CHAPTER 7

SURFACE RUNOFF FROM COAL-MINE WATER IRRIGATED FIELDS

7.1 Introduction

The possibility of irrigating crops using mine water at commercial scale was tested in a sequence of field trials (Chapters 3 to 6), where several field crops and pasture species were successfully grown. The Soil Water Balance (SWB) model was also improved to simulate several crop rotations (Chapter 6) and to predict the long-term effects of various management scenarios on the soil water and salt balance (Annandale *et al*., 2001).

Runoff could be generated from irrigated fields, depending on rainfall amount and intensity, topography, soil type, soil water content, vegetation cover and land use (Mishra & Singh, 2003). Runoff quantity can be measured by erecting V-notch weirs at the lowest end of the irrigated fields, where runoff converges. Runoff quantity and quality measurements are important to determine salt loads from coal-mine water irrigated fields, that may end up in surface waters. Conducting long-term field experiments to quantify runoff from fields is expensive, so models are usually used. In this chapter, modifications made to SWB, with model calibration and validation simulations to estimate runoff, are presented.

7.2 Modelling surface runoff

Reliable estimation of runoff quantity is essential for runoff quality considerations. There are different techniques to estimate amount of runoff. The most commonly used method is the Soil Conservation Services Curve Number (SCS-CN), developed in (1949) in the USA (SCS, 1971). The SCS-CN method is characterized by the equation:
$Q = (P - 0.2S)^2 / (P + 0.8S)$ where Q is the Runoff, P is Precipitation and S Initial abstraction (stored on the surface, intercepted, and infiltrated water), all in mm. S is derived from
$S = (25000/CN)-250$.
CN is known as the curve number, and is determined from antecedent soil water content (AWC), which is an index of soil wetness, for different hydrological soil groups in the USA. A higher curve number indicates the response from a field with a fairly uniform soil with a low infiltration capacity. A low curve number gives the response expected from a field with

good infiltration. The curve number could vary from 0 to 100 (Mishra & Singh, 2003). Models such as CropSyst (Stöckle & Nelson, 2000) and GLEAMS (Leonard *et al*., 1987) use this same SCS-CN method to estimate runoff. The SCS-CN approach, however, does not consider the quality of runoff.

The practical application of this procedure to estimate runoff should be simple and direct. It relies on the determination of the curve numbers, which are widely documented in the literature for various land uses and soil types (NEH-4, 1985; Chow *et al*., 1988; Pilgrim & Cordery, 1993). In spite of its apparent simplicity, difficulties come in with the determination of antecedent soil water conditions (AMC) when applying the model outside the USA, as these soils are often not classified into the four hydrological soil groups A, B, C and D, used by the model.

Models in South Africa such as ACRU (Schulze, 1986), also use the SCS-CN method, where S is modified as the soil water deficit to saturation of a thin surface layer, and is calculated as part of the daily soil water balance. The thickness of the surface layer used in this calculation is important. If the whole profile is taken, for instance, runoff may never be simulated.

SWB also estimates surface runoff on the basis of the SCS-CN approach. It is driven by daily rainfall and irrigation, and relates the S value, called the runoff parameter (Rop) in the model, to the irrigated field's characteristics. This approach of SWB to estimate runoff, however, did not consider antecedent water content of the surface layer and the possibility that water flowing over the field could come into contact with salts in the soil surface. The objective of the study was, therefore, to modify initial abstraction (S) in the original SCS-CN model by including the soil water deficit of the top layer, calculated from the daily soil water balance. In addition, a thin soil surface layer parameter to consider salt mixing at the surface was included to improve estimates of salt runoff.

The SWB model

In SWB, when crops are overhead irrigated or if it rains, plant leaves intercept some water. However, if the rain plus irrigation is less than can be intercepted by the canopy, none will reach the soil. However, if rainfall or overhead irrigation is more than can be intercepted by the canopy, some will reach the soil, and if this water is greater than or equal to the antecedent water content deficit to saturation of the upper most soil layer, runoff is assumed to occur. The calculation of Q was modified, therefore, as follows:

If $P+I > AWC$, then $Q = ((P+I) - AWC)^2 / ((P+I) + 0.8Rop)$ Where
P - precipitation (mm)
I - irrigation (mm)
AWC - antecedent water content $AWC = (WCSat[1]-WC[1])dz[1]$ (mm)
WCSat[1] - saturated water content of layer 1 ($m\ m^{-1}$)
WC[1] - water content of layer 1 ($m\ m^{-1}$)
dz[1] - thickness of layer 1 (mm)
Rop - the runoff parameter (mm)

The water that runs off an irrigation site was assumed to have the same salt concentration as the rainfall or irrigation in the original version of SWB (Annandale *et al*., 1998). However, runoff salts can vary greatly from the rainfall or irrigation salinity, especially after dry periods, as salt at the surface concentrates due to evaporation. When a rainfall event occurs, accumulated salts near the surface of the soil, mix with the storm flow and result in a higher salinity than that of the rainfall. Therefore, a thin surface layer component, the salt mixing depth was included into the runoff procedure, in order to take this into account. The mixing layer is part of the top layer used in the daily water balance calculation. This concept was adopted from ACRU (Schulze, 1986), where the salt mixing layer is treated separately. In SWB the salt mixing layer is considered to be within the top layer. A diagrammatic representation of runoff and salt mixing is shown in Figure 7.1.

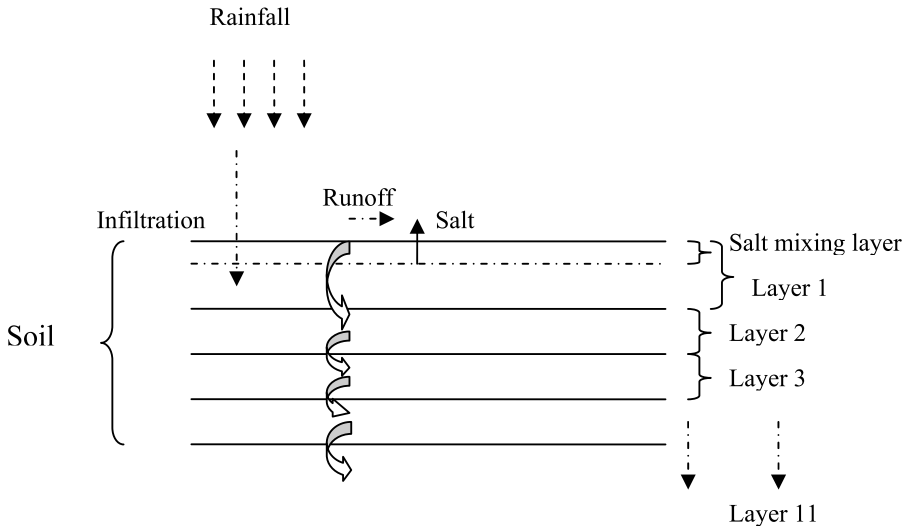


Figure 7.1 Diagrammatic representation of runoff and salt mixing with runoff

Salts in solution in the salt mixing layer are added to the salts in the runoff water.

7.3 Model calibration

Crop related model parameters are discussed in Chapters 3 and 6. Required weather and management input data are, planting date, latitude, altitude, rainfall and irrigation water amounts and quality, as well as maximum and minimum daily temperature, were used as input to the model. In the absence of measured data, SWB estimates solar radiation, vapour pressure and wind speed according to the FAO recommendations (Allen *et al*., 1998). Required soil input data include volumetric field capacity, permanent wilting point and a runoff parameter to calculate runoff based on the SCS method (Stewart *et al*., 1976). In addition, initial volumetric soil water content, the content of soluble and exchangeable ionic species, as well as initial gypsum and lime are required for each soil layer.

The runoff parameter (Rop) was estimated for the sites, as shown in Figure 7.2. Salt interception by the crop canopy was ignored, as it is assumed to be washed off with the next irrigation or rainfall event. Runoff was assumed to take place only when rainfall after interception is subtracted, fills up layer 1 to saturation. The salt mixing depth was assumed to be within this layer.

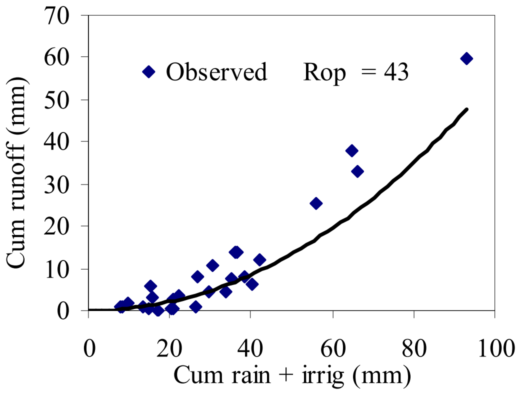


Figure 7.2 Runoff parameter (Rop) estimated from cumulative (cum) rainfall plus irrigation and cumulative runoff for several storm and runoff events

The model was run with the Rop value selected a number of times to evaluate simulated runoff quantity by changing the thickness of layer 1. Once this estimate seemed satisfactory, a number of simulations were again run, this time changing the salt mixing depth while keeping the thickness of layer 1 constant. Only the first year's runoff measurements were compared with modelled output values for the calibration exercise. The salt mixing depth that statistically produced the best runoff estimates was selected and used to validate the model.

Independent data sets, not used in the calibration exercise, were used for model evaluation. Predicted and measured values were compared using qualitative (graphical) and quantitative (statistical) criteria to evaluate the model's capabilities. To assess goodness of fit and accuracy of simulated values, mean absolute error (MAE), expressed as a percentage was determined. MAE is calculated as:

$$MAE = 100\sum_{n=1}^{n=N}\left[{(P_i - O_i)} \big/ {NO_m} \right]$$

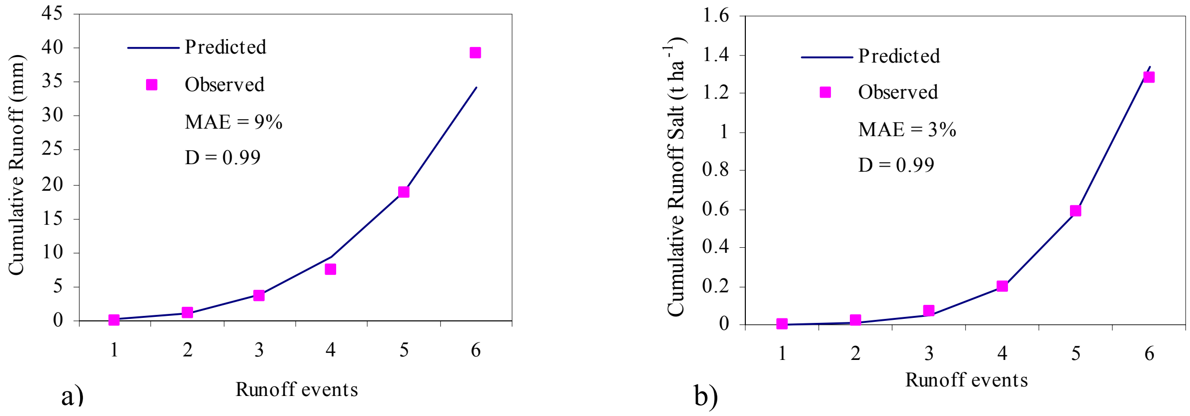
Where P_i and O_i are the *i*th predicted and observed values of the runoff data, O_m mean observed values and N is the number of observed values. Willmott's index of agreement (D) was also used to show how well the predicted and observed deviations correspond to each other. It varies between one and zero, with one representing perfect agreement and zero a complete disagreement, and is expressed as:

$$D = 1 - \left[\frac{\sum_{i=1}^{N} (P_i - O_i)^2}{\sum_{i=1}^{N} \left[/ P_i^{'} / + / O_i^{'} / \right]^2} \right]$$

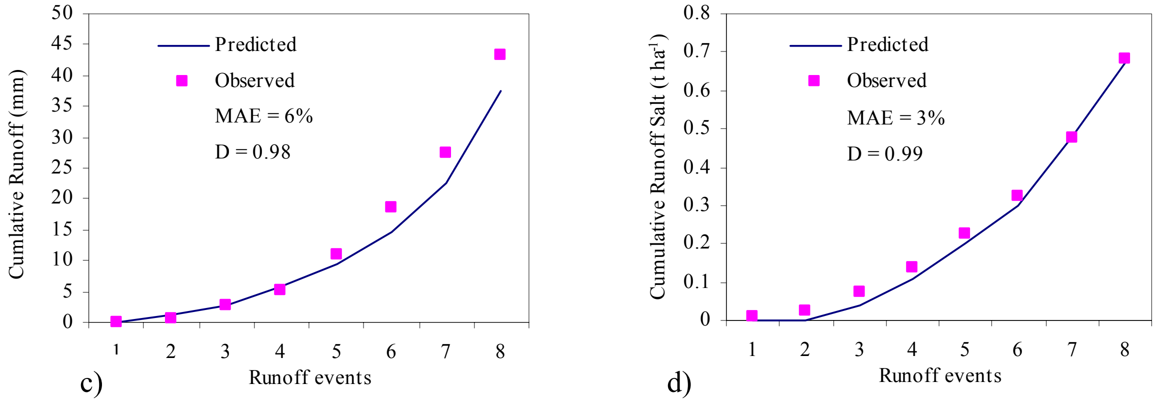
Where $P_i^{'} = P_i - O_m$, $O'_i = O_i - O_m$ and O_m is the mean of the observed values.

According to De Jager (1994), the acceptable reliability criteria for these parameters are D >0.8 and MAE < 20%.

The results of the simulations indicated that runoff generation was sensitive to water content of the top layer, bulk density, Rop and salt mixing depth. The model's predictions were generally quite close to measured values. Results of model calibration for runoff quantity and quality simulated with a top soil layer thickness of 0.2 m and salt mixing depth of 0.002 m are indicated in Figures 7.3 a-d.



Pivot TWF



Pivot Major

Figure 7.3 Model calibration for runoff quantity and quality for Pivot TWF (a) and (b), and Pivot Major (c) and (d), Summer season 2000/01. MAE is mean absolute error and D is Wilmotts' index of agreement

7.4 Measured runoff

Measured runoff totaled 8% of the overall rainfall at TWF, and 6% for Major for the trial period (Table 7.1). The differences in runoff are most likely due to differences in slope between the two fields. The total salt added to the sites depended on the amount of irrigation applied to each field. Table 7.1 summarizes rainfall and amount of irrigation applied and salts added to the irrigated fields. The first runoff events after the dry winter season always carried the highest amount of salts, on average 75% of the total salt load.

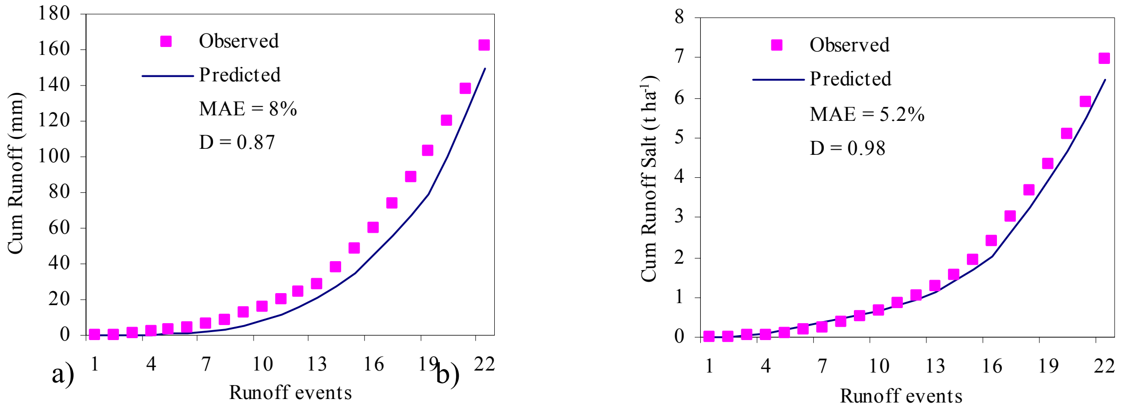
Table 7.1 Summary of measured rainfall, irrigation and salt added between 2000 and 2006 at TWF and Major

Parameters (measured)	Tweefontein (20 ha)	Major (30 ha)
Irrigation	4126 mm	4770 mm
Rain	3986 mm	4067 mm
Salt added	2059 t (103 t/ha)	2748 t (91.6 t/ha)
Salt runoff	192 t (9.6 t/ha)	231 t (7.7 t/ha)
Runoff	310 mm (8%)	226 mm (6%)

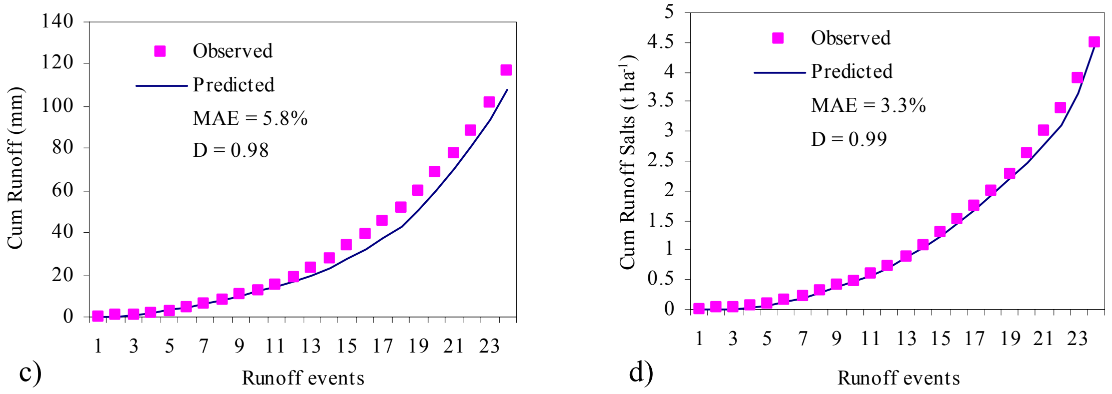
7.5 Model validations

Independent data sets of measured surface water and salt runoff was compared to SWB predictions. Runoff events due to irrigation system failures were excluded from the comparisons, as the pivot failed to move and applied the water in one position, and amount of irrigations could not be measured. The runoff water from such system failures also does not get the opportunity to interact with the whole field surface.

Runoff predicted by SWB generally followed the seasonal pattern of the observations. The model predicted a total of 149 mm of runoff for TWF and 107 mm for Major, while the measured runoff was 163 mm and 117 mm (Figure 7.4).



Pivot TWF



Pivot Major

Figure 7.4 Predicted and measured runoff quantity and quality 2002-2006

SWB also simulated the cumulative runoff salts to be 7 t ha^{-1} for TWF and 4.6 t ha^{-1} for Major, whereas the measurements for these sites were 6.8 and 4.4 t ha^{-1}. When individual runoff event predictions are compared with observations, the model tended to over predict smaller events and under predicted larger runoff events. Model sensitivity analysis 20% has been performed by increasing the mixing depth layer and layer 1. Simulations were performed and the percentage changes of several output values were recorded. A large salt mixing depth was, as expected, observed to increase salt runoff by more than 20% and a small increase in layer 1 increased the runoff volume by 20%. Generally, the model estimated the cumulative runoff fairly well for both sites.

Including a salt mixing depth and antecedent soil water content gave reasonable predictions of runoff quantity and quality. Runoff predicted by the SWB model seems quite reasonable after calibration, and can be used in the assessment of the impact of large-scale irrigation on water resources.

Conclusions

SWB was evaluated for runoff quantity and quality after introducing antecedent water content as a variable and salt mixing depth as a site specific parameter. The model gave good estimations of runoff quantity and quality after calibration. This will be helpful in modelling soil water and salt balances for several scenarios of long-term irrigation with mine water. SWB output can now be used as input into a surface water model to illustrate the possible effect of large scale irrigation on surface water resources. Further improvements can still be made to better represent runoff quantity and quality, but in its current improved form, SWB can provide credible estimates of runoff from coal-mine water irrigated fields.

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CHAPTER 8

GENERAL CONCLUSIONS AND RECOMMENDATIONS

For successful coal-mine water irrigation, the following, criteria's are essential: (1) selection of salt tolerant crops; (2) careful irrigation water management; (3) fertilization that accounts for the ions being added with irrigation water; and, (4) selection of a well drained site to facilitate leaching of slightly soluble salts.

The required leaching to prevent the unsustainable build up of salts in the soil profile could externalize the salt problem for the mine, except perhaps when rehabilitated soils are irrigated which could facilitate the interception of the leachate for reuse or further treatment.

8.1 Conclusions

The sustainability of irrigation with coal-mine water from the point of view of crop production and soil resources was assessed. Several crops and pastures species were able to grow successfully. The main findings are discussed below:

Crops like sugarbeans, wheat, maize, potatoes and pastures were very successfully produced. In the short to medium-term (eight years), irrigation with gypsiferous mine-water on a commercial scale proved to be agriculturally sustainable, with no noticeable negative impact on the soil. It is expected that soils will accumulate large masses of gypsum over time, but this is not seen as a problematic.

Particular attention should be given to K fertilization, as it becomes unavailable due to high Ca and Mg levels in the soil when irrigating with gypsiferous water. In this study, wheat yields were as high as 8 t ha^{-1}, potatoes produced over 50 t ha^{-1} and maize yields of 10 t ha^{-1} were achieved. It is clear, therefore, that good commercial production is feasible with gypsiferous water.

Pasture production with Na_2SO_4 rich mine effluent was also feasible, at least in the short term (three years) but would need a very well-drained profile and a large leaching fraction to prevent unsustainable salt build up. Unfortunately, these waters do not present much opportunity for gypsum precipitation, which is able to drastically reduce the salt load of the receiving waters in the case of calcium sulphate rich mine water irrigation.

The $NaHCO_3$ water studied was very concentrated and of extremely poor quality for irrigation. Salt tolerant crops can be grown with this water if a high leaching fraction is used, together with the application of gypsum as a source of Ca to displace adsorbed Na that causes dispersion, which results in serious soil physical problems. The likely environmental impact of the essential extreme leaching fraction, does not make this the best approach for mining to manage waters of these qualities.

Although, irrigation with coal-mine water involves complex interactions between crop, soil, water quality, hydrology and geohydrology, interest from farming companies to continue irrigating with this water indicates the commercial potential. The fact that gypsum precipitates in the soil, its slow redissolution, and the attenuation of leached salts below the root zone, makes irrigation with $CaSO_4$ and $MgSO_4$ rich waters a simple solution that could be used as a water reuse strategy in the mining industry.

Modelling

This modelling study evaluated the SWB model for its accuracy in simulating several crop rotations. SWB predicted crop growth, water balance and salt content of the soil reasonably well. This gives confidence that SWB can be used to predict various scenarios to determine the likely impact of the long-term use of such waters on crop production and soil properties. The validation of the chemical equilibrium and solute transport subroutines in SWB was done by comparing model estimates of soil solution ion concentration, to measurements from suction cups and wetting front detectors. The comparisons were made for six years of data. In general, the model predicted soil solution concentrations quite closely to the measured values. SWB was also evaluated for predictions of runoff quantity and quality, considering the antecedent water content as a variable and salt mixing depth as a parameter. The model estimates were quite reasonable, and this adds value to long-term scenario simulations, where credible estimates of leaching and runoff will be valuable inputs into surface and groundwater models. These, in turn, are needed to predict offsite effects of large-scale irrigation with mine water, should this be sanctioned one day. In future, further improvements can be made to better model runoff quantity and quality, but in its current improved form, SWB is a sound modelling tool for predicting runoff from coal-mine water irrigated fields.

8.2 Recommendations

This thesis investigating the field scale environmental impact and sustainability of irrigation with coal-mine water, has identified areas in which further investigation and research are required. Recommendations made are divided into two sections: the first deals with the monitoring component and recommends additional field studies; the second is oriented towards large-scale irrigation modelling, based on the knowledge gained through this study.

Field monitoring

It is recommended that monitoring at Kleinkopjé Colliery continues, as an extremely valuable research site with a well monitored history of irrigation (18 successive cropping seasons) with mine water has been established. Surface runoff and groundwater volumes and quality should also be monitored closely to generate more data to better model this process. In order to deal with the concentrated leachate from gypsiferous, Na_2SO_4 and $NaHCO_3$ rich mine water irrigated fields, other agricultural technologies should be considered. A Serial Biological Concentration (SBC) (Blackwell *et al*., 2001) approach could be used to concentrate up the water, so there would be less to treat, but it would be of a higher salinity. SBC requires substantial engineering to collect leachate waters for re-use or treatment. This may be conveniently and cost effectively implemented on rehabilitated open cast mine lands through careful site selection that ensures leachate reports to some known position. The cost-benefit analysis of SBC should be evaluated by the mining industry. It may be that the main aim of irrigation would not be to generate revenue out of agricultural production with this water, but rather to just have a green canopy using as much water as possible to concentrate up the leachate, and save on treatment costs.

Large-scale irrigation

For consideration of future large-scale irrigation with mine water, the following aspects should be noted. Site selection is very important. Careful consideration of sustainability of irrigation on the site selected is important. Local geology and geohydrological properties, the proximity to sensitive water users (human consumption and the environment), aquifer vulnerability, drainage properties and possibility of mitigation should be considered in detail prior to commissioning mine water irrigation sites (Vermeulen *et al*. 2008). If large-scale irrigation is implemented, groundwater monitoring must be an integral part of the operation plan. This should include monitoring within the irrigated areas and also boreholes down-gradient of such activities, which could be used for compliance monitoring. Negotiation with the regulators, such as the Department of Water Affairs and Forestry (DWAF), to fix threshold levels at which action should be taken to mitigate the impact or even to cease irrigation activities, must be part of such a monitoring plan.

Finally, engineering requirements should also be considered to assess the feasibility of implementation. In particular, the following need to be considered: siting of irrigated fields; areas required to utilize the available water; cost assessment; operational skill development; monitoring requirements; irrigation management; cost comparison with other options such as reuse on mine sites for road wetting and coal beneficiation; and, treatment of water to an acceptable level to supply to other users.