The Mine Woodlands Project in the Witwatersrand Basin gold fields of South Africa: strategy and progress

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Abstract Several hundred unlined mine tailings storage facilities (TSFs) occur in the Witwatersrand Basin gold fields (WBG) situated in north-central South Africa. Acid rock drainage (ARD) seeps from these structures into surrounding lands, water courses and groundwater, posing a risk to the environment and human health. This paper reviews progress with a large-scale phytoremediation research programme (the Mine Woodlands Project, MWP), in which trees are planted in seepage pathways to increase evapotranspiration and, through hydraulic control and contaminant sequestration/immobilization, reduce the spread of contaminants. We describe the research strategy, summmarize results to date, and highlight the main constraints that need to be overcome.

Key Words gold tailings dams, South Africa, ARD, phytoremediation, woodlands, evapotranspiration

Introduction

The Witwatersrand Basin gold fields (WBG) comprise an area of approximately 25 000 km^2 in north-central South Africa. Gold and uranium mines are located along the northern and western margins of this basin. Tailings are hydraulically deposited on large unlined tailings storage facilities (TSF). These TSFs number several hundred and total approximately 400—500 km^2 in area (Marsden, 1986). They contain an estimated 6 billion tonnes of tailings (Chevrel et al., 2003). Many years of saline and acid rock drainage (ARD) from the saturated tailings has resulted in artificially elevated groundwater levels and extensive contamination of soils, streams, sediments and groundwater (Rudd, 1973; Funke 1990; Coetzee 1995; Rösner et al., 2001; Naiker et al., 2003; Coetzee and Winde, 2006; Winde et al., 2004). Contaminants include sulphates and chlorides, a range of heavy metals and radioactive ions. Levels sometimes exceed environmental standards (Coetzee and Winde, 2006). Many mines are nearing the end of their lives, and closure planning is assuming more importance. A prerequisite of Government closure certificates is that sustainable and long-term control measures are in place to mitigate environmental contamination. Phytoremediation measures are far less costly than engineering solutions (Weiersbye, 2007), and experience globally has shown that this approach may be effective and sustainable.

The Mine Woodlands Project (MWP)

The aim of this research project is to show the effectiveness of planted woodlands in reducing or preventing the spread of mine drainage water from TSFs, and providing a sustainable, low-cost solution to the pollution threat. The establishment of deep-rooted plants to exert hydraulic control and minimize the flux of contaminants in groundwater is a well established technology (ITRC, 2009) that relies on the abstraction of water and ions by the living plant, and the phytoimmobilization of ions in the rhizosphere. Suitable species of trees that are planted at sufficiently high densities are able to increase the rate of evapotranspiration (ET) and absorption of soil and groundwater. Substantially higher rates of ET following establishment of trees is predicted for sites in the WBG. The original vegetation surrounding most TSFs is dominated by seasonally-dormant, shallow-rooted grasslands, which are known to be relatively low water users (Dye et al., 2008). By replacing grasslands with deep-rooted trees, higher leaf areas and shorter or no seasonal dormancy, ET can be greatly increased. Woodland establishment is expected therefore to reduce the flow of water and contaminants through shallow aquifers and saturated soil horizons into adjacent lands and surface drainage channels. The second beneficial effect of trees lies in their potential to immobilize contaminants, either sequestered within their large biomass, or bound in the rhizosphere (Dickinson, 2000; Pulford and Watson, 2003).

Quantifying ET differences

Sap flow studies (based on the heat pulse velocity technique) have been undertaken in several species of trees to estimate their annual transpiration (Dye, et al., 2008; 2009). These have included both exotic and indigenous species, growing on contrasting soil types over both perched and deeper polluted groundwater. Trees growing on sites where roots can access shallow water tables can attain high annual rates of transpiration in the range of 1 000 to 1 400 mm. In contrast, trees on sites with deep water tables below the rooting depth are limited to annual transpiration rates in the region of 700 mm, corresponding largely to annual rainfall plus subsoil water storage. A series of studies has taken place to characterize the annual ET from "baseline" vegetation types that are common in the vicinity of TSFs. It is important to establish their water-use, so that the ET difference between existing vegetation and planted woodlands may be estimated. The Bowen ratio and Eddy Covariance micrometeorological techniques were used to measure annual ET above reeds and riparian grass/sedge vegetation, while ET from non-riparian grassland was estimated from a strong non-linear relation to MAP (Dye et al., 2008). Annual ET from grass-dominated vegetation in both riparian and non-riparian habitats amounts to approximately 570 mm. Results thus demonstrate that a potentially large difference in annual ET exists between pre- and post-woodland establishment.

Constraints and opportunities surrounding woodland development

The natural vegetation occurring within the WBG falls within the Savanna Biome and the Grassland Biome (Mucina and Rutherford, 2006). While trees and shrubs may be locally abundant, especially in run-on zones and riparian zones, the mean annual rainfall in the WBG (500 to 800 mm) is generally too low to permit the development of forest or closed canopy woodland. The area is therefore considered unsuitable for forestry, and the success of woodlands is dependent on access by the trees to seepage from TSFs or other mine water to augment rainfall. Access to water tables is difficult to establish from root excavation studies due to the great depths to which tree "sinker" roots can penetrate (Canadell et al., 1996). It can more easily be inferred from the water status of trees during the long winter dry season. Canopy water status in turn can be estimated using remote-sensing imagery and tools to record water stress in trees that already exist in the landscape (Govender, 2010). A comprehensive study of the use of earth observation systems to detect dry season tree stress at three mining regions in the WBG is providing insights into which site conditions permit trees to access seepage or groundwater (Govender, 2010).

Commercial Eucalyptus, Pinus and Acacia plantations in most high-rainfall regions of South Africa have been found to be detrimental to catchment water yields (Scott et al., 2000). Legislation and permitting systems are in place to limit the extent of exotic tree plantations. The current legislation preventing the establishment of some Eucalyptus species on mine-polluted sites may be unnecessarily restrictive in cases where the environment is transformed and degraded, and this issue needs to be resolved in the near future. Further controls on the establishment of exotic species of trees are specified by legislation designed to protect South Africa from alien invasive plants. Many introduced trees are extremely vigorous and capable of high rates of transpiration. They therefore also pose a threat to catchment water yields, as well as to the biodiversity of areas covered by natural vegetation. Lists of species believed to be potentially invasive have been compiled. Such species have been excluded from MWP trials. The MWP is currently investigating the usefulness of 48 indigenous tree species to try to minimize the use of exotic tree species. Species found to have good survival and reasonable growth rates include Tamarix usneoides, Searsia lancea, Searsia pendulina and Combretum erythrophyllum. Compared to eucalypts, these species are much slower to develop closed canopies and reach harvestable timber sizes, and also produce crooked stems. They are thus unlikely to be suitable for commercial wood production in the foreseeable future. They are rather viewed as semi-permanent, non-commercial woodlands, with primary benefits being in terms of non-timber products, carbon sequestration and soil rehabilitation.

Experience in mitigating sodium and chloride-dominated salinity in Australia has shown that while increased densities of trees can raise ET and lower water tables, their viability over time may be compromised by an accumulation of salts in the rooting zone which raises the osmotic potential of the rhizosphere and reduces the availability of water to the trees (Thorburn, 1999). Tree vigor, and therefore tree water-use, may then seriously decline. This highlights the importance tracking the fate of contaminants, and the uptake and immobilization potential of the various tree species. Trials established on a range of site types are yielding information on growth and survival, and this will continue until the trees reach maturity. In the case of the faster growing species, this could be as early as 10—12 years after planting. Soil analyses within plots will continue over this period to look for contaminant build-up in the root zone. Above-ground biomass of the more successful tree species is being monitored at intervals, as well as the sequestrated contaminants in leaves, seed, wood, roots and the rooting zone. Threats to the performance of woodlands in terms of pollution control include damage by fire, and attack by pathogens, especially at times of drought stress. The latter is particularly prevalent in Eucalyptus and Casuarina trees.

Integrated hydrological modeling

Integrated hydrological simulations required to investigate the effectiveness of established woodlands in containing mine-contaminated water will be performed in two localities (AngloGold Ashanti's Vaal River and West Wits mining operations) where woodlands trials commenced in 2003, and where much site information is available. Results from detailed studies of tree sap flow and vegetation ET, as well as borehole and stream-flow records will be used to validate model output. A preliminary geotechnical report (Vivier, 2005) assesses the seepage from a 484 ha tailings dam at Vaal River to be 547 500 m^3/a, indicating that the establishment of 137 ha of trees with an increased annual ET of 400 mm may be sufficient to match this rate of seepage (Dye et al., 2008).

Conclusions

Woodlands hold considerable promise as sustainable solutions to the control of AMD in the WBG, despite being complex systems requiring many years for trees to develop, and for the subtleties of site-species interactions to become evident. Nevertheless, considerable progress has been made, and the comprehensive evidence of higher ET rates from woodlands, as well as sequestration of sulphur and metals, has placed the strategy on a firm footing. Current emphasis is on the fate of contaminants sequestered in substrate and biomass, harvesting strategies to remove these from sites, the need to broaden understanding of woodland impacts through spatial mapping of ET using earth observation systems, and linkage of enhanced ET to soil water and groundwater movement from TSFs.

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