessed	1	8	83
5	"3/L/25"	"2627BB/L/43	3	1	3	0.07	slime	Fully rehabilitated	1	2	49
6	"3/L/24"	"2628AA/L/23	4	3	3	0.11	slime	Fully rehabilitated	1	2	56
7	"3/A/15"	"2628AA/A/33	5	1	3	0.04	sand	Footprint (developed)	2	4	44
8	"3/L/41"	"2628AA/L/26	3	2	3	0.15	slime	Fully rehabilitated	1	2	54
9	"3/A/30"		1	2	3	0.11	sand	Footprint (unrehabilitated)	2	6	88
10	"3/L/42"	"2628AA/L/29	4	3	3	0.16	slime	Fully rehabilitated	1	2	34
11	"3/A/15A"		4	2	3	0.08	sand	Footprint (unrehabilitated)	2	6	43
12	"3/L/36"	"2628AA/L/22	4	1	3	0.17	slime	Footprint (intersection)	1	4	50
13	"3/L/38"	"2628AA/L/13	4	2	3	0.04	slime	Footprint (developed)	1	4	52
14	"3/A/16"		4	2	3	0.05	sand	Footprint (developed)	2	4	45
15	"3/L/39"	"2628AA/L/34	4	3	3	0.13	slime	Footprint (rehabilitated)	1	5	53
16	"3/A/13 A"	"2628AA/A/8"	5	1	3	0.09	sand	Fully rehabilitated	2	2	87
17	"3/L/35"	"2628AA/L/19	5	1	3	0.07	slime	Fully rehabilitated	1	2	84
18	"3/A/9 Selby		5	1	3	0.03	sand	Footprint (unrehabilitated)	2	6	10
19	"3/L/21"	"2628AA/A/6"	5	1	3	0.10	slime	Footprint (unrehabilitated)	1	6	18
20	"3/A/13 "		4	2	1	0.14	sand	Footprint (rehabilitated)	2	5	85
21	"3/L/33"	"2628AA/L/12	5	2	1	0.07	slime	Footprint (unrehabilitated)	1	6	79
22	"3/A/8 A Dump	"2628AA/A/4"	4	2	3	0.24	sand	Footprint (rehabilitated)	2	5	12
23	"3/A/4"	"2627BB/A/32	4	1	3	0.06	sand	Footprint (rehabilitated)	2	5	60
24	"3/A/3"	"2627AA/A/2"	4	1	3	0.08	sand	Footprint (unrehabilitated)	2	6	19
25	"3/L/49 "	"2627BB/L/8"	5	1	3	0.09	slime	Footprint (unrehabilitated)	1	6	8
26	"3/L/9 North	"2627BB/L/79	5	1	3	0.06	slime	Fully rehabilitated	1	2	9
27	"3/L/10"	"2627BB/L/77	4	2	3	0.08	slime	Footprint (unrehabilitated)	1	6	15
28	"3/L/12"	"2627BB/L/78	4	3	3	0.10	slime	Footprint (unrehabilitated)	1	6	14
29	"3/L/11"	"2627BB/L/76	4	3	3	0.15	slime	Footprint (unrehabilitated)	1	6	13
30	"3/A/6 "	"2627BB/A/33	4	2	3	0.14	sand	Footprint (unrehabilitated)	2	6	7

Appendix B: Witwatersrand Tailings Impoundments

Index	Dump No	Geog No	Mine	Lat	Lon	Final Analysis
31	"3/L/13"	"2628AA/L/1"	Crown Gold Recoveries	27.99832	-26.22830	Footprint, very good
32	"3/A/7"	"2628AA/A/3"	Crown Gold Recoveries	28.00838	-26.22630	Footprint, medium
33	"3/L/18"	"2625AA/L/8"	Crown Gold Recoveries	28.01678	-26.22690	Removed / undetected
34	"3/L/7"	"2627BB/L/74	Crown Gold Recoveries	27.97232	-26.22510	Wet, good, deposition
35	"3/L/6"	"2627BB/L/73	Crown Gold Recoveries	27.96532	-26.22490	Footprint, good
36	"3/L/4"	"2627BB/L/70	Langlaagte	27.95759	-26.21550	Dry, good, reprocessing
37	"3/L/5"	"2627BB/L/69	Crown Gold Recoveries	27.95366	-26.22500	Wet, very good
38	"3/L/8"	"2627BB/L/72	Crown Gold Recoveries	27.96571	-26.23950	Wet, very good
39	"3/L/2"	"2627BB/L/71	Langlaagte	27.96172	-26.20880	Wet, good, reprocessing
40	"3/A/2"	"2627BB/A/31	Langlaagte	27.96880	-26.21110	Dry, good, reprocessing
41	"3/A/1-"	"2627BB/A/39	Consolidated Main Reef	27.95009	-26.19730	Dry, medium, reprocessing
42	"3/L/1"	"2627BB/L/68	Consolidated Main Reef	27.94833	-26.19200	Dry, bad, reprocessing
43	"2/L/5"	"2627BB/L/67	Consolidated Main Reef	27.93651	-26.18950	Footprint, good
44	"2/L/3"	"2627BB/L/62	Consolidated Main Reef	27.92744	-26.20200	Dry, good, reprocessing
45	"2/L/4"	"2627BB/L/65	Consolidated Main Reef	27.93439	-26.20300	Dry, medium, reprocessing
46	"2/L/2"	"2627BB/L/61	Consolidated Main Reef	27.92853	-26.20710	Dry, medium, reprocessing
47	"2/L/1"	"2627BB/L/64	Consolidated Main Reef	27.92461	-26.21100	Footprint, very good
48	"2/L/6"	"2627/BB/63"	Consolidated Main Reef	27.92861	-26.18590	Wet, medium, reprocessing
49	"3/L/32"	"2628AA/L/7"	Robinson Deep	28.01889	-26.25190	Vegetated, medium, inactive
50	"2/L/7"	"2627BB/L/59	Rand Leases	27.91112	-26.18330	Wet, good, inactive
51	"2/L/8"	"2627BB/L/58	Rand Leases	27.90567	-26.19730	Vegetated, medium, inactive
52	"2/L/10"	"2627BB/L/55	Rand Leases	27.89398	-26.19350	Vegetated, good, inactive
53	"2/L/9"	"2627BB/L/52	Rand Leases	27.89242	-26.20040	Vegetated, bad, inactive
54	"2/A/5"		Rand Leases	27.89188	-26.17470	Footprint, very good
55	"2/L/15"		Rand Leases	27.88884	-26.17370	Removed / undetected
56	"2/A/6"	"2627BB/A24"	Durban Deep	27.87851	-26.18050	Dry, good, deposition
57	"2/L/16"	"2627BB/L/51	Durban Deep	27.87448	-26.18280	Vegetated, medium, inactive
58	"2/L/17"	"2627BB/L/49	Durban Deep	27.86906	-26.17950	Vegetated, very good, inactive
59	"2/L/18"	"2627BB/L48"	Durban Deep	27.86918	-26.17870	Vegetated, very good , inactive
60	"2/L/20"	"2627BB/L/46	Durban Deep	27.85759	-26.17190	Dry, medium, reprocessing

Appendix B: Witwatersrand Tailings Impoundments

Index	Dump No	Geog No	Status	Cond No	Activity	Size	Type	Status	Type No	Prelim	OrigInd
31	"3/L/13"	"2628AA/L/1"	4	1	3	0.15	slime	Footprint (road-cut)	1	4	5
32	"3/A/7"	"2628AA/A/3"	4	3	1	0.19	sand	Currently being reprocessed	2	3	23
33	"3/L/18"	"2625AA/L/8"	5	2	3	0.31	slime	Partly reprocessed	1	8	3
34	"3/L/7"	"2627BB/L/74	2	2	2	0.99	slime	Deposition slimes dam	1	1	75
35	"3/L/6"	"2627BB/L/73	4	2	3	0.02	slime	Footprint (unrehabilitated)	1	6	2
36	"3/L/4"	"2627BB/L/70	1	2	1	0.51	slime	rehabilitated (road-cut)	1	2	78
37	"3/L/5"	"2627BB/L/69	2	1	2	1.41	slime	Deposition slimes dam	1	1	73
38	"3/L/8"	"2627BB/L/72	2	1	2	1.52	slime	Deposition slimes dam	1	1	74
39	"3/L/2"	"2627BB/L/71	2	2	1	0.23	slime	Fully rehabilitated	1	2	77
40	"3/A/2"	"2627BB/A/31	1	2	1	0.23	sand	Fully rehabilitated	2	2	76
41	"3/A/1-"	"2627BB/A/39	1	3	1	0.25	sand	Currently being reprocessed	2	3	64
42	"3/L/1"	"2627BB/L/68	1	4	1	0.42	slime	Currently being reprocessed	1	3	66
43	"2/L/5"	"2627BB/L/67	4	2	3	0.06	slime	Rehabilitated	1	7	65
44	"2/L/3"	"2627BB/L/62	1	2	1	0.25	slime	Rehabilitated	1	2	68
45	"2/L/4"	"2627BB/L/65	1	3	1	0.18	slime	Rehabilitated	1	2	69
46	"2/L/2"	"2627BB/L/61	1	3	1	0.48	slime	Rehabilitated	1	10	70
47	"2/L/1"	"2627BB/L/64	4	1	3	0.35	slime	Partly rehabilitate	1	7	71
48	"2/L/6"	"2627/BB/63"	2	3	1	0.07	slime	Partly rehabilitate	1	7	67
49	"3/L/32"	"2628AA/L/7"	3	3	3	0.48	slime	Fully rehabilitated	1	2	91
50	"2/L/7"	"2627BB/L/59	2	2	3	0.02	slime	Rehabilitated	1	7	98
51	"2/L/8"	"2627BB/L/58	3	3	3	0.08	slime	Fully rehabilitated	1	2	95
52	"2/L/10"	"2627BB/L/55	3	2	3	0.08	slime	Fully rehabilitated	1	2	96
53	"2/L/9"	"2627BB/L/52	3	4	3	1.33	slime	Partly rehabilitate	1	8	94
54	"2/A/5"		4	1	3	0.06	sand	No data	2	99	99
55	"2/L/15"		5	1	3	0.04	slime	No data	1	99	97
56	"2/A/6"	"2627BB/A24"	1	2	2	0.05	sand	No data	2	99	103
57	"2/L/16"	"2627BB/L/51	3	3	3	0.41	slime	No data	1	99	104
58	"2/L/17"	"2627BB/L/49	3	1	3	0.05	slime	No data	1	99	108
59	"2/L/18"	"2627BB/L48"	3	1	3	0.05	slime	No data	1	99	106
60	"2/L/20"	"2627BB/L/46	1	3	2	0.08	slime	No data	1	99	102

Appendix B: Witwatersrand Tailings Impoundments

Index	Dump No	Geog No	Mine	Lat	Lon	Final Analysis
61	"2/L/21"	"2627BB/L/41	Durban Deep	27.85292	-26.17120	Vegetated, good, inactive
62	"2/A/8"	"2627BB/A20"	Durban Deep	27.85222	-26.17360	Dry, medium, reprocessing
63	"2/A/11"	"2627BB/A/23	Durban Deep	27.86796	-26.16710	Vegetated, medium, inactive
64	"2/A/16"	"2627BB/A/21	Durban Deep	27.85818	-26.15770	Dry, medium, reprocessing
65	"4/L/14"	"2628AA/L/60	Simmer and Jack	28.15038	-26.20710	Vegetated, medium, inactive
66	"4/A/4"		Simmer and Jack	28.14446	-26.20960	Dry, bad, reprocessing
67	"4/A/3"		Simmer and Jack	28.14070	-26.21260	Dry, medium, inactive
68	"4/A/2"	"2628AA/A/27	Simmer and Jack	28.14076	-26.21140	Dry, bad, reprocessing
69	"4/L/10"	"2628AA/L/56	Simmer and Jack	28.14358	-26.21380	Footprint, good, inactive
70	"4/L/15"		Simmer and Jack	28.14975	-26.21510	Vegetated, very Good, inactive
71	"4/L/26"	"2628AA/L/51	City Deep	28.13067	-26.21470	Footprint, good
72	"4/A/11"	"2628AA/A/24	City Deep	28.12671	-26.21550	Footprint, medium
73	"4/A/10"	"2628AA/A/23	City Deep	28.12372	-26.20890	Removed / undetected
74	"4/L/25"	"2628AA/L/44	City Deep	28.11740	-26.21800	Dry, medium, reprocessing
75	"4/L/2"	"2628AA/L/40	City Deep	28.10608	-26.21430	Footprint, medium
76	"4/L/1"	"2628AA/L/36	City Deep	28.10024	-26.21680	Dry, good, reprocessing
77	"4/A/8"	"2628AA/A/19	City Deep	28.11238	-26.21800	Footprint, good
78	"3/L/47"		City Deep	28.09809	-26.21450	Dry, good, reprocessing
79	"3/A/19"	"2628AA/A/19	City Deep	28.09351	-26.21480	Removed / undetected
80	"3/A/17"	"2628AA/A/15	City Deep	28.06999	-26.22830	Dry, good, deposition
81	"3/L/45"	"2628AA/L/32	City Deep	28.06840	-26.23030	Dry, good, deposition
82	"3/L/44"	"2628AA/L31"	City Deep	28.06400	-26.23110	Vegetated, medium, inactive
83	"4/L/3"	"2628AA/L/38	City Deep	28.09716	-26.23110	Vegetated, very good, inactive
84	"4/L/4"	"2628AA/L/41	City Deep	28.10565	-26.23270	Vegetated, very good, inactive
85	"4/L/5"	"2628AA/L/45	City Deep	28.11481	-26.23520	Vegetated, good, inactive
86	"4/L/6"	"2628AA/L/48	City Deep	28.11967	-26.23190	Vegetated, medium, inactive
87	"4/L/7"	"2628AA/L/52	Simmer and Jack	28.12864	-26.23240	Vegetated, good, inactive
88	"4/L/8"	"2628AA/L/53	Simmer and Jack	28.13412	-26.22520	Dry, bad, inactive
89	"4/A/14"	"2628AA/A/65	Rose Deep	28.16488	-26.20200	Footprint, bad, inactive
90	"4/L/29"	"2628AA/L/65	Rose Deep	28.16467	-26.20410	Footprint, medium,

Appendix B: Witwatersrand Tailings Impoundments

Index	Dump No	Geog No	Status	Cond No	Activity	Size	Type	Status	Type No	Prelim	OrigInd
61	"2/L/21"	"2627BB/L/41	3	2	3	0.10	slime	No data	1	99	107
62	"2/A/8"	"2627BB/A20"	1	3	2	0.06	sand	No data	2	99	105
63	"2/A/11"	"2627BB/A/23	3	3	3	0.03	sand	No data	2	99	113
64	"2/A/16"	"2627BB/A/21	1	3	2	0.14	sand	No data	2	99	101
65	"4/L/14"	"2628AA/L/60	3	3	3	0.20	slime	Partly rehabilitate	1	7	139
66	"4/A/4"		2	4	1	0.04	sand	Partly reprocessed	2	8	132
67	"4/A/3"		1	3	1	0.21	sand	Partly reprocessed	2	8	131
68	"4/A/2"	"2628AA/A/27	2	4	1	0.09	sand	Partly reprocessed	2	8	130
69	"4/L/10"	"2628AA/L/56	4	2	3	0.31	slime	Footprint (unrehabilitated)	1	6	136
70	"4/L/15"		3	1	3	0.02	slime	Fully rehabilitated	1	2	140
71	"4/L/26"	"2628AA/L/51	4	2	1	0.15	slime	Footprint (unrehabilitated)	1	6	27
72	"4/A/11"	"2628AA/A/24	4	3	1	0.13	sand	Footprint (unrehabilitated)	2	6	33
73	"4/A/10"	"2628AA/A/23	5	1	3	0.05	sand	Partly rehabilitated	2	7	47
74	"4/L/25"	"2628AA/L/44	1	3	1	0.22	slime	Partly reprocessed	1	8	25
75	"4/L/2"	"2628AA/L/40	4	3	3	0.34	slime	Fully rehabilitated	1	2	37
76	"4/L/1"	"2628AA/L/36	1	2	1	0.08	slime	Footprint (rehabilitated)	1	5	30
77	"4/A/8"	"2628AA/A/19	4	2	3	0.05	slime	Footprint (unrehabilitated)	1	6	26
78	"3/L/47"		1	2	1	0.06	slime	Footprint (unrehabilitated)	1	6	61
79	"3/A/19"	"2628AA/A/19	5	1	3	0.24	sand	Fully rehabilitated	2	2	31
80	"3/A/17"	"2628AA/A/15	1	2	2	0.21	sand	Footprint (unrehabilitated)	2	6	29
81	"3/L/45"	"2628AA/L/32	1	2	2	0.13	slime	Footprint (unrehabilitated)	1	6	32
82	"3/L/44"	"2628AA/L31"	3	3	3	0.21	slime	Fully rehabilitated	1	2	35
83	"4/L/3"	"2628AA/L/38	3	1	3	0.36	slime	Fully rehabilitated	1	2	39
84	"4/L/4"	"2628AA/L/41	3	1	3	0.19	slime	Fully rehabilitated	1	2	36
85	"4/L/5"	"2628AA/L/45	3	2	3	0.35	slime	Footprint (developed)	1	4	41
86	"4/L/6"	"2628AA/L/48	3	3	3	0.25	slime	Partly rehabilitate	1	7	40
87	"4/L/7"	"2628AA/L/52	3	2	3	0.31	slime	Fully rehabilitated	1	2	133
88	"4/L/8"	"2628AA/L/53	1	4	3	0.57	slime	Partly reprocessed	1	8	134
89	"4/A/14"	"2628AA/A/65	4	4	3	0.12	sand	Footprint (unrehabilitated)	2	6	143
90	"4/L/29"	"2628AA/L/65	4	3	3	0.22	slime	Footprint (unrehabilitated)	1	6	145

Appendix B: Witwatersrand Tailings Impoundments

Index	Dump No	Geog No	Mine	Lat	Lon	Final Analysis
91	"4/A/30"	"2628AA/L/66	Rose Deep	28.17177	-26.19940	Vegetated, very Good, inactive
92	"4/L/30"	"2628AA/L/66	Rose Deep	28.17252	-26.20220	Vegetated, very Good, inactive
93	"4/L/36"	"2628AA/L/76	ERPM	28.18725	-26.19950	Footprint, medium,
94	"4/L/38"	"2628AA/L/72	ERPM	28.18871	-26.20440	Footprint, medium,
95	"4/A/19"		ERPM	28.18282	-26.20790	Footprint, bad, inactive
96	"4/L/39"	"2628AA/L/77	ERPM	28.19157	-26.21030	Vegetated, medium, inactive
97	"4/L/22"	"2628AA/L/79	ERPM	28.19898	-26.20120	Footprint, medium,
98	"4/A/6"		ERPM	28.20514	-26.20450	Footprint, good, inactive
99	"4/L/24"	"2628AA/L/81	ERPM	28.20704	-26.20790	Footprint, good, inactive
100	"4/L/31"	"2627AA/L/67	ERPM	28.17583	-26.18690	Footprint, good, inactive
101	"4/A/16"		ERPM	28.17862	-26.19060	Footprint, medium,
102	"4/L/32"	"2627AA/L/68	ERPM	28.18175	-26.19140	Footprint, medium,
103	"4/L/34"	"2628AA/L/71	ERPM	28.18483	-26.18960	Footprint, medium,
104	"4/L/33"	"2627AA/L/69	ERPM	28.18191	-26.19450	Footprint, medium,
105	"4/A/17"	"2628AA/A/37	ERPM	28.18782	-26.19300	Footprint, medium,
106	"4/L/35A"	"2628AA/L/78	ERPM	28.19636	-26.18600	Footprint, medium,
107	"4/A/21"		ERPM	28.22659	-26.19670	Footprint, good, inactive
108	"4/L/42"	"2628AA/L/87	ERPM	28.22651	-26.19820	Footprint, good, inactive
109	"4/L/43"	"2628AA/L/86	ERPM	28.22252	-26.20750	Footprint, medium,
110	"4/A/22"		ERPM	28.22649	-26.21130	Footprint, medium,
111	"4/L/44"	"2628AA/L/90	ERPM	28.23149	-26.21010	Footprint, good, inactive
112	"4/L/45"	"2628AA/L/91	ERPM	28.24635	-26.21290	Footprint, medium,
113	"4/L/46"	"2628AA/L/92	ERPM	28.24244	-26.22690	Footprint, good
114	"4/A/24"		ERPM	28.24316	-26.22610	Footprint, good, inactive
115	Daggafontein		ERGO	28.31530	-26.34450	Wet, good, deposition
116	"5/L/13"		New Modderfontein	28.33348	-26.22050	Footprint, medium,
117	"5/L/8"	"2628AB/L/17	New Modderfontein	28.35024	-26.20270	Vegetated, good, inactive
118	"5/L/9"	"2628AB/L/14	New Modderfontein	28.35505	-26.20560	Footprint, good, inactive
119	"5/A/3"		New Modderfontein	28.34928	-26.19720	Footprint, bad, inactive
120	"5/L/6"	"2628AB/L/13	New Modderfontein	28.35130	-26.19460	Vegetated, good, inactive

Appendix B: Witwatersrand Tailings Impoundments

Index	Dump No	Geog No	Status	Cond No	Activity	Size	Type	Status	Type No	Prelim	OrigInd
91	"4/A/30"	"2628AA/L/66	3	1	3	0.07	sand	Fully rehabilitated	2	2	142
92	"4/L/30"	"2628AA/L/66	3	1	3	0.45	slime	Fully rehabilitated	1	2	144
93	"4/L/36"	"2628AA/L/76	4	3	3	0.28	slime	Footprint (unrehabilitated)	1	6	179
94	"4/L/38"	"2628AA/L/72	4	3	3	0.07	sand	Footprint (unrehabilitated)	2	6	176
95	"4/A/19"		4	3	3	0.06	sand	Footprint (developed)	2	4	175
96	"4/L/39"	"2628AA/L/77	3	3	3	0.45	slime	Partly rehabilitate	1	7	174
97	"4/L/22"	"2628AA/L/79	4	3	3	0.10	slime	Footprint (rehabilitated)	1	5	173
98	"4/A/6"		4	2	3	0.18	sand	Footprint (rehabilitated)	2	5	170
99	"4/L/24"	"2628AA/L/81	4	2	3	0.22	slime	Footprint (rehabilitated)	1	5	171
100	"4/L/31"	"2627AA/L/67	4	2	3	0.08	slime	Footprint (rehabilitated)	1	5	187
101	"4/A/16"		4	3	3	0.06	sand	Footprint (unrehabilitated)	2	6	181
102	"4/L/32"	"2627AA/L/68	4	3	3	0.07	slime	Footprint (unrehabilitated)	1	6	184
103	"4/L/34"	"2628AA/L/71	4	3	3	0.09	slime	Footprint (unrehabilitated)	1	6	183
104	"4/L/33"	"2627AA/L/69	4	3	3	0.23	slime	Footprint (unrehabilitated)	1	6	185
105	"4/A/17"	"2628AA/A/37	4	3	3	0.13	sand	Footprint (unrehabilitated)	2	6	186
106	"4/L/35A"	"2628AA/L/78	4	3	3	0.05	slime	Footprint (unrehabilitated)	1	6	180
107	"4/A/21"		4	2	3	0.06	sand	Footprint (rehabilitated)	2	5	165
108	"4/L/42"	"2628AA/L/87	4	2	3	0.16	slime	Footprint (rehabilitated)	1	5	166
109	"4/L/43"	"2628AA/L/86	4	3	3	0.55	slime	Footprint (unrehabilitated)	1	6	164
110	"4/A/22"		4	3	3	0.36	sand	Footprint (unrehabilitated)	2	6	163
111	"4/L/44"	"2628AA/L/90	4	2	3	0.09	slime	Footprint (unrehabilitated)	1	6	162
112	"4/L/45"	"2628AA/L/91	4	3	3	0.50	slime	Footprint (unrehabilitated)	1	6	161
113	"4/L/46"	"2628AA/L/92	4	2	3	0.11	slime	Footprint (unrehabilitated)	1	6	158
114	"4/A/24"		4	2	3	0.02	sand	Footprint (unrehabilitated)	2	6	159
115	Daggafontein		2	2	2	9.40	slime	Deposition slimes dam	1	1	266
116	"5/L/13"		4	3	3	0.10	slime	Footprint (unrehabilitated)	1	6	220
117	"5/L/8"	"2628AB/L/17	3	2	3	0.28	slime	Fully rehabilitated	1	2	239
118	"5/L/9"	"2628AB/L/14	4	2	3	1.38	slime	Footprint (unrehabilitated)	1	6	216
119	"5/A/3"		4	4	3	0.19	sand	Footprint (unrehabilitated)	2	6	240
120	"5/L/6"	"2628AB/L/13	3	2	3	0.13	sand	Fully rehabilitated	2	2	237

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Index	Dump No	Geog No	Mine	Lat	Lon	Final Analysis
121	"5/L/12"	"2628AB/L/20	New Modderfontein	28.35834	-26.20950	Footprint, medium,
122	"5/A/2"		New Modderfontein	28.36385	-26.21190	Footprint, medium,
123	"5/L/25"	"2628AB/L/24	Grootvlei Mine	28.37548	-26.19150	Footprint, medium,
124	"5/A/11"	"2628AB/A/8"	Grootvlei Mine	28.37472	-26.19450	Footprint, medium,
125	"5/A/8"		New Modderfontein	28.38108	-26.18600	Vegetated, medium, inactive
126	"5/L/24"	"2628AB/L/25	New Modderfontein	28.38202	-26.18020	Footprint, bad, inactive
127	"5/L/2"	"2628AB/L/2"	New Modderfontein	28.33986	-26.19050	Footprint, good, inactive
128	"5/L/3"	"2628AB/L/5"	New Modderfontein	28.34630	-26.18850	Footprint, medium,
129	"5/L/1"	"2628AB/L/3"	New Modderfontein	28.34157	-26.18590	Footprint, medium,
130	"5/L/4"	"2628AB/L/8"	New Modderfontein	28.35095	-26.18960	Footprint, medium,
131	"5/A/7"		New Modderfontein	28.35535	-26.18040	Dry, bad, active re
132	"5/L/14"		New Modderfontein	28.34120	-26.18020	Footprint, medium,
133	"5/A/5"		New Modderfontein	28.34594	-26.17900	Footprint, bad, inactive
134	"5/L/19"	"2628AB/L/11	New Modderfontein	28.35267	-26.17550	Footprint, good, inactive
135	"5/L/20"	"2628AB/L/10	New Modderfontein	28.35868	-26.17810	Vegetated, good, inactive
136	"5/A/6"		New Modderfontein	28.35950	-26.17090	Vegetated, good, inactive
137	"5/L/21"	"2628AB/L/21	New Modderfontein	28.36038	-26.17560	Vegetated, good, inactive
138	"5/A/4"		New Modderfontein	28.33374	-26.18120	Dry, bad, deposition
139	"5/L/26"	"2628AB/L/26	Grootvlei Mine	28.39588	-26.17790	Vegetated, medium, inactive
140	"5/A/9"	"2628AB/A/11	Modderfontein B	28.40243	-26.18130	Footprint, medium,
141	"6/A/1"		East Geduld	28.43224	-26.20130	Footprint, good, inactive
142	"7/L/15"	"2628AD/L/13	East Daggafontein/ Dagga	28.41228	-26.33250	Vegetated, good, inactive
143	"7/L/9"	"2628AD/L/19	Sub Nigel	28.44451	-26.36840	Footprint, medium,
144	"7/L/2"	"2628BC/L/1"	East Daggafontein/ Dagga	28.49466	-26.31180	Footprint, good, inactive
145	"7/L/3"	"2628AD/L/24	East Daggafontein/ Dagga	28.48060	-26.32160	Vegetated, medium, inactive
146	"6/L/20"	"2628AD/L/22	East Daggafontein/ Dagga	28.49365	-26.28230	Footprint, good, inactive
147	"6/L/19"	"2628AD/L/21	East Daggafontein/ Dagga	28.48405	-26.27530	Footprint, good, inactive
148	"6/L/15"	"2628AB/L/41	East Geduld	28.45416	-26.22300	Dry, good, inactive
149	"6/L/16"	"2628AB/L/37	Grootvlei Proprietary	28.48191	-26.24190	Dry, medium, inactive
150	"6/L/14"		East Geduld	28.47559	-26.21350	Vegetated, medium, inactive

Appendix B: Witwatersrand Tailings Impoundments

Index	Dump No	Geog No	Status	Cond No	Activity	Size	Type	Status	Type No	Prelim	OrigInd
121	"5/L/12"	"2628AB/L/20	4	3	3		slime	Footprint (unrehabilitated)	1	6	219
122	"5/A/2"		4	3	3	0.38	sand	Footprint (unrehabilitated)	2	6	221
123	"5/L/25"	"2628AB/L/24	4	3	3	0.87	slime	Footprint (unrehabilitated)	1	6	246
124	"5/A/11"	"2628AB/A/8"	4	3	3	0.25	sand	Footprint (unrehabilitated)	2	6	247
125	"5/A/8"		3	3	3	0.40	sand	Footprint (unrehabilitated)	2	6	215
126	"5/L/24"	"2628AB/L/25	4	4	3	0.39	slime	Footprint (unrehabilitated)	1	6	214
127	"5/L/2"	"2628AB/L/2"	4	2	3	0.19	slime	Footprint (unrehabilitated)	1	6	231
128	"5/L/3"	"2628AB/L/5"	4	3	3	0.10	slime	Footprint (unrehabilitated)	1	6	232
129	"5/L/1"	"2628AB/L/3"	4	3	3	0.32	slime	Footprint (unrehabilitated)	1	6	230
130	"5/L/4"	"2628AB/L/8"	4	3	3	0.34	slime	Footprint (unrehabilitated)	1	6	233
131	"5/A/7"		1	4	1	0.31	sand	partly reprocessed	2	8	235
132	"5/L/14"		4	3	3	0.15	slime	Footprint (unrehabilitated)	1	6	242
133	"5/A/5"		4	4	3	0.11	slime	Footprint (unrehabilitated)	1	6	241
134	"5/L/19"	"2628AB/L/11	4	2	3	0.04	slime	Footprint (rehabilitated)	1	5	236
135	"5/L/20"	"2628AB/L/10	3	2	3	0.03	slime	Fully rehabilitated	1	2	234
136	"5/A/6"		3	2	3	0.28	sand	Partly rehabilitate	2	7	225
137	"5/L/21"	"2628AB/L/21	3	2	3	0.09	slime	Fully rehabilitated	1	2	223
138	"5/A/4"		1	4	1	0.21	sand	Partly rehabilitate	2	8	229
139	"5/L/26"	"2628AB/L/26	3	3	3	0.55	slime	Unrehabilitated	1	9	244
140	"5/A/9"	"2628AB/A/11	4	2	3	0.19	sand	Footprint (unrehabilitated)	2	6	251
141	"6/A/1"		4	2	3	0.14	sand	Footprint (rehabilitated)	2	5	254
142	"7/L/15"	"2628AD/L/13	3	2	3	0.85	slime	Fully rehabilitated	1	2	280
143	"7/L/9"	"2628AD/L/19	4	3	3	0.50	slime	Footprint (unrehabilitated)	1	6	283
144	"7/L/2"	"2628BC/L/1"	4	2	3	1.60	slime	Footprint (rehabilitated)	1	5	275
145	"7/L/3"	"2628AD/L/24	3	3	3	0.42	slime	Partly reprocessed	1	8	276
146	"6/L/20"	"2628AD/L/22	3	2	3	0.91	slime	Footprint (rehabilitated)	1	5	273
147	"6/L/19"	"2628AD/L/21	3	2	3	0.61	slime	Footprint (rehabilitated)	1	5	272
148	"6/L/15"	"2628AB/L/41	1	2	3	0.09	slime	Unrehabilitated	1	9	258
149	"6/L/16"	"2628AB/L/37	1	3	3	1.12	slime	Unrehabilitated	1	9	268
150	"6/L/14"		3	3	3	0.65	slime	Partly rehabilitate	1	7	260

Appendix B: Witwatersrand Tailings Impoundments

Index	Dump No	Geog No	Mine	Lat	Lon	Final Analysis
151	"6/L/11"	"2628AB/L/32	East Geduld	28.43548	-26.20780	Footprint, good, inactive
152	"5/L/27"	"2628AB/L/27	Grootvlei Mine	28.39967	-26.21060	Footprint, good, inactive
153	"5/A/10"	"2628AB/A/10	Grootvlei Mine	28.39419	-26.22090	Footprint, medium,
154	"6/L/4"		New Estate Area	28.41951	-26.24400	Vegetated, good, inactive
155	"5/L/32"	"2628AD/L/5"	SA Land Exploration Gold	28.35039	-26.30520	Dry, bad, inactive
156	"5/L/31"	"2628AD/L/4"	SA Land Exploration Gold	28.36164	-26.29020	Footprint, good, inactive
157	"5/L/29"	"2628AD/L/1"	Van Dyk Cons.	28.30494	-26.27520	Vegetated, medium, inactive
158	"2/L/36"		Randfontein	27.76715	-26.20570	Dry, good, deposition
159	"2/L/34"		Randfontein	27.76862	-26.20980	Vegetated, medium, inactive
160	"2/L/33"		Randfontein	27.77224	-26.21130	Vegetated, medium, inactive
161		"2627BB/L/22	Randfontein	27.78589	-26.20210	Wet, good, deposition
162	"1/L/41"	"2627BA/L/1"	Randfontein	27.69712	-26.12680	Dry, bad, inactive
163	"1/L/40"	"2627BA/L/2"	Randfontein	27.69791	-26.13180	Dry, bad, inactive
164	"1/L/38"	"2627BA/L/5"	Randfontein	27.71251	-26.13140	Wet, good, deposition
165	"1/L/39"	"2627BA/L/4"	Randfontein	27.71238	-26.12390	Wet, good, deposition
166	"1/L/24"	"2627BB/L/3"	West Rand Cons	27.76512	-26.12370	Dry, good, deposition
167	"1/A/13"	"2627BB/A/3"	West Rand Cons	27.76714	-26.12000	Dry, medium, inactive
168	"1/L/25"		Randfontein	27.76880	-26.13130	Dry, good, deposition
169	"1/L/26"	"2627BB/L/4"	West Rand Cons	27.76292	-26.13330	Dry, very good, inactive
170	"1/A/14"	"2627BB/A/1"	Randfontein	27.75946	-26.13300	Dry, good, inactive
171	"1/L/17"	"2627BB/L/17	Luipaardsvlei	27.77639	-26.12120	Removed / undetected
172	"1/L/12"	"2627BB/L/16	Luipaardsvlei	27.78022	-26.13820	Dry, very good, inactive
173	"1/L/10"	"2627BB/L/24	Luipaardsvlei	27.79018	-26.12020	Removed / undetected
174	"1/L/8"	"2627BB/L/20	Luipaardsvlei	27.78166	-26.11490	Removed / undetected
175	"1/A/7"	"2627BB/A/7"	Luipaardsvlei	27.78510	-26.11670	Removed / undetected
176	"1/L/9"	"2627BB/L/23	Luipaardsvlei	27.78851	-26.11460	Dry, good, inactive
177	"1/A/12"	"2627BB/A/2"	West Rand Cons	27.76830	-26.11160	outside
178	"1/L/28"	"2627BB/L/19	West Rand Cons	27.74773	-26.13430	Footprint, good, inactive
179	"1/A/30"		Randfontein	27.72910	-26.13940	Vegetated, medium, deposition
180	"1/L/37"	"2627BA/L/6"	Randfontein	27.72392	-26.13740	Dry, medium, inactive

Appendix B: Witwatersrand Tailings Impoundments

Index	Dump No	Geog No	Status	Cond No	Activity	Size	Type	Status	Type No	Prelim	OrigInd
151	"6/L/11"	"2628AB/L/32	4	2	3	0.18	slime	Footprint (unrehabilitated)	1	6	255
152	"5/L/27"	"2628AB/L/27	4	2	3	1.29	slime	Footprint (rehabilitated)	1	5	248
153	"5/A/10"	"2628AB/A/10	4	3	3	0.15	slime	Footprint (unrehabilitated)	1	6	249
154	"6/L/4"		3	2	3	1.12	slime	Fully rehabilitated	1	2	261
155	"5/L/32"	"2628AD/L/5"	1	4	3	0.58	slime	Unrehabilitated	1	9	263
156	"5/L/31"	"2628AD/L/4"	4	4	3	1.13	slime	Footprint (rehabilitated)	1	5	262
157	"5/L/29"	"2628AD/L/1"	3	3	3	0.14	slime	Partly rehabilitate	1	7	264
158	"2/L/36"		1	2	2	0.30	slime	Unrehabilitated	1	9	211
159	"2/L/34"		3	3	3	0.06	slime	No data	1	99	209
160	"2/L/33"		3	3	3	0.05	slime	No data	1	99	208
161		"2627BB/L/22	2	2	2	1.84	slime	Deposition slimes dam	1	1	212
162	"1/L/41"	"2627BA/L/1"	1	4	3	0.83	slime	Unrehabilitated	1	9	207
163	"1/L/40"	"2627BA/L/2"	1	4	3	0.61	slime	Unrehabilitated	1	9	206
164	"1/L/38"	"2627BA/L/5"	2	2	2	0.65	slime	Deposition slimes dam	1	1	204
165	"1/L/39"	"2627BA/L/4"	2	2	2	1.20	slime	Deposition slimes dam	1	1	205
166	"1/L/24"	"2627BB/L/3"	1	2	2	0.67	slime	Unrehabilitated	1	9	151
167	"1/A/13"	"2627BB/A/3"	1	3	3	0.06	sand	No data	2	99	148
168	"1/L/25"		1	2	2	0.76	slime	No data	1	99	199
169	"1/L/26"	"2627BB/L/4"	1	1	3	0.19	slime	Unrehabilitated	1	9	150
170	"1/A/14"	"2627BB/A/1"	1	2	3	0.10	sand	No data	2	99	191
171	"1/L/17"	"2627BB/L/17	5	1	3	0.02	slime	No data	1	99	116
172	"1/L/12"	"2627BB/L/16	1	1	3	0.73	slime	No data	1	99	120
173	"1/L/10"	"2627BB/L/24	5	1	3	0.12	slime	No data	1	99	118
174	"1/L/8"	"2627BB/L/20	5	1	3	0.20	slime	No data	1	99	119
175	"1/A/7"	"2627BB/A/7"	5	1	3	0.14	sand	No data	2	99	115
176	"1/L/9"	"2627BB/L/23	1	2	3	0.09	slime	No data	1	99	117
177	"1/A/12"	"2627BB/A/2"	6	0	0	0.30	sand	No data	2	99	149
178	"1/L/28"	"2627BB/L/19	4	2	3	0.09	slime	No data	1	99	152
179	"1/A/30"		3	3	2	0.78	sand	Partly reprocessed	2	8	195
180	"1/L/37"	"2627BA/L/6"	1	3	3	0.17	slime	No data	1	99	203

Appendix B: Witwatersrand Tailings Impoundments

Index	Dump No	Geog No	Mine	Lat	Lon	Final Analysis
181	"1/L/36"	"2627BA/L/12	Randfontein	27.73469	-26.13340	Vegetated, good, inactive
182	"1/A/19"		Randfontein	27.72673	-26.16080	Footprint, medium,
183	"1/L/32"	"2627BA/L/7"	Randfontein	27.72150	-26.16260	Footprint, medium,
184	"1/L/30"		Randfontein	27.72158	-26.17040	Footprint, medium,
185	"1/A/18"	"2627BA/A/3"	Randfontein	27.72249	-26.17280	Footprint, medium,
186	"1/A/17"		Randfontein	27.71702	-26.17950	Dry, medium, deposition
187	"1/A/10"	"2627BB/A/5	Randfontein	27.71663	-26.18610	Footprint, good
188	"1/A/6"		Luipaardsvlei	27.80215	-26.11940	Vegetated, medium, inactive
189	"1/L/1"	"2627BB/L/31	Luipaardsvlei	27.81320	-26.13910	Removed / undetected
190	"1/L/13"		Luipaardsvlei	27.82149	-26.12520	Dry, medium, deposition
191	"1/A/4&5"	"2627BB/A/10	Luipaardsvlei	27.81453	-26.12350	Vegetated, medium, inactive
192	"1/A/2"		Luipaardsvlei	27.82607	-26.12840	Wet, good, deposition
193	"1/L/2"	"2627BB/L/34	Luipaardsvlei	27.82733	-26.12780	Wet, good, deposition
194	"3/L/19"	"2628AA/L/6"	Crown Gold Recoveries	28.01780	-26.23310	Dry, good, inactive
195	Rooikraal	"2628AD/L/2"	Deposition Sites	28.29462	-26.36030	Wet, good, inactive
196	"7/L/4"	"2628BC/L/2"	East Daggafontein/ Dagga	28.49791	-26.32090	Vegetated, good, inactive
197	"7/L/5"	"2628BC/L/3"	East Daggafontein/ Dagga	28.49622	-26.32650	Dry, medium, inactive
198	"7/L/6"	"2628BC/L/6"	East Daggafontein/ Dagga	28.50236	-26.32700	Dry, medium, inactive
199	"6/L/17"	"2628AB/L/39	Grootvlei Proprietary	28.49604	-26.23360	Wet, good, deposition
200	"6/L/17A"	"2628AB/L/38	Grootvlei Proprietary	28.49050	-26.22190	Dry, bad, inactive
201	"6/L/2"	"2628AB/L/40	East Geduld	28.49185	-26.19990	Footprint, good, inactive
202	"6/L/3"	"2628AB/L/30	East Geduld	28.40840	-26.19740	Footprint, good, inactive
203	"5/L/17"	"2628AB/L/18	New Modderfontein	28.36126	-26.16680	Vegetated, good, inactive
204	"5/L/22"	"2628AB/L/22	New Modderfontein	28.36789	-26.16890	Vegetated, very Good, inactive
205	"4/L/27"	"2628AA/L/63	Rose Deep	28.15174	-26.19830	Footprint, medium,
206	"4/L/28"	"2628AA/L/64	Rose Deep	28.15624	-26.19650	Footprint, good, inactive
207	"4/L/20"	"2628AA/L/50	City Deep	28.12958	-26.20590	Vegetated, very Good, inactive
208	"4/L/12"	"2628AA/L/57	Simmer and Jack	28.13918	-26.20570	Vegetated, medium, inactive
209	"4/L/41"	"2628AA/L/83	ERPM	28.21396	-26.20360	Footprint, good, inactive
210	"4/A/20"		ERPM	28.21423	-26.20170	Footprint, good, inactive

Appendix B: Witwatersrand Tailings Impoundments

Index	Dump No	Geog No	Status	Cond No	Activity	Size	Type	Status	Type No	Prelim	OrigInd
181	"1/L/36"	"2627BA/L/12	3	2	3	0.07	slime	No data	1	99	202
182	"1/A/19"		4	3	3	0.07	sand	No data	2	99	193
183	"1/L/32"	"2627BA/L/7"	4	2	3	0.17	slime	No data	1	99	201
184	"1/L/30"		4	3	3	0.09	slime	No data	1	99	194
185	"1/A/18"	"2627BA/A/3"	4	3	3	0.05	sand	No data	2	99	192
186	"1/A/17"		1	3	2	0.09	sand	No data	2	99	189
187	"1/A/10"	"2627BB/A/5	4	2	3	0.16	sand	No data	2	99	190
188	"1/A/6"		3	3	3	0.04	sand	No data	2	99	126
189	"1/L/1"	"2627BB/L/31	5	1	3	0.20	slime	No data	1	99	124
190	"1/L/13"		1	3	2	0.09	slime	No data	1	99	121
191	"1/A/4&5"	"2627BB/A/10	3	3	3	0.05	sand	No data	2	99	123
192	"1/A/2"		2	2	2	0.03	sand	No data	2	99	128
193	"1/L/2"	"2627BB/L/34	2	2	2	0.02	slime	No data	1	99	125
194	"3/L/19"	"2628AA/L/6"	1	2	3	0.13	slime	Footprint (unrehabilitated)	1	6	4
195	Rooikraal	"2628AD/L/2"	2	2	2	0.60	slime	Deposition slimes dam	1	1	72
196	"7/L/4"	"2628BC/L/2"	3	1	3	0.70	slime	Fully rehabilitated	1	2	277
197	"7/L/5"	"2628BC/L/3"	1	3	3	0.29	slime	Unrehabilitated	1	9	278
198	"7/L/6"	"2628BC/L/6"	1	3	3	0.44	slime	Unrehabilitated	1	9	279
199	"6/L/17"	"2628AB/L/39	2	2	1	1.14	slime	Unrehabilitated	1	9	269
200	"6/L/17A"	"2628AB/L/38	1	4	3	0.84	slime	Unrehabilitated	1	9	270
201	"6/L/2"	"2628AB/L/40	4	2	3	0.17	slime	Footprint (rehabilitated)	1	5	253
202	"6/L/3"	"2628AB/L/30	4	2	3	0.53	slime	Footprint (rehabilitated)	1	5	259
203	"5/L/17"	"2628AB/L/18	3	2	3	0.85	slime	Fully rehabilitated	1	2	227
204	"5/L/22"	"2628AB/L/22	3	1	3	0.13	slime	Fully rehabilitated	1	2	224
205	"4/L/27"	"2628AA/L/63	4	3	3	0.10	slime	Footprint (rehabilitated)	1	5	146
206	"4/L/28"	"2628AA/L/64	4	2	3	0.21	slime	Footprint (rehabilitated)	1	5	147
207	"4/L/20"	"2628AA/L/50	3	1	3	0.05	slime	Fully rehabilitated	1	2	51
208	"4/L/12"	"2628AA/L/57	3	3	3	0.02	slime	Unrehabilitated	1	9	137
209	"4/L/41"	"2628AA/L/83	4	2	3	0.16	slime	Footprint (unrehabilitated)	1	6	168
210	"4/A/20"		4	2	3	0.04	sand	Footprint (rehabilitated)	2	5	167

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Index	Dump No	Geog No	Mine	Lat	Lon	Final Analysis
211	"4/L/50"	"2628AA/L/71	ERPM	28.21921	-26.25480	Dry, bad, inactive
212	"3/L/20"	"2628AA/L/5"	Crown Gold Recoveries	28.01049	-26.23430	Dry, good, inactive
213	"3/L/17"	"2628AA/L/9"	Crown Gold Recoveries	28.02100	-26.22300	Removed / undetected
214	"2/L/24"	"2627BB/L/35	Durban Deep	27.83890	-26.19900	Dry, very, deposition
215	"7/L/7"	"2628BC/L/5"	Marievale	28.49836	-26.34360	Dry, medium, inactive
216	Benoni Slimes	"2628AD/L/29	Van Dyk Cons.	28.32661	-26.28760	Dry, bad, deposition
217	"3/L/34"	"2628AA/L/11	Robinson Deep	28.03309	-26.21500	Removed / undetected
218	"3/L/14"	"2628AA/L/9"	Crown Gold Recoveries	28.00243	-26.22390	Footprint, good
219	"2/A/1"	"2627BB/A/29	Consolidated Main Reef	27.93693	-26.18820	Footprint, good
220	"2/A/2 -"	"2627BB/A/28	Consolidated Main Reef	27.93103	-26.18670	Wet, medium, reprocessing
221	"2/A/3"	"2627BB/A/27	Rand Leases	27.91156	-26.18430	Dry, medium, inactive
222	"2/A/7"	"2627BB/A/22	Durban Deep	27.86117	-26.17270	Dry, good, deposition
223	"2/L/22"	"2627BB/L/47	Durban Deep	27.86620	-26.16680	Vegetated, very good, inactive
224	"2/L/31"		Durban Deep	27.85184	-26.15820	Dry, medium, deposition
225	"2/L/25"	"2627BB/L/43	Durban Deep	27.85655	-26.16020	Dry, medium, deposition
226	"4/L/13"	"2628AA/L/59	Simmer and Jack	28.14621	-26.21070	Vegetated, good, inactive
227	"4/A/9"	"2628AA/A/20	City Deep	28.11724	-26.21480	Dry, good, inactive
228	"4/A/7"		City Deep	28.11028	-26.20750	Footprint, good
229	"4/A/18"	"2628AA/A/15	ERPM	28.18090	-26.20240	Footprint, medium,
230	"4/L/37"	"2628AA/L/70	ERPM	28.18370	-26.20240	Vegetated, medium, inactive
231	"4/L/23"	"2628AA/L/82	ERPM	28.20878	-26.20310	Footprint, good, inactive
232	"4/L/35"	"2628AA/L/75	ERPM	28.19091	-26.19360	Footprint, medium,
233	"4/L/47"	"2628AA/L/80	ERPM	28.22831	-26.24150	Dry, bad, inactive
234	"4/L/48"	"2628AA/L/84	ERPM	28.21744	-26.24040	Dry, bad, inactive
235	"4/L/49"	"2628AA/L/85	ERPM	28.21831	-26.24620	Dry, bad, inactive
236	"4/L/40"	"2628AA/L/80	ERPM	28.20501	-26.21280	Vegetated, good, inactive
237	WITHOK	"2628AD/L/3"	ERGO	28.32393	-26.36540	Dry, medium, inactive
238	"5/A/1"		New Modderfontein	28.33112	-26.21130	moved / undetected = redevelop
239	"5/L/23"	"2628AB/L/23	New Modderfontein	28.36891	-26.17640	Dry, medium, inactive
240	"5/L/18"	"2628AB/L/12	New Modderfontein	28.35685	-26.17270	Vegetated, good, inactive

Appendix B: Witwatersrand Tailings Impoundments

Index	Dump No	Geog No	Status	Cond No	Activity	Size	Type	Status	Type No	Prelim	OrigInd
211	"4/L/50"	"2628AA/L/71	1	4	3	0.59	slime	Deposition slimes dam	1	1	157
212	"3/L/20"	"2628AA/L/5"	1	2	3	0.15	slime	Footprint (unrehabilitated)	1	6	22
213	"3/L/17"	"2628AA/L/9"	5	1	3	0.91	slime	Fully rehabilitated	1	2	6
214	"2/L/24"	"2627BB/L/35	1	5	2	2.07	slime	Unrehabilitated	1	9	109
215	"7/L/7"	"2628BC/L/5"	1	3	3	0.50	slime	Unrehabilitated	1	9	281
216	Benoni Slimes	"2628AD/L/29	1	3	1	0.97	slime	Unrehabilitated	1	9	265
217	"3/L/34"	"2628AA/L/11	5	2	3	0.05	slime	Partly reprocessed	1	8	82
218	"3/L/14"	"2628AA/L/9"	4	2	3	0.18	slime	Footprint (rehabilitated)	1	5	16
219	"2/A/1"	"2627BB/A/29	4	2	1	0.07	sand	Partly rehabilitaed	2	7	62
220	"2/A/2 -"	"2627BB/A/28	2	3	1	0.04	sand	Rehabilitated	2	2	63
221	"2/A/3"	"2627BB/A/27	1	3	3	0.02	sand	Rehabilitated	2	7	93
222	"2/A/7"	"2627BB/A/22	1	2	2	0.08	sand	No data	2	99	110
223	"2/L/22"	"2627BB/L/47	3	1	3	0.02	slime	No data	1	99	111
224	"2/L/31"		1	3	2	0.04	slime	No data	1	99	114
225	"2/L/25"	"2627BB/L/43	1	3	2	0.04	slime	No data	1	99	100
226	"4/L/13"	"2628AA/L/59	3	2	3	0.07	slime	Partly rehabilitate	1	7	138
227	"4/A/9"	"2628AA/A/20	1	2	3	0.10	sand	Fully rehabilitated	2	2	28
228	"4/A/7"		4	2	3	0.03	sand	Footprint (unrehabilitated)	2	6	42
229	"4/A/18"	"2628AA/A/15	4	3	3	0.09	sand	Footprint (unrehabilitated)	2	6	178
230	"4/L/37"	"2628AA/L/70	3	3	3	0.73	sand	Partly rehabilitate	2	7	177
231	"4/L/23"	"2628AA/L/82	4	2	3	0.31	slime	Footprint (unrehabilitated)	1	6	169
232	"4/L/35"	"2628AA/L/75	4	3	3	0.15	slime	Footprint (unrehabilitated)	1	6	182
233	"4/L/47"	"2628AA/L/80	1	4	3	0.97	slime	Unrehabilitated	1	9	155
234	"4/L/48"	"2628AA/L/84	1	4	3	0.76	slime	Deposition slimes dam	1	1	154
235	"4/L/49"	"2628AA/L/85	1	4	3	0.97	slime	Deposition slimes dam	1	1	156
236	"4/L/40"	"2628AA/L/80	3	2	3	0.19	slime	Partly rehabilitate	1	7	172
237	WITHOK	"2628AD/L/3"	1	3	3	4.80	slime	Deposition slimes dam	1	6	267
238	"5/A/1"		5	1	3	0.17	sand	Footprint (developed)	2	4	243
239	"5/L/23"	"2628AB/L/23	1	3	3	0.37	slime	Unrehabilitated	1	9	222
240	"5/L/18"	"2628AB/L/12	3	2	3	0.05	slime	Partly rehabilitate	1	7	226

Appendix B: Witwatersrand Tailings Impoundments

Index	Dump No	Geog No	Mine	Lat	Lon	Final Analysis
241	"7/L/1"	"2628AD/L/23	East Daggafontein/ Dagga	28.48061	-26.30370	Footprint, good, inactive
242	"6/L/18"	"2628AD/L/20	East Daggafontein/ Dagga	28.47197	-26.27710	Footprint, good,
243	"6/L/1"	"2628AB/L/34	Modderfontein B	28.45250	-26.19310	Footprint, good,
244	"2/L/35"		Randfontein	27.77020	-26.20840	Dry, good, deposition
245	"1/A/9"		Luipaardsvlei	27.77984	-26.12220	Removed / undetected
246	"1/L/15"	"2627BB/L/19	Luipaardsvlei	27.78189	-26.14550	Vegetated, very good, inactive
247	"1/L/29"	"2627BA/L/9"	Randfontein	27.71993	-26.18130	Dry, medium, deposition
248	"5/L/16"	"2628AB/L/9"	New Modderfontein	28.35071	-26.16610	Vegetated, good, inactive
249			Pan Vlak	-26.24320	27.75150	Unknown

Appendix B: Witwatersrand Tailings Impoundments

Index	Dump No	Geog No	Status	Cond No	Activity	Size	Type	Status	Type No	Prelim	OrigInd
241	"7/L/1"	"2628AD/L/23	4	2	3	0.58	slime	Footprint (rehabilitated)	1	5	274
242	"6/L/18"	"2628AD/L/20	4	2	3	0.88	slime	Footprint (rehabilitated)	1	5	271
243	"6/L/1"	"2628AB/L/34	4	2	3	1.59	slime	Footprint (rehabilitated)	1	5	252
244	"2/L/35"		1	2	2	0.14	slime	Unrehabilitated	1	9	210
245	"1/A/9"		5	1	3	0.04	sand	No data	2	99	127
246	"1/L/15"	"2627BB/L/19	3	1	3	0.27	slime	No data	1	99	122
247	"1/L/29"	"2627BA/L/9"	1	3	2	0.19	slime	No data	1	99	200
248	"5/L/16"	"2628AB/L/9"	3	2	3	0.50	slime	Partly rehabilitate	1	7	228
249			6	1	2	0.00	slime	Undefined	0	0	99