

CHAPTER 1

GENERAL INTRODUCTION

1.1 Introduction

South Africa's coal industry is the second biggest mining sector after gold, with sales contributing 16% to export revenue in 2003 (R20 billion in 2000) or 4% of the GDP. Mining impacts upon the natural water environment and its effect may be manifest throughout the life cycle of the mine, and even long after mine closure. According to Younger *et al.* (2004), the potential impacts of mining on the water environment are a) disruption of hydrological pathways, b) seepage of contaminated leachate into aquifers, c) disposal of saline mine water, and d) depression of the water table around the dewatered zone.

The impacts of mining arising from the disruption of hydrological pathways and seepage of contaminated leachate into aquifers tend to be relatively localised and limited compared to disposal of mine water (Younger *et al.*, 2004). Disposal of mine water is a worldwide problem, occurring wherever operating mines, both underground and opencast workings are found (Pulles *et al.*, 1995). The quality of the mine water depends largely on the chemical properties of the geological materials that come into contact with it (Thompson, 1980). Salts in solution usually cause such waters to be unsuitable for direct discharge into river systems and can limit other potential down stream uses.

Management options for saline mine water in South Africa are discussed in detail by Pulles (2006) and are summarized as (1) pollution prevention at source, (2) reuse and recycling of polluted water to minimize the volume of polluted water being discharged, (3) treatment of effluents should be implemented if the problem cannot be solved through prevention, reuse and recycling, (4) discharge of treated effluent, which is considered as the last resort. Pulles (2006) also reports that utilization of poor quality water for irrigation could be considered as a water reuse strategy that may have application, especially in the post closure phase.

Coal-mines in South Africa have adopted these water management strategies; however, some have excessive volumes of water, and not all of it can easily be taken care of following the four hierarchical management options (Gunther, 2006).

Reasonable estimates of volumes of mine-water stored and generated are available for a number of active mines in the central Witbank Coalfields (Mpumalanga Province, South Africa), which is one of the biggest Coalfields in the country. Grobbelaar *et al.*, (2004) indicate that 360 Mℓ d⁻¹ may be generated after closure of the entire Mpumalanga Coalfields. For the Olifants Catchment, a volume of 170 Mℓ d⁻¹ is suggested. Not all this water will report to the same locality, and several sub-areas where water will decant from the mines are envisaged. The expected discharge at each decant position ranges between 12 and 40 Mℓ d⁻¹. These volumes of decant water have the potential to support in excess of 6 000 ha of irrigation in the Olifants Catchment alone. On a site-specific scale, Kleinkopjé Colliery (Witbank, Mpumalanga) for instance, has 12 x 10⁶ m³ of water stored underground, and it is estimated from pumping and water level data that the daily water make is in the order of 14 Mℓ d⁻¹ (Grobbelaar *et al.*, 2004). This is sufficient to sustain an irrigated system of some 500 to 700 ha, depending on the particular cropping system chosen (Jovanovic *et al.*, 2002). If the proposed Waterberg Coal Bed Methane (CBM) operation (Waterberg Coalfields, Limpopo Province) is found to be feasible and commissioned, a total volume of 2 million m³ of mine water will be generated per year, and this will continue for 30 years.

Most mines in these coalfields produce waters dominated by calcium and magnesium sulphates, and have near neutral pH values. The southern fields have high pH and also carbonates such as calcite and dolomite that make waters alkaline (Usher *et al.*, 2003). Treatment of these mine waters will minimize pollution of water resources. However, this needs complex technologies with associated high costs to bring the water quality to a condition acceptable for release into natural watercourses. Interest has been growing in finding ways that can decrease the production of contaminated water and make its treatment less costly.

In the early 80s, the potential to use gypsiferous mine-water for irrigation of field crops was first evaluated in South Africa by Du Plessis (1983), using the steady-state chemical equilibrium

model of Oster & Rhoades, (1975). Du Plessis (1983) predicted the amount of salt that would leach, and could potentially contaminate groundwater, and found that irrigating with gypsum rich water would result in lower soil- and percolate salinity compared to irrigation using a chloride rich water of otherwise similar ionic composition. This could be attributed to precipitation of gypsum in the soil. The increased sodium hazard caused by gypsum precipitation was not expected to seriously affect soil physical properties and crop yield using a typical gypsiferous mine-water for irrigation (Du Plessis, 1983).

The potential use of mine-water for agricultural crops was tested in a series of field trials from 1993-2000 (Jovanovic *et al.*, 1998; Annandale *et al.*, 1999; Annandale *et al.*, 2001). The results of these studies indicated that crops were able to tolerate the salinity of gypsiferous waters and were grown successfully on a commercial scale, at least in the short term (Annandale *et al.*, 2001; Jovanovic *et al.*, 2002). The long-term crop performance and environmental impact, that is, the field scale sustainability of irrigation with mine water, however, had to be evaluated. Since long-term field experiments are expensive, time-consuming and produce only site-specific information, computer simulation models were required to predict the performance of various crops irrigated with different water qualities, on different soil types and under different climatic conditions. The Soil Water Balance (SWB) model is a crop growth-soil salinity model developed and validated during previous studies (Annandale *et al.*, 1999), and was found to offer detailed insight into water and salt balances in space and time. However, short-term experiments may not provide conclusive evidence that these waters can be sustainably used for agricultural crops, and this raised several research questions for further study. The critical research questions raised were as follows:

1. According to Jovanovic *et al.* (1998), higher crop yields could be obtained under irrigation with gypsiferous mine water compared to dry land production, and dry season production is also possible under irrigation. This conclusion was drawn only for crops irrigated with lime treated acid mine drainage (gypsum rich water). What if the composition and concentration of the coal-mine water, the soil type and weather were different to those in their studies? Will it still be possible to grow crops and what management practices would be required? What would the effect of prolonged use of different qualities of coal-mine water on the soil chemical and physical properties, crop yield and plant nutrition?

2. Annandale *et al.* (2001), from their three years of commercial scale field experiments, concluded that possible nutritional problems, like for example deficiencies in K, Mg and NO_3 , occurring due to Ca and SO_4 dominating the system, can be solved through fertilization management. What are the most limiting nutrients in crops irrigated with different qualities of coal-mine water? Could one use standard fertilization recommendations on such soils irrigated with different qualities of coal-mine water?

3. According to Annandale *et al.* (2001), soil salinity of irrigated soils increased compared to the beginning of the trial, and saturated extract electrical conductivity fluctuated around 200 mS m^{-1} , which is typical for a saturated gypsum solution. Did gypsum precipitate in these irrigated fields? If so, how much gypsum precipitated in these coal-mine water irrigated soils?

4. According to Annandale *et al.* (2001), the SWB model was validated for the sites where the field trials were carried out, and these validations were done for a few seasons by simulating single growing periods at a time. Could SWB be improved to simulate actual crop rotations in order to validate the sustainability of irrigation with different qualities of coal-mine water from the point of view of crop production and soil chemical properties?

5. The impact of irrigation with gypsiferous mine water on groundwater quality was assessed, and the groundwater quality did not show significant deterioration over the monitoring period (Annandale *et al.*, 2001). In order to study the impact of soluble salts or redissolved precipitated gypsum from irrigated sites on surface water quality, SWB needs to be able to simulate runoff reliably. Is there enough confidence in the simulated runoff output values of SWB to be used for large scale impact assessment by geohydrological modellers?

In order to answer these critical questions, a research project titled “The environmental impact and sustainability of irrigation with coal-mine water” was initiated.

The objectives of this research were:

1. To investigate the sustainable use of different qualities of coal-mine water for the production of various crops under different soil and climatic conditions;
2. To investigate the impact of irrigation with gypsum rich mine water on the chemical properties of the soil and ascertain whether or not there is precipitation of gypsum in these irrigated soils;
3. To study any nutrient imbalances in plant tissues that could occur as a result of ions in the irrigation water, and to evaluate the suitability of standard fertilization recommendations for mine water irrigated soils;
4. To evaluate the SWB model for its accuracy in simulating several crop rotations and to evaluate the sustainability of irrigation with coal-mine water from the point of view of crop production and soil chemical properties, using measurements taken during the experiment and relevant outputs generated by SWB, and
5. To improve and validate the runoff quantity and quality estimates of SWB, to ensure this is simulated reliably.

1.2 Research approach

The general approach was to establish several commercial and plot scale experimental sites in the Republic of South Africa, that could offer a range of soil, weather, crop and water quality conditions. The commercial scale experiments were set up in the Mpumalanga Province, close to Witbank (Kleinkopjé Colliery) and near Secunda (Syferfontein Colliery), and in the Free State Province, near Vereeniging (New Vaal Colliery). Kleinkopjé (Anglo Coal) included three centre pivot irrigated fields of between 20 and 30 ha each, and at New Vaal, also an Anglo Coal-mine, a single 10 ha pivot was set up. The Sasol mine, Syferfontein, had a 20 ha pivot site. Figure 1.1 is regional map of Republic of South Africa showing the location of the research sites.

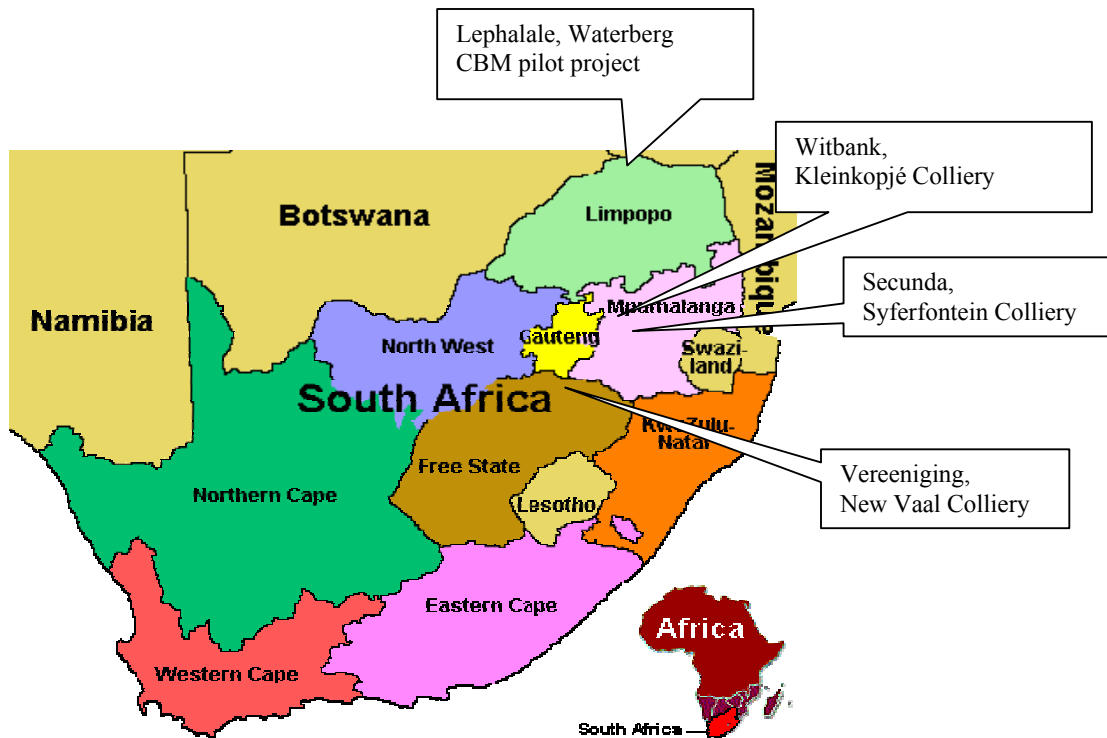


Figure 1.1 Regional map of irrigation mine water research sites

In the commercial scale studies at Kleinkopjé, agronomic field crops such as maize, wheat and potatoes were selected, depending on the interest of the mines and/or commercial farmers managing the fields. An intensive cycle of 3 vegetable crops (peas/sweetcorn/pumpkins) was also attempted at New Vaal, but waterlogging was problematic due to poor site selection. Perennial pastures were planted at Syferfontein due to the highly saline irrigation water and very heavy clay soil. Due to the installation of a conveyer belt between Kriel and Sasol that ran through middle of the irrigated field, the trials at Syferfontein were discontinued after two years of monitoring. The plot scale experimental site was set up in the Limpopo Province, 25 km north of Lephalale (Ellisras), at the Anglo Coal, Waterberg Coal Bed Methane (CBM) Pilot Project. In this experiment, drip and sprinkler irrigation systems were used on a 0.14 ha trial site, and test crops were selected based on their salinity tolerance and adaptation to the hot climate of the Waterberg area. The crops studied were: cotton, barley, Bermuda grass and ryegrass. Water qualities, soils, cropping systems investigated are summarized in Table 1.1

Table 1.1 Summary of water qualities, soils and cropping systems

	Kleinkopjé (Anglo Coal)	New Vaal (Anglo Coal)	Syferfontein (Sasol)	Waterberg (Anglo Coal)
Water quality (mS m ⁻¹)	Ca/Mg/SO ₄ EC = 300-500	Na/Ca/SO ₄ EC = 110	Na ₂ SO ₄ EC = 370	NaHCO ₃ EC = 750
Soil	Clay loam	Sandy soil	Heavy clay	Sandy clay
Cropping system	Maize-wheat- potatoes (17 seasons)	Maize-wheat- vegetables (7 seasons)	Pasture species (9 harvests)	Barley-ryegrass, cotton-Bermuda grass (2005/2006)

Each mine generates different water qualities depending on the geological properties of the site. This is useful to assess the sustainability of irrigation with different water qualities as well as to validate the chemical equilibrium subroutine of the SWB model. Kleinkopjé generates two waters of similar qualities, both being rich in CaSO₄ and MgSO₄ (Jacuzzi and Tweefontein waters). Water from Jacuzzi was replaced during the project with water from New Vleishaft Dam, because of deteriorating pH. The electrical conductivity (EC) of New Vleishaft Dam water started off at around 250 mS m⁻¹ in 1997, but climbed steadily to a value of 320 mS m⁻¹ by the end of 2005 and started to decrease in 2006. At Tweefontein Pan, the EC started off a little higher than the New Vleishaft Dam water at around 300 mS m⁻¹, and was fairly stable for several years until 2001. An increase in EC to a level of 500 mS m⁻¹ was observed by the end of 2005 at Tweefontein Pan, which decreased again in 2006. Syferfontein generates quite saline water (EC around 370 mS m⁻¹) with high concentrations of Na and SO₄. It is, of course, difficult to precipitate gypsum in the profile with a sodium sulphate dominated water quality. New Vaal generates water with an EC around 130 mS m⁻¹, and this water is predominantly rich in CaSO₄ with some NaCl. The Waterberg Coal Bed Methane (CBM) water is withdrawn from a depth of 250 m during methane gas production, and is very saline-sodic, dominated by NaHCO₃, with an EC around 800 mS m⁻¹ and SAR of 85 (mmol ℓ⁻¹)^{0.5}.

It was also fortunate that crop response on a wide range of soil types could be monitored. Soils ranged from very sandy (<10% clay) at New Vaal and Waterberg, to a very heavy clay soil

(>60% clay) at Syferfontein. Soils at Kleinkopje were medium textured. Soil profiles were also of varying depths, and were on both rehabilitated and unmined sites.

The approach was to monitor the crop growth, soil water and salt balance under these widely varying conditions, and then to attempt to model the dynamics of the system.

1.3 Thesis outline

The thesis is written in a series of Chapters, each contributing to the research questions and objectives stated above. A review of the existing local (South African) and international knowledge available on irrigation with saline and/or saline sodic water is presented in Chapter 2. In this Chapter, modelling the effects of saline sodic irrigation on crop growth, irrigation with mine water in southern Africa, runoff and drainage from mine water irrigated fields and possible impacts of mine water on surface waters are discussed. This chapter is followed by six more. Chapter 3 details field sites, location, experimental layout, water qualities, soil, weather, modelling and data processing. Chapter 4 is on production and plant nutrition of the crops under investigation. Chapter 5 covers the impact of irrigation with coal-mine water on soil chemical properties. Chapter 6 presents modelling of the field scale environmental impact of irrigation with coal-mine water from the point of view of crop production and soil chemical properties in the medium-term to long-term. Chapter 7 broadens the applicability of the field scale modelling by investigating surface runoff quantity and quality of mine water irrigated fields. Chapter 8 summarizes important results and makes recommendations for further studies.

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