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# Assessing groundwater access by trees growing above contaminated groundwater plumes originating from gold tailings storage facilities

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# ABSTRACT

Deep-level gold mining in the Witwatersrand Basin Goldfields (WBG) of central South Africa is characterised by the production of extensive unlined tailings storage facilities (TSFs) comprising large quantities of pulverised rock and water contaminated with salts and a wide range of other inorganic pollutants (Weiersbye *et al*., 2006). There are more than 200 such TSFs covering a total area of more than 400 $km^2$ (Rosner *et al*., 2001), and significant contaminated "footprint" areas occur after removal and reprocessing of the original TSFs (Chevrel *et al*., 2003). It is estimated that the Witwatersrand Basin contains six billion tons of gold and uranium tailings (Chevrel *et al*., 2003), 430 000 tons of uranium (Council of Geoscience, 1998; Winde, 2004a; b; c) and approximately 30 million tons of sulphur (Witkowski and Weiersbye, 1998a). An estimated 105 million tons of waste per annum is generated by the gold mining industry within the WBG (Department of Tourism, Economic and Environmental Affairs, 2002; Chamber of Mines of South Africa, 2004).

A major environmental problem resulting from deep level mining in the WBG is the contaminated water that seeps from TSFs into adjacent lands and groundwater. Van As (1992) reported on the significant environmental hazards resulting from the storage of highly pulverised pyrite rock waste in TSFs (Straker *et al*., 2007). Adjacent lands become polluted through near-surface seepage, and this is enhanced by the movement of polluted groundwater in shallow aquifers that are commonly 1-30 m below ground (Funke, 1990; Hodgson *et al*., 2001; Rosner *et al*., 2001; Naicker *et al*., 2003). The impact of the mines and the TSFs extends far beyond their localities (Cogho *et al*., 1990). The Vaal River catchment receives a large proportion of the pollutants from WBG mining activities, with consequent acidification and salinisation of surface and ground waters. Salt discharges to the Vaal River were estimated to be 170 000 t/annum (Best, 1985), whereas discharges from the Free State gold mines south of the Vaal catchment were estimated at 350 000 t/annum of salts (Cogho *et al*., 1990). Concern also exists over the spread of dangerous contaminants such as uranium, chromium and mercury (Coetzee *et al*., 2006; Winde, 2009).

Engineering solutions to these problems are hindered by the large sizes and great extent of TSFs, the high and indefinite costs involved, and the typically low hydraulic conductivity in affected aquifers, which makes the "pump and treat" option impractical. An alternative phytoremediation strategy is to establish belts or blocks of trees in strategic areas surrounding

the TSFs in order to reduce the seepage of contaminated water into adjacent lands and groundwater bodies. The major reasons why trees are likely to have a greater impact on seepage water than the existing grasslands that characterise the area around most TSFs in the WBG, are that some tree species have the potential to develop very deep root systems and to continue transpiring water throughout the year. This is in contrast to seasonally dormant grasslands. In addition, some tree species are known to be tolerant to salts and other pollutants. Trees are thus potentially able to reach deep water tables, take up large quantities of water, and remove some of the pollutants in this water. It is crucial for a successful implementation of this strategy to know on what sites trees are able to access mine seepage water, and consequently maintain a high year-round rate of water use. If this access is limited, then growth and water use will be curtailed during the long winter dry season, and control of seepage will be considerably below potential.

A primary aim of this study was to develop methodologies to discriminate between water-stressed and non-water-stressed trees currently growing in three gold mining districts (Welkom, Vaal River, West Wits) within the WBG. This information was required to assess what site types are likely to support adequate tree growth and permit high rates of water use and seepage control. The tree species selected were those most widely occurring in these areas, and include the non-native species *Eucalyptus sideroxylon* A. Cunningham ex Woolls and *Eucalyptus camaldulensis* Dehnhardt, as well as the indigenous species *Searsia lancea* L.f. Various remote sensing technologies including leaf-level spectroscopy, satellite and airborne remote sensing images were evaluated for their usefulness in detecting levels of winter-time water stress. Four commonly used ground-truthing techniques (predawn leaf water potential, leaf chlorophyll fluorescence, leaf chlorophyll and carotenoid pigment content, and leaf water content) were used for localised measurements of plant water stress and for ground-truthing of remotely sensed data on 75 sample sites and 15 sample sites. This study provided a unique opportunity to test and compare the use of stress reflectance models derived from different remote sensing data acquired at different spatial and spectral resolutions (i.e. multispectral and hyperspectral) for the same geographical location.

The use of remote sensing to examine the spectral responses of vegetation to plant stress has been widely described in the scientific literature. A collation of published spectral reflectance indices provided the basis for investigating the use of hand-held remote sensing technology to detect plant water stress, and was used as a stepping stone to further develop spectral plant

water stress relationships for specific tree species in this study. Seventy seven spectral reflectance indices and specific individual spectral wavelengths useful for detecting plant water stress, plant pigment content, the presence of stress related pigments in vegetation, and changes in leaf cellular structure, were investigated using hand-held spectroscopy. Ground-based measurements of plant water stress were taken on 75 sample trees. In this study, the measurement of predawn leaf water potential has been identified as a key methodology for linking remotely sensed assessments of plant water stress to actual plant water stress; a reading of -0.8 MPa was used to separate stressed trees from unstressed trees in the landscape (Cleary and Zaerr, 1984). The results of the predawn leaf water potential measurements ranged from -0.56 to -0.68 MPa at unstressed sites, and from -0.93 to -1.78 MPa at stressed sites. A novel approach of using spectral reflectance indices derived from previous studies was used to identify specific indices which are applicable to South Africa and to the three species investigated in the WGB. Maximal multiple linear regression models were derived for all possible combinations of plant water stress measurements and the 77 spectral reflectance indices extracted from leaf-level spectral reflectance data, and included the interactions of district and species. The results of the multiple linear regression models indicated that the (695/690) index, DATT index (850-710)/(850-680), near infra-red index (710/760) and the water band (900/970) index performed well and accounted for more than 50% of the variance in the data. The stepwise regression model derived between chlorophyll b content and the DATT index was selected as the "best" model, having the highest adjusted $R^2$ of 69.3%. This was shown to be the most robust model in this application, which could be used at different locations for different species to predict chlorophyll content at the leaf-level.

Satellite earth observation data were acquired from two data sources for this investigation; the Hyperion hyperspectral sensor (United States Geological Survey Earth Resources Observation Systems) and the Proba Chris pseudo-hyperspectral sensor (European Space Agency). The Hyperion sensor was selected to obtain high spatial and spectral resolution data, whereas the Proba Chris sensor provided high spatial and medium spectral resolution earth observation data. Twelve vegetation indices designed to capture changes in canopy water status, plant pigment content and changes in plant cellular structure, were selected and derived from the satellite remote sensing imagery. Ground-based measurements of plant water stress undertaken during late July 2004 were used for ground-truthing the Hyperion image, while measurements undertaken during July 2005 and August 2005 were used for ground-truthing the Proba Chris images. Predawn leaf water potential measurements undertaken for the three

species, ranged from -0.42 to -0.78 MPa at unstressed sites, and -0.95 to -4.66 MPa at stressed sites. Predawn leaf water potentials measured for *E. camaldulensis* trees sampled in species trials in Vaal River were significantly different between stressed and non stressed trees ($t = 3.39$, 8df, $P = 0.009$). In contrast, *E. camaldulensis* trees sampled near a pan within the Welkom mining district, which had greater access to water but were exposed to higher concentrations of salts and inorganic contaminants, displayed differences in total chlorophyll content ($t = -2.20$, 8df, $P = 0.059$), carotenoid content ($t = -5.68$, 8df, $P < 0.001$) and predawn leaf water potential ($t = 4.25$, 8df, $P = 0.011$) when compared to trees sampled on farmland. *E. sideroxylon* trees sampled close to a farm dam in the West Wits mining district displayed differences in predawn leaf water potential ($t = 69.32$, 8df, $P < 0.001$) and carotenoid content ($t = -2.13$, 8df, $P = 0.066$) when compared to stressed trees further upslope away from the water source. Multiple linear regressions revealed that the predawn leaf water potential greenness normalised difference vegetation index model, and the predawn leaf water potential water band index model were the "best" surrogate measures of plant water stress when using broad band multispectral satellite and narrow-band hyperspectral satellite data respectively. It was concluded from these investigations that vegetation indices designed to capture changes in plant water content/plant water status and spectral changes in the red edge region of the spectrum, performed well when applied to high spectral resolution remote sensing data. The greenness normalised difference vegetation index was considered to be a fairly robust index, which was highly correlated to chlorophyll fluorescence and predawn leaf water potential. It is recommended that this index has the potential to be used to map spatial patterns of winter-time plant stress for different genera/species and in different geographical locations.

Airborne remote sensing surveys were conducted to investigate the application of high spatial resolution remote sensing data to detect plant water stress. Multispectral airborne imagery was acquired by Land Resource International (PTY) Ltd, South Africa. Ground-based measurements of plant water stress were carried out during July and August 2005.Four individual spectral bands and two vegetation spectral reflectance indices, which are sensitive to changes in plant pigment content, were derived from the processed multispectral images *viz*. red, green, blue and near-infrared spectral bands and the normalised difference vegetation index (NDVI) and greenness normalised difference vegetation index (GNDVI).The results of the multispectral airborne study revealed that carotenoid content together with the green spectral waveband resulted in the "best" surrogate measure of plant water stress when using broad-band multispectral airborne data.

Airborne remote sensing surveys were conducted by Bar-Kal Systems Engineering Ltd, Israel, to investigate the application of hyperspectral airborne imagery to detect plant water stress. Six vegetation spectral reflectance indices designed to capture changes in plant pigment and plant water status/content, were derived from the processed hyperspectral images. When using airborne hyperspectral data, predawn leaf water potential with the normalized difference water index was selected as the most appropriate model. It was concluded, upon evaluation of the multiple linear regression models, that the airborne hyperspectral data produced several more regression models with higher adjusted $R^2$ values ($R_a^2$ range 6.2 - 76.2%) when compared to the airborne multispectral data ($R_a^2$ range 6 - 50.1).

Exploration of relationships between vegetation indices derived from leaf-level, satellite and airborne spectral reflectance data and ground-based measurements used as "surrogate" measures of plant water stress, revealed that several prominent and recurring spectral reflectance indices could be applied to identify species-specific plant water stress within the Welkom, Vaal River and West Wits mining districts. The models recommended for mapping and detecting spatial patterns of plant water stress when using different sources of remote sensing data are as follows:

- the chlorophyll b DATT spectral reflectance model when derived from leaf-level spectral reflectance data, can be applied across all three mining districts
- the predawn leaf water potential GNDVI spectral reflectance model and predawn leaf water potential water band index spectral reflectance model when utilising satellite multispectral and hyperspectral remote sensing data
- carotenoid content green band spectral reflectance model can be used for airborne multispectral resolution data
- predawn leaf water potential NDVI spectral reflectance model is best suited for airborne high spatial and hyperspectral resolution data.

These results indicate that measurements of predawn leaf water potential and plant pigment content have been identified as key methodologies for ground-truthing of remotely sensed data and can be used as surrogate measures of plant water stress.

Some preliminary research was undertaken to evaluate if wood anatomy characteristics could be used as a non-destructive and rapid low-cost survey approach for identifying trees which

are experiencing long-term plant stress. Seventy two wood core samples were extracted and analysed. Predawn leaf water potential measurements were used to classify stressed and unstressed trees. Relative differences in radial vessel diameter, vessel frequency and wood density were examined. Comparison of the radial vessel diameter and vessel frequency measurements revealed significant differences in three of the five comparative sampling sites ($p < 0.05$). The results of the density analyses were significantly different for all five comparative sampling sites ($p < 0.01$). In general, trees experiencing higher plant water stress displayed smaller vessel diameters, compared to less stressed or healthy trees. Sites which were influenced by high levels of contaminated water also displayed smaller vessel diameters, indicating that the uptake of contaminants could affect the wood anatomy of plants. Trees considered to be experiencing higher plant water stress displayed higher vessel frequency. This preliminary study showed that plant stress does influence the wood anatomical characteristics (radial vessel diameter, vessel frequency and wood density) in *E. camaldulensis*, *E. sideroxylon* and *S. lancea* in the three mining districts.

Spatial patterns of trees, mapped in the three gold mining districts, Welkom (27º57´S, 26º34´E) in the Free State Province, Vaal River (26º55´S, 26º40´E) located in the North West Province, and West Wits (26º25´S, 27º21´E) located in Gauteng, which were not experiencing winter-time water stress were correlated to site characteristics such as average soil depth, percent clay in the topsoil, groundwater chloride and sulphate concentrations, total dissolved solids, electrical conductivity and groundwater water level. The spectral reflectance model derived between predawn leaf water potential and the green normalised difference vegetation index using broad-band multispectral Proba Chris satellite data was used to map spatial patterns of unstressed trees across the three mining districts. Very high resolution (75 cm) multispectral airborne images acquired by LRI in 2005 were used to demarcate and classify vegetation using the maximum likelihood supervised classification technique. Interpolated surfaces of groundwater chloride and sulphate concentrations, total dissolved solids, electrical conductivity, pH and groundwater table levels were created using the kriging geostatistical interpolation technique for each mining district. Random sample analyses between stressed and unstressed trees were extracted in order to determine whether site characteristics were significantly different (using t-tests). Site characteristic surfaces which were significantly different from stressed areas were spatially linked to trees which were not experiencing winter-time plant water stress for each tree species investigated in each mining district. This spatial correlation was used to make recommendations and prioritise sites for the

establishment of future block plantings. Analysis of the site characteristic data and the geophysical surveys undertaken in the three mining districts which provided detailed information on groundwater saturation and an indication of the salinity conditions, confirmed the presence of relatively shallow and saline groundwater sources. This would imply that tree roots could access the relatively shallow groundwater even during the dry winter season and assist in containing contaminated groundwater seeping into surrounding lands.

***Keywords*** : airborne imagery, ground-based measurements of plant water stress, hyperspectral, leaf-level spectroscopy, multispectral, satellite imagery, spatial patterns of unstressed trees, spectral reflectance indices