IMPACT OF IRRIGATION WITH GYPSIFEROUS MINE WATER ON THE WATER RESOURCES OF PARTS OF THE UPPER OLIFANTS BASIN

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ABSTRACT

The generation of large quantities of mine wastewater in South African coal mines and the needs for a cost effective, as well as an environmentally sustainable manner of mine water disposal, have fostered interests in the possibility of utilizing mine water for irrigation. Such a possibility will not only provide a cost-effective method of minimizing excess mine drainage, as treatment using physical, chemical and biological methods can be prohibitively expensive, but will also stabilize the dry-land crop production by enhancing dry season farming. Considering the arid to semi-arid climate of South Africa, the utilization of mine water for irrigation will also boost the beneficial exploitation of the available water resources and relieve the increasing pressure on, and the competition for, dwindling amounts of good quality water by the various sectors of the economy. The disposal of excess gypsiferous mine water through irrigation has been researched in a few collieries in the Witbank area. In this study, the assessment of the impacts of using gypsiferous mine water for irrigation were carried out in parts of the Upper Olifants basin upstream of Witbank Dam, using the *ACRU2000* model and its salinity module known as *ACRUSalinity*. The study area was chosen on the bases of locations of previous field trials and the availability of mine water for large-scale irrigation.

The primary objectives of the study were the development of relevant modules in *ACRU2000* and *ACRUSalinity* to enable appropriate modelling and assessment of the impact of large-scale irrigation with mine water and the application of the modified models to the chosen study area. The methodology of the study included the modifications of *ACRU2000* and *ACRUSalinity* and their application at three scales of study, *viz*. centre pivot, catchment and mine scales. The soils, hydrologic and salt distribution response units obtained from the centre pivot scale study were employed as inputs into the catchment scale study. The soils, hydrologic and salt distribution response units obtained from the catchment assessment were in turn applied in similar land segments identified in the mine used for the mine scale study. The modifications carried out included the incorporation of underground reservoirs as representations of underground mine-out areas,

multiple water and associated salt load transfers into and out of a surface reservoir, seepages from groundwater into opencast pits, precipitation of salts in irrigated and non-irrigated areas and the incorporation of a soil surface layer into *ACRUSalinity* to account for the dissolution of salts during rainfall events.

Two sites were chosen for the centre pivot scale study. The two sites (Syferfontein pivot of 21 ha, located in Syferfontein Colliery on virgin soils; Tweefontein pivot of 20 ha, located in Kleinkopje Colliery on rehabilitated soils) were equipped with centre pivots (which irrigated agricultural crops with mine water), as well as with rainfall, irrigation water and soil water monitoring equipment. The pivots were contoured and waterways constructed so that the runoff could leave the pivots over a weir (at Tweefontein pivot) or flume (at Syferfontein pivot) where the automatic monitoring of the quantity and quality of runoff were carried out. The runoff quantities and qualities from the pivots were used for verification of the modified *ACRU2000* and *ACRUSalinity*. The catchment scale study was on the Tweefontein Pan catchment, which was a virgin area mainly within the Kleinkopje Colliery, draining into the Tweefontein Pan. The data on the water storage and qualities in Tweefontein Pan, as well as the soil water salinities in the irrigated area located within the catchment were used for verification of results. In the catchment scale study, different scenarios, including widespread irrigation on virgin and rehabilitated soils, were simulated and evaluated. For the mine scale study, the Kleinkopje Colliery was used. The colliery was delineated into 29 land segment areas and categorized into seven land use types, on the basis of the vegetation and land uses identified in different parts of colliery.

The centre pivot and catchment scale studies indicated that the impacts of irrigation with low quality mine water on the water resources are dependent on the soil types, climate, the characteristics and the amount of the irrigation mine water applied, whether irrigation was on virgin on rehabilitated soils and the status of the mine in terms of whether a regional water table has been re-established in an opencast mining system or not. The studies further indicated that the irrigation of agricultural crops with low quality mine water may lead to increases in soil water salinity and drainage to groundwater, but that the mine water use for irrigation purposes can be successfully carried out as most of the water input onto the irrigated area will be lost through total evaporation and a significant proportion of the salt input, both from rainfall and irrigation water, will either be precipitated in the soil horizons or dissolved in the soil water of the soil horizons. By irrigating with a saline mine water therefore, the salts associated with the low quality mine water can be removed from the water system, thereby reducing the possibility of off-site salt export and environmental pollution. On-site salt precipitation, however, may lead to accumulation of salts in the soil horizons and consequent restriction of crop yields. Therefore, efficient cropping practices, such as leaching and selection of tolerant crops to the expected soil salinity, may be required in order to avoid the impact of long-term salinity build up and loss of crop yields.

The simulated mean annual runoff and salt load contribution to Witbank Dam from the Kleinkopje Colliery were 2.0 x 10^3 Ml and 392 tons respectively. The mean annual runoff and salt load represented 2.7% and 1.4% of the average water and salt load storage in Witbank Dam respectively. About 45% of the total water inflow and 65% of the total salt load contribution from the study area into Witbank Dam resulted from groundwater storage. From the scenario simulations, the least salt export would occur when widespread irrigation is carried out in rehabilitated areas prior to the re-establishment of the water table due to a lower runoff and runoff salt load. It may therefore be a better water management strategy in active collieries if irrigation with mine water is carried out on rehabilitated soils.

In conclusion, this research work has shown that successful irrigation of some (salt tolerance) crops with low quality mine water can be done, although increases in the soil water salinity of the irrigated area, runoff from the irrigated area and drainage to the groundwater store can occur. Through the modifications carried out in the *ACRU2000* model and the *ACRUSalinity* module in this research work, a tool has been developed, not only for application in the integrated assessment of impact of irrigation with mine water on water resources, but also for the integrated assessment and management of water resources in coal-mining environments in South Africa.

PREFACE

The research described in this thesis was undertaken in the School of Bioresources Engineering and Environmental Hydrology, University of KwaZulu-Natal, Pietermaritzburg, under the direct supervision of Professor S. A. Lorentz and co-supervision of Professor J. G. Annandale and Dr. M. P. McCartney.

The study represents original work by the author and has not been submitted in any form for any degree or diploma to any University. Where use has been made of the work of others, it has been duly acknowledged in the text.

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Olufemi Abiola Idowu	Date
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Professor S. A. Lorentz	Date

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DEDICATION

This thesis is dedicated to my father, **Mr. Samuel Ojerinde Idowu** and mother, **Mrs. Clementina Abeni Idowu**, for their love for their children, education and the Truth.

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A = surface area of the surface reservoir (m^2)

A_{irr} = area of the irrigated area (m^2)

$A_{non\text{-}irr}$ = area of the non-irrigated area (m^2)

A_s = seepage area of the aquifer into the mine-pit reservoir (m^2)

A_{ur} = area of the underground reservoir roof (m^2)

b = thickness of the rock layer through which leakage into the underground reservoir occurs (m)

BF = baseflow volume (l)

c = surface reservoir constant (dimensionless)

C_{bf} = baseflow concentration (mg/l)

C_{decay} = the minimum asymptotic salinity after the underground reservoir had been fully flooded and flushed (mg/l)

C_{dsf} = salt concentration of delayed stormflow (mg/l).

C_i = salt concentration of the i-th horizon or groundwater store on previous day, which represents initial value (mg/l)

C_{ir} = surface reservoir salinity at the end of the current time step of simulation (mg/l)

C_{i-1} = surface reservoir salinity at the end of the previous time step (mg/l)

C_{in} = average salt concentration of the total inflow into the underground reservoir (mg/l)

Cin_i = average salt concentration of water flowing into the surface reservoir (mg/l)

$C_{initial}$ = salt concentration before salt generation or salt decay in the concentration (mg/l)

C_{peak} = the peak salinity at the end of flooding in the underground reservoir (mg/l)

C_{qf} = quickflow salinity (mg/l)

C_r = rainfall salt concentration (mg/l)

C_{run} = salt concentration of runoff water (mg/l)

C_{run_adj} = salt concentration of runoff from adjunct impervious areas (mg/l)

C_{run_irr} = salt concentration of runoff water from irrigated areas (mg/l)

C_{run_ni} = salt concentration of runoff from non-irrigated lands (mg/l)

c_s = coefficient of seepage into underground reservoir (dimensionless)

C_{sat} = the saturation value, which represents the maximum salt concentration (mg/l)

C_{sf} = stormflow salinity (mg/l)

C_{trs_dam} = salt concentration of water imported into the surface reservoir (mg/l)

C_{upd_i} = updated salt concentration of the i-th horizon or groundwater store on current day (mg/l)

$C_{updated}$ = updated salt concentration in the underground reservoir (mg/l)

Cur_i = underground reservoir salinity at the end of the current day of simulation (mg/l)

Cur_{i-1} = updated underground reservoir salinity at the end of the previous day (mg/l)

$Curi_i$ = salt concentration of inflowing water into the underground reservoir (mg/l)

$Curo_i$ = average salinity of the outflow from the underground reservoir (mg/l)

D = elevation of the bottom of the surface reservoir (m)

d = thickness of the surface reservoir bottom sedimentation (m)

$DISS1$ = dissolved precipitated salt (mg)

$d_{s\,lay}$ = soil surface layer depth (m)

e = surface reservoir exponent (dimensionless)

F = volume of water in a surface reservoir (m^3)

G = groundwater from the non-irrigated area that mixes with that from the irrigated area (m)

h = depth of the groundwater table below the bottom of the surface reservoir (m)

H = elevation of the groundwater table underlying the surface reservoir (m)

h_g = depth of groundwater store (m)

H_{is} = historical colliery production (ton ROM)

I = current (A)

i = hydraulic gradient (dimensionless)

I_{dam} = total water inflow to the surface reservoir on the day including rain falling on surface of the reservoir (l)

k = salt uptake rate constant (dimensioless)

K = vertical saturated hydraulic conductivity of the surface reservoir bottom clogged layer (m/ day)

K_{aq} = hydraulic conductivity of the aquifer (m/day)

k_{decay} = rate constant during salt decay process in the underground reservoir (dimensionless)

k_g = the geometric factor (dimensionless)

K_r = hydraulic conductivity of the layer of rock below the aquifer (m/ day)

k_{uptake} = rate constant during the salt uptake process in the underground reservoir (dimensionless)

L_{in} = leakage volume into the underground reservoir (l)

L_{sal} = salt concentration of the leakage into the underground reservoir (mg/l)

MS_{SAL} = mixed stormflow salinity (mg/l)

$NetRFL_{Vol}$ = volume of net rainfall (litres)

$NetRFL$ = depth of net rainfall (m)

p = depth of the capillary fringe (m)

p_a = apparent resistivity (Ω m)

P_{rd} = colliery production (ton ROM/annum)

Q = flow over a weir/flume (m^3/s)

QF = total quickflow volume (l)

QF_a = stormflow leaving the land on the day of the event (l)

Qin_i = water inflow to the surface reservoir on the current time step (l)

$Qout_i$ = water outflow from the surface reservoir for the current time step (excluding evaporation loss) (l)

Q_s = amount of seepage into a mine-pit reservoir (m^3/day)

Q_{ur} = leakage into the underground reservoir (m^3/day)

$Quri_i$ = volume of all water inflow into the underground reservoir on the current day of simulation (l)

$Quro_i$ = volume of water outflow from the underground reservoir for the current day of simulation (l)

r = height of the surface reservoir water surface above the bottom of the reservoir (m)

R = water elevation in the surface reservoir (m)

RE_{in} = seepage volume from overlying surface reservoir (l)

RE_{sal} = salt concentration of seepage from the surface reservoir into underground reservoir (mg/l)

RFL_{dam} = volume of rain falling on the reservoir surface (l)

RFL_{dam} = volume of rain falling on the reservoir surface (l)

RUN_{adj_dam} = runoff from adjunct impervious areas inflowing to the surface reservoir (l)

RUN_{adj_dam} = runoff from adjunct impervious areas into the surface reservoir (l)

RUN_{irr} = runoff from irrigated areas (l)

RUN_{irr} = runoff from irrigated areas (l)

RUN_{ni} = runoff flowing into the reservoir from non-irrigated lands (l)

RUN_{ni} = runoff flowing into the surface reservoir from non-irrigated lands (l)

S = seepage from the underground reservoir (m^3)

SF_d = fraction of delayed stormflow contributing to quickflow (l)

S_i = volume of water stored in the surface reservoir at the current time step (l)

S_{i-1} = volume of water stored in the surface reservoir at the end of the previous time step (l)

S_{irr} = incremental drainage into the groundwater of an irrigated area (m^3)

$SL_{inflows}$ = salt load from any other surface inflows (mg)

SL_{qf} = salt load associated with the total quickflow volume for the day (mg)

SL_{RFL} = salt load from rainfall (mg)

SL_{run} = the salt load associated with runoff water (mg)

SL_{SSL} = salt load in the soil surface layer (mg)

$S_{non\text{-}irr}$ = incremental drainage into the groundwater of a non-irrigated area (m^3)

Sur_i = volume of water stored in the underground reservoir at the current day of simulation (l)

Sur_{i-1} = volume of water stored in the underground reservoir at the end of the previous day (l)

t = contact time of net rainfall with salts in the surface layer (min)

T = groundwater from the irrigated area that mixes with that from the non-irrigated area (m)

TR_{in} = volume of water imported into the underground reservoir for the day (l)

TR_{sal} = salt concentration of the water imported into the underground reservoir (mg/l)

TRS_{dam} = total water imported into the surface reservoir (l)

t_s = time step of simulation (day)

$T_{s,i}$ = previous day amount of precipitated salt (mg)

$T_{s,i}$ = the amount of precipitated salt in the surface layer (mg)

$T_{s,i+1}$ = current amount of precipitated salt in the surface layer (mg)

V = updated volume of water in the underground reservoir (m^3)

V = voltage (V)

V = volume of water seepage from a surface reservoir (m^3)

$V_{s,l}$ = water content of soil surface layer as a depth (m)

w = water level height above a weir or flume (m)

W = vertical percolation rate of water into underground reservoir (m/ day)

WLA = sulphate waste load allocation to a specific colliery ($tonSO_4$/annum)

WR = water to soil ratio (m/m)

$WV_{inflows}$ = water volume from any other surface inflows (litres)

x = current production allocation factor ($tonSO_4$/tonROM)

y = historical production allocation factor ($tonSO_4$/tonROM/annum)

α, β, k_{diss} = salt dissolution constants (dimensionless)

θ_{sVol} = water content of the soil surface layer as a volume (litres)

LIST OF ABBREVIATIONS

2D	= Two dimensional
ACRU	= Agricultural Catchments Research Unit (Model)
ALD	= Anoxic limestone drains
AMD	= Acid Mine Drainage
CSES	= Clean Stream Environmental Services
DWA	= Directorate of Water Affairs
DWAF	= Directorate of Water Affairs and Forestry
EC	= Electrical Conductivity
EMPR	= Environmental Management Programme Report
EP	= Electrical profiling
ERT	= Electrical Resistivity Tomography
FEFLOW	= Finite Element subsurface FLOW system
GDP	= Gross Domestic Product
Ha	= Hectares
MAP	= Mean annual precipitation
MAR	= Mean annual runoff
NWRS	= National Water Resource Strategy
OLC	= Open limestone channels
PRW	= Plant Return Water Dam
RMS	= Root mean square
ROM	= Run of Mine
SAPS	= Successive alkalinity producing systems
SCS	= Soil Conservation Service

SWB	= Soil water balance
TDS	= Total dissolved solids
TWQR	= Target Water Quality Range
USGS	= United States Geological Service
VES	= Vertical electrical sounding

1. INTRODUCTION

1.1 Background

The subject studied in this research work encompasses the impact assessment of using gypsiferous mine water for irrigation in parts of the Upper Olifants basin in South Africa. Large amounts of gypsiferous mine water are generated by the coal mines in South Africa. In the Mpumalanga coalfields and the Olifants basin where the study area is located, an estimate of 360 Ml/d and 170 Ml/d respectively, may be generated after the closure of the mines (Grobbelaar *et al.*, 2004). The disposal of the large amount of generated mine water constitutes a general problem to the mining industry. Conventional treatment systems using physical, chemical and biological methods can be prohibitively expensive and the concentrations of salts and other constituents render the water unsuitable for direct discharge to the river systems, except in periods of high rainfall when an adequate dilution capacity is present and controlled release is allowed by the Department of Water Affairs and Forestry (DWAF). The needs for a cost effective, as well as an environmentally sustainable manner of mine water disposal, have fostered interests in the possibility of utilizing mine water for irrigation in suitable soils, which could include rehabilitated mined land. Such mine water utilization could solve both the problems of the disposal of the large quantities of the mine water generated and inadequacy of water for cultivation, especially in the dry winter months. The potentials offered by such mine water utilization will depend on the availability of the water in proximity to suitable soil (Tanner *et al.*, 1999), the resultant soil water and salt balance for different cropping systems, the choice of irrigation management strategies (Jovanovic *et al.*, 2001), and the impact of the irrigation drainage water on the local, or possibly regional water resources. The focus of this study is the impact on water resources. The study combines field investigations at different scales and involves the modifications and use of *ACRU2000*, together with its salinity module called *ACRUSalinity*, for the impact assessment of irrigation with low quality mine water. The new object-oriented version of *ACRU* agrohydrological model is called *ACRU2000*. This study builds on previous field-scale research. However, it is the first attempt to evaluate the likely impacts of large-scale use of gypsiferous mine water for irrigation at a catchment scale, with due consideration to the different components of the hydrological system.

The choice of *ACRU2000* with its hydrosalinity module is predicated on two main factors. Both *ACRU2000* and *ACRUSalinity* were developed in the School of Bioresources Engineering and Environmental Hydrology of the University of KwaZulu-Natal, and adequate resources, especially in terms of expert knowledge and experience, are available to guide their application and the necessary modifications for this study. However, while *ACRU* had been extensively used and applied both locally and internationally (Schulze *et al.*, 1995a), *ACRUSalinity* had only recently been developed and the need existed to apply it as widely as possible in order to benefit from its capabilities, identify its limitations and make improvement. Secondly, this study is meant to provide an integrated assessment of water resources at the different scales of study, taking into consideration precipitation, infiltration, percolation, evaporation, runoff, deep seepage and solute transport processes. The tool for the integrated assessment should be fine (in terms of time and spatial scales) and detailed enough to accommodate modelling of a range of scenarios that may characterise the hydrological components identified in the study area. *ACRU2000* and *ACRU*Salinity conform to these requirements.

To assess the impact of the use of gypsiferous mine water for irrigation in this study, parts of the Upper Olifants basin upstream of Witbank Dam are chosen as the areas of investigation for the following reasons. Coal mining has been recognized as the dominant activity in the Witbank Dam catchment with respect to the pollution and degradation of the surface water resources (Department of Water Affairs and Forestry, 1993). The extensive coal mining that is taking place in the Upper Olifants, by as many as 29 collieries, generates large quantities of gypsiferous mine water. For example, Kleinkopje Colliery, located near Witbank, had 12 million m^3 of water stored in one of its reservoirs and the estimated rate of generation was 14 Ml day^{-1} (Annandale *et al.*, 2002). Therefore, large quantities of gypsiferous mine water are available in Witbank Dam catchment for the kind of large scale irrigation that this study intends to assess. Related to this is the fact that the Witbank Dam catchment experiences summer rainfall, typically less than

700 mm per annum. The available mine water in the area, therefore, may be a potential source of supplementary water for summer farming and adequate water for winter farming. Secondly, related local field scale trials had been going on at sites within the Witbank Dam catchment since 1997. Therefore, it is expedient for this study to make use of the available data from some of the field trials in order to carry out the impact assessment within a colliery with adequate volume of mine water. This also provides a good enough basis to carry out the research work at different levels, proceeding from a centre pivot scale to a catchment scale and then to a mine scale.

1.3 Objectives of Study

The general aim of this research work is the development of a tool for the impact assessment on water resources as a result of large scale irrigation with low quality mine water, based on the modifications carried out in the *ACRU2000* model and the *ACRUSalinity* module. It includes studies at centre pivots, catchment and mine scales, with a focus on the assessment of the impact on the Witbank Dam. The study includes four centre pivots (Tweefontein, Syferfontein, Major and Fourth), which are located at two different mines in the Upper Olifants basin. The runoff from two of the centre pivots were monitored in this study, viz. Tweefontein pivot (on rehabilitated soils) and Syferfontein pivot (on unmined soils). The mine scale study is at the Kleinkopje Colliery in which three of the centre pivots are located. The catchment scale study is on the Tweefontein Pan catchment, which lies mainly within the Kleinkopje Colliery.

Insights into surface water and groundwater responses to large-scale irrigation with coal mine water are provided in this study, as well as a sound basis for assessing the potential impact of irrigation with similar mine effluents on water resources in other parts of South Africa.

The specific objectives of this study include:

- The development of relevant modules in the *ACRU2000* model and the *ACRUSalinity* module to enable adequate modelling and assessment of the impact of large scale irrigation with gypsiferous mine water on both the surface water and groundwater resources;

- A pivot scale assessment of the effect of irrigation with mine water at the centre pivots located in a virgin (i.e. unmined) and rehabilitated soil, with the intention of determining inputs relevant to catchment and mine scale studies;
- A catchment scale assessment, using the Tweefontein Pan catchment, with the aim of assessing the impact of irrigation with mine wastewater on the water resources of the catchment;
- Application of the modified *ACRU2000* and *ACRUSalinity* model to Kleinkopje Colliery, with focus on the impact assessment of the water contributed from the colliery, both in quantity and quality, to Witbank Dam;
- Modelling of different scenarios on the chosen colliery with respect to impact of irrigation with gypsiferous mine on the Witbank Dam; and
- Recommendation on the kinds of measurements, observations and monitoring that may be required for the impact assessment of large scale irrigation of agricultural crops with mine effluents on catchments water resources.

1.3 Outline of Chapters

The background to the study and the research objectives are presented in this chapter, Chapter 1, while the study area is described in Chapter 2. The study area is described within its broader hydrological and physical environments, and so a description, starting from the Upper Olifants basin to Kleinkopje Colliery to Tweefontein Pan catchment and to the centre pivots is provided. A literature review on areas related to the scope of the research work is presented in Chapter 3. The relevance and uniqueness of this study is stressed in the literature review. The methodologies of the study in described in Chapter 4 and it covers methodologies adopted for the pivot, catchment and mine scale studies. The model employed in this study is *ACRU2000*, along with its salinity module *ACRUSalinity*. This research work involves the modification of the *ACRU2000* model and the *ACRUSalinity* module in order to include processes appropriate for the assessment of the use of gypsiferous mine water for irrigation in the study area. The description of the *ACRU2000* model and the *ACRUSalinity* module are therefore considered necessary in order to provide enough background and understanding on the modifications carried out in both of them. In Appendix A, is a section that contains the description of both the *ACRU2000* model and the *ACRUSalinity* module. The description of the modifications carried out in the *ACRU2000* model and the *ACRUSalinity* module are provided in Chapter 5. The new objects added to both the *ACRU2000* model and the *ACRUSalinity* module, as well as their description are presented in Appendices B and C respectively, while the code validation of the major modifications carried out are presented in Appendix D. The modelling requirements for the use of the *ACRU2000* model and the *ACRUSalinity* module, as employed in this research work, are presented in Chapter 6, followed by the presentation of results and discussion of the application the model at the different scales of study in Chapters 7 and 8. Chapter 7 addresses the pivot scale study while Chapter 8 addresses the catchment and mine scale studies. Conclusions and recommendations in Chapter 9 complete the main body of the research work, followed by references and appendices in Chapters 10 and 11 respectively.

2. DESCRIPTION OF THE STUDY AREA

The study area of this research work lies in the Upper Olifants basin upstream of the Witbank Dam. A general description of the basin, as background information, is therefore, firstly provided. While the mine scale study is carried out on the Kleinkopje Colliery, the catchment scale study is carried out on the Tweefontein Pan catchment. The pivot scale studies are on the Tweefontein and Syferfontein pivots. Therefore, the description of the Upper Olifants basin is followed by that of the Kleinkopje Colliery, which in turn is followed by the description of the Tweefontein catchment. The description of the Tweefontein and Syferfontein pivots completes the chapter. In this way, the study area is described within its broader and physical environments and provides the reader with enough background information on the different parts of the study area.

2.1 Description of Upper Olifants Basin

The description of the Upper Olifants basin covers its location, climatological and hydrological conditions, land use and land cover, physiography, geology and geohydrology. However, as the study area lies within the Witbank Dam catchment, emphasis is placed on the catchment.

2.1.1 Location of Upper Olifants Basin

The Upper Olifants basin is located in the Mpumalanga Province, in the northeastern part of the Republic of South Africa, around longitude 26^0 15'S and latitude 29^0 30' E (Figure 2.1). It constitutes the upper part of the Olifants River basin and the area of study lies within the Witbank Dam catchment (Figures 2.1 and 2.2). The Olifants catchment is a sub-catchment of the Limpopo River basin and it is shared by South Africa and Mozambique.

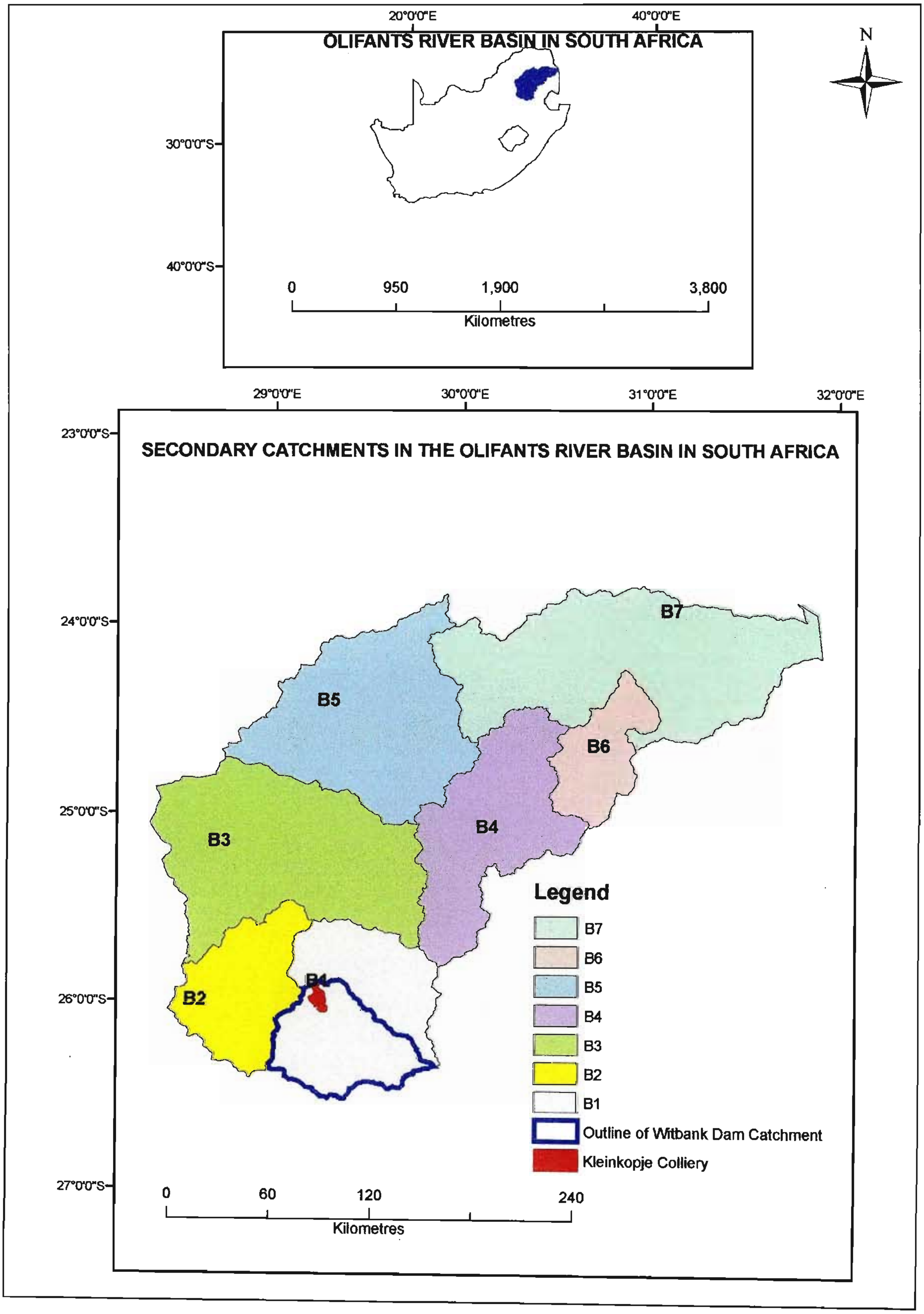


Figure 2.1: Olifants River Basin and its Secondary Catchments in South Africa

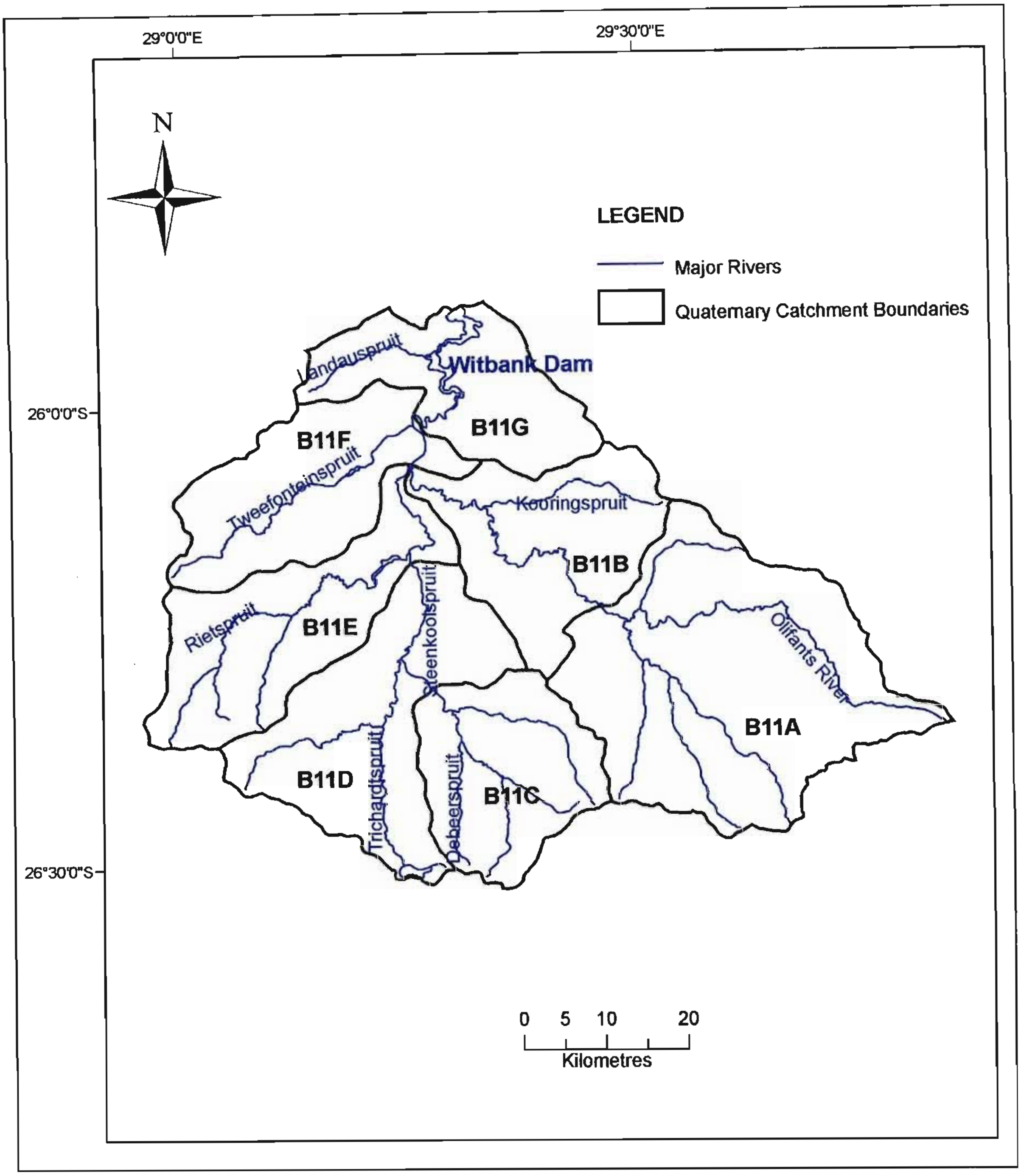


Figure 2.2: Upper Olifants Quaternary Catchments and major rivers upstream of Witbank Dam

2.1.2 Climatological and Hydrological Conditions

The Olifants River joins the Limpopo River in Mozambique before flowing into the Indian Ocean. There are 22 Primary Drainage Regions in South Africa, of which Olifants is one. Within the Olifants are seven Secondary, 13 Tertiary and 114 Quaternary Catchments. The Quaternary Catchments are the smallest catchment units used in the management and planning of water resources at the national level in South Africa. Tables 2.1 – 2.3 show the median monthly precipitation, mean monthly A-pan equivalent potential evaporation and the mean monthly potential evapotranspiration (Penman-Montieth) for each of the Secondary Catchments in the Olifants basin in South Africa. Figure 2.3 shows these parameters for the Secondary Catchment B1 in which the area upstream of Witbank Dam is located.

The Upper Olifants River basin, upstream of Witbank dam, is located within the B11 Tertiary Catchment and comprises six DWAF Quaternary Catchments numbered B11A to B11F (Figure 2.2). The major rivers in the Witbank Dam catchment, the Olifants River and Steenkoolspruit, have their headwaters in the Highveld grasslands around Bethal. Several tributaries, including Trichardtspruit, Koringspruit, Rietspruit, Tweetfonteinspruit and Debeerspruit drain into the major rivers (Figure 2.2). Table 2.4 contains a summary of the major rivers and their naturalised mean annual runoff (MAR). The depth of the MAR (in mm) is obtained by dividing the catchment area by the MAR (in m^3). Little difference exists in the MAR, as a depth of about 37 mm was calculated for all the rivers. The little difference between the MAR for the rivers in terms of depth may be an indication of the little differences in the climatic variability and the soil moisture storage capacities in the different parts of the Witbank Dam catchment.

The drainage patterns of the Witbank Dam catchment have been extensively modified by small farm dams, large impoundments and river/stream diversions. The largest of the impoundments is the Witbank Dam, which is a large municipal dam with a capacity of 104 Mm^3 and a surface area of 16.81 km^2. The Witbank Dam catchment has an area of 3 302.53 km^2 with a mean annual runoff (for virgin catchment conditions) of 122.14 Mm^3 (Department of Water Affairs and Forestry, 1993).

The mean annual flow for the whole of the Olifants basin is 2040 Mm^3 (McCartney *et al.*, 2004). The mean annual rainfall in the catchment varies between 600 mm and 800 mm and occurs mainly in the summer, while the mean annual A-pan evaporation varies between 1 640 mm and 1 860 mm.

Table 2.1: Mean monthly and annual precipitation (mm) for each of the Secondary Catchments in the Olifants basin (derived from Schulze, 1997 in McCartney *et al.*, 2004)

Water Management Region	Secondary Catchment	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Annual
Upper Olifants River	B1	63.1	111.2	106.3	114.6	83	70.2	35.1	9.8	0.1	0.0	0.5	14.9	608.8
	B2	57.2	102.9	103.6	112.9	83	72.4	32.7	9.2	0.1	0.0	0.1	12.7	586.8
Upper Middle Olifants River	B3	47.3	98.9	97.6	101.8	79.1	63.7	31.0	6.8	0.0	0.0	0.0	10.2	536.4
Mountain Region	B4	52.8	107.1	110.6	110.9	85.9	70.1	37.3	8.6	0.3	0.1	0.3	13.4	597.4
Lower Middle Olifants Region	B5	37.1	82.1	88.7	89.9	71.4	53.0	27.5	5.1	0.1	0.1	0.1	8.5	463.6
Lower Olifants Region	B6	50.4	105.7	127.3	127.3	114.8	89.1	44.5	12.4	1.8	2.4	2.5	14.8	693.0
	B7	30.7	68.3	91.8	91.8	76	56.1	30.2	6.2	0.4	1.0	0.6	7.2	460.3
Entire Basin		45.5	92.4	99.4	102.4	80.5	63.8	32.4	7.5	0.2	0.4	0.4	10.7	535.6

Table 2.2: Mean monthly and annual potential evapotranspiration (Penman-Montieth) (mm) for each of the Secondary Catchments in the Olifants basin (derived from Schulze, 1997 in McCartney *et al.*, 2004)

Water Management Region	Secondary Catchment	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Annual
Upper Olifants River	B1	149.5	150	156.9	149.4	124.4	122.8	95.8	77.4	60.5	67.7	96.6	126.2	1377.2
	B2	160.8	161.5	167.6	160.1	132.3	129.4	99.8	81.2	63.4	70.5	100.5	133.3	1460.4
Upper Middle Olifants River	B3	163.8	165.9	172.1	169.6	140.7	135.8	102.9	84.6	66.6	73.8	103.2	134.7	1513.7
Mountain Region	B4	141.8	142.5	146.2	144.5	119.3	120.6	97.9	81.3	63.6	69.6	95.0	121.2	1343.5
Lower Middle Olifants Region	B5	156.9	163	165.8	168.5	137.3	135.7	105.1	87.2	69.3	75.9	103.0	118.9	1486.6
Lower Olifants Region	B6	139.4	141.7	144.7	143.7	122.3	121.2	99.7	82.9	65.3	71.2	95.0	131.2	1358.3
	B7	149.4	158.8	164.9	167.5	142.4	137.0	105.1	87.4	71.0	78.9	102.9	127.5	1492.8
Entire Basin		153.2	157.1	162.3	160.9	133.9	131.1	101.8	83.9	66.5	73.5	100.5	128.7	1453.4

Table 2.3: Mean monthly A-pan equivalent potential evaporation (mm) for each of the Secondary Catchments in the Olifants basin (derived from Schulze, 1997 in McCartney *et al.*, 2004)

Water Management Region	**Secondary Catchment**	**Oct**	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**
Upper Olifants River	B1	210.8	205.6	215.1	204.8	170.5	173.0	141.0	125.0	102.8	115.0	156.1	188.5
	B2	226.6	220.8	228.4	217.5	179.8	180.2	145.5	129.4	106.1	118.1	160.8	198.5
Upper Middle Olifants River	B3	230.8	226.1	233.3	228.6	189.7	187.3	149.0	133.2	110.2	122.0	163.6	200.1
Mountain Region	B4	199.9	195.0	199.9	197.4	162.9	169.1	143.6	130.6	107.4	117.5	152.8	180.8
Lower Middle Olifants Region	B5	221.2	220.7	221.6	222.5	181.4	181.9	148.7	133.0	110.8	121.2	159.2	193.4
Lower Olifants Region	B6	194.1	192.3	195.9	194.4	165.0	167.8	143.3	130.4	107.5	117.1	149.7	174.9
	B7	201.3	209.4	214.6	217.3	183.1	178.6	143.2	125.7	105.8	117.5	150.0	179.2
Entire Basin		213.7	212.6	218.1	215.2	178.7	178.6	145.4	129.6	107.5	118.8	156.5	188.8

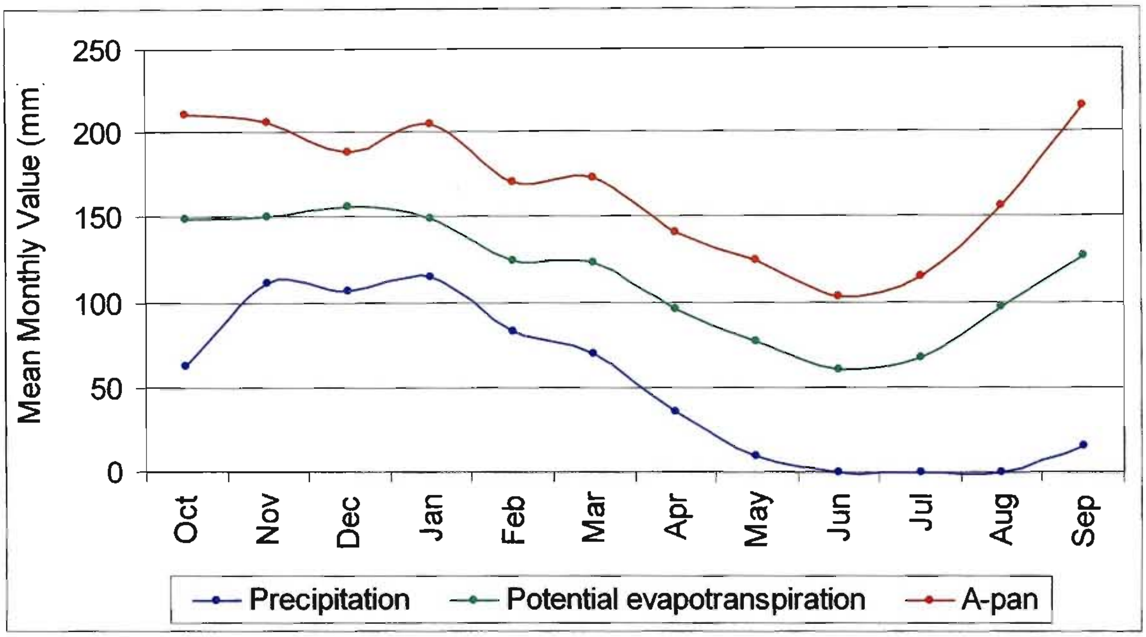


Figure 2.3: The mean monthly precipitation, potential evapotranspiration and A-pan equivalent potential evaporation for Secondary Catchment B1 (derived from Schulze, 1997 in McCartney *et al*, 2004)

Table 2.4: Surface areas and mean annual runoff of some rivers in the upper Olifants, upstream of Witbank Dam (Department of Water Affairs and Forestry, 1993)

River/Stream	**Catchment area (km^2)**	**MAR+ (million m^3)**	**MAR+ (mm)**
Trichardtspruit	107.54	3.98	37.0
Koringspruit	137.78	5.09	36.9
Rietspruit	394.33	14.58	37.0
Saaiwaterspruit	235.23	8.70	37.0
Tweefonteinspruit	107.10	3.96	37.0
Steenkoolspruit	805.59	29.78	37.0
Naauwpoortspruit	90.65	3.35	37.0
Boesmankranspruit	124.93	4.62	37.0
Olifants River	1 282.57	47.42	37.0
Witbank Dam*	16.81	0.62	37.0
TOTAL	3 302.53	122.14	3.70

* Witbank Dam catchment refers to the direct runoff to the dam from upstream areas
+ MAR values are for virgin catchment conditions

Not all water demands from the urban and industrial sector are supplied with water generated from within the Witbank Dam catchment, as water is transferred from the Rand Water Board to some towns like Davel, Trichart, Kincross, Devon and Leandra. Water is also transferred from the Usutu, Komati and Vaal River

(Grootdraai Dam) systems located outside of the Olifants River systems to the power stations and some collieries located in the Witbank Dam catchment. Duhva and Komati power stations are supplied by the Komati Government Water Scheme, while the Kriel power station is supplied by the Usutu Government Water Scheme. The Matla power station is supplied from the Grootdraai Dam as an addition to the supply from the Usutu-Vaal Government Water Scheme. The collieries supplied by the transfer from the Usutu Transfer system include Kriel, Khutala and Douglas (Vlakeage), while the Komati Transfer system supplies Koornfontein and Goedehoop.

2.1.3 Land Use and Land Cover

The main land use practices in the Witbank Dam catchment include coal mining and rain-fed agriculture. Figure 2.4 presents a coverage of the main land uses. Power generation by four ESKOM coal-fired power stations are located at Matla, Kriel, Komati and Duhva within the Witbank Dam catchment. A total of 29 major collieries, where both underground and opencast mining take place, are located in the catchment (Department of Water Affairs and Forestry, 1993). The locality plan of the power stations and mine lease areas are shown in Figure 2.5. The map is in the rectangular coordinate system in which locations are measured from the equator and the central meridian in metres. The mines generate large quantities of gypsiferous water, part of which is allowed to be released directly into the river systems by DWAF, especially in the periods of high rainfall, when adequate dilution capacity is available. The large volume of surplus water is stored in surface reservoirs and underground mined-out areas. Opencast mining in the Upper Olifants involves the stripping of the layers of soils overlying the coal seam, removing the coal and back filling with the spoil. The spoil is then overlain with topsoil to form a rehabilitated soil terrain. Such rehabilitated soils are the target for application of irrigation with mine water in this study. Underground mining is conducted by both board-and-pillar and high extraction methods. However, high extraction methods have only been applied to a limited degree because of the abundance of shallow coal, which can be mined by opencast methods (Hodgson and Krantz, 1998). The total number of hectares in Mpumalanga underlain by exploitable coal reserves has been put at 1.03 million (Schoeman *et al.*, 2002).

Commercial farming constitutes the dominant land use activity in Witbank Dam catchment and it takes the form of both dry land (rain-fed) and irrigation farming. Rain-fed agriculture was limited to summer. The potential of utilizing mine water for irrigation of agricultural crops therefore exists in the Upper Olifants, especially in the dry winter months when rainfall can be inadequate for farming. Irrigation, using the mine water, could also be carried out in the summer as a supplement to insufficient rainfall. This is important when viewed against the fact that the Upper Olifants is located in one of the most fertile and important agricultural areas in South Africa (Annandale *et al.*, 2001).

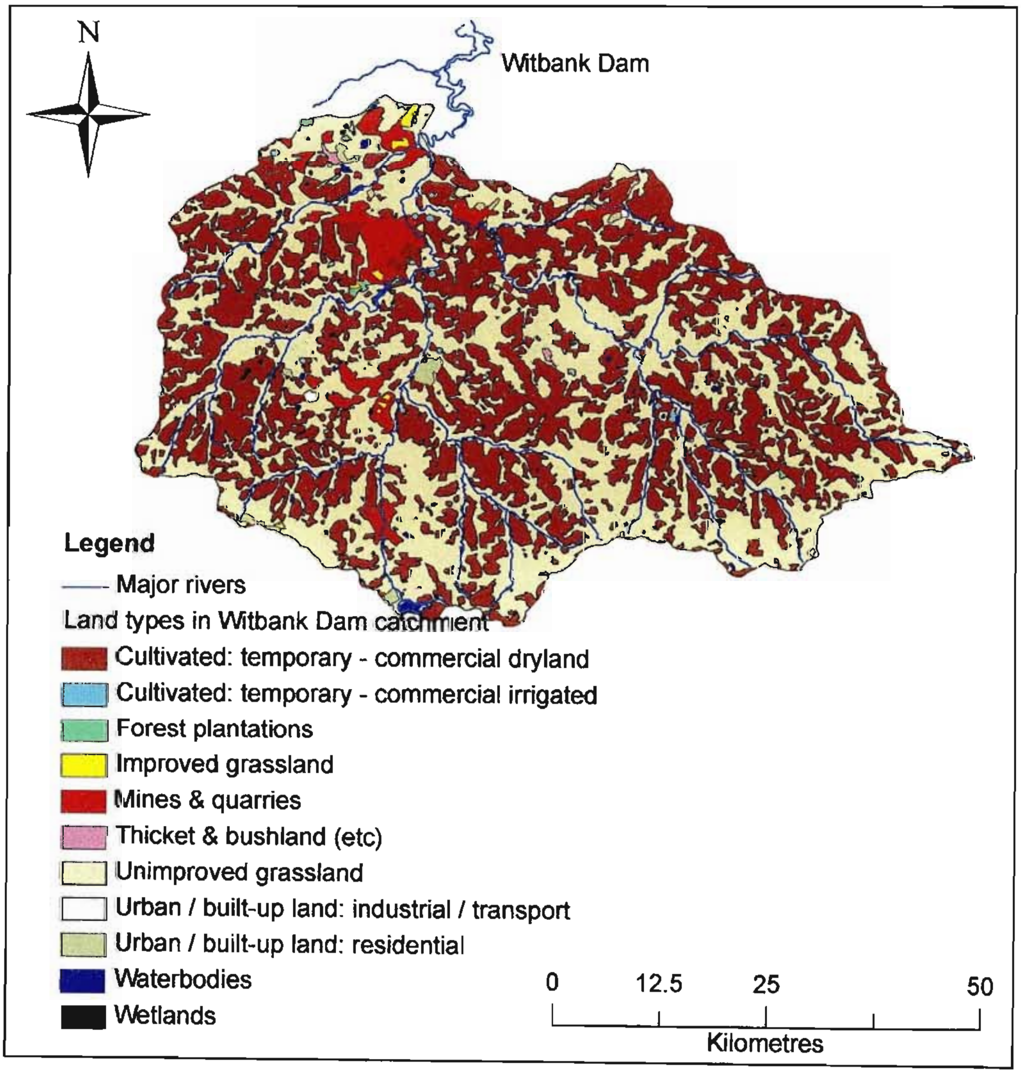


Figure 2.4: The land use in the Upper Olifants basin upstream of Witbank Dam (adapted from Thompson, 1996)

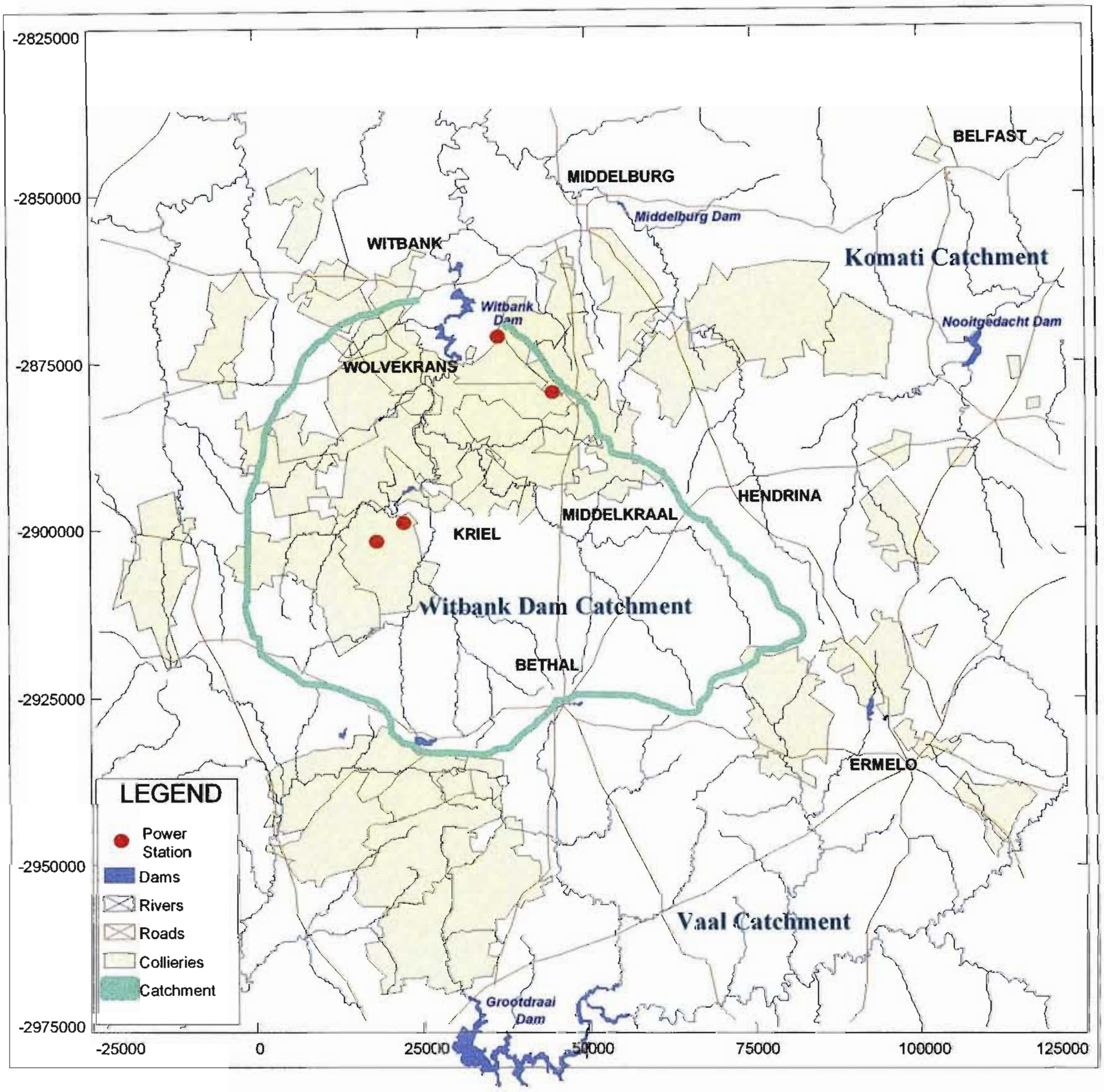


Figure 2.5: Locality plan of the power stations and mine lease areas in the study area (adapted from Grobbelaar, 2004)

The Mpumalanga Highveld has an average of approximately 30-40% arable and 10-15% prime crop-land as compared to the 12% arable and 4% high potential crop-land figures for the whole of South Africa (Annandale *et al.*, 2001). Half of the high potential land available to commercial agriculture in South Africa is situated in and around Mpumalanga coal fields (Schoeman *et al.*, 2002). Crops produced on irrigated and rain-fed areas are primarily maize, lucerne, potatoes and sunflowers.

Urban development in the Witbank Dam catchment is limited to small towns especially on the Highveld ridge. Such towns included Kinross, Trichardt, Bethal and Kriel.

2.1.4 Physiography, Geology and Geohydrology

The topography of most parts of the Witbank Dam catchment is generally undulating, with the exception of the headwater areas which are steep. The altitude ranges from 1 762 m in the highveld headwater areas around Bethal to 1 520 m at the outlet of the catchment around Witbank Dam.

The geology of the Upper Olifants catchment consists of the rocks of the Ecca Group and Dwyka Formation of the Karoo Supergroup (Hodgson and Krantz, 1998). The different groups of sediments that constitute the geological sequence of Karoo Supergroup are shown in Figure 2.6.

Drakensberg Volcanics		Basalt	**Jurassic**
Stormberg Group	Clarens	Cross-bedded sandstone	**Triassic**
	Elliott	Red mudstone and sandstone	
	Molteno	Sandstone, conglomerate and mudstone	
Beaufort Group	Tarkastad Subgroup	Burgersdorp Formation	
		Katberg Sandstone	
	Adelaide Subgroup	Green, grey and purple mudstones	**Permian**
		Sandstone	
Ecca Group		Shale and sandstone	
Dwyka Group		Tillite and diamictite	**Carboniferous**

Figure 2.6: The Karoo Supergroup (Botha *et al.*, 1998).

The Ecca Group rocks consist predominantly of sandstone, siltstone, shale and coal. Combinations of these rocks types are often found in the form of interbedded siltstone, mudstone and coarse-grained sandstone. Two coalfields, namely Witbank and Highveld, are distinguishable within the Ecca Group. The Ecca Group overlies the Dwyka Group (loosely referred to as Dwyka tillite) which consists of tillite, siltstone and sometimes a thin shale development. The upper portion of the Dwyka Group may have been reworked, in which case, carbonaceous shale and even inclusions of coal, may be found. In both the Ecca and Dwyka Groups are extensive intrusions of dolerite dykes and sills. The Dwyka sediments are underlain by a variety of rock types, such as Bushveld Complex in the north, Witwatersrand Supergroup in the south, Waterberg Supergroup in the northwest and Transvaal Supergroup in the west.

Three distinct superimposed groundwater systems are present within the Upper Olifants basin (Hodgson and Krantz, 1998). They are classified as the upper weathered Ecca aquifer, the fractured aquifers within the unweathered Ecca sediments and the aquifer below the Ecca sediments (pre-karoo aquifers). The Ecca sediments are weathered to depths of between 5 – 12 m below the surface and the upper weathered aquifer is associated with this weathered zone, with the water often found within the a few metres below the surface. This aquifer is generally low yielding (range 100 – 2000 l/hour) because of its insignificant thickness, and it is recharged by rainfall, with the percentage of recharge estimated to be in the order of 1 – 3% of the annual rainfall (Kirchner *et al.*, 1991). However, with a weathered system such as the Ecca in which sediments range from coarse-grained sands to clays, highly variable recharge values, reflecting the composition of the sediments and degree of weathering, may be expected. Isolated values as high as 15% of the MAP have been reported by Hodgson and Krantz (1998), although they believed that a general recharge value of 3% in the Upper Olifants was realistic. Rainfall that infiltrates into the weathered rock reaches an impermeable layer, on top of which lateral flow consequently occurs in the direction of the surface slope until obstructed by a barrier such as a dolerite dyke, paleotopographic highs in the bedrock or where the surface topography cuts into the groundwater level at streams. The qualities of water in some boreholes tapping water from the weathered aquifer, and their statistics, are illustrated in Table 2.5. The good quality of the water can be attributed to the many years of dynamic groundwater flow through the weathered sediments, which has washed away all the leachable salts in the zone. The fractured Ecca aquifer consists of competent rocks such as sandstones, with secondary structures being in the form of fractures, cracks and joints. The secondary structures are generally limited to the top 30 m below the surface and many have been constricted because of the compressional forces that act within the earth's crust (Hodgson and Krantz,1998).

The qualities of water in some boreholes tapping water from the fractured aquifer, and their statistics, are illustrated in Table 2.6. The water in the fractured aquifer contains higher salt loads than the water in the upper weathered aquifer. This can be attributed to the longer contact time between the water and the rock. The occasional high chloride and sodium levels were attributed to boreholes located close to areas where salts naturally accumulated, such as in water pans (Hodgson and Krantz, 1998). The pre-Karoo aquifer is also secondary in nature, being associated with the fractures located in the granitic rocks that underlie the Dwyka Group. The aquifer is low yielding because of low recharge characteristics, consequent upon the overlying impermeable Dwyka tillite, and its water is of inferior quality with high levels of fluoride, associated with the granitic rocks of the aquifer.

Table 2.5: Water qualities and statistics within the upper weathered Ecca aquifer in the Olifants basin (Hodgson and Krantz, 1998)

Statistics	pH	Chloride (mg/l)	Sulphate (mg/l)	Magnesium (mg/l)	Sodium (mg/l)	Calcium (mg/l)	EC (mS/m)
Mean	6.23	3.0	1.8	3.1	10.7	12.3	13.0
Median	6.05	2.0	2.0	3.0	8.0	10.0	13.0
Mode	6.00	1.0	2.0	2.0	5.0	6.0	18.0
Standard Deviation	1.23	3.3	1.4	1.9	6.2	8.9	6.2
Minimum	5.02	0.0	0.0	0.0	3.0	1.0	3.7
Maximum	6.98	16.0	6.0	8.0	33.0	35.0	25.0
Number of samples	41	41	41	41	41	41	41

Table 2.6: Water qualities ad statistics within the fractured Ecca aquifer in the Olifants basin (Hodgson and Krantz, 1998)

Statistics	pH	Chloride (mg/l)	Sulphate (mg/l)	Magnesium (mg/l)	Sodium (mg/l)	Calcium (mg/l)	EC (mS/m)
Mean	8.05	53.0	24.0	15.0	105.0	32.0	64.0
Median	8.04	22.0	20.0	10.0	65.0	27.0	58.0
Mode	7.70	8.0	10.0	8.0	30.0	22.0	59.0
Standard Deviation	0.45	78.0	18.0	13.0	89.0	18.0	34.0
Minimum	6.75	5.0	1.0	1.0	7.0	5.0	15.0
Maximum	8.95	463.0	80.0	69.0	330.0	76	145.0
Number of samples	76	76	76	76	76	76	76.0

2.2 Kleinkopje Colliery

The sections that follow are general descriptions of the Kleinkopje Colliery.

2.2.1 Location and Mining Activities

Kleinkopje Colliery is situated at approximately 25^0 53' S and 29^0 10' E. It is about 15 km southwest of Witbank and the N12 highway, which links Johannesburg with Witbank, passes through the northern part of the colliery (Figure 2.7). The colliery is also accessible by the tertiary roads that branch off the main Witbank-Bethal route. The location of the colliery in the Witbank Dam catchment is shown in Figure 2.8. It lies to the southwest of Witbank Dam, adjacent to the Olifants River and straddles the Tweefonteinspruit. The Tweefonteinspruit joins the Olifants at about 1 km south of Wolvekrans, which is adjacent to the colliery. In the northern part of the colliery, the Landauspruit passes through the colliery before terminating in the Witbank Dam. Considering the river network and the proximity of the colliery to Witbank Dam, discharges from the colliery are expected to have a direct impact on the amount and quality of water in Witbank Dam. Therefore, assessment of extensive irrigation with gypsiferous mine water around Kleinkopje Colliery, as carried out in this research work, is focused on the assessment of the impact on the Witbank Dam.

The Kleinkopje Colliery is one of the six coal mines wholly owned by Amcoal (Anglo American Coal Corporation Limited), which is one of South Africa's largest coal producers. The colliery was commissioned in 1978 to provide coal for the export market. Presently, however, the mine produces pulverized coal injection and thermal coal for export, as well as metallurgical, washed and sized coal for the domestic market (Aggregate and Mining Group, 2005). The production level of the colliery was recently increased from approximately 7.6 million to 8 million run-of-mine (ROM) tons of bituminous coal a year (Clean Stream Environmental Services, 2004; Aggregate and Mining Group, 2005) and the life of the colliery is expected to terminate in 2025. The economic reserves at Kleinkopje Colliery in June 2002 totalled 226 822 million ROM tons, which was expected to yield approximately 128 485 million tons of saleable products. At present, coal is mined by opencast operations; underground board-and-pillar mining operations ceased in 1991. Three of the four pivots involved in this study (Tweefontein, Major and Fourth) are located within the Kleinkopje Colliery. The fourth, Syferfontein pivot, is located in the Syferfontein Colliery, which is one of the mining operations of Sasol that supplies coal to Sasol's synthetic fuels and chemical plants in South Africa. Syferfontein Colliery engages in both underground and opencast coal mining and its relative position to Kleinkopje Colliery is shown in Figures 2.7 and 2.8.

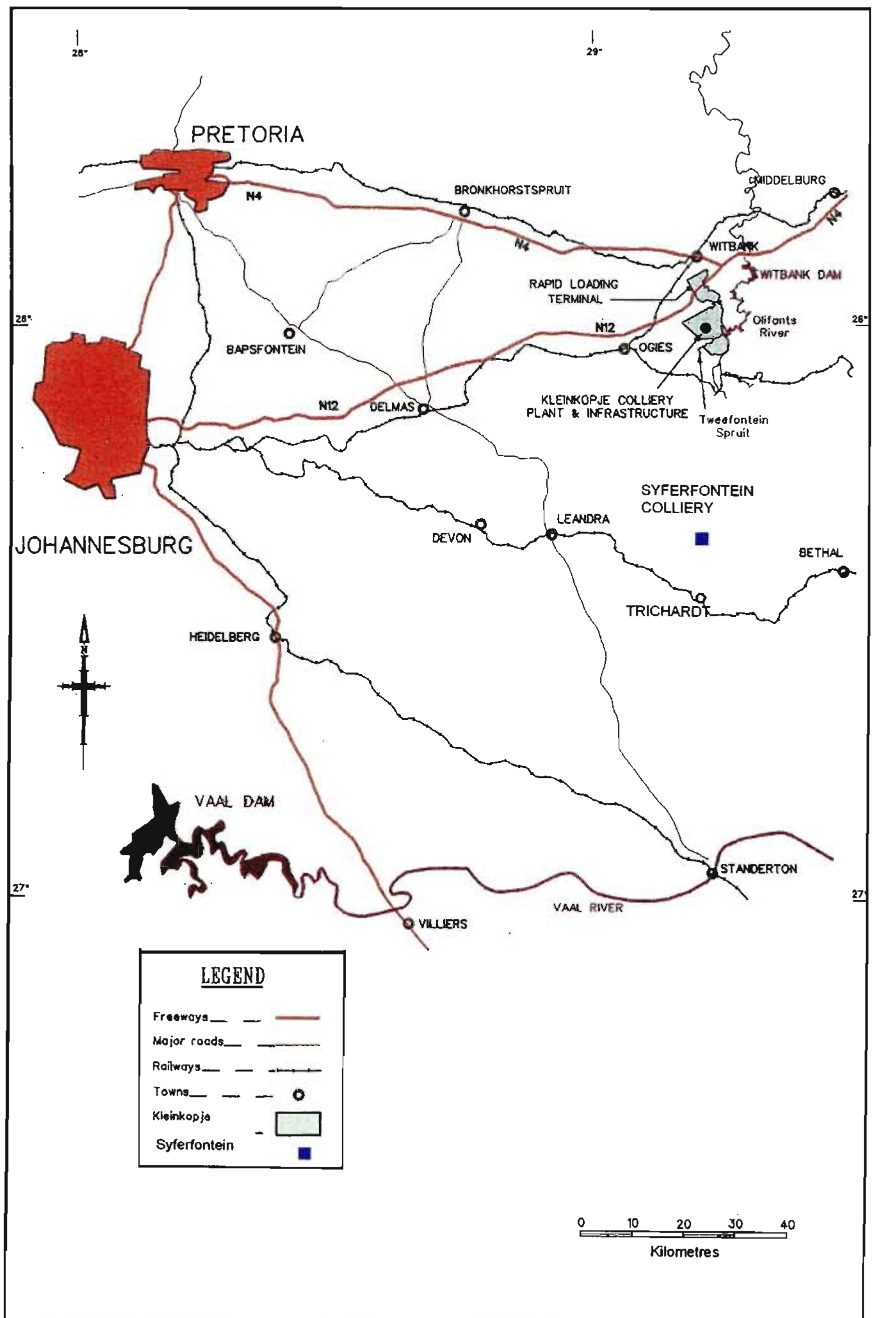


Figure 2.7: Locality plan of Kleinkopje and Syferfontein Collieries (adapted from Clean Stream Environmental Services, 2004)

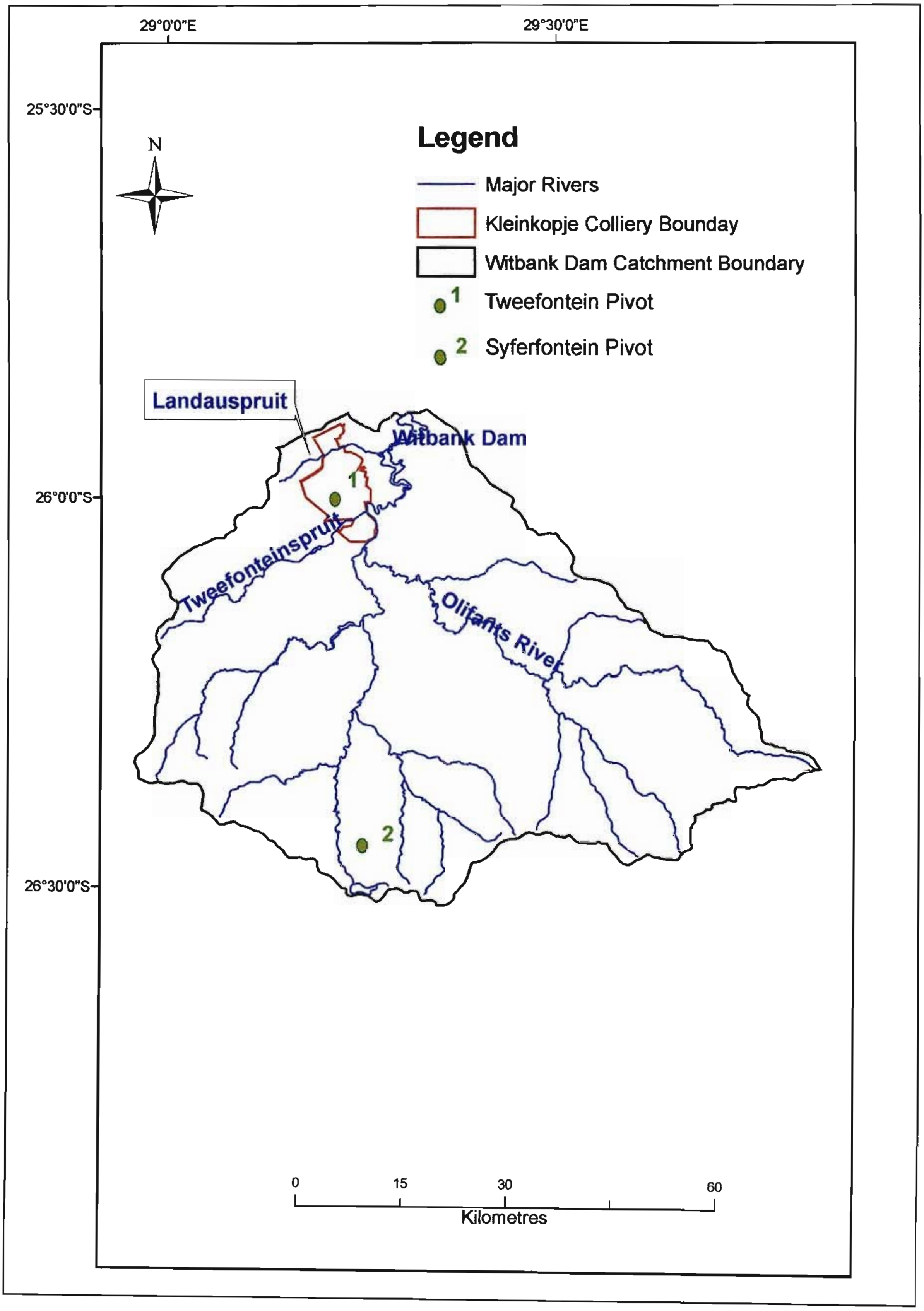


Figure 2.8: Location of Kleinkopje Colliery and the monitored centred pivots in the Upper Olifants basin upstream of Witbank Dam

2.2.2 Water Management in Kleinkopje Colliery

Water management in Kleinkopje Colliery is complex and includes reclamation of coal spoils and rehabilitation of mined-out areas, channelling of clean and dirty water, active treatment of domestic wastewater water and the use of mine water for dust alleviation and irrigation.

The main sources of water in the Kleinkopje Colliery include

- Olifants River,
- Municipal water supply,
- Rainfall, and
- Flooded old underground workings.

The Tweefonteinspruit and Landauspruit are not water sources for the colliery.

Coal spoils and discards are rehabilitated to reduce the ingress of air and water, which in turn could reduce the oxidation of pyrite and subsequent acidification within the coal and thereby prevent water pollution. The rehabilitation methods are discussed in Section 3.5. In order to accomplish the separation of clean from dirty water, a network of cut-off trenches has been constructed in the colliery. The locations of the cut-off trenches include defunct shafts, up-slope of opencast pits and around surface complex and coal discard facilities. Clean storm water runoff is disposed off by means of clean water cut-off trenches, which direct the water to the Olifants River or Tweefonteinspruit (Figure 2.9). The dirty water cut-off trenches have been constructed round the coal-processing complex and the dirty water is made to run through silt traps before discharging into the Plant Return Water (PRW) Dam (Figure 2.9). An example of the dirty water cut-off trench is shown in Figure 2.10. The dirty water caught in the PRW Dam is re-used in the plant's beneficiation process as well as for dust suppression on haul roads. Dirty water, which discharges into opencast workings, is pumped to various holding dams from where it is used for dust suppression and irrigation of agricultural crops. The holding dams include Plant Return Water (PRW) Dam, 2A Dam, Tweefontein Pan, Erickson Dam1 and 2, and Block 5 West Holding Dam (Figure 2.9). Some of the holding dams, e.g. Tweefontein Pan, are used as evaporation pans.

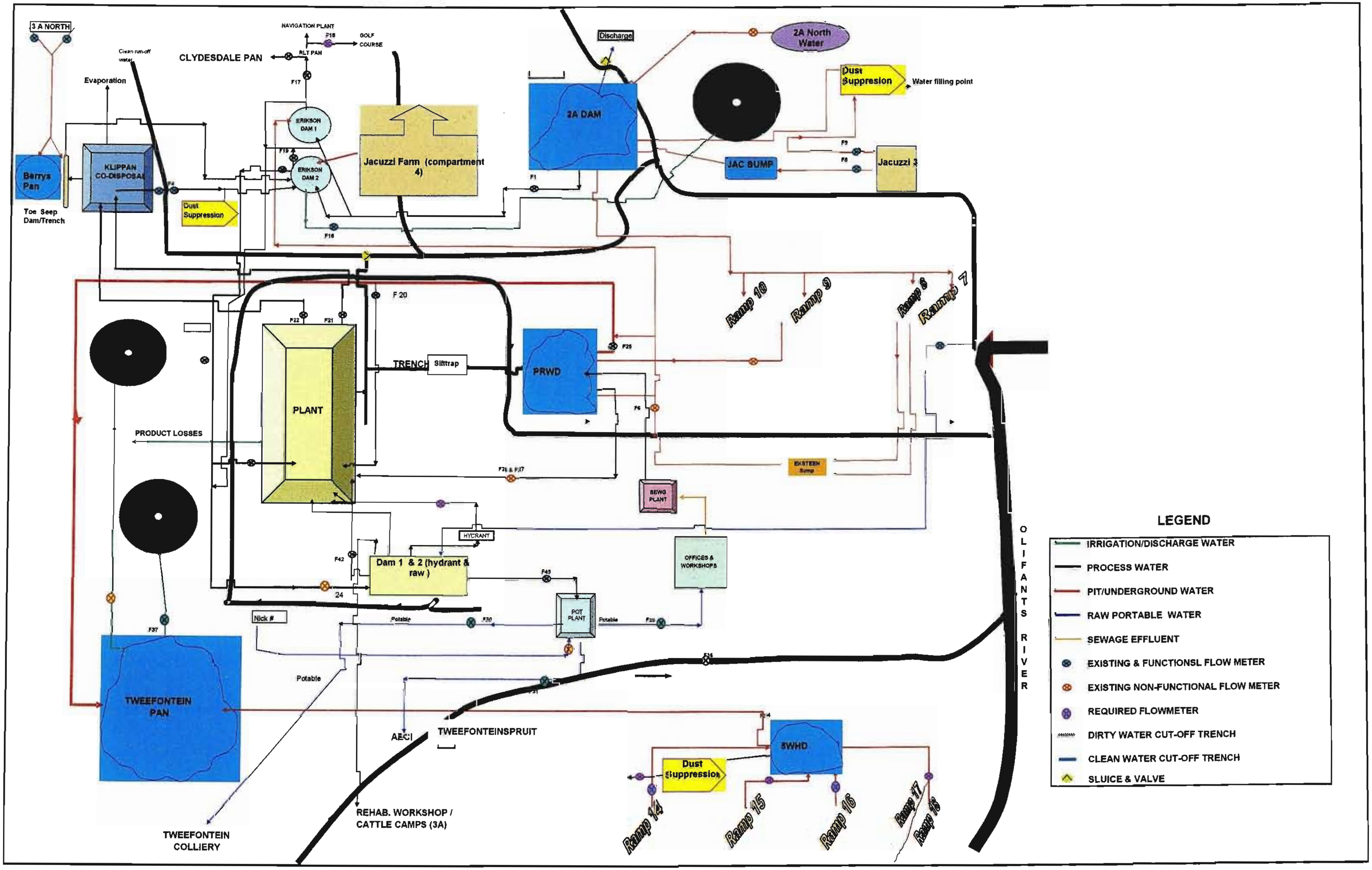


Figure 2.9: The water reticulation system in Kleinkopje Colliery (adapted from the Kleinkopje Colliery database)

Figure 2.10: Dirty water cut off trench with flowing dirty water in Kleinkopje Colliery (taken by O. Idowu 25/6/2005)

In order to minimise ingress of groundwater into underground workings, the following strategies are employed in the colliery:

- Installation of cut-off trenches around all defunct shafts,
- Sealing of all known cable and geological exploration holes,
- Filling in and sealing of all ground collapses that may occur due to shallow underground mining,
- Compaction and rehabilitation of discard dumps, and
- Rehabilitating mined-out workings in a sloping manner to ensure that water runs off and development of ponds prevented.

There were no boreholes extracting groundwater in Kleinkopje Colliery. Kleinkopje Colliery only uses boreholes for groundwater monitoring purposes.

2.3 Tweefontein Pan Catchment

The catchment scale study is carried out on the Tweefontein Pan catchment. The catchment is unmined and it lies almost entirely within the Kleinkopje Colliery. It has an area of 4.7 km^2 and its most visible land feature is the existence of the Tweefontein Pan. The Tweefontein Pan is a surface reservoir and the whole of the Tweefontein Pan catchment drains into it. No channel drains water out of the reservoir nor the catchment, thereby making the reservoir an internal draining reservoir. The reservoir is used for storage and evaporation of water pumped from opencast mining areas in Kleinkopje Colliery. The capacity and surface area (at maximum capacity) of the Tweefontein Pan reservoir are 4 000 Ml and 1.5 km^2 respectively. The water in the reservoir has a typical salinity of 1920 mg/l, and it is the source of irrigation water to the Tweefontein pivot, which is just outside of the catchment. However, within the catchment area is a centre pivot of 30 ha (Fourth) which is also irrigated with water from the Tweefontein Pan reservoir, and an underground reservoir of an estimated capacity of 2 x 10^9 Ml. The Tweefontein pivot and another pivot located at another mine (Syferfontein Colliery), the Syferfontein pivot, are used for the pivot scale study and are described in the remaining part of this chapter.

2.4 The Tweefontein Pivot

The Tweefontein pivot, established in 1997, is located within the Kleinkopje Colliery at around longitude 29^0 12' E, latitude 26^0 00' S (Figure 2. 8). It has an altitude of 1 570 m above sea level. The pivot irrigates 20 ha of rehabilitated soil, using water from the Tweefontein Pan, which holds the water pumped from active opencast pits. The water has a typical electrical conductivity (EC) of 300 mS/m. The pivot is rehabilitated with topsoil of varying depth overlying coal spoil. The spoil is about 40 m thick, according to the Kleinkopje Colliery mine rehabilitation officials and the average depth to spoil, on the basis of core depths taken on a 40 x 40 m grid, was about 0.93 m (Annandale *et al.*, 2002). Crops that have been planted on the pivot included maize, wheat and potato.

2.5 The Syferfontein Pivot

The Syferfontein pivot, established in 2002, is located within the Syferfontein Colliery around longitude 29^0 20'E and latitude 23^0 64'S (Figure 2.8). It has an altitude of 1 610 m above sea level. The centre pivot irrigates virgin (unmined) soil of about 20.6 Ha with water from a nearby dam within the colliery, which has a typical salinity of 380 mS/m. The pivot is planted to pastures, which are Fescue (cv. lewag) (*Festcua arundinaceae*), Lucerne (cv. SA standard) (*Medicago satival),* Fescue (cv. Demeter) (*Fescue arundinaceae*), Eragrostis (*Eragrostis curvula*), Kikuyu (*Pennisetum clandestinum*) and Rye grass (*Lolium perenne*) (Beletse, 2004).

3. LITERATURE REVIEW

The literature review provides information on the different aspects of this study, with the relevance and uniqueness of the study stressed. The following aspects are considered:

- Impact of mining on the water resources of the Upper Olifants basin,
- Mine water management,
- Controlled release of saline water during flood conditions,
- Use of gypsiferous mine water for irrigation,
- Rehabilitated mine soils,
- Water in underground collieries,
- Surface water – groundwater interactions,
- Mine water and salt balances, and
- Electrical resistivity survey.

As this research involves the modification of the *ACRU2000* model and the *ACRUSalinity* module, their description is considered necessary in order to provide enough background information that will enable the understanding of the modifications carried out in both of them in Chapter 5. The description is provided in Appendix A.

3.1 Impact of Mining on the Water Resources of the Upper Olifants Basin

Coal mining has been identified as the dominant activity in the Witbank Dam catchment with respect to pollution and degradation of water resources (DWA, 1993). This is evident in the deterioration of rivers as they transverse coal mining areas. The deterioration is due mainly to increase in sulphate concentration. Figure 3.1 shows an example of two locations along the Olifants River, upstream of Witbank Dam, with increases in sulphate concentration and the electrical conductivity (EC) as the river flows from Middelkraal to Wolvekrans between 1991 and 2002. The sulphate concentration and EC are higher at Wolvekrans, which is about 40 km downstream of Middelkraal because there are significant mining operations between Middelkraal and Wolvekrans (Figure 2.5). The formation of acid mine drainage from coal mining activities by the oxidation of sulphides minerals and the subsequent neutralization by base metals in rocks, lead to increases in sulphate concentration and EC, which may have been reflected in the quality of water in the streams into which the mine water has drained.

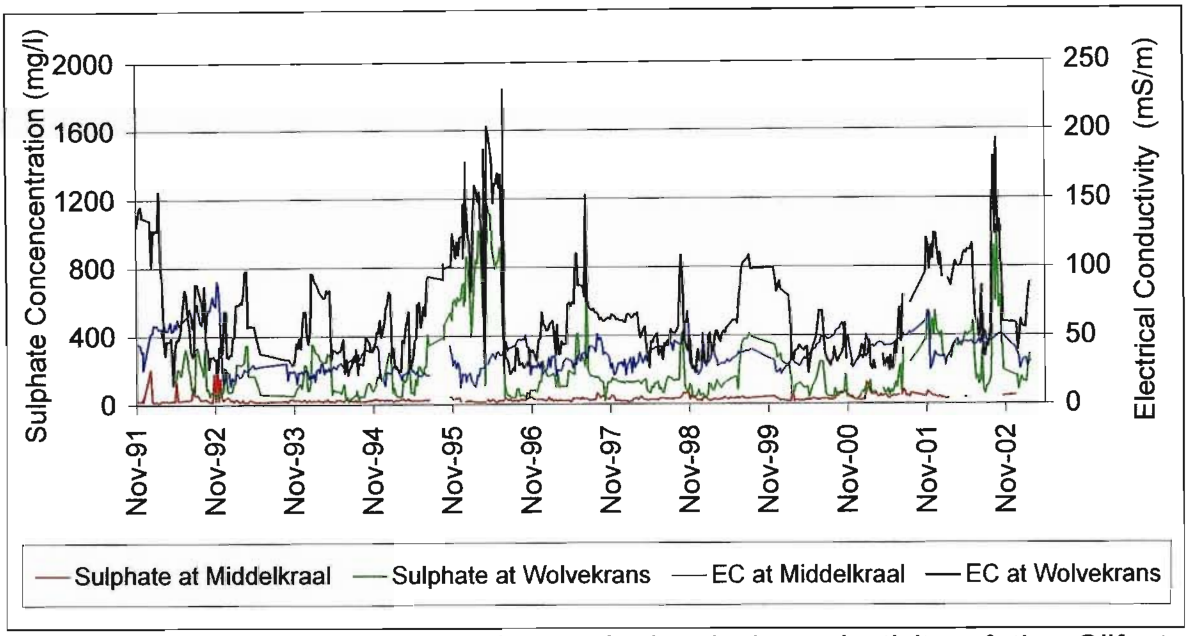


Figure 3.1: Sulphate concentration and electrical conductivity of the Olifants River at Middelkraal and Wolverans, 1991-2003 (Data Source, Department of Water Affairs and Forestry, 2003)

The sources of pollution from mining activities can be point or non-point sources. The United States Environmental Protection Agency (1997) describes a point source of pollution as a single identifiable source of pollution or a stationary location from which pollutants are discharged into a receiving water body, while a non-point source is described as a diffuse pollution source without a single point of origin. Typical point sources of mine water pollution are drains from adits and mine water discharges from pipes and ditches, while typical non-point sources of pollution from coal mines include runoff from waste piles, rehabilitated and unmined areas; atmospheric deposition; and seepage from mine waste ponds. The largest source of sulphate pollution associated with coal mining in the Witbank Dam catchment has been identified as being diffuse in origin (Department of Water Affairs and Forestry, 1993; Brown, 1997). It has been estimated that non-point sources associated with coal mining activities contribute 68% of the total sulphate load emanating from the catchment. Point sources of mining origin only contribute 2-3% of the total sulphate load entering Witbank Dam. In Table 3.1, the annual sulphate masses exported into Witbank Dam in terms of pollution sources, are given. Increased diffuse pollution as a result of many years of coal mining has resulted in a gradual decline in the water quality in the Witbank Dam. This trend is observable in Figure 3.2. The water quality in the dam has declined from less than 50 mg/l sulphate and 30 mS/m EC in 1979 to over 200 mg/l sulphate and 60 mS/m in 2003.

Table 3.1: Sulphate source loads exported to Witbank Dam (Department of Water Affairs and Forestry, 1993)

Sulphate Source	Annual Sulphate Load	
	Mass (tons SO_4/a)	Percentage
Natural weathering, atmospheric deposition and agriculture	2440.0	19.8
Municipal sewage treatment plants	387.0	3.1
Power station effluents	796.0	6.5
Coal Mining		
• Point sources	320.0	2.6
• Diffuse sources	8373.0	68.0
Total Catchment Export	12316.0	100.0

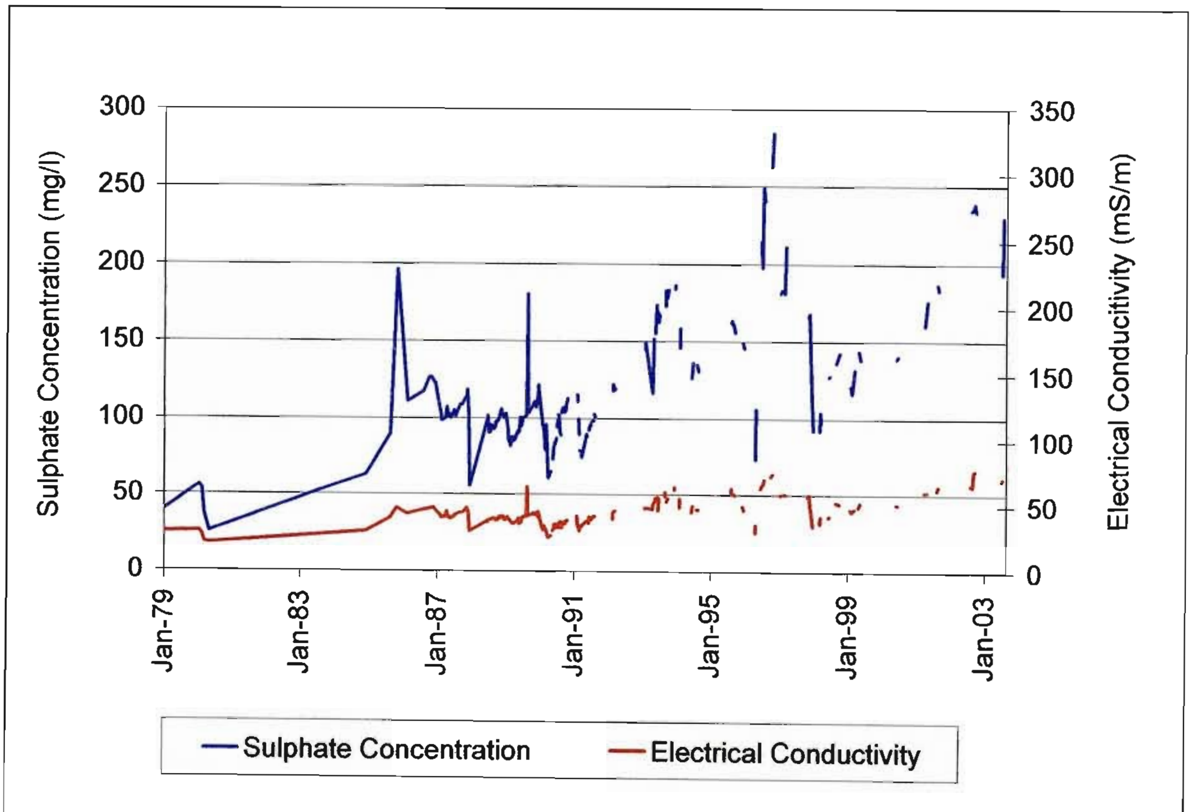


Figure 3.2: Sulphate concentration and electrical conductivity in Witbank Dam, 1979-2003 (Data Source, Department of Water Affairs and Forestry, 2003)

In the analysis of the future water quality scenarios carried out by Department of Water Affairs and Forestry (1993) on the Witbank Dam catchment, it was recognised that the future management of salinity in the catchment would require the control of mining related non-point sources of salinity and the control of the periodic point source discharges from the power stations. These two sources, historically, contributed an estimated 77% of the total catchment sulphate export (see Table 3.1). Consequently, the operation of the power stations as zero discharge facilities and a 45% reduction in the mining related non-point sources has been identified as the most attractive management approach to salinity control in the Witbank Dam catchment (Department of Water Affairs and Forestry, 1993). It was believed that the approach would arrest the steady increase in the salinity levels observed and enable the water quality to lie within the Target Water Quality Range (TWQR) of 0 – 200 mg/l set for sulphates in the South African Water Quality Guidelines for domestic water use (Department of Water Affairs and Forestry, 1996). In line with the choice of this approach, guidelines, based on Equations 3.1 and 3.2, were developed for sulphate waste load allocation to collieries. The guidelines incorporated the following allocation criteria: size of the mine, expressed in terms of tons of the Run Off Mine (ROM) annual production; age of the mine, expressed in terms of total ton of ROM produced and mining technology and which distinguishes between opencast mining and underground mining.

Underground collieries, $$WLA = x\,(P_{rd}) + y\,(H_{is}) \quad (3.1)$$

Opencast collieries, $$WLA = 1.4x\,(P_{rd}) + 1.4y\,(H_{is}) \quad (3.2)$$

where

WLA = sulphate waste load allocation to a specific colliery ($tonSO_4$/annum),

P_{rd} = colliery production (ton ROM/annum),

H_{is} = historical colliery production (ton ROM),

x = current production allocation factor ($tonSO_4$/tonROM), and

y = historical production allocation factor ($tonSO_4$/tonROM/annum).

The proposed sulphate waste allocation was also meant to curb a number of collieries that were discharging sulphate waste loads which were in excess of the proposed catchment guideline of 96 *gSO_4/ton* ROM and prevent periodic discharge of large volumes of saline water from mine dewatering operations (Department of Water Affairs and Forestry,1993).

Considering the potential mining activities have in the pollution of water resources, a tool that is capable of periodically assessing the water resources of mines in an integrated manner, taking all the components of the hydrological cycle and the South African environment into consideration, is necessary. This type of tool is presently not available. The modifications to the *ACRU2000* model and the *ACRUSalinity* module in this study, although they are focussed on assessing the impact of using gypsiferous mine water for irrigation, they take the nature of water resources occurrence and pollution in the coal mining environment in South Africa into consideration, and will therefore enable the applicable of the model in the integrated assessment of the water resources in coal mines.

3.2 Mine Water Management

Different types of techniques have been developed for the management of water in coal (and other metal) mines. The management practices are usually directed at abatement or control of acid mine drainage (AMD). Considering the inherent variability between mines and the environmental conditions in which they are located, some water management techniques that are effective in some situations may not be effective in others. Therefore, selection and employment of the appropriate technique is very important in the effective management of water in mines. Skousen *et al.* (1998) have grouped the technologies available to abate and control the pollution of AMD in mines into four:

- Overburden/refuse reclamation techniques,
- Engineered structural techniques,
- Active treatments technique, and
- Passive system techniques.

Overburden/refuse reclamation techniques often have a number of elements which may include selective handling of the acid-producing materials, the addition of alkaline materials which serve to either neutralize the acid generated or retard the oxidation of pyrite, encapsulation of the acid-producing material, removal of toxic material by re-mining or reprocessing, and inhibition of pyrite oxidation by bactericides through the incorporation of sewage sludge or by inundation of the acid-producing materials. In South Africa, spoil heaps and mine dumps are typically rehabilitated by coverage with soil and vegetation (Ward, 1984). Because of the prevalence of this practice in South Africa, a review on the rehabilitation of mine soils is presented in another section (Section 3.5) of this chapter.

Engineered structural techniques involve the channelling of surface waters or mine waters in order to control volume, direction and contact time with spoils and thereby minimize generation of acid mine drainage. The fundamental principle is usually to keep clean and dirty water separated. This technique also includes the construction of impoundments to store mine water from where it can then be reused, treated or disposed off as evaporated water. Clean water diversion, separation of clean and dirty water and the collection of mine water in pollution control dams are practices carried out by several mines in South Africa (Pulles *et al.*, 1995).

Active treatment techniques involve treating mine drainage with alkaline chemicals to raise water pH, neutralize acidity and precipitate metals. Although effective, active treatment is expensive when the cost of equipment, chemicals, and manpower are considered (Skousen *et al.*, 1990). Liming of acid leachates in a treatment plant is conducted in a number of instances in South Africa. In contrast to active treatment techniques, passive system techniques do not require continuous chemical inputs and they take advantage of naturally occurring chemical and biological processes to cleanse contaminated mine waters. They are efficient and require minimum inputs, low investment costs as well as low operating costs (Woulds and Ngwenya, 2004; Sheoran and Sheoran, 2006). The primary passive technologies include constructed wetlands, anoxic limestone drains (ALD), vertical flow systems such as successive alkalinity producing systems (SAPS), limestone ponds, and open limestone channels (OLC). Passive treatment in the South African mining industry appeared to be an unexplored area as no literature was found on it. This may be because the technology of passive treatment for mine water is relatively new. However, considering the low cost of passive systems in addition to minimum supervision and operational requirements, the technique may find relevance in mine water management in South Africa. Remediation of mine water discharges has been achieved using passive treatment technology in different parts of the world, including United States of America, Canada, Germany and Scotland (Kalin *et al.*, 2005). At Blairingone, in Fife, Scotland, the closure of an opencast mine was followed by the emergence of a highly ferruginous discharge (≤ 118 mg/l total Fe) from an adit. The discharge caused highly visible staining of the bed of the River Devon for a distance of 2 km downstream of the adit. Following the diversion of the adit discharge into a natural aerobic wetland prior to the final outflow to the River Devon, the final discharge to the river had 2 mg/l or less of total iron, so that the river was no longer stained at all (Younger, 2001).

The controlled releases of mine water during flood conditions and use of mine water for irrigation are two other mine water management strategies that have been under consideration for some time now in South Africa. They are discussed in following two sections (Sections 3.3 and 3.4). For their implementation to be successful however, adequate tools for the assessment of their impact on water resources are imperative. It is within this context that this study finds its relevance.

3.3 Controlled Release of Saline Water during Flood Conditions

The release of saline mine water into river systems when assimilative capacity is available has been recognised as an attractive option in mine water management in South Africa, as the costs of release are generally lower than that of treatment (Coleman *et al.*, 2003). However, in accordance with the Department of Water Affairs and Forestry's hierarchy of water management, the release of polluted water into the river system can only be considered after source controls, waste minimization, recycling and treatment have been implemented. Any water containing waste left after the hierarchy has been considered can be released to the receiving water body under set rules and controlled conditions. The release can be in the form of a constant release as a sewage treatment plant discharge, or can be managed to coincide with periods of high flows in the receiving water when assimilative capacity, usually determined based on acceptable water quality concentrations, is present.

The feasibility of controlled discharge of excess mine water during periods of high flows was first investigated in the Witbank Dam catchment as a result of the water management problems associated with the wet 1995/1996 hydrological year in the Upper Olifants catchment (Coleman *et al.*, 2003). The 1995/1996 hydrological year was the wettest of a 70-year record and the runoff from the Witbank Dam catchment was estimated to be 6 to 7 times the historical Mean Annual Runoff. Uncontrolled releases of excess mine water, decant and seepage during the wet hydrological year resulted into a deterioration in the water quality of the Witbank Dam. The sulphate concentration increased from approximately 80 $mgSO_4/l$ to 319 $mgSO_4/l$ from April to September 1996. That was the highest level of salinity ever recorded in the Dam. The feasibility investigation indicated that assimilative capacity would be available during average and above average runoff flows as large dilution capacity exists during flood events. The controlled release of mine water during flood events is therefore a water management option to mines, which can complement other management efforts, such as improved rehabilitation of mine-disturbed land, treatment of mine water and recycling, and re-use of water. A further advantage of synchronising the releases of mine water with high flood conditions, apart from alleviating excess water accumulation and deterioration on the mines is that the released water can become a supplementary water resource without necessarily having a negative effect on quality. The controlled release of mine water is not a well developed practice in the water resources field in South Africa. A trial project, successfully undertaken in the Witbank Dam catchment in 1996/97, has been modified and extended to include the Middelburg Dam catchment (Coleman *et al.*, 2003).

3.4 Use of Gypsiferous Mine Water for Irrigation

Gypsiferous mine water is generated by the mining of coal, as well as in other closed underground workings, through the formation of sulphuric acid resulting from the exposure of sulphide minerals (commonly pyrite, FeS_2) to oxidizing conditions and water. Ivarson *et al.* (1978) describe three main reactions involved in the production of sulphuric acid from pyrite, namely:

$$2FeS_2 + 7O_2 + H_2O \rightarrow 2FeSO_4 + 2H_2SO_4 \quad (3.3)$$

$$4FeSO_4 + 2H_2SO_4 + O_2 \rightarrow 2Fe_2\,(SO4)_3 + 2H_2O \quad (3.4)$$

$$3Fe_2\,(SO4)_3 + 12H_2O \rightarrow 2HFe_3\,(SO_4)_2(OH)_6 + 5H_2SO_4 \quad (3.5)$$

Equations 3.3 and 3.5 represent chemical reactions, while Equation 3.4 is a result of bacteriological action. In addition, whereas Equations 3.3 and 3.4 are oxidation reactions, Equation 3.5 is anaerobic. Consequently, exclusion of oxygen in Equations 3.3 and 3.4, or the elimination of bacteria (*Thiobacillus ferrooxidants*) in Equation 3.5, will limit the formation of acid (Thompson, 1980). Natural neutralization of the sulphuric acid, generated by the reactions represented in the equations above, may occur by its reaction with base metals found in rocks. However, where natural neutralization is inadequate, the water may remain highly acidic, making artificial neutralization using calcium carbonate ($CaCO_3$), calcium oxide (CaO) or calcium hydroxide ($Ca\,(OH)_2$) necessary. The reaction with acid solution, using $CaCO_3$, is given in Equations 3.6 and 3.7 (Rose *et al.*, 1998):

$$CaCO_3 + 2H+ \rightarrow Ca^{2+} + H_2CO_3 \quad (3.6)$$

$$H_2CO_3 \rightarrow CO_2 + H_2O \quad (3.7)$$

The consequence of neutralization is the precipitation of $CaSO_4$ and the making of the liquid effluent pH-neutral, saline and gypsiferous, with an electrical conductivity (EC) typically in the range of 130 to 290 mS/m, due mainly to high concentration of Ca^{2+} and SO_4^{2-} (Jovanovic *et al.*, 2001). Significant heavy metals concentrations are not associated with gypsiferous mine water due to the neutral pH of the water.

The shortage of water resources of good quality is becoming an important issue in the arid and semi-arid zones, for which reason, availability of water resources of marginal quality such as drainage water, saline groundwater and treated wastewater have become an important consideration (Beltran, 1999). South Africa is predominantly semi-arid, with 65% of the country receiving less than 500 mm of rain annually and the average annual potential evaporation over most parts of the country ranging from 1 100 mm to more than 3 000 mm (DWA, 1986; NWRS, 2002). The abundance of large quantities of low quality mine water from the coal mining industry in South Africa therefore offers the possibility of making water available for farming activities in suitable areas, especially during the periods of low or no rainfall. The use of poor quality waters for irrigation has been observed to require three changes from standard irrigation practices (Oster, 1994):

- Selection of appropriate salt-tolerant crops;
- Improvements in water management and, in some cases, the adoption of advanced irrigation technology; and
- Maintenance of soil-physical properties to assure soil tilth and adequate soil permeability to meet crop water and leaching requirements.

Four major environmental hazards can be associated with the use of saline water for irrigation (Rhoades *et al.*, 1992). They are:

- Loss in soil productivity due to salinity and water logging,
- Pollution of associated water resources with salts and toxicants by drainage,
- Damage to the associated ecosystems, and
- Increased risk to public health resulting from water pollution and water logging.

The potential use of the gypsiferous mine water for crop irrigation was first evaluated in South Africa by Du Plessis (1983) with results indicating limited effects on soil physical properties and crop yield. Barnard *et al.* (1998) carried out a feasibility study on the use of mine water for irrigation of a wide range of crop and pasture species over a period of three years at Landau Colliery, Kromdraai Opencast section, near Witbank. They concluded that use of mine water for irrigation of crops would present no soil salinity or crop production problems within the relatively short period of 3 years if careful fertilization management was carried out. Annandale *et al.* (1999) have carried out a long term simulation of irrigation with gypsiferous mine water, using data from a field trial carried out at Landau Colliery, Kromdraai Opencast section. The simulation was for a period of 30 years of irrigation with gypsiferous water on sandy soil with pearl-oats rotation, followed by 20 years of dry summer cropping. It was found that a substantial volume of mine water can be used and significant masses of salt disposed off through high frequency irrigation of crops throughout the year. The soil appeared to act as an effective salt sink with large quantities of calcium sulphate precipitated over the 30 years and negligible amounts of remobilization thereafter. Similar results were obtained in a field trial established at Kleinkopje Colliery in Witbank with a part objective of determining the impact of irrigation with mine water on virgin and rehabilitated soils (Annandale *et al.*, 2001; Jovanovic *et al.*, 2002). From the results, irrigation with gypsiferous mine water was not expected to cause any unacceptable salinity build-up in the soil and crop yields were generally satisfactory, although yield on rehabilitated soil was low in comparison with that on virgin soil, probably due to soil compaction, late planting date and hail damage. Water logging in certain areas of the fields indicated that rehabilitated land especially, should be properly prepared and, where necessary, water-ways be built to prevent yield loss. The groundwater impact was limited, indicating the presence of a buffer zone or low permeability materials between the cropped profile and groundwater.

All the previous studies to date have focussed on field scale impacts. Considering the reported high potential of mine wastewater for irrigation of agricultural crops from the field studies, it is necessary that the impacts of large-scale irrigation with mine water on both surface water and groundwater resources, which may result from widespread application of mine wastewater, be assessed. Such an assessment could make impact predictable and enable design of adequate policies and structures that can guarantee more effective planning and management of water resources. In a recent study, Annandale *et al.* (2006) evaluated the potential impact of irrigation with a large amount of mine water on the groundwater of sub-areas west of Witbank, using the numerical modelling package FEFLOW (Diersch, 1988), with the results from field scale studies as inputs. However, effective water resources assessment and management, are best considered at catchment scales (Global Water Partnership, 2000), taking into consideration the land uses and all the essential components of the hydrological cycle. Such a consideration not only enables an integrated assessment of water resources in the different components of a hydrological system, but also facilitates a broader planning and management programme with a wider context (which includes downstream stakeholders) than impacts at field and farm scales, or on a single component of the hydrologic cycle. To assess widespread irrigation with mine water, a catchment approach has therefore been adopted in this study to areas which form part of the Upper Olifants basin, in the Mpumalanga coalfields. The approach enables the development and application of a tool that could be used not only for a catchment scale assessment of the impact of irrigation with mine water, but also for an integrated assessment of the water resources in a colliery, as well scenario studies in the usage and management of mine water resources.

3.5 Rehabilitated Mine Soils

The ways in which mine soils are commonly rehabilitated in South Africa have been described by Schoeman *et al.* (2002). Coal stripping involves the complete removal of overburden above the coal in adjacent strips approximately 40 m wide. Following removal of the coal by a dragline, the material from the adjacent strip (a mixture of shattered rock and soft overburden) is dumped into the void and graded to form the new surface topography (Figure 3.3).

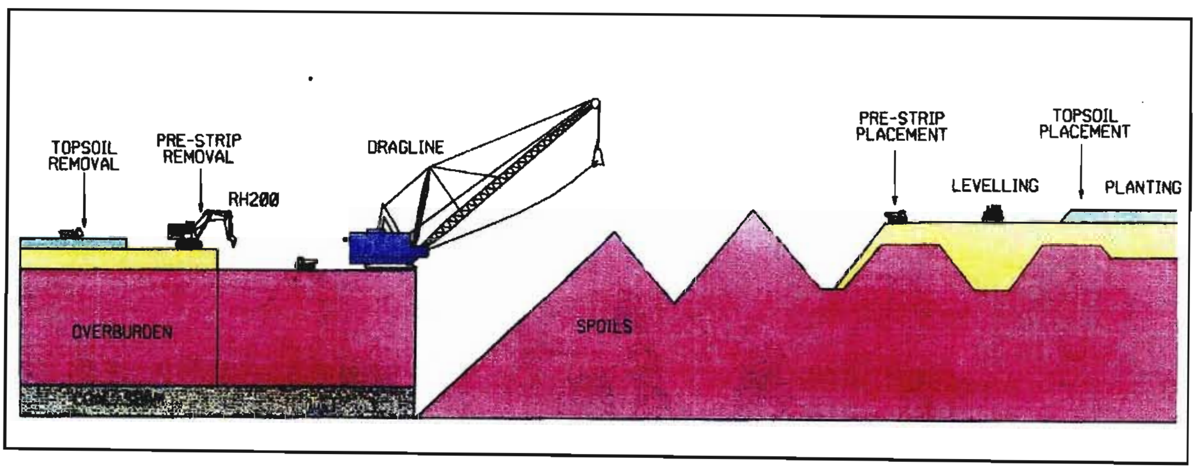


Figure 3.3: Diagrammatic representation of opencast mining operation (EMPR, 1994)

Usable soil materials stripped ahead of the mining are then replaced on the new surface with trucks or bowlscrapers. Because of the large soil volumes involved, heavy machines are required and these exert a considerable compactive force on the soil over which they travel. Various soil amelioration and re-vegetation operations then follow on the re-established land surface to complete the rehabilitation process. Soil profile reconstruction during the reclamation of mine waste dumps and establishment of vegetative covers are well-recognized rehabilitation practices and targets of the modern mining industry (Kopittke *et al.*, 2004). The end product of the rehabilitated land displays a high degree of random variability (De Villiers, 1992) and differs from normal agricultural soils in that the upper layer usually has a lower organic matter while the deeper layers have a higher total organic matter (Tanner, 1993). Characteristically, therefore, rehabilitated mine soils are binary as regards their provenance, and consist of an upper part that is mainly soil-like (cover soil) and a lower part that is mainly clastic (spoil) (Tanner, 1993).

Several previous studies in Mpumalanga with regard to the productivity of mine soils, cover soil depth and compaction, profile development, classification and characterization, are documented in Schoeman *et al.* (2002). In a study of soil formation in spoil material between 1 and 18 years, Viljoen (1992) observes that dense layers appear to become less obvious over time and that coarse fragments in the upper spoil appear to weather rather rapidly. The clay content of the upper spoil and signs of wetness increase over time, particularly in low-lying landscape positions. Little evidence of pedogenetic re-organization in profiles that were ten or more years old has been noted, although dark, fissile shales in particular, appear to soften and disintegrate quite rapidly (De Villiers, 1992). The soil/spoil interface has been observed to present a barrier to roots in some profiles, but not in others (Tanner, 1993). The ability of roots to penetrate into spoils was related to the depth of the cover soil and it was found probable that compaction was the major cause of the differences observed.

The availability of rehabilitated soils in the mining environment where a large amount of low quality mine water is also available, could make such soils targets for irrigated agriculture using the available low quality mine water. Considering that rehabilitated soils are different from normal agricultural soils, it is necessary that the impact such irrigated agriculture may have on the local and regional water resources is assessed.

3.6 Water in Underground Collieries

Coal mining in South Africa takes place both on the surface and underground. Underground mining takes place when the coal seams are too deep for economical removal of the overburden and subsequent extraction of the coal. The average depth of underground mining in South Africa has been reported to be 80 m (Lloyd, 2002). However, underground coal mining in South Africa can be classified as shallow or deep (Hodgson and Krantz, 1998). Whereas shallow underground mining mines into the weathered aquifer, deep underground mining does not. In Mpumalanga Province, the underground mines are located below the aquifers (Hodgson *et al.*, 2001; Lloyd, 2002). Literature is replete with the effects of underground mining on both the local aquifers and the environment in general (Lloyd, 2002; Hodgson *et al.*, 1985; Bell *et al.*, 2001; Heath, *et al.*, 2004, Donovan *et al.*, 2000). The effects include fracturing and collapse of the overburden above the mined coal, land surface subsidence, influx of groundwater from overlying strata and deterioration of water quality. The severity of the effects depends on whether the mine is working or abandoned, the mining methods used and the geological conditions. Of particular importance, however, are the rate of groundwater influx into underground mines and the short- and long-term water quality evolution of underground mine water and its drainage. Significant and sustained influx may deplete the groundwater in the surrounding aquifers and yields to boreholes. The rate of flooding of underground mines has been found to determine the quality of water in the mines (Donovan *et al*, 2003; Lambert *et al.*, 2004). The understanding of the water quality evolution in underground mines allows an estimate of the longevity of acid discharge which will aid adequate and rational planning for the remediation of mine water pollution and the short- and long-term costs of treatment (Younger, 1997; Demchark *et al.*, 2002). In the UK, one of the regulatory issues regarding closure of underground mines is the amount and quality of long-term discharge of water after they have fully flooded.

The rate of groundwater influx into areas of underground extraction has been shown to be controlled by three main factors (Hodgson *et al.*, 1985):

- transmissivity (which is a function of the hydraulic conductivity and the thickness),
- storage coefficient or specific yield, and
- the degree of fracturing of the overlying rocks.

The effect of a change in storage coefficient value is not as drastic as that of a change in transmissivity value. The prediction of the size and shape of cracks above underground mined out areas is difficult, if not impossible, which in turn is a major handicap to calculating the rate of influx into mines. Following the cessation of dewatering, which is usually after mine abandonment, influx of water leads to a gradual flooding of the mined voids and the adjoining strata until groundwater achieves a new equilibrium, either by surface discharge of mine water, in which case, the surface discharges balance the rate of rainfall recharge or by controlled pumping and treatment (Hodgson *et al.*, 1985).

It has been widely observed that the quality of groundwater sampled during and after complete flooding of an underground mine may be far poorer than that encountered during mining (Cairney and Frost, 1975; Hodgson *et al.*, 1985; Younger, 2000). The deterioration in water quality is attributable mainly to acid formation as a result of chemical and bacterial oxidation of pyrite (FeS_2) and other sulphide minerals that may be present in the overlying strata, coal-seams and worked mine. The oxidation of pyrite has been described in Section 3. 4 and the controlling equations presented in Equations 3.3 - 3.5. As the underground mine gets flooded, the water level in the mine rises and the contaminant loading increases as more and more pyrite is oxidised and base exchange occurs, until a peak contaminant loading is reached when the mine is fully flooded. The process of water table rise as the mine voids gradually flood is commonly referred to as 'water table rebound' or 'groundwater rebound' (Younger, 1997). Once a mine void begins to overflow, a gradual process of flushing occurs, resulting in a general decrease in contaminant concentrations over time (Younger, 1997; Donovan *et al.*, 2000; Younger, 2002; Lambert *et al.*, 2004). The reason for this is that pyrite oxidation in the absence of dissolved oxygen can occur only where alternative strong oxidants (e.g. nitrate and ferric ions) are present in large concentrations, which is unlikely to be the case at depth in flooded mined systems. In mined-out areas where mine discharge water quality has been observed to improve after flooding, an important common factor has been the absence of atmospheric oxygen in the system (Wood *et al.*, 1999; Lambert *et al.*, 2004). Flooding of mines serves to limit the oxygen supply, and thus to control the dissolution of pyrite. It also removes the readily soluble ferrous/ferric hydroxyl-sulphate salts accumulated on the walls of the mine voids. However, where the water table lies near the ground surface in flooded workings, substantial acidity can be generated seasonally (Younger, 1997) by:

- Pyrite oxidation in the unsaturated zone, forming iron hydroxysulphate solids:

$$3FeS_2 + 11.5O_2 + 15H_2O \rightarrow Fe^{(2+)} Fe^{(3+)} (SO_4)_4.14H_2O + 2SO_4^{2-} + 2H^+ \qquad (3.8)$$

  where FeS_2 is solid pyrite, O_2 is dissolved or gaseous oxygen, H_2O is liquid water or atmospheric humidity, $Fe^{(2+)} Fe^{(3+)} (SO_4)_4.14H_2O$ is a hydroxysulphate solid called romerite, SO_4^{2-} is dissolved sulphate and H^+ represents hyrdomium ions (proton acidity) (Younger, 2000);
- Dissolution of the hydrosulphates when the water table rises; and
- Renewed pyrite oxidation on 'clean' mineral surfaces in the unsaturated zone (after the water table falls again)

Based on the above description, Younger (1997) explains that it is theoretically possible for flooded workings to continue generating acidic drainage for many decades, if not centuries. He also distinguishes between 'vestigial acidity' and 'juvenile acidity'. Vestigial acidity arises from pyrite oxidation products that were flushed into solution during regional water table rebound, leading to highly polluted 'first flush', while juvenile acidity arises primarily from pyrite oxidation during seasonal water table fluctuations. The reduction in mine water salt load after flooding has been ascribed to reflect the diminution of vestigial acidity by flushing. The decline does not usually result in good quality water flowing from the mine, but rather an asymptotic level of contamination is approached, which may persist for decades (and possibly centuries). For example, Figure 3.4 shows a comparison of two below drainage mines in the same area in NW West Virginia in the USA (Donovan, 2000). Even though Fe and acidity are substantially different between the two otherwise similar mines, discharge monitoring of the two mines over a period of 12 -15 years after flooding reveals the tendency towards virtually identical acidities and iron concentrations. The observation suggests that there may be a long-term near equilibrium state with respect to chemistry of the discharge from the mines.

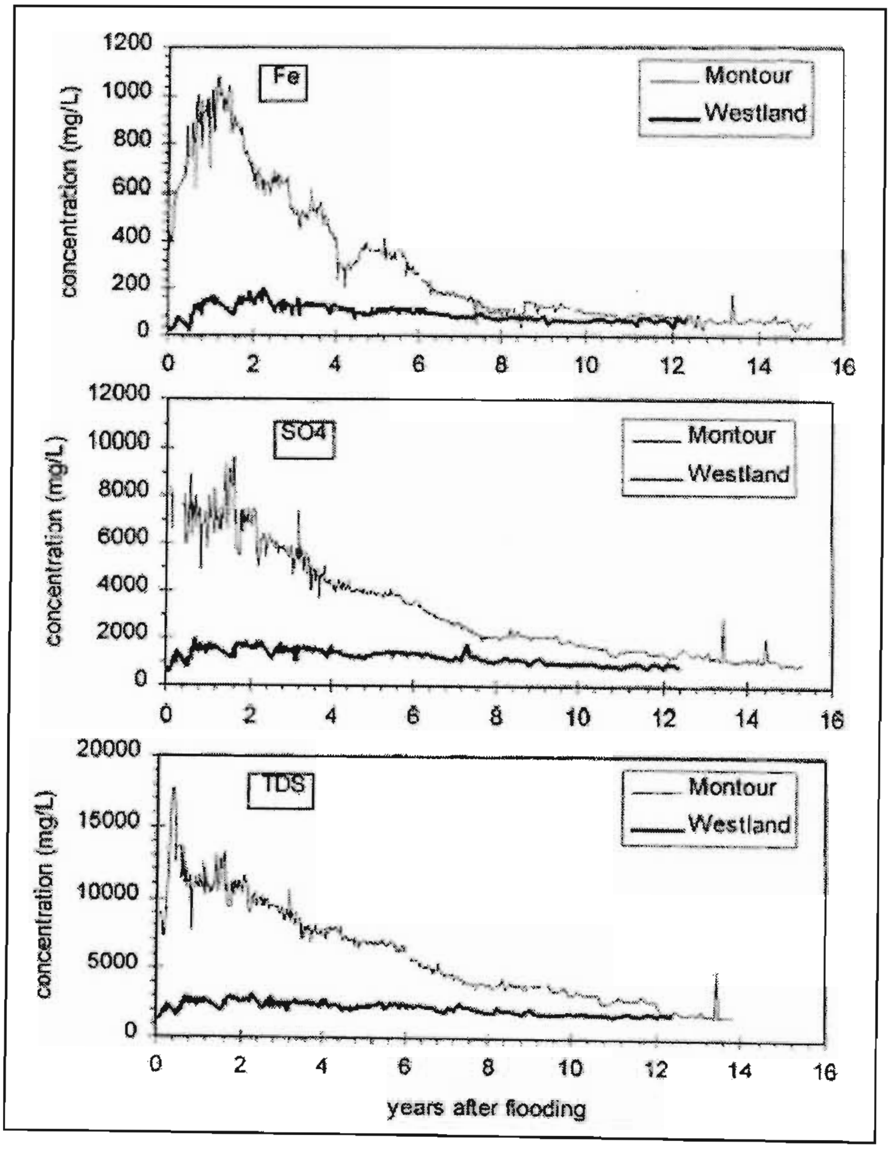


Figure 3.4: Comparison of post-flooding chemistries between Westland and Montour mines in West Virginia, USA: (top) Fe, (middle) SO_4, (bottom) TDS

3.7 Surface Water – Groundwater Interactions

The impact of the use of mine water for irrigation of agricultural crops on the water resources of an area will be highly dependent on the nature of the interaction between surface water and subsurface water, with rainfall, irrigation water, water in streams and reservoirs constituting the surface water and the water generally found in transit in the vadose zone above the water table and the water found in aquifers below the water table constituting the subsurface water. Kelbe and Germishuyse (2000) identify the main hydrological processes involved in the interaction between surface water and groundwater as rainfall, infiltration, percolation, evaporation, transpiration, runoff and deep seepage. The processes can be prudently represented and conveniently understood in terms of groundwater recharge and discharge (Figure 3.5).

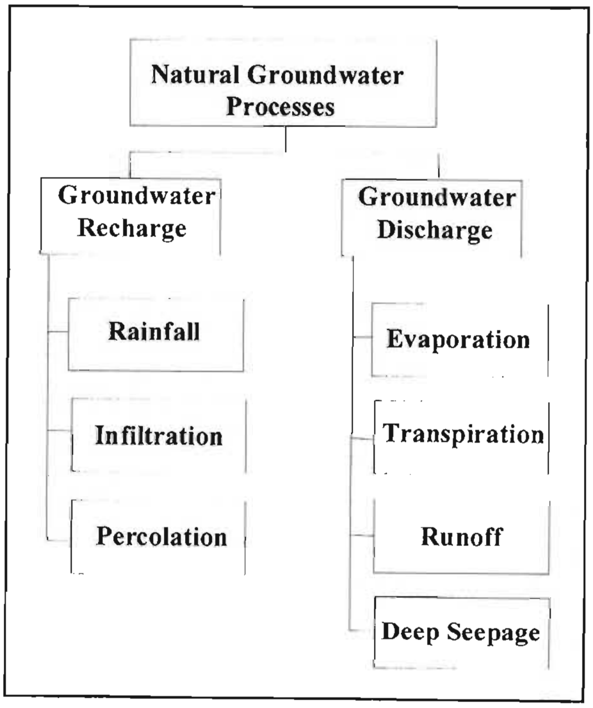


Figure 3.5: The principal processes involved in surface water and groundwater interactions (after Kelbe and Germishuyse, 2000)

Surface water-groundwater interactions with respect to groundwater recharge and discharge occur at local, intermediate and regional scales (Brunke and Gonser, 1997; Lorentz *et al.*, 2003). Local upwelling (groundwater discharge) and downwelling (groundwater recharge) processes tend to be determined more by geomorphological features such as discontinuities in slope and depth, riffle-pool sequences and changes in the direction of flow, than by geological properties, whereas large-scale processes are determined more by geological properties of the catchment. Groundwater in local flow system flows to a nearby discharge area, whereas in a regional flow system, water travels a greater distance than the local flow system and often discharges to major rivers, large lakes or oceans. An intermediate flow system is characterised by one or more topographic highs and lows located between its recharge and discharge areas, but, unlike the regional flow system, does not occupy both the major topographic high and the bottom of the basin. Areas of pronounced topographic relief tend to have dominant local flow systems and areas of nearly flat relief tend to have dominant intermediate and regional flow systems. In describing variations in groundwater recharge patterns in subterranean systems however, the physical characteristics of the hydrological systems are classified by Kelbe and Germishuyse (2000) into the following four conceptual landscapes depicting extremes of hydro-geological features:

1. Vertical flow system in a homogenous, uniform, porous media;
2. Vertical and lateral flow system in a heterogeneous, non-uniform, porous medium;
3. Complex interaction of matrix and fractured recharge systems distinguishable from the fractured and porous (matrix) systems; and
4. Thin soil mantle overlying fracture rock recharge zone above regional groundwater system.

In Class 1uniform recharge, the flow path is dominantly vertical along the line of least resistance through the soil matrix in the unsaturated zone, while lateral flow occurs in the saturated zone. This line of least resistance may be expected to have a lateral orientation and hence initiate lateral flow at times, but it is not likely to be significant enough to constitute pronounced or prolonged interflow to a stream discharge.

In Class 2 non-uniform recharge, unlike that in Class 1, lateral flow that reaches a discharge point may occur in the unsaturated zone because of the heterogeneity of the hydraulic characteristics of the system, which encourages variable zones of moisture content that may lead to localised zones of saturation and flows in a lateral direction. Heterogeneity in regards to preferential flow of water through macropores or a rapid conducting material can also be included here. Lorentz (2001) has reported this phenomenon for the Weatherly catchment in the northeast of the Eastern Cape Province of South Africa, where lateral flow in the soil profile above the deeper groundwater table contributed to rapid runoff through macropore conductance during intense or large volume events, with little or no influence on the deeper groundwater. This is what Beven (1989), cited by Sophocleous (2002) and Newman *et. al.* (1998), have defined as interflow and lateral subsurface stormflow respectively and what Dunne and Black (1970) have indicated can grade into return flow by which subsurface water can contribute to overland flow. Preferential subsurface flow paths, such as paleo-channels, can also extend direct connections between rivers and groundwater in the subterranean landscape (Sophocleous, 1991).

In Class 3 complex recharge processes, both vertical and lateral flows are involved in a case in which a perched intermediate recharge zone in the unsaturated layer impact on the interactive mechanisms for recharging the underlying fractured aquifer.

Unlike the case of Class 3, no perched condition occurs in Class 4, as flow has vertical and horizontal paths in the unsaturated zone that are linked directly with the underlying fractured aquifer. Classes 3 and 4 are important in South Africa in view of the fact that in over 90% of the land surface of South Africa, groundwater occurs in secondary aquifers where fractures and dissolution channels predominate (Vegter, 2001). At catchment scale, it is conceivable that responses may be dominated by a single mechanism out of the four or by a combination of mechanisms, depending on the magnitude of rainfall event, the antecedent soil-moisture conditions of the catchment, heterogeneity in soil hydraulic properties and geology.

In comparison to recharge, groundwater discharge in the four conceptual landscapes occurs through processes that are controlled by the laws of gravity and surface tension, entailing capillary rise in the vadose zone, evapotransipration, lateral outflow through a surface boundary and direct abstraction (Sophocleous, 2002). With specific reference to streams (surface water), groundwater recharge and discharge occur respectively, through seepage from streams into aquifers and flow of groundwater into the streams respectively. The interactions can be placed into three basic categories (Figure 3.6):

- the surface water body gaining water from inflow of groundwater (effluent),
- the surface water body losing water to groundwater by outflow (influent), or
- the surface water body disconnected from the groundwater system (perched).

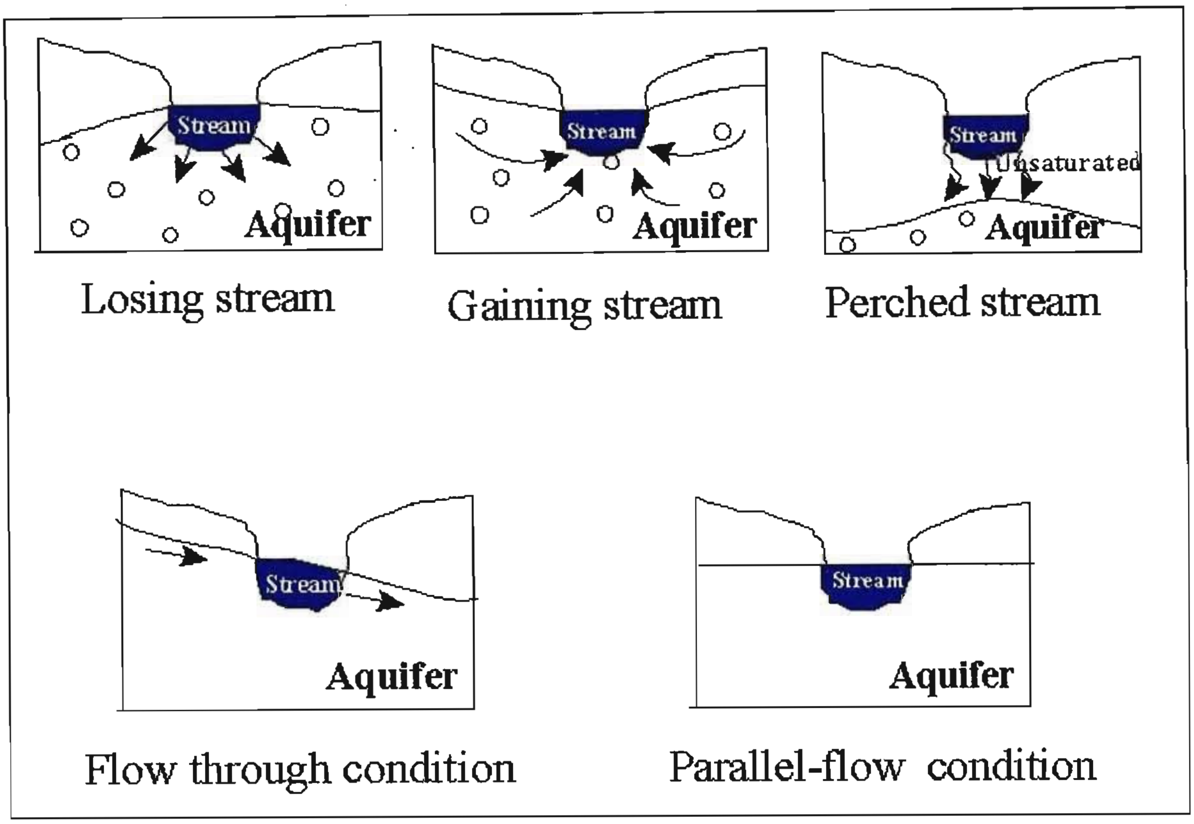


Figure 3.6: Classes of streams with respect to interaction with groundwater

Two other classes can be included with the three basic classes above (Woessner, 2000), *viz*. flow-through and parallel-flow. A flow–through condition occurs when the channel stage is less than the groundwater head on one bank and is greater than the head at the opposite bank, such that the surface water is gaining on one bank and losing on the other. A parallel-flow condition occurs when the channel stage and groundwater level head are equal. It is possible for the flow direction to vary along a stream, with some reaches receiving groundwater and other reaches losing water to groundwater. Furthermore, flow direction can change in very short time frames as a result of individual storms causing focused recharge near the stream-bank, temporary flood peaks moving down the channel, transpiration of groundwater by streamside vegetation or groundwater pumping (Winter *et al.*, 2002). Woessner (2000) and Sophocleous (2002) have indicated that the hydrologic exchange of groundwater and rivers in a landscape is controlled by

- the distribution and magnitude of hydraulic conductivities within the channel and the associated aquifer and in the vadose zone overlying the aquifer,
- the relation of stream stage to the adjacent groundwater level, and
- geomorphology, especially in terms of the geometry and position of the stream channel within the alluvial plain.

The ultimate need for the understanding of surface water – groundwater interactions is in the area of effective water resources management (Winter, 1995; Bouwer and Maddock III, 1997; Woessner, 2002; Winter, 2002). It has been acknowledged that effective water resources management is best logically considered with the catchments as planning units (Global Water Partnership, 2000) and Morrice *et. al.*, (1997) has demonstrated the need for comparison of catchment scale perspectives of surface water - groundwater linkage in order to establish catchment scale differences. Therefore, assessments of surface water-groundwater interactions should be tailored along eventual considerations and understanding at basin-wide or catchment scales. In mining environments, for example, the understanding of surface water – groundwater interactions is important and must be considered when addressing the mine water and salt balances. Catchment scale assessments may require investigations at local scales for the necessary data collection required for adequate understanding of the interactions and the necessary tools for extrapolating results from local to basin-wide or catchment scales. In this regard, Sophocleous (2002) states that the choice of appropriate temporal and spatial scales for conducting such investigations is critical, because the particular site and time of the year in which experiments are performed are likely to dramatically influence results.

3.8 Mine Water and Salt Balances

Water and salt balances have been recognized as powerful tools in the assessment and management of water in mines (Pulles *et al.*, 1996). The reason for this is that, if done properly, water and salt balances can indicate where the mine's water losses and pollution sources are and thereby facilitate the development of the appropriate management strategies to address the indicated sources. Not only can water and salt balances indicate the contributions to pollution from diffuse sources, but they can also be used to test what-if scenarios with the mine water systems and thereby enable the assessment of effects of different conditions and options with one, two or more circuits on the mine in general. In order to be useful, however, a water balance must take into account all in- and outflows from the mine's various water circuits and ascribe accurate flow rates to each of them (Pulles *et al.*, 1996). In addition to the requirement of an accurate water balance for the salt balance computations, the total salt concentrations for each of the major routes in the circuit must be accurately known.

For the coal mining industry in South Africa, Pulles *et al.* (2001) constructed a generic water balance to reflect the industry-wide patterns with regard to water sources, usage and disposal based on a 4-stage process shown Figure 3.7.

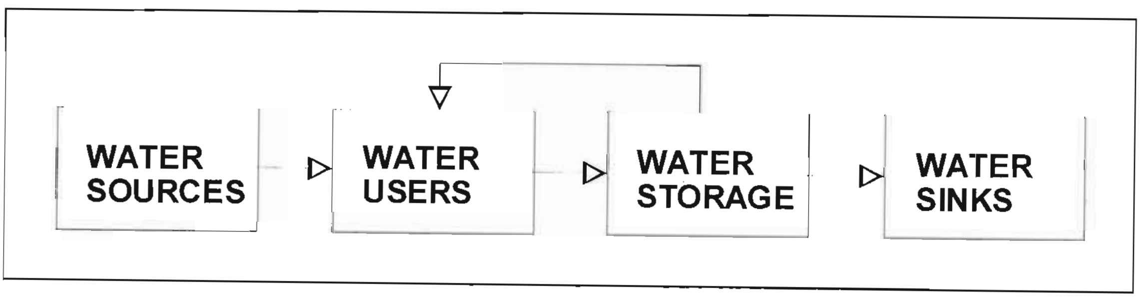


Figure 3.7: Four-stage process involved in water and salt balances in the coal mining industry in South Africa (after Pulles *et al.*, 2001)

The water sources include rainfall, groundwater, river water and local supply board water, while the water uses include such uses as for domestic, road wetting, beneficiation, mine workings, irrigation, the slurry dam, potable water and sewage treatment. Water storage can be for potable water, treated water and dirty water, which may include water pumped from mine workings, plant process water, slurry dam return water and contaminated storm water. Water sinks include discharge to rivers, total evaporation, surface water on coal product and coarse discard and human consumption. A similar generic water balance model is that developed for opencast mine water systems by van Niekerk (1997). The model was designed to simulate, predict and understand the water flow and water quality aspects of a single, selected opencast pit. It therefore concentrates on the pit and does not integrate the pit water system with the total mine water complex.

3.9 Electrical Resistivity Survey

Electrical resistivity survey is a geophysical exploration method used for determining the subsurface resistivity (i.e. the reciprocal of conductivity) distribution associated with the geohydrology of a site and potentially the distribution of contaminants (Sharma, 1986; Loke, 2000). Resistivities of rock formations vary over a wide range, depending on material constituents of the rock, density, porosity, pore size and shape, water content and quality, and temperature (Lewis, 2003; Samuoëlian *et al.*, 2005). Therefore, there is no general correlation of lithology with resistivity and calibration of results with control borehole lithologic log may be essential. Nevertheless, a broad classification is possible according to which clays and marls, sands and gravels, limestones and crystalline rocks stand in order of increasing resistivity (Sharma, 1986; Loke 2000).

Resistivity measurements are traditionally made by injecting electrical current into the ground through two current electrodes (Cl and C2 in Figure 3.11) and measuring the resulting voltage difference at another two potential electrodes (P1 and P2 in Figure 3.11). The electrodes consist of metal stakes driven into the ground. From the current (I) and voltage (V) values, an apparent resistivity (p_a) is calculated with Equation 3.4 (Loke, 2000):

$$p_a = k_g \frac{V}{I} \qquad (3.9)$$

where k_g is the geometric factor which depends on the arrangement of the four electrodes. Different electrode spacing arrangements have been adopted for field practice, the most common being Wenner and Schlumberger arrangements (Sharma, 1986; Todd, 2005) shown in Figure 3.8.

(a) (b)

Figure 3.8: Wenner (a) and Schlumberger (b) electrode arrangements and their geometric factors (adapted from Loke, 2000)

The calculated resistivity obtained using Equation 3.9 is not the true resistivity of the subsurface, but an "apparent" value, which is the resistivity of a homogeneous ground that will give the same resistance value for the same electrode arrangement. The relationship between the "apparent" resistivity and the "true" resistivity is a complex relationship (Loke, 2004). To estimate the true subsurface resistivity, a geophysical inversion of the measured apparent resistivity values using a computer program must be carried out (Loke, 2004). In geophysical inversion, a model that gives a response similar to the actual measured values is found. The model is an idealised mathematical representation of a section of the earth and it has a set of model parameters that are the physical quantities estimated from the observed data. The model response is the synthetic data that can be calculated from the mathematical relationships defining the model for a given set of model parameters. The model parameters are the resistivity values of the model, while the observed data is the measured apparent resistivity values. All inversion methods essentially try to determine a model for the subsurface whose response agrees with the measured data subject to certain restrictions (Loke, 2004).

There are two traditional resistivity survey techniques, *viz.* one dimensional vertical electrical sounding (VES) of limited lateral control and electrical profiling (EP), which is limited to a constant depth (Sharma, 1986). VES is used to determine the variation of resistivity with depth below a given point on the ground surface. The procedure is based on the fact that the current penetrated continuously deeper with increasing separation of the current electrodes. EP is used to detect lateral variation in the resistivities. In EP, the spacing between the electrodes remains fixed, but the entire array is moved along a straight line, thereby giving some information about the lateral changes in the subsurface resistivity without detecting vertical resistivity changes. The limitations associated with classical VES and EP techniques have been overcome with improvement in technology and computer processing power, which now allow 2D and 3D electrical resistivity surveys (Loke, 2004; Samuoëlian *et al.*, 2005). 2D electrical surveys are the most practical economic compromise between obtaining very accurate results and keeping the survey costs down (Loke, 2000; 2004). They provide resistivity changes in the vertical direction, as well as in the horizontal direction along the survey line. Although the magnitude of resistivity is important, the information obtained from the lateral and vertical changes in resistivity (i.e. spatial distribution) is often diagnostic (Lewis, 2003).

Electrical resistivity surveys have been intensively used for the engineering and environmental site assessment of the subsurface. Halihan *et al.* (2005) have used the techniques in the mapping of the pollution extent of contaminants (NAPLs – NonAquaeos Phase Liquids) and they have been used in precision agriculture, where the spatial measurement of within-field soil differences associated with topsoil thickness and soil water differences were used as a measure of root zone suitability for crop growth and yield (Kitchen *et al.*, 1999; Johnson *et al.*, 2003; Corwin and Lesch, 2005). Other applications were in groundwater exploration and pollution studies (MacDonald *et al.*, 2001; Reinhard *et al.*, 2002; Sharma and Baranwal, 2005), mineral exploration (Ferguson *et al.*, 1999) and soil water movement (Michota *et al.*, 2001; Abraham and Lucius, 2004).

3.10 Conclusions

From the various studies reviewed in this chapter, it can be concluded that effective management of the low quality water generated from opencast and underground coal mining activities is crucial in the prevention of both surface water and groundwater pollution. Several management strategies are implemented in South Africa and include treatment, controlled releases during periods of high flows, rehabilitation of mined lands and separation of clean and dirty water. The possibility of using the low quality for irrigation has fairly been investigated in South Africa and successes have been reported. The investigations so far, however, are limited to field scale assessment of crop production, soil characteristics and the quantity and quality of drainage water. Integrated assessment of the impact on water resources that may result from large-scale application and an adequate tool for such an assessment are lacking. These, therefore, call for the development and application of a tool that can adequately assess, in an integrated manner, the impact of using low quality mine water for irrigation of agricultural crops on water resources. Such a tool, however, can be complemented by other techniques used in environmental site assessment, such as the 2D electrical resistivity survey. The following chapter discusses the methodology employed in this study for the assessment of the impact of irrigation with low quality mine water.

4. METHODOLOGY

The methodology adopted in this study enables a detailed assessment of the impact of large-scale irrigation with gypsiferous mine water on the surface water as well as groundwater resources of parts of the Upper Olifants basin. It entails literature review on the different aspects of this study, evaluation of historical data, application of Java Programming Language in the modifications to the *ACRU2000* model and the *ACRUSalinity* module, as well as studies at pivot, catchment and mine scales. Literature review has been presented in Chapter 3. The other aspects of the methodology adopted in this research work are presented in the sections below.

4.1 Evaluation of Historical Data

Field trials, in which several crops were irrigated with centre pivots using mine waters, have been carried out in the study area before the commencement of this research work (Jovanovic *et al.*, 2001; Annandale *et al.*, 2002). The field trials were established at Kleinkopje Colliery, close to Witbank, and at Syferfontein Colliery, close to Secunda. The field trials at Kleinkopje involved three centre pivots, with two on virgin (unmined) soils, and the third on a rehabilitated land. The trial at Syferfontein was on unmined land. The measurements carried out during the trials formed part of the data evaluated and employed in the present research work. The measurements included the following (Annandale, 2002):

- Atmospheric measurements using automatic weather stations,
- Physical properties of soil materials related to bulk densities, water retention and hydraulic conductivity,
- Soil water content and chemical properties using a variety of equipment such as tipping bucket rain gauges, tensiometers, heat dissipation sensors, neutron water metering, time domain reflectometry, ceramic cup soil water sampling and laboratory analyses of irrigation water,
- Soil chemical analyses on a seasonal basis,
- Runoff volumes and quality measured at a crump weir built at the lowest points below two of the three centre pivots at Kleinkopje Colliery, and

- Groundwater quality monitoring in the unmined areas.

Apart from the data on from previous field trials on the irrigation of crops with mine water, other data evaluated included rainfall, stream flow and water quality at different locations in the Witbank Dam catchment, including the amount and quality of water in storage in Witbank Dam.

4.2 Development of Computer Code in Java Programming Language

The development of necessary code in Java Programming Language in the *ACRU2000* model and *ACRUSalinity* module was undertaken, taking into consideration some of the unique features of the environment of the study area. Some of the unique features taken into consideration included the occurrences of underground mined-out areas, surface pans, springs, multiple transfers of water from one storage source to other sources or multiple withdrawals of water from a storage source for various uses, controlled releases from mine water storage facilities and seepage of water from groundwater into opencast mining areas. The code development to address these unique features and are presented in Chapter 5. The computer codes were checked for errors by computing the mass balances of water and salts in the relevant components of the *ACRU2000* model and *ACRUSalinity* module and then comparing them with simulated output of the overall mass balance. Comparable results are an indication that the computer codes are free of errors. According to Konikow (2002), the validity of computer codes can be assessed in a model by the ability of the model to conserve mass. However, to carry out and document detailed code validation for all the algorithms underlying every modified and added process in this study will not only be time intensive, but also voluminous. Therefore, in this thesis, the checking of only the major codes modified or added to *ACRU2000* and *ACRUSalinity* are documented. They are presented in Appendix B. Nevertheless, for all the processes modified or added to both *ACRU2000* and *ACRUSalinity*, mass balance computations were carried out after every modification and addition, in order to correct any error that may have arisen therefrom.

4.3 Studies at Centre Pivot, Catchment and Mine Scales

This study was carried out at centre pivot, catchment and mine scales. The choice of focus at the three levels hinged on the need to carry out a comprehensive assessment of mine water use for irrigation of agricultural crops in the study area. The foci of the assessments are on the responses of the subsurface soil water, surface water and groundwater to irrigation of agricultural crops with coal mine water. Simulations, using the *ACRU2000* model and the *ACRUSalinity* module, were carried out at the three levels of study in order to elucidate the underlying hydrological processes involved in the responses. Daily rainfall and irrigation water application, runoff and subsurface flows, were analysed in order to assess the impact which widespread use of mine water for irrigation of agricultural crops would have on the water resources of the study area. The methodologies employed at the centre pivot, catchment and mine scales are presented in the sections that follow in that order.

4.3.1 Centre Pivot Scale Studies

Two sites, already equipped with centre pivots under irrigation with mine water at the commencement of this study, were chosen for the centre pivot scale study. They were the Syferfontein and Tweefontein pivots. While the Syferfontein pivot was on unmined soils, the Tweefontein pivot was on rehabilitated soils. The locations of the pivots and their descriptions have been presented in Chapter 2. In the pivot scale studies, verification of *ACRU2000* and *ACRUSalinity* was carried out and the water and salt balances for the two pivots determined, in order to provide insight into the temporal distribution of water and salts in the subsurface, and how irrigation of agricultural crops, using mine water, would impact on both the runoff and groundwater of the centre pivot areas. The monitoring of the quantity and quality of runoff from the pivots were done in order to obtain the required data for the verification of outputs from simulations. The simulated results were verified with the observed daily runoff volume and the daily runoff salt load, calculated from the observed runoff volume and salinity. Regression analyses, as well as checksums, were employed to evaluate the efficiency of simulations. The results from the simulations of the two pivots were used for comparing the impact of irrigation with mine water on a pivot located in a rehabilitated land (Tweefontein) and the one located on a virgin land (Syferfontein). By comparing the results obtained from the two pivots with the **crop tolerance and yield potential of selected crops as influenced by irrigation water and soil water salinity** (Ayers and Westcot, 1994), **examples of crops that can be successfully irrigated at the two pivots are given.** A summary of the simulations carried out at pivot scale is presented in Table 4.1, while a summary of the available data for the pivot scale study is presented in Table 4.2. Results from the pivot studies, were used as inputs into the *ACRU2000* model and the *ACRUSalinity* module for the catchment and mine scale studies.

The *ACRU2000* model and the *ACRUSalinity* module were run in the lumped mode for the scale studies and the irrigated pivots were made to be part of land segments that were a little bigger than the pivots. That was done because, in *ACRU2000*, an irrigated field was conceptualised as part of a larger land segment, and so could not be simulated alone. However, water and salt balance results could be output separately for the irrigated centre pivots. Considering that the areas of the pivots were small, the fraction of the generated stormflow that will appear on the same day at the pivot outlet was set at 0.9 (Smithers *et al.*, 1995).

2D electrical resistivity surveys were conducted at the Syferfontein, Tweefontein and Major pivots (Major pivot is one of the three centre pivots located within the Kleinkopje Colliery and it is on an unmined soil). The focus and the methodology used for 2D resistivity surveys are described after the monitoring carried out at the Tweefontein and Syferfontein pivots have been described.

4.3.1.1 The Tweefontein Pivot

The runoff volume and salinity from the Tweefontein pivot were monitored in order to have observed data for the verification of the simulation of the pivot and for the computation of the water and salt balances. In order to facilitate adequate drainage and monitoring of the runoff from the pivot, contouring and construction of waterways were carried out so that the runoff could leave the pivot over a crump weir from where the automatic monitoring of the quantity and quality of runoff were carried out, using a Campbell logger CR10X and an *ISCO* 3700 portable sampler. The logger was programmed to determine the height of water above the weir every second and convert it to flow using the formula:

$$Q = 1.585 \times 5 \times w^{2.5} \tag{4.1}$$

where Q is the flow (m^3/s), w is the water level above the weir (m) and *1.585*, *5* and *2.5* are coefficients dependent on the shape and size of the weir. The average height of water above the weir and the flow rate every 5 minutes were determined and stored along with the day, date, time and voltage of the battery. The time interval for the determination of the flow rate was changed to 5 minutes after a time interval of 2 minutes was discovered to be too frequent and was therefore filling up the storage capacity of the data logger more quickly. The logger was set up such that when the volume of flow amounted to 25 m^3, the logger would trigger a signal to the *ISCO* sampler. The *ISCO* sampler would then collect a sample of volume 450 ml, reset itself and get ready to sample when the volume of flow amounts to 25 m^3 again. Based on the experience with the volume of runoff from the pivot, the sampling volume interval of 25 m^3 was adequate for monitoring the quality of the runoff from the pivot. The bottle number, day, date and time of sampling were stored in the data logger. The *ISCO* sampler was programmed to stop sampling when water samples had been deposited in all the 24 available bottles. The download of data from the data logger and collection of water samples from the *ISCO* sampler were usually carried out fortnightly. After collection of the water samples, they were sent to the laboratory for chemical analysis.

The observed total runoff volume from the pivot for a day was calculated by adding up the average total volume of flow, computed at 5 minutes interval, for that day. The observed salt load for a day was determined from the electrical conductivity (EC) of all the water samples collected by the *ISCO* sampler on that particular day by calculating the average EC of all the samples. The average EC was then converted to average TDS (in mg/l) by multiplying the average EC, in *umhos/cm*, by 0.64 (Raghunath, 1987). The total daily salt load of the runoff for a particular day was finally calculated by multiplying the average TDS of runoff for that day by the total runoff volume for the day.

Table 4.2: Summary of the simulations carried out

No	Scale	Description	Area	Simulation Period	Comment
1	Field	1. Tweefontein Pivot	20 ha	April 2003 – March 2004	Verification of *ACRU2000* and *ACRUSalinity* at pivot scale on rehab soils
		2. Syferfontein Pivot	21 ha	May 2003 – April 2004	Verification of *ACRU2000* and *ACRUSalinity* at pivot scale on virgin soils
2	Small catchment	Tweefontein Pan catchment	4.7 km^2	1999 – 2004	
		Scenarios 1. Baseline 30 ha virgin irrigated (Fourth pivot) 20 ha rehab irrigated (Tweefontein pivot)			Verification of *ACRU2000* and *ACRUSalinity* at catchment scale
		2. Alternative source of irrigation water (from the underground reservoir) 30 ha virgin irrigated (Fourth pivot) 20 ha rehab irrigated (Tweefontein pivot)			Assessment of widespread irrigation on virgin soils with available mine water in the catchment
		3. Widespread irrigation on virgin soils 160 ha virgin irrigated 20 ha rehab irrigated (Tweefontein pivot)			Assessment of widespread irrigation on irrigated soils with available mine water in the catchment
		4. Widespread irrigation on rehabilitated soils (Pre – and post- water table establishment) 120 ha rehab irrigated 20 ha rehab irrigated (Tweefontein pivot)			
3	Mine	Kleinkopje Colliery	92 km^2	1999 - 2004	
		Scenarios 1. Baseline 600 ha virgin irrigated (Fourth and Major pivots) 20 ha rehab irrigated (Tweefontein pivot)			Verification of *ACRU2000* and *ACRUSalinity* at mine scale
		2. Widespread irrigation on virgin soil 600 ha virgin 20 ha rehab (Tweefontein pivot)			Assessment of widespread irrigation on virgin soils in Kleinkopje Colliery and impact on Witbank Dam
		3. Widespread irrigation on rehabilitated soil (Pre – and post- water table establishment) 600 ha rehab irrigated 60 ha virgin irrigated (Fourth and Major pivots)			Assessment of widespread irrigation on rehabilitated soils in Kleinkopje Colliery and impact on Witbank Dam

Table 4.2: Summary of available data

No	Scale	Available Data
1	Pivot (Tweefontein and Syferfontein)	Climate data (daily rainfall, temperature and wind speed) Daily irrigation water application Daily irrigation water salinity Daily runoff volume Daily runoff salinity Daily soil water salinity Soil water retention characteristics (wilting point, drained upper limit and porosity) Depth of topsoil on rehabilitated soils (Tweefontein)
2	Small catchment (Tweefontein Pan catchment)	Climate data (daily rainfall, temperature and wind speed) Irrigation water application to the Fourth and Tweefontein pivots Irrigation water salinity (Fourth and Tweefontein pivots) Daily soil water salinity in irrigated area (Fourth pivot) Daily volume of water storage in Tweefontein Pan Daily salinity of water in storage in Tweefontein Pan Volume of water pumped into Tweefontein Pan Surface area of Tweefontein pan 1:10 000 orthophoto maps
3	Mine (Kleinkopje Colliery)	Climate data (rainfall, temperature, wind speed) Irrigation water application to the Fourth, Tweefontein and Major pivots Irrigation water salinity (Fourth, Tweefontein and Major pivots) Soil water salinity in irrigated area (Fourth and Tweefontein pivots) Volume of water storage in Tweefontein Pan Salinity of water in storage in Tweefontein Pan Seepage from Landau underground reservoir Salinity of water in surface reservoirs (Berries Pan, Klippan Penstock, 2A dam, Plant Return Water Dam) Daily water storage in Witbank Dam Daily water salinity in Witbank Dam Daily salinity of Tweefonteinspruit as it enters and exits Kleinkopje Colliery Topographical map Water reticulation system map

The monitoring of the runoff from the Tweefontein pivot was started in March 2003 and lasted for about a year. Figure 4.1 shows the Tweefontein weir, with an insert of the Campbell data logger and the *ISCO* water sampler. The observed daily runoff and salinity are presented in Tables E1 and E2 (Appendix E) respectively.

Figure 4.1: Tweefontein weir with the safe for the Campbell data logger and *ISCO* water sampler

The weather conditions at the Tweefontein pivot were monitored with an automatic weather station located adjacent to it, about 100 m from the edge. The weather station location was surrounded by grass and the meteorological conditions were assumed to be representative of the Tweefontein pivot. The weather station predated this research work and was put in place by the University of Pretoria research group, which was one of the collaborators in the whole project of impact assessment of the use of gypsiferous mine water for irrigation. The following data were recorded with the weather station:

- Temperature and relative humidity with a CS-500 Vaisala temperature and humidity probe;
- Solar radiation with a Li-Cor LI-200 pyranometer;
- Wind speed with an R.M. Young cup anemometer; and
- Rainfall amount and intensity with a tipping bucket Texas Electronics Inc. rain gauge.

Rainfall recorded with the weather station could be different from the rainfall occurring within the pivot. Moreover, irrigation water application within the pivot needed to be monitored, along with the soil moisture conditions. Therefore, a soil monitoring station was located within the pivot, together with tipping bucket rain gauges, which measured the amount and intensity of rainfall and irrigation. The instrumentation at the soil monitoring station is presented in Table 4.3. Rainfall and irrigation amounts measured, along with some of the data collected at the automatic weather station, served as inputs to the models employed in this research work.

4.3.1.2 The Syferfontein Pivot

As in the Tweefontein pivot, and for the same purpose, contouring and construction of waterways were carried out so that the runoff could be led off the pivot over an H flume from where the automatic monitoring of the quantity and quality of runoff were carried out, using a Campbell logger CR 510 and an *ISCO* 3700 portable sampler. The same set up of the logger and *ISCO* sampler as in the Tweefontein pivot were employed at the Syferfontein pivot. However, the flow over the flume was calculated using the formula

Table 4.3: Instrumentation at soil monitoring stations at the Tweefontein and Syferfontein pivots

Location	Instrumentation					
	Tipping bucket rain gauges	Heat dissipation sensors	Neutron probe access tube	TDR probes	Ceramic cup soil water samplers	Wetting front detectors
Tweefontein	2 No.	5 No. Depths: 0.1, 0.3, 0.5, 0.7 and 0.9 m	2 No. Depths:1 m and 2 m	8 No. Depths: 0.1, 0.2, 0.3, 0.4, 0.5, 0.7 and 1m	3 No. Depths:0.4, 1 and 1,4 m	2 No. Depths: 0.3 and 0.6 m
Syferfontein	2 No.	5 No. Depths:0.5, 0.15, 0.25, 0.35, and 0.45 m	2 No. Depths?	5 No. Depths: 0.5, 0.15, 0.25, 0.35 and 0.45 m	2 No. Depths; 0.4 and 1 m	1 No. Depth: 0.3 m

NB: No = Number of items

$$Q = 0.004\,w + 0.59\,w^2 + 0.012\,w^3 + 0.71\,w^4 \qquad (4.2)$$

where Q and w are as defined in the Tweefontein pivot. Figure 4.2 shows the Syferfontein flume, the Campbell logger and *ISCO* water sampler. For the same reason as in Tweefontein, an automatic weather station and a soil monitoring station were located at the Syferfontein pivot. The instrumentation of the soil monitoring station is presented in Table 4.3. The monitoring of the runoff from the Syferfontein pivot started in May 2003 and lasted for about a year. The observed daily runoff and salinity are presented in Tables E3 and E4 of Appendix E respectively.

Figure 4.2: Syferfontein H flume

4.3.1.3 2D Electrical Resistivity Survey

The 2D electrical resistivity surveys at both centre pivots were carried out with two main objectives, *viz*. to

- Determine and interpret the subsurface resistivity distribution in order to define the subsurface conditions that may arise from irrigation with gypsiferous mine water, and
- Compare the subsurface resistivity distribution of soils that may characterise the rehabilitated mine soils (typified by Tweefontein) and unmined soils (typified by Syferfontein and Major; Major being another centre pivot in Kleinkopje Colliery investigated with the resistivity survey) as a result of irrigation with gypsiferous mine water.

An ABEM SAS 1000 Terrameter and ES 464 switching unit, with 4 multicore cables and 25 stainless steel pegs, were used for the 2D electrical resistivity survey. At each of the centre pivots, two surveys were performed, the first with an electrode separation of 2.5 m and the second with a spacing of 5 m, using the "roll-along" surveying method. The Wenner long (5 m) in conjunction with the Wenner short (2.5 m) measuring protocols were used. In order to account for variation in resistivities in the vertical as well as the horizontal directions, 2D model interpretations of the apparent resistivities obtained from the electrical resistivity survey were carried out using RES2DINV program, which uses the smoothness-constrained least-squares inversion technique to determine the appropriate resistivity of the subsurface (Loke, 2000; 2004). The 2D model interpretations are presented in pseudosections in this study. The RMS (root – mean – square) value gives the difference between the model of the subsurface obtained using the inversion programme and the one from apparent resistivity values. To ensure a correct interpretation of the 2D pseudosections, they were compared with the lithologic logs of boreholes located within, or close to the pivots. Borehole lithologic logs were only available for the Syferfontein and Major pivots however. The borehole lithologic logs are presented in Appendix F.

4.3.2 Catchment Scale Study

The catchment scale study was carried out on the Tweefontein Pan catchment using the modified *ACRU2000* model and the *ACRUSalinity* module, with the model run in the lumped mode for the entire catchment. The catchment has been described in Chapter 2. The entire drainage area of Tweefontein Pan was delineated and digitized using 1:10 000 orthophoto maps. The catchment is No 8 in the figure showing the delineated land segment areas in Kleinkopje Colliery (Figure 4.3).

The simulation of the catchment spans a period of 5 years (1999 – 2004) in which adequate data on the water storage in the reservoir as well as irrigation water application to the Fourth and Tweefontein pivots were available. In simulating the Tweefontein Pan catchment, all the water pumped into and out of the Tweefontein Pan were taken into consideration. Similarly taken into consideration were the return flow into the reservoir from the Fourth pivot and the occurrence of underground mined-out area. The available data on the volume and quality of water in storage in Tweefontein Pan, as well as the salinities of soil water within the irrigated area, were used for verification study (Table 4.2). The soils, hydrological and salt distribution response units obtained from the verification study were taken as typical and therefore used in similar land segments identified in Kleinkopje Colliery for the mine scale study.

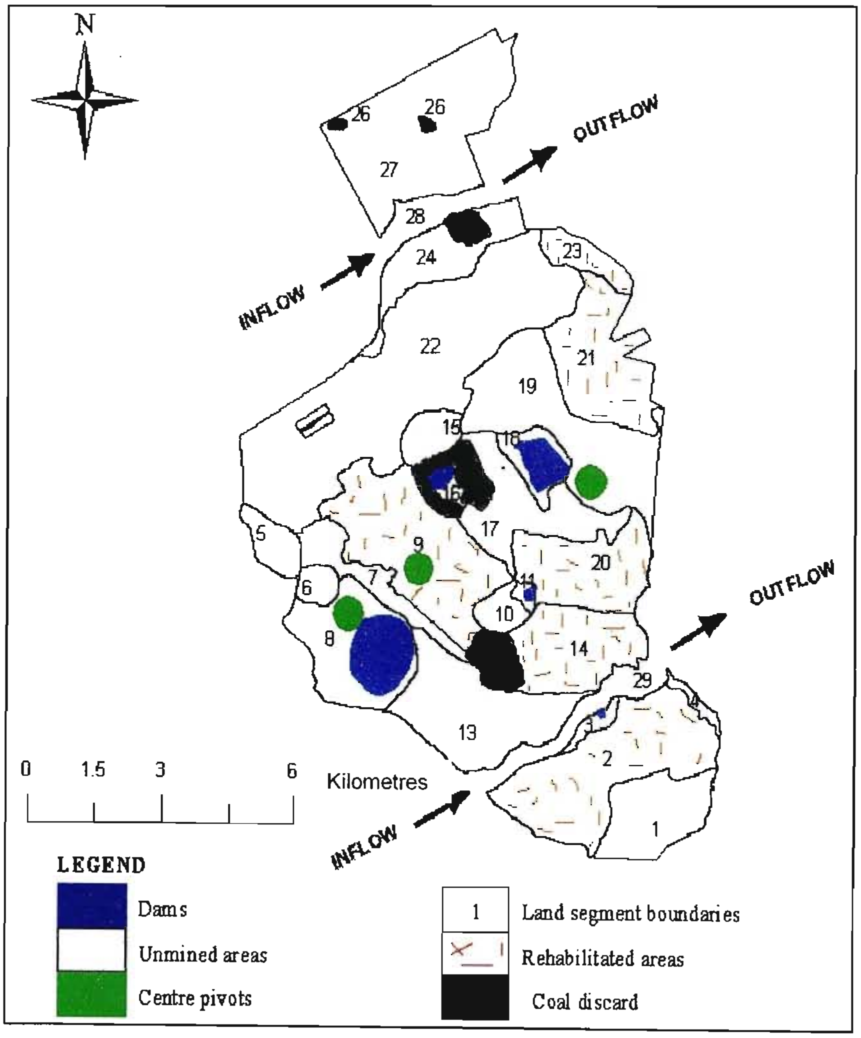


Figure 4.3: Delineated land segment areas in Kleinkopje Colliery

The choice of the Tweefontein Pan catchment was dictated by its representativeness of the other land segment areas delineated in Kleinkopje Colliery in terms of the presence of many of the hydrological components identified in the colliery (e.g. irrigated area, surface reservoir, underground reservoir, non-irrigated area) and the availability of relevant data.

Four scenarios were simulated in the catchment scale study. Summaries of the scenarios simulated and the available data are presented in Tables 4.1 and 4.2 respectively. The baseline scenario was used for the verification of the modifications carried out in both *ACRU2000* and *ACRUSalinity* at catchment scale. The impact of widespread irrigation on the water resources in the catchment was investigated by irrigating as much area as the water in storage in the reservoir could adequately irrigate within the period of simulation on both virgin and rehabilitated soils. The impact of irrigation with an alternative source of mine water other than that from Tweefontein Pan was investigated by sourcing the water for irrigation in the catchment from the mine water occurring in the underground reservoir within the catchment. The scenarios simulated enabled the assessment of the temporal variation of the volume and salinity of water in storage in the Tweefontein Pan, as well as the volume and salinity of the return flow from the irrigated area and the runoff from the non-irrigated area in the catchment. The catchment scale study demonstrates the necessity for adequate integrated assessment of the water resources in a watershed in order to predict and manage the volume of water and the mass of salt export, as well as the likely impact of irrigation on the quantity and quality of the source of irrigation water supply.

4.3.3 Mine Scale Study

The focus of the mine scale study was the application of the modified *ACRU2000* and *ACRUSalinity* to Kleinkopje Colliery, with the aim of assessing the impact of the salt load and water outflow from the colliery, under widespread irrigation with the available mine water, on the Witbank Dam. The application of the modified *ACRU2000* and *ACRUSalinity* to Kleinkopje Colliery included the different hydrological components that characterise the mine. The impact assessment on Witbank Dam was carried out by evaluating the water and salt load contributions from the colliery into Witbank Dam and comparing them with the volume of water and the mass salt load in storage in the dam. The data on daily water storage and the periodic salinity of water in Witbank Dam were obtained from DWAF. The salt load in the dam for a particular day was computed as the product of the amount of water in storage and the recorded salinity of the water in the dam for that particular day.

Kleinkopje Colliery was chosen for the mine scale study because one of the centre pivots monitored in this study, the Tweefontein pivot, was located in the Colliery. In addition, two other centre pivots within Kleinkopje Colliery were being irrigated with mine water in a field trial that was being conducted by the University of Pretoria Department of Plant Production and Soil Science. Therefore, the necessary understanding and cooperation that had been cultivated with the mine's management from the field trial activities could be utilized for carrying out this research work. Details of the methodologies used for the mine scale study are presented in the sections that follow.

4.3.3.1 Assemblages of Inventories of Water Sources, Storages and Discharges

Water sources, storages, transfers and management in a mine environment can be complex and may comprise various water sources, multiple water abstractions and transfers, complex water reticulation systems and management strategies. In order to identify the particular characteristics of the colliery's hydrological system that needed be translated into the *ACRU2000* model and the *ACRUSalinity* module as hydrological components and variables, inventories of water sources, storages, discharges and transfers of water from one storage facility to another, were assembled. The inventories also included the qualities of the water concerned. The inventories were prepared from the Kleinkopje Colliery database in the forms of spreadsheets and spanned a period of fives years (1999 – 2004) in which data were available.

4.3.3.2 Delineation of Kleinkopje Colliery into Land Segment Areas

In order to model Kleinkopje Colliery spatially as a hydrological system using *ACRU2000* and *ACRUSalinity*, the colliery was divided into 29 inter-linked land segment areas on the basis of the land use types recognized in the colliery, as well as the topography of the colliery. The land segments were then digitised and surface water flow configured with due consideration to the topography of the colliery. The delineated land segment areas are shown in Figure 4.3. In agreement with modifications carried out and the way *ACRU2000* is structured, each of the land segments could contain more than one land use type, sub-area or components such an irrigated area, a non-irrigated area, a surface dam and an underground reservoir. The main objectives of the delineation were to represent the different land use types and management practices in Kleinkopje as discrete units in order to make it possible for the hydrological responses of each of the delineated areas to be modelled explicitly. The land use types taken into consideration include:

- Rehabilitated areas,
- Unmined (virgin) areas,
- Irrigated areas,
- Coal dumps/waste discards areas,
- Formal residential low density areas,
- Wetlands with grasses,
- Surface dams, and
- Underground mined-out areas

A 1:15 000 topographical map of the colliery with contour intervals of 1 m was obtained from the Kleinkopje Management and used for the delineation and flow configuration of the land segments. The delineation of Kleinkopje into land segment areas enabled the parameterisation of soil and vegetation characteristics in the different parts of the colliery as required in the *ACRU2000* model. In addition, with the delineation, the areal extent of each delineated land segment and the parameters associated with different land use categories could be altered as necessary, when the hydrology of different land use scenarios is to be simulated.

4.3.3.3 Simulation of Kleinkopje Colliery using *ACRU2000* and *ACRUSalinity*

A multi-scale approach was adopted in the simulation of Kleinkopje Colliery using the *ACRU2000* model and the *ACRUSalinity* module. The first was at centre pivot scale. The Tweefontein pivot was used for this, as explained in Section 4.2. The second was at catchment scale. The catchment investigated was the Tweefontein Pan catchment (see Section 4.3.2). The third level was the simulation of the whole of the Kleinkopje Colliery as an inter-linked hydrological system. The multi-scale approach is necessary because of the lack of adequate relevant data in many of the delineated land segments. The approach therefore enabled the use of the soils, hydrological and salt distribution parameters and response units verified in the pivot and Tweefontein Pan catchment studies in other land segments of similar land uses. The Tweefontein pivot was on a rehabilitated soil, while the Tweefontein Pan catchment was made up of virgin (unmined) soils. Therefore, the soil, hydrological and salt distribution response units and parameters employed in the verification studies at centre pivot level for a rehabilitated soil and at catchment level for a virgin soil were used in setting up similar land segments in the colliery for *ACRU2000* and *ACRUSalinity* runs.

In order to assess the use of gypsiferous mine water for irrigation in Kleinkopje Colliery and evaluate its impact on Witbank Dam, different scenarios were simulated (Table 4.1). These included:

- Baseline conditions of the colliery with three centre pivots under irrigation with mine water,
- Widespread use of mine water for irrigation on virgin soils, and
- Widespread use of mine water for irrigation on rehabilitated land areas.

The simulations of the widespread irrigation with mine water on virgin and rehabilitated land areas were carried out by altering the areal extent and the corresponding hydrological, as well as the salt distribution response units, associated with the different land use types when the assessment of the use of mine water for irrigation in a different land use scenario was to be assessed. For example, for the assessment of the impact of widespread use of mine water for irrigation on an unmined land segment, the areal extent of the irrigated area in the land segment was increased to represent the extent of interest while the areal extent of the non-irrigated area was reduced correspondingly. To adequately assess the different scenarios, the results obtained from the simulation of the baseline conditions were compared with the results obtained from the simulations of widespread irrigations on virgin and unmined land areas. The land use type taken as the baseline in each land segment was the one in existence as at July 2004 in the colliery. These are described in Section 6.1 and 6.5.

In investigating the impacts of widespread irrigation with mine water, a distinction was made between a rehabilitated irrigated area before and after the re-establishment of the regional water table. Prior to the re-establishment of the water table, percolating water will gradually accumulate in depressions at the bottom of the mined-out area, with the water table gradually rising until a decanting level is reached and the water table re-established. Consequently, the contribution of baseflow to runoff may be insignificant, unlike after the re-establishment of water table when groundwater will flow in the direction of the hydraulic gradient and contribute to runoff. The implication is that the pre-existing or regional water table might not be established until opencast mining activities have ceased. Taking all of these into consideration, during the simulations of rehabilitated areas prior to the re-establishment of the water table, the contribution of baseflow to runoff was set at zero, whereas during the simulations representing post-water table re-establishment, the default value of 0.02% of the daily volume of groundwater in storage was used.

The summary of the available data for mine scale verification study are presented in Table 4.2. The modelling requirements and discussion of input variables employed in the simulations at all the three scales of study are presented in Chapter 6. The simulations carried out on the Kleinkopje Colliery demonstrated the possible use of the modified *ACRU2000* model and the *ACRUSalinity* module as tools for the mine water management in collieries.

5. MODIFICATIONS TO *ACRU2000* AND *ACRUSalinity*

This chapter deals with the modifications added to the *ACRU2000* model and the and *ACRUSalinity* module in this study. The description of the *ACRU2000* model and the *ACRUSalinity* module in their present forms are necessary in order to provide enough background and understanding on the modifications carried out in both of them. Therefore, in Appendix A, is a section that contains the description of both the *ACRU2000* model and the *ACRUSalinity* module in their present forms.

5.1 Modifications to *ACRU2000*

In mines located throughout the Upper Olifants catchment, low quality mine water has been stored in reservoirs located either underground or on the ground surface. The surface reservoirs occur as natural pans, constructed evaporation areas and water from groundwater seepage or surface runoff into pits created from opencast mining, while the underground reservoirs comprise old workings of mined-out underground areas. In order to be able to adequately assess the impact of large-scale use of gypsiferous mine water for irrigation in a mining environment, the relationship of the reservoirs, from which the irrigation water may be obtained, with other components of the hydrological system (in *ACRU2000* and *ACRUSalinity*), needs to be better understood and adequately represented. The relationship consists of the interaction of the water in reservoirs with both surface water and groundwater. Presently, surface reservoirs are already constituted as a component in *ACRU2000* in *CDam*, but underground reservoirs are not. Therefore, modifications carried in the *ACRU2000* model involve the addition of a new hydrological component to represent the underground reservoir and the addition of new Process and Data objects, which take the relationship of the new component with groundwater, surface reservoirs and the pumping of water into and out of it into consideration. The estimation of seepage losses from surface reservoirs has also been modified to include an option that makes seepage a function of the amount of water in storage.

In this study, a distinction is made between surface reservoirs (i.e. dams or pans) and bodies of water which accumulate in pits created from opencast mining. The pits are found in the opencast coal mining window areas. They usually contain water with origins from groundwater seepage and surface runoff from areas with gradients towards the pit. In this study, the bodies of water found in the pits created from opencast mining are referred to as mine-pit reservoirs and are treated as special surface reservoirs. Codes, which represent their interaction with other components of the hydrological system, have been developed in both *ACRU2000* and *ACRUSalinity*. The following sections address the above modifications as well as the other modifications carried out in this study.

5.1.1 Surface Reservoirs

The relationships of surface reservoirs with the other components in the hydrological system are presented in "Reservoir Yield Analysis" of the user documentation on *ACRU* (Schulze *et al.*, 1995c). In the reservoir yield analysis, the need to make seepage losses a function of the amount of water in storage and for it to interact with the groundwater system were identified as necessary in this research work. In *ACRU 300 series*, the daily seepage is defaulted to 0.0006 x storage capacity of the dam. However, in *ACRU2000*, one can enter the amount of seepage one desires. What this implies, however, is that seepage losses remain constant throughout the year, irrespective of the reservoir volume, which may not reflect the dynamics with which surface reservoir interacts with groundwater. For example, it has been suggested that the constant seepage assumed for surface reservoirs was responsible for reported significant increases in baseflow during dry periods in subcatchments where farm dams were included in the simulation of parts of Upper Olifants (Department of Water Affairs and Forestry, 2001). Consequently, the Department of Water Affairs and Forestry (2001) suggested that seepage from reservoirs be made proportional to the storage state or water depth in a reservoir. The need to adequately represent seepage from surface reservoirs is considered important in this study because seepage reduces the amount of water which may occur in surface reservoirs and, therefore, from the potential for abstraction of mine water for irrigation. *ACRU2000* is presently structured to transfer estimated seepage to the downstream reaches along with overflow and normal flow, without any interaction with the groundwater system. In this study, an option has therefore been created in *ACRU2000* that makes the seepage from surface reservoirs a function of the volume of water in storage. In addition, algorithms have been introduced to describe the interaction between reservoir and the groundwater system depending on the comparative levels of water in the reservoir and the underlying aquifer. In this way, consideration is given to the loss or gain of salts from the surface reservoir and the groundwater system. Also introduced are algorithms that deal with the peculiar conditions encountered in the mine scale study. These were the occurrence of mine-pit reservoirs, underground reservoirs below surface reservoirs and controlled releases.

5.1.1.1 Seepage

In this study, two options have been created in *ACRU2000* for the estimation of reservoir seepage and the way it interacts with other components of the hydrological cycle. The first option, carried out by the *PDamSeepage Process,* is the original way by which a user specified constant is used. The other option incorporated into *ACRU2000* in this study is carried out by *PDamSeepageOlufemi Process.*

The *PDamSeepageOlufemi* Process estimates the possible seepage from surface reservoirs into the groundwater system based on the amount of water in storage in the reservoir and the pressure gradients between the underlying water table and the bottom of the reservoir. If the water table lies below the bottom of the reservoir, seepage flows percolate to the water table. Bouwer and Maddock III (1997) have explained that the seepage between a channel with accumulation of clogging deposits and the adjacent aquifer is unsaturated. The clogging layers usually have a low hydraulic conductivity, which restricts seepage rates to values that are less than the saturated hydraulic conductivity of the usually coarser underlying materials. This causes the material below the clogging layer to become unsaturated, with gravity flow dominating. The underlying material then drains to a water content whereby the corresponding unsaturated hydraulic conductivity is numerically equal to the seepage rate and a unit hydraulic gradient induced. This seepage rate can be calculated by applying Darcy's law to the flow through the saturated clogging layer, if the thickness and hydraulic conductivity of this layer are known. The Process, *PDamSeepageOlufemi*, determines the amount of seepage using Equation 5.1. The equation is based on Darcy's law and it is similar to that employed to simulate the volume of water exchange between canals and aquifers by Yan and Smith (1994).

$$V = K * (R - H) * A * t/d \qquad (5.1)$$

where

V = volume of water seepage (m^3),

K = vertical saturated hydraulic conductivity of the reservoir bottom clogged layer (m/day),

R = water elevation in the reservoir (m),

H = elevation of the groundwater table underlying the reservoir (m),

A = surface area of the reservoir (m^2),

t_s = time step in the calculation (day) ,

d = thickness of the reservoir bottom sedimentation (m), and

K/d = k_{hi}, hydraulic impedance of the low permeability layer at the bottom of the reservoir (day^{-1})

If (as in Figure 5.1):

D = elevation of the bottom of the reservoir (m),

r = height of the reservoir water surface above the bottom of the reservoir (m),

h = depth of the groundwater table below the bottom of the reservoir (m),

and the time step of calculation is taken as one day, considering that *ACRU2000* is a daily time step model, then Equation 5.1 becomes

$$V = k_{hi} ((D + r) - (D-h)) * A \qquad (5.2)$$

$$= k_{hi} (D + r - D + h) \qquad (5.3)$$

$$= k_{hi} (r + h) * A \qquad (5.4)$$

$$= k_{hi} (A * r + A * h) \qquad (5.5)$$

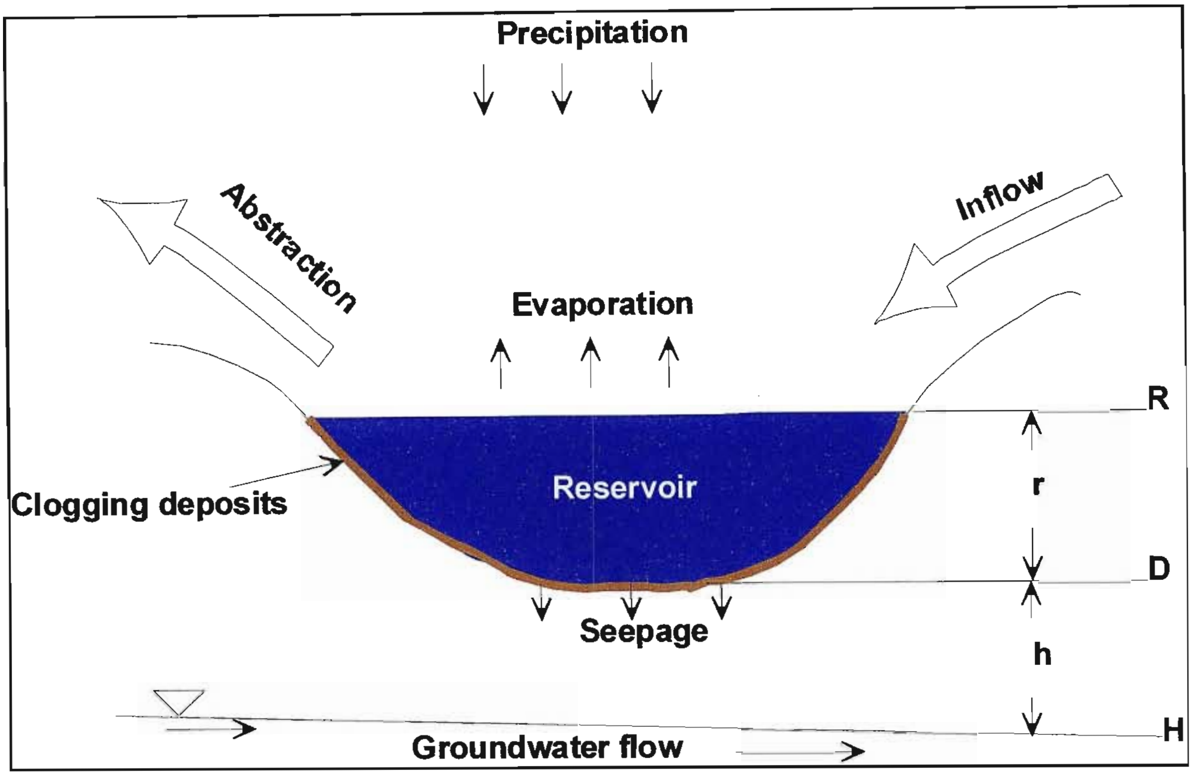


Figure 5.1: Surface reservoir inflows and outflows.

For a particular storage volume, the seepage will increase linearly with groundwater level drop until the top of the capillary fringe has dropped below the clogging layer at the bottom of the reservoir and an unsaturated zone created between the reservoir bottom and the capillary fringe (Bouwer and Maddock III, 1997). At this point, which Bouwer and Maddock (1997) observed is often reached before the groundwater level has dropped to about I m below a stream, seepage losses would have reached the maximum value and further lowering of the groundwater levels would not increase seepage flows. Thus, the seepage rate is the same for a groundwater depth of 3 m below the bottom of the stream with about 3 m of unsaturated zone as for a groundwater depth of 30 m below the stream with about 30 m of unsaturated zone, or, for that matter, for an infinitely deep water table below an infinitely thick unsaturated zone. Thus, it is assumed that a unit hydraulic gradient is induced at about 1 m below the base of the reservoir. Conversely, a rising groundwater level will not reduce seepage losses as long as the groundwater level is more than about 1 m below the bottom of the stream. Therefore for a particular soil type underlying a surface reservoir and a particular storage volume in a reservoir, the maximum seepage will occur just when the depth of the capillary fringe, which varies for different soil types, drops below the bottom of the reservoir. By substituting the h in Equation 5.5 with the depth of the capillary fringe for a particular soil type therefore, the maximum seepage from the reservoir for a particular reservoir storage volume and surface area can be determined using Equation 5.6.

$$V \quad = \quad k_{hi}\,(F + Ap) \qquad (5.6)$$

where F (i.e. $A*r$) is taken as being equivalent to the volume of water in the reservoir and p is the depth of the capillary fringe. In Table 5.1 are the heights of capillary fringes utilised in *ACRU* for eleven soil texture classes. The range of values of p as indicated in *ACRU* may therefore fall between 850 mm for sand and 1850 mm for clay loam.

Table 5.1: Heights of capillary fringes (mm) utilised in *ACRU* for eleven soil texture classes (Bodenkunde, 1982 in Kienzle and Schulze, 1995)

Texture Class Number	Texture Class	Height of Capillary Fringe (mm)
1	Clay	1100
2	Loam	1100
3	Sand	850
4	Loamy sand	1300
5	Sandy loam	1300
6	Silty loam	1850
7	Sandy clay loam	1100
8	Clay loam	1850
9	Silty clay loam	1300
10	Sandy clay	1300
11	Silty clay	1100

Equation 5.6 therefore takes into consideration the volume and surface area of the reservoir, the type and thickness of soil material at the bottom of the reservoir as well as the depth of the water table below the bottom of the reservoir, with respect to the depth of the capillary fringe. The approach described above for the estimation of reservoir seepage is common for simulating the interaction between surface water and groundwater. It has been considered valid for a situation in which the exchange of groundwater and surface water occurs through a discrete,

low permeability layer at the boundary of a surface water channel, and has served as the basis for the development and analysis of leakage relationship from channels, canals and reservoirs (Nemeth and Solo-Gabriele, 2003).

In using Equation 5.6, the initial storage volume at the beginning of a simulation should be supplied, after which the value will depend on the amount of inflow and outflow from the reservoir. The value of *A* at a particular storage volume is obtained in *ACRU2000* thorough a relationship derived for such in Schulze *et al.* (1995c):

$$A \quad = \quad cF^{e} \tag{5.7}$$

where c and e are the reservoir constant and exponent of the area:volume relationship respectively. If the mathematical relationship between the water surface area and the volume is known, the variables c and e can be specified. Otherwise, the default values of 7.2 and 0.77 respectively can be used, as these describe typical values derived from measured information (Tarboton and Schulze, 1992).

According to the approach described, seepage will normally lead to a local rise in the water table. Therefore, the seepage calculated by Equation 5.6 is added to the groundwater store from where baseflow (determined in *ACRU* as a fraction of the amount of groundwater in storage) occurs. The flow diagram for the above description is presented in Figure 5.2. The major assumptions of the above method of estimating seepage from a surface reservoir are that

- the equations assume that seepage occurs through the bottom of the reservoir only in the vertical direction and that the sides of the reservoir are impenetrable,
- the surface area of the reservoir is assumed to be the surface through which seepage takes place, and
- since both the hydraulic conductivity and thickness of the clogging layer may be difficult to obtain, the two are combined as the hydraulic impedance.

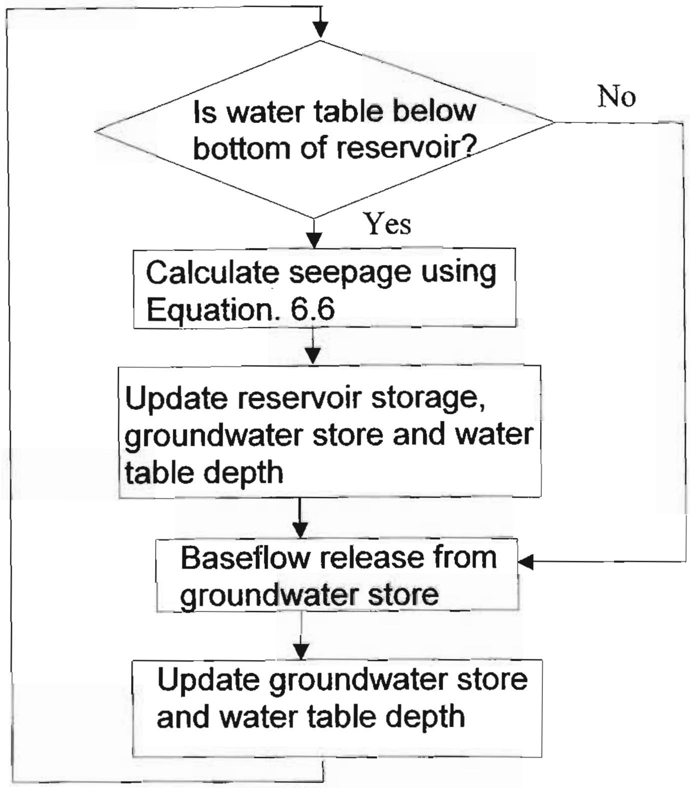


Figure 5.2: Flow diagram for estimating reservoir seepage

The data objects created for the purpose of the modification are listed in Table A4 of Appendix B and include *DHydraulicImpedance*, *DSurfaceReservoirDepth* and *DDepthCapillaryFringe* for storing the values of the hydraulic impedance, depth of the surface reservoir and depth of the capillary fringe respectively. The *PDamSeepageOlufemi* Process and its relationship with other Class objects are depicted in Figure 5.3.

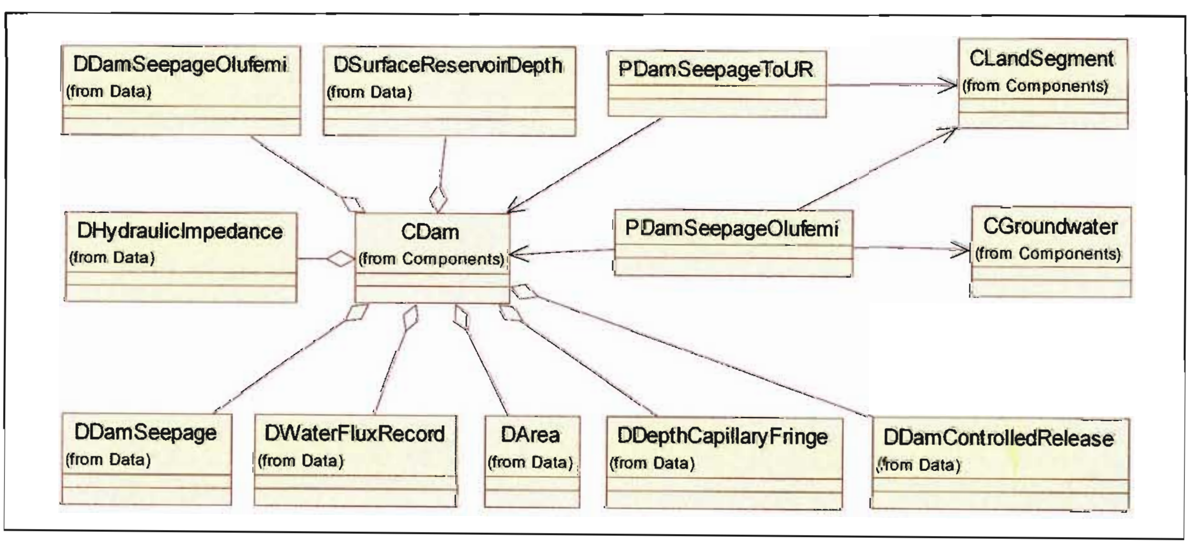


Figure 5.3: Class diagram of the *PDamSeepageOlufemi* Process and other associated Class objects

A particular condition (as encountered in this study) may occur in which a coal bed occurring within the rock layers underlying a surface reservoir has been mined, thereby creating an underground mined-out area beneath the surface reservoir into which water from the reservoir can seep. Another Process, *PDamSeepageToUR*, has been created in this study to deal with this particular condition. The *PDamSeepageToUR* Process transfers an estimated amount of seepage from a surface reservoir into an underground reservoir that may be underlying the surface reservoir. Underlying this Process is the assumption that for a surface reservoir that is underlain by an underground reservoir (i.e. an underground mined-out area), some amount of water will drain directly from the surface reservoir, through the rock layers underlying the surface reservoir, into the underground reservoir. The Data object, *DSeepageOlufemi*, was created for storing the amount of water estimated to be involved in the movement of water through the aquifer into the underground reservoir.

5.1.1.2 Mine-pit reservoirs

Mine-pit reservoirs are specific to opencast mining environments and they are considered as special surface reservoirs in this study. They represent bodies of water that accumulate in opencast pits in mining window areas. A typical example of a water body in an opencast mine-pit in Kleinkopje Colliery is shown in Figure 5.4.

Figure 5.4: An example of accumulation of water in an opencast pit in Kleinkopje Colliery (photo by O. Idowu 26/06/2005)

Four sources of water may accumulate in the mine-pit reservoir. They are:

- rainfall,
- seepage into the pit of groundwater from aquifers adjacent to the pit,
- runoff into the pit from adjacent areas sloping towards the pit, and
- water that is employed in the dousing of fire resulting from the burning of coal on exposure to the air or water used for dust suppression.

Water losses from the mine-pit reservoir result from the following:

- evaporation,
- pumping of water from the pit in order for opencast mining to proceed unhindered, and
- seepage of water from the pit into streams and the underlying aquifers.

Based on observations in nine opencast collieries in the Olifants Catchment, Hodgson and Krantz (1998) listed the sources of water in a mine-pit as a function of the average annual rainfall or total ingress of water into a pit (Table 5.2).

Table 5.2: Water recharge characteristics for opencast mining in the upper Olifants basin (Hodgson and Krantz, 1998)

Sources which contributes water	Vol. of water as percentage of rainfall	Suggested average values
Rain onto ramps and voids	20-100% of rainfall	70% of rainfall
Rain onto unrehabilitated spoils (runoff and seepage)	30-80% of rainfall	60% of rainfall
Rain onto levelled spoils (runoff)	3-7% of rainfall	5% of rainfall
Rain onto levelled spoils (seepage)	15-30% of rainfall	20% of rainfall
Rain onto rehabilitated spoils (runoff)	5-15% of rainfall	10 of rainfall
Rain onto rehabilitated spoils (seepage)	5-10% of rainfall	8% of rainfall
Surface runoff from pit surroundings into pits	5-15% of total pit water	6% of total pit water
Groundwater seepage	2-15% of total pit water	10% of total pit water

Seepage into the pit emanates from two sources. The first is the aquifer encountered during opencast mining. Seepage from such an aquifer occurs because of the hydraulic gradient in the direction of the pit due to the drawdown effected by pit dewatering. In the case of weathered aquifers associated with weathered zones that occur within a few metres below surface in the study area (Hodgson and Krantz, 1998), the amount of this seepage will be dependent on the amount of precipitation, saturated aquifer thickness and the hydraulic characteristics of the aquifer. Seepage, however, can also be from fractures in the unweathered rocks, which may be encountered at depth in the mining depth profile, and from the coal seam itself. This seepage from surrounding fractured rock as a percentage of the total amount of water in the pit is typically very small in collieries located in the Upper Olifants Catchment (Hodgson and Krantz, 1998). This is because the Ecca rock yields very little water and seepage is mainly from the upper weathered aquifer, which is recharged by rainfall. The second source of seepage into an opencast mine-pit is the water from rainfall, which moves through the spoil and percolates into the pit (Figure 5.5). The amount of this type of seepage depends on the percentage of rehabilitated spoils and the kinds of rehabilitation carried out. Unrehabilitated spoil heaps form a part of the disturbed areas within an opencast mine. The spoil heaps usually have high rainfall recharge potential due to the coarse nature of the porous medium (Hodgson and Krantz, 1998). If the unrehabilitated spoils cover a large area, a considerable amount of rainfall can penetrate into the spoil without much obstruction and appear as seepage in the pit (Figure 5.5). As much as 80% of rainfall onto unrehabilitated spoils can find its way into the pit (Table 5.2). Surface runoff from the surrounding areas is usually diverted away from the opencast pits by cut-off trenches. However, despite the precautionary measures, some surface runoff still enters the pits. An average of 6% of the total water in mine pits located in the Upper Olifants basin has been reported as coming from the surface runoff from the surrounding areas of the opencast pits (Table 5.2).

The *PMinePitDamSeepage* Process determines the amount seepage into a mine-pit reservoir. This separate Process is created for the determination of the seepage because of its uniqueness to a mine-pit reservoir. Other water movement into and out of the reservoir, such as transfer of water into it from other land segment components, precipitation onto the reservoir water surface and evaporation, are as originally determined by the reservoir yield analyses in *ACRU2000*.

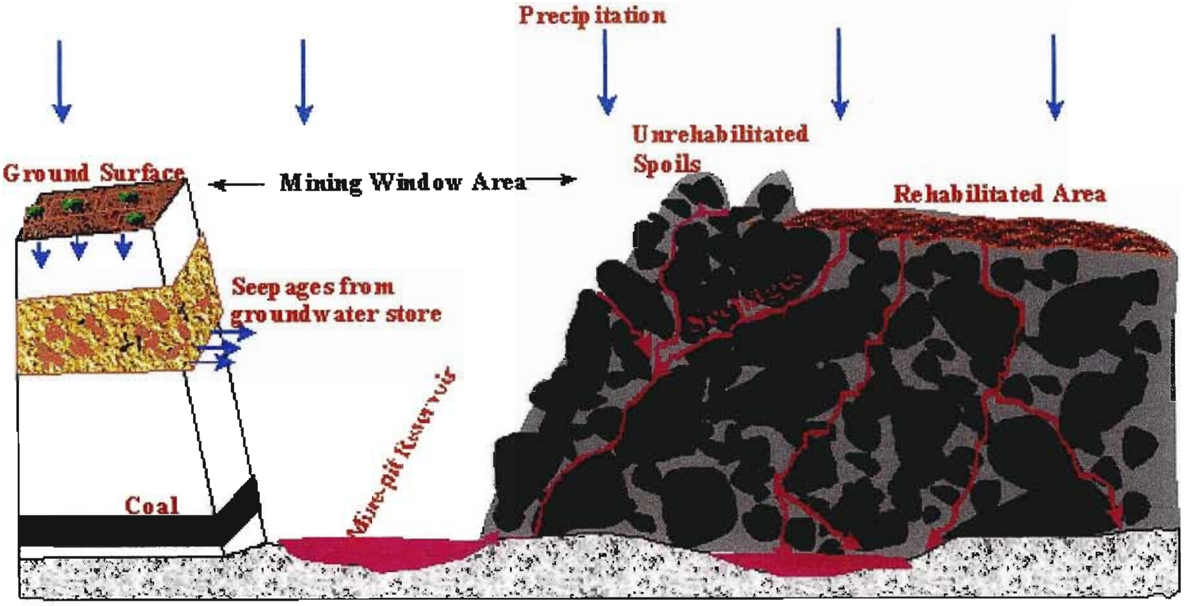


Figure 5.5: A diagram of a mine-pit reservoir showing seepage into it

The potential seepage into the reservoir from the aquifer encountered within the total mining depth is determined by the *PMinePitDamSeepage* Process, using Equation 5.8. The equation is a form of Darcy's law that takes into consideration the fact that the seepage is through the cross-sectional area of the aquifer through which water seeps into the pit (Todd and Mays, 2005).

$$Q_s = K_{aq} i A_s \qquad (5.8)$$

where

Q_s = seepage amount (m^3/day),

K_{aq} = hydraulic conductivity of the aquifer (m/day),

i = hydraulic gradient (dimensionless), and

A_s = seepage area of the aquifer into the mine-pit reservoir (m^2).

The actual seepage will depend on not only the hydraulic gradient, hydraulic conductivity and cross-sectional area through which water seeps into the pit as in Equation 5.8, but also on the actual amount of water in groundwater storage. The data objects created for this process are listed and described in Table A4 of Appendix B. The amount of seepage is stored in the *DSeepToMinePitDam* Data Object created for the purpose. Groundwater storage in *ACRU* is dependent on saturated vertical drainage/recharge from the subsoil horizon into the groundwater store, from which baseflow may be generated. *ACRU* therefore conceptualises groundwater storage as being unconfined (or leaky) and dependent on the percolation of water through the soil profile to the water table, in which case, the seepage area may be limited to the saturated thickness of the aquifer only. The *PMinePitDamSeepage* Process therefore does not determine the seepage that may be associated with a confined aquifer within the mining profile or the coal seam. However, such seepage, when determined, can be included in the water budgeting of the mine-pit reservoir by considering it as "pumped water" into the reservoir. The seepage from the aquifer adjacent to the reservoir has been conceptualised as coming from the groundwater of the land segments adjacent to the ones in which the mine-pit reservoir is located. This is in fact so, as the cutting face of the land segment in which the mine-pit is located, is conceptualised as forming the boundary of that land segment. The *PMinePitDamSeepage* Process was therefore created to accept any number of land segments indicated in the land segment menu file as the sources of seepage into the pit. A Data Object, *DMinePitDamSeepLandSegList*, was created for the input of an array of land segments considered as sources of seepage water into the pit. Therefore, depending on the configuration of the area being simulated, as many land segments as considered appropriate, can be entered into the land segment menu. The choice of land segments, however, should be guided by the direction of ground water flow, as may be indicated by the water table contours or topography, and the proximity to the mine-pit reservoir. Equation 5.8 requires information on the area of seepage into the reservoir. The *PMinePitDamSeepage* Process determines the area as the product of the mining window distance (length) and the average height of the groundwater in storage in all the listed land segments contributing to the pit. The *PMinePitDamSeepage* Process determines average height of groundwater in storage internally by dividing the total amount of water in storage in all the contributing land segments by their total area. After the determination of the amount of seepage into the pit by Equation 5.8, the *PMinePitDamSeepage* Process then deducts the amount of seepage into the pit from the groundwater in storage in the indicated land segments, in proportions commensurate with each of the indicated land segment's area.

The second source of seepage into the mine-pit reservoir is from the movement of water through the spoils into the pit (Figure 5.4). This seepage has two components and both are within the same land segment in which the mine-pit reservoir is located. The first is from the area that contributes runoff directly into the reservoir. This area is usually constituted by unrehabilitated spoil material behind the operating cut of the dragline. This area has a high rainfall recharge potential as rain water usually penetrates into the spoil without much obstruction (Hodgson and Krantz, 1998). The amount of seepage from this area is therefore dependent on the percentage of the whole land segment constituted by the unrehabilitated spoil material. This amount of contribution into the reservoir is determined by stipulating the percentage of the whole land segment occupied by the unrehabilitated spoil, through which direct contribution of runoff into the reservoir can take place (i.e. PCCDAM in the land segment menu). An input Data Object, *DDamCatchmentPercent*, had already been created in *ACRU2000* for this purpose. Considering the high rate of rain water penetration through spoils, the *PMinePitDamSeepage* Process has been constructed in such a way that all of the water which goes into groundwater storage in the area stipulated in the land segment menu as contributing runoff directly into the reservoir, ends up in the reservoir. The second component of seepage through the spoil into the mine-pit reservoir comes from the remaining part of the land segment which has been rehabilitated. Rehabilitation in an opencast mining area is usually carried out in such a way that no surface flow goes into the pit. However, part of rainfall which infiltrates the rehabilitated area and drains though the soils into groundwater storage can seep through the spoils underlying a rehabilitated area into the mine-pit reservoir. This was taken into consideration in this study by creating a Data Object, *DSeepFraction,* which *stores* the fraction of the amount of groundwater in storage constituted by this type of seepage. Therefore, the seepage is determined as a fraction of the amount of the groundwater store of the rehabilitated land segment in which the mine-pit reservoir is located. The fraction is specified by the user in the land segment menu and the *PMinePitDamSeepage* Process multiplies the fraction with the amount of groundwater store in order to determine the amount of seepage into the pit. The Data Object, *DSeepFromSameLandSegToMineDam* stores the amount of seepage. In case an irrigated area exists within the rehabilitated land segment, the same fraction of the amount of water in ground store as specified by the user is calculated and then made to occur as seepage into the reservoir. The *PMineSeepage* Process and its associated Class objects are depicted in Figure 5.6.

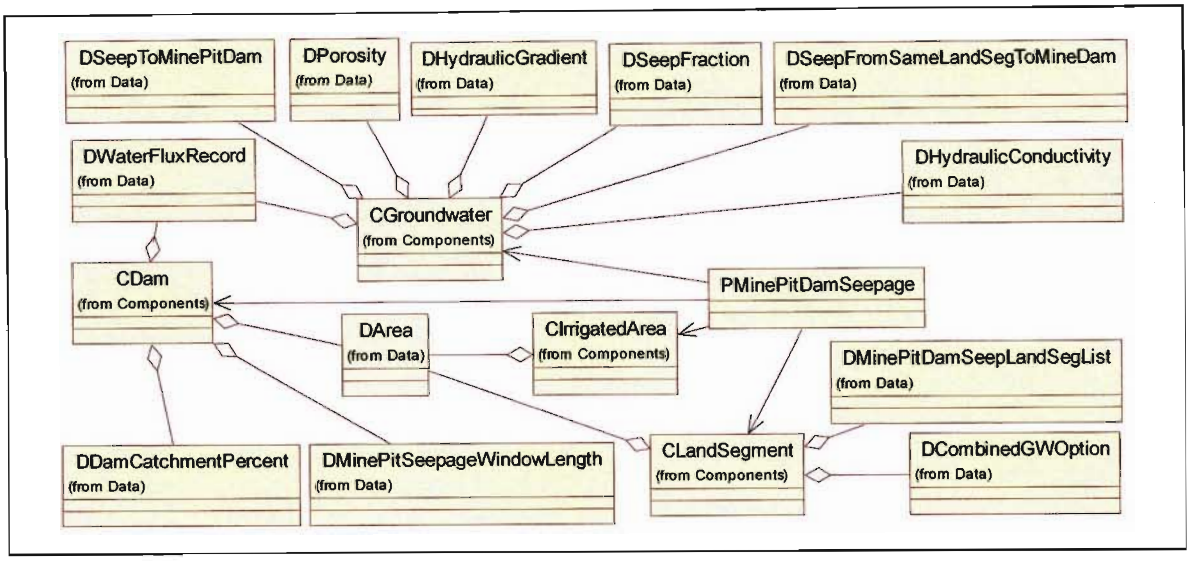


Figure 5.6: Class diagram of the *PMinePitDamSeepage* Process and other associated Class objects

5.1.1.3 Controlled Releases

Controlled releases from coal mines are permitted during periods of high flow conditions, as explained in Section 3.3. The occasional releases are from reservoirs in which mine waters are stored. It is, therefore, necessary to include the amount of controlled water released into the reservoir water budgeting of *ACRU2000*. This is done in this study by creating a separate Process called *PDamControlledRelease*. The process obtains the amount of water released (in m^3) from a surface reservoir on a daily basis from the hydrometerological file where the date and the corresponding amounts of water released can be entered by the user. It then subtracts the amount of the controlled release from the current reservoir water storage and transfers it to the downstream reach. The *PMinePitDamSeepage* Process neither predicts nor determines the amount of controlled release that should be taken from a reservoir and it is therefore not based on any rule. The user needs to specify the amount of release using the historic record of such releases, which is then taken inconsideration in the reservoir water budgeting. The amount of controlled release is stored in the *DDamControlledRelease* Data Object created for the purpose.

5.1.2 Water Transfers

In *ACRU*, water can be transferred into and out of a dam from a land segment other than from the one being modelled. This is presently carried out by *PDamPumpIn* and *PDamDraftRequirement* Process objects in conjunction with the *PWaterTransfer* Object. The total water transferred for a month, which is entered by the user into the menu file, is converted to constant daily amounts for that month by dividing the amount entered by the number of days in the month. Transfer of water from one part of a mine to another is very common and usually constitutes an important part of water management strategies. The transfer into a reservoir, for example, can vary considerably from day to day and be from different sources with significant differences in salinity levels. *ACRU2000* is not presently structured to adequately handle multiple transfers of water from different sources into a surface reservoir. Consequently, a modification was carried out to enable multiple transfers of water into a surface resevoir. The *PMineDamPumpIn* Process object allows transfers of water from six different sources into a surface reservoir. The water transfers from each of the six sources, as entered by the user in a daily time series data, is added to the current water volume in the dam for budgeting purposes. The *PMineDamDraftRequirement* Process enables water withdrawn from the reservoir to be taken into consideration in reservoir water budgeting. The total amount of water withdrawn, which is entered by the user as a daily time series data, is subtracted from the current water storage in the reservoir. The *DMineDamDraft* object stores the daily values. The switch for enabling this modification is stored in the *DMineDamWaterTransferOption* Data Object.

5.1.3 Spring Discharge

Consideration of the occurrence of springs in an area being simulated has been incorporated into *ACRU2000*. Springs are formed when groundwater emerges from the ground surface as a result of one or more of the following (Raghunath, 1987):

- when an impermeable bed, overlain by a permeable bed, intercepts the sloping surface of the natural ground or hill side;
- when a sloping permeable bed is interrupted by a dyke;
- when a sloping bed is interrupted by an impermeable bed due to the presence of a fault; or
- when the natural slope of the ground surface intercepts the water moving along the interconnected joints or solution channels present in a rock.

The spring discharge, as conceptualised in this study, either joins the streamflow and flow out of the area being simulated or joins a surface reservoir, which can be internal or external. The *PSpringFlow* Process object is responsible for transferring water, which occurs as spring discharge, from the groundwater store of an irrigated or non-irrigated area, either to a surface reservoir or to the runoff from a land segment area. The discharge has to be entered as a measured discharge by the user. The *DSpringFlow* Data object stores the daily amount of measured spring discharge while the *DSpringFlowOption* Data object switches the option on or of. When switched on, the amount of water occurring as spring discharge for the day is converted to a depth by dividing the amount of spring discharge with the area of the catchment. The depth is then subtracted from the groundwater store of both the irrigated and non-irrigated area in amounts commensurate to their respective areas, before being added to the water in a surface reservoir or made to join the runoff from the land segment area.

5.1.4 "Saturated" Drainage Water Movement

In *ACRU*, "saturated" drainage is defined as the amount of soil water in excess of the drained upper limit that drains out of a soil horizon (Schulze *et al.*, 1995b). The water in excess of the drained upper limit in the topsoil and subsoil horizons drains into the subsoil horizon and below the root zone into groundwater store respectively. In *ACRU2000*, the saturated drainage water movement in a non-irrigated area was carried out by two Process objects - *PABResponse* and *PBFResponse*. The *PABResponse* describes the movement of water from the topsoil horizon into the subsoil horizon while the *PBFResponse* describes movement of water from the subsoil horizon into the groundwater store. The two Processess have recently been combined in the *PSatDownwardFlow* (Thornton-Dibb *et al.*, 2005). In an irrigated area, the "saturated" drainage process is carried out by the *PIrrigSubSurfaceFlow* Process object. In this study, both the *PSatDownwardFlow* and the *PIrrigSubSurfaceFlow* objects have been modified to include an option for the combination of the groundwater in an irrigated area with that in the non-irrigated area. Because the non-irrigated and irrigated areas are modelled as different spatial components in *ACRU2000*, when water of high salinity for example, is used for irrigation, the salinity of the water involved in the "saturated" drainage process is similarly high and reflected eventually in the salinities of soil water and groundwater. As groundwater is not static and its movement dependent on the hydraulic gradient, mixing of the groundwater from the irrigated and non-irrigated areas occurs and leads to the dilution of the salinity of the groundwater associated with the irrigated area and increase in the salinity of the whole land segment groundwater body. For this reason, an option has been added to *ACRU2000* in which the groundwater from both the non-irrigated area and the irrigated can be combined and baseflow generated from the resulting groundwater in terms of both quantity and quality. The option may be activated if the global effect of irrigation on the groundwater of the whole land segment is desired. The switch for the option is stored in the *DCombinedGWOption* Data object. When the option is switched on, the "saturated" drainage that should go into groundwater storage of an irrigated area mixes with the groundwater of the non-irrigated area, after which the baseflow for the whole land segment area is generated. As groundwater is stored in terms of depth in *ACRU2000*, the incremental amount of drainage into groundwater of the irrigated area involved in the mixing, is in terms of the total areas of the irrigated and non-irrigated areas, as expressed in Equation 5.9. The incremental drainage into the groundwater of the non-irrigated area is similarly stored in terms of the total area of both the irrigated and non-irrigated land segment areas using Equation 5.10. The total incremental drainage into the groundwater of the whole land segment is calculated using Equation 5.11. The total groundwater in storage for the whole land segment and from which baseflow is generated is the addition of the previous day groundwater in storage and the total incremental drainage into groundwater.

$$T = S_{irr}/(A_{irr} + A_{non\text{-}irr}) \quad (5.9)$$

where

T = the amount of groundwater from the irrigated area involved in the mixing (m);

S_{irr} = incremental drainage into the groundwater of an irrigated area (m^3);

A_{irr} = area of the irrigated area (m^2); and

$A_{non\text{-}irr}$ = area of the non-irrigated area (m^2).

$$G = S_{non\text{-}irr}/(A_{irr} + A_{non\text{-}irr}) \quad (5.10)$$

where

G = the amount of groundwater from the non-irrigated area involved in the mixing (m); and

$S_{non\text{-}irr}$ = incremental drainage into the groundwater of a non-irrigated area (m^3);

Total incremental drainage into groundwater in storage = $T + G$ (5.11)

5.1.5 Underground Reservoirs

In order to take into consideration the presence of underground reservoirs in the study area, a new component, referred to as *CUndergroundReservoir*, has been added to *ACRU2000*. The new component is the hydrological representation of underground reservoirs, which contain water stored or that occurs in underground mined-out areas. Gains to the underground mined-out area are groundwater leakages from the surrounding aquifers and the water transferred into underground reservoir for storage, while losses are made up of water abstracted from the reservoir (e.g. for irrigation), seepage away from the reservoir, decants when the reservoir is full and the amount of controlled release that may be carried out. In the study area, the underground mined-out areas lie below the aquifers so that groundwater drains from the overlying strata into the mined out area (Hodgson *et al.*, 2001). In the conceptualisation of the underground reservoir within *ACRU2000* therefore, it is assumed that the water that is in the groundwater storage can drain into the underground reservoir for storage.

A number of Data and Process objects store the attributes and describe the processes associated with *CUndergroundReservoir*. New attributes (Data objects) are created for the new component, while it also makes use of existing data objects in *ACRU2000*. The new attributes are listed and described in Table A5 of Appendix B. The existing attributes in *ACRU2000* used by the new component include *DWaterFluxRecord*, *DDamSeepage*, *DDamFullCapacity* and *DArea*. The main Process objects created for the purpose of water budgeting in *CUndergroundReservoir* include *PLeakageInput* and *PURWaterBudget,* while those for salt budgeting include *PUndergroundReservoirCompSalinity*, *PURSaltUptake*, *PURSaltDecay* and *PURSaltStacking.*

Underground reservoir water budgeting is carried out by the *PURWaterBudget* Process in conjunction with the *PLeakageInput* Process. The *PLeakageInput* Process determines the leakage into the underground reservoir from the overlying aquifers and then transfers it to the *PURWaterBudget* Process, which determines the current storage in the underground reservoir based on other inflows and outflows. The determination of the leakage is placed in a separate process (*PLeakageInput*) in case a change is required in future in the expressions describing this process. In this way, changes to the leakage estimation process will have no effect on any of the other processes. Considering the nature of groundwater and underground reservoirs occurrence in the study area (the underground reservoirs are below the aquifers), a simple technique of estimating leakage into underground reservoirs is employed in this study. The process includes estimating the vertical leakage of water from the overlying aquifer, through a layer of rock, into the reservoir. The situation in which groundwater from the overlying aquifer flows through a permeable layer of rock into the reservoir can be likened to a case of an aquifer underlain by a semi-permeable strata (referred to as a leaky aquifer) through which leakage occurs into an underlying aquifer (Figure 5.7).

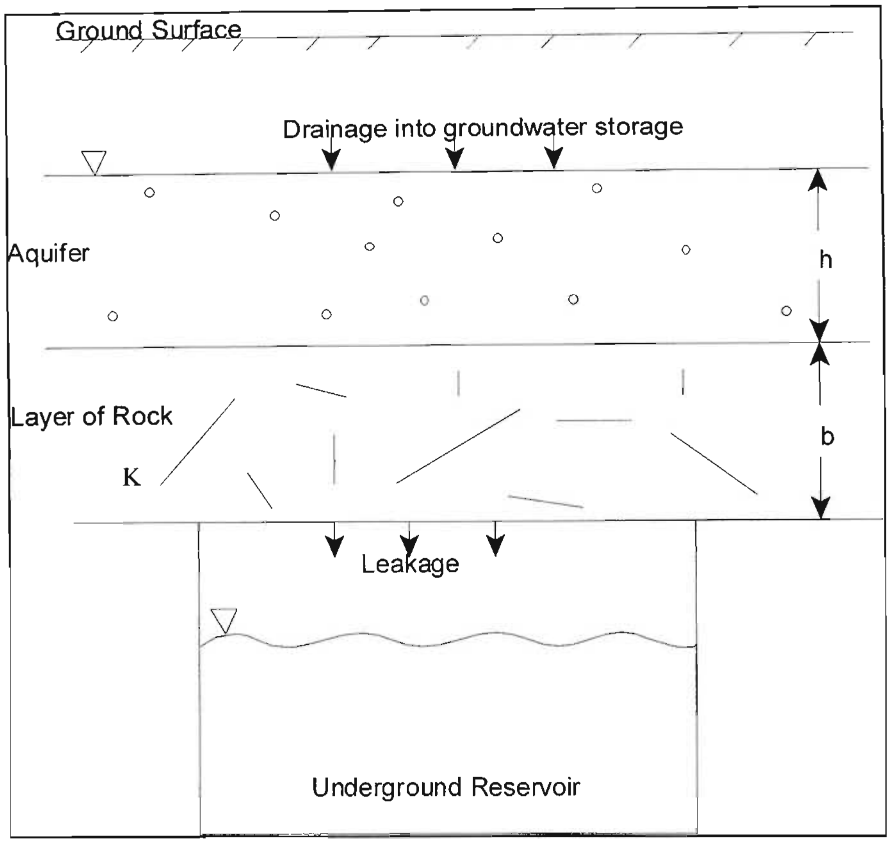


Figure 5.7: A diagram showing leakages into an underground reservoir

The vertical percolation rate of water through the layer rock underlying the aquifer into the underground reservoir is a scalar discharge per unit area, which is computed directly from Darcy's Law using Equation 6.12, on the assumption that changes in storage in the layer underlying the aquifer are neglected (McWhorther and Sunada, 1984).

$$W = K_r \, h_g / b \qquad (5.12)$$

where

W = is the vertical percolation rate (m/day),

K_r = hydraulic conductivity of the layer of rock below the aquifer (m/day),

b = thickness of the layer through which percolation/leakage occurs (m), and

h_g = depth of groundwater store (m).

The symbol b represents the vertical distance from the bottom of the aquifer to the top of the underground reservoir. Therefore, K_r/b is taken as the hydraulic impedance of the soil or rock materials overlying the reservoir through which leakage takes place. The vertical leakage from the aquifer, through the rock layer separating the aquifer and underground reservoir, is determined using

$$Q_{ur} = WA_{ur} \tag{5.13}$$

where

Q_{ur} = leakage into the underground reservoir (m^3/day), and

A_{ur} = area of the underground reservoir roof (m^2).

Leakage determination by *PLeakageInput* takes into consideration the amount of water in groundwater storage, which is influenced by the amount of drainage (recharge) from the subsoil horizon into the groundwater store as structured in *ACRU2000*. The amount of groundwater store is defined by *h* in Equations 5.12. The equations are confirmed by the observations of Hodgson *et al.* (2001) which show that the factors which control influx of water into underground areas in Mpumalanga area are the hydraulic conductivity of the rock and the rate of groundwater recharge. The Darcian flow assumed for the determination of leakage of water into underground mined-out areas in this study may not be valid in a case where faults, fractures and fissures are very common; in which case, non-Darcian flow may predominate. However, the natural tendency of sealing of fissures by disintegrated argillaceous materials, such as shale and mudstone which are common in South African coalfields (Hodgson *et al*, 2001), may limit such effects. In addition, the level of complexity of the Darcian approach, which is commensurate with other process representations in *ACRU2000*, adequately describes the geology of the coalfields.

After leakage determination, the *PURWaterBudget* Process updates the amount of water in the groundwater store by subtracting leakage from it. It is from the amount left of the groundwater store that the baseflow is generated through the coefficient of baseflow response. The coefficient of baseflow response is therefore the fraction of water from the groundwater store that becomes streamflow on a particular day (Schulze, 1995c). Similarly, the current amount of water in the reservoir is updated by adding the leakage. The leakage is added to the reservoir's current capacity only if the current amount of water in the reservoir is lower than the stipulated capacity of the reservoir. If the addition of the leakage volume would result in the reservoir store being greater than its capacity, then, the leakage becomes overflow and is transferred, along with seepage, to a decanting location specifiable by indicating the relevant component into which it should occur. The seepage is calculated as a fraction of the updated volume of water in the reservoir, using a seepage coefficient as follows:

$$S = c*V \qquad (5.14)$$

where

S = seepage from the underground reservoir (m^3),

c_s = coefficient of seepage (dimensionless), and

V = updated volume of water in the underground reservoir (m^3).

The current volume of the reservoir is updated again once the amount of seepage has been subtracted from the volume of water in the reservoir. The flow diagram for underground reservoir water budgeting is shown in Figure 5.8. The daily update of the water stored in the underground reservoir includes the amounts of water that may be transferred into the reservoir for storage and the amount that may be abstracted for different uses, such as irrigation and water treatment.

Two additional component objects, *CURPumpInSource* and *CURDraftSink*, were created for the purposes of transferring and abstracting water and salts to and from an underground reservoir. The *CURPumpInSource* represents components external to the system being modelled that provides water or salts imported into the underground reservoir while *CURDraftSink* represents components external to the system being modelled that receives water or salts exported from the simulated system. The daily transfer or abstraction of water from the underground reservoir is carried out by the user stipulating the amounts in a daily data series, which are then stored in their respective data objects and aggregated to *CURPumpInSource* and *CURDraftSink* respectively. In the *PURWaterBudget*

Process, the daily transfer is taken from the *CURPumpInSource* and added to the current water store in the underground reservoir while the daily abstraction is subtracted from the volume in storage in the underground reservoir and added to the *CURDraftSink* component object. The two component objects are therefore used as artificial storage components for managing the input and removal of water and salts from the underground reservoir.

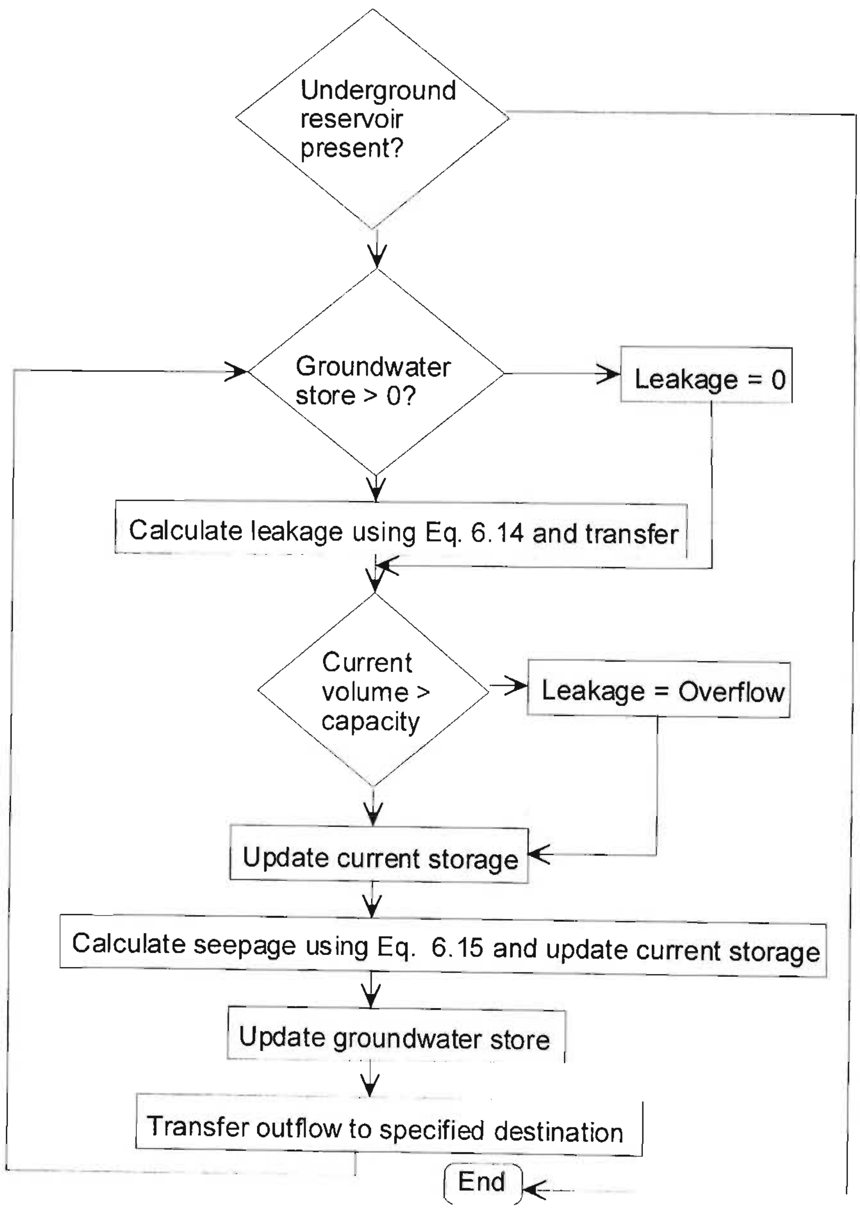


Figure 5.8: Flow diagram representing underground reservoir water budgeting

In conjunction with the CWaterTransfer object, which already exists in *ACRU2000* for surface reservoirs, the *PURWaterBudget* Process enables irrigation water to be abstracted from the underground reservoir and transffered to *CIrrigationSystem* (also already existing in *ACRU2000* for irrigation water application), from where the water is applied to an irrigated area. The *PLeakageInput* and *PURWaterBudget* Processes take into consideration the possible occurrence of an irrigated area that is underlain by an underground mined-out area by applying the same process of leakage determination and water budgeting in the underground reservoir, described for a non-irrigated area above, to an irrigated area. The underground reservoir water budgeting does not include subterranean flows between mines as these would require the determination of the amount of flows involved, the groundwater flow paths and migration routes, as well as the interconnectivity between adjacent mining operations, all of which are beyond the scope of this study.

In addition to the Process and Data objects created for the incorporation of an underground reservoir into *ACRU2000*, the following existing Control Objects in *ACRU2000* have been modified to include the possibility of occurrence of an underground reservoir in a land segment area being modelled: *AOldNewAcruVariableReference*, which maps all *DData* object class names to their acronym for input and output purposes; *AAcru2000StandardComponents,* which decides on the components of the area being modelled to set up as stipulated by the user; *AOldFormatStandardInput,* which provides and coordinates access to user inputs with similar text file format to that of the earlier versions of *ACRU*; and *AAcru2000StandardProcesses,* which contains and arranges all Process objects, and decides on which processes to set up and run for an area being modelled (Clark *et al.*, 2001b).

The *PURWaterBudget* Process allows the destination of natural outflows from an underground reservoir to be specified. This allows due consideration to be given to the location of the decanting point or destination of water emanating from the reservoir, which may not necessarily be the downstream reach. The destination may depend on the interconnectedness of the subterranean mined-out areas, the hydraulic gradient and the topography of the area being simulated. A String Data object, *DUndergroundResWaterDest*, stores the destination of the natural outflow from the reservoir, which is input in the land segment menu file. Any natural outflow from the underground reservoir, such as seepage, controlled release and spill flow, are transferred to the water store of the component represented by the specified destination. The possibility of controlled release from an underground reservoir was also incorporated into the water budgeting process of an underground reservoir. The *PURWaterBudget* Process obtains the amount of controlled water released (in m^3) from an underground reservoir on a daily basis from the hydrometerological file, where the date and the corresponding amounts of water released is entered by the user. The amount is than subtracted from the current underground reservoir water storage and transferred to the specified destination. The Process neither predicts nor determines the amount of controlled release that should be taken from an underground reservoir. The user needs to specify the amount of releases using the historic record of such releases. The relationship of the underground reservoir with other Component and Process objects are depicted in Figure 5.9.

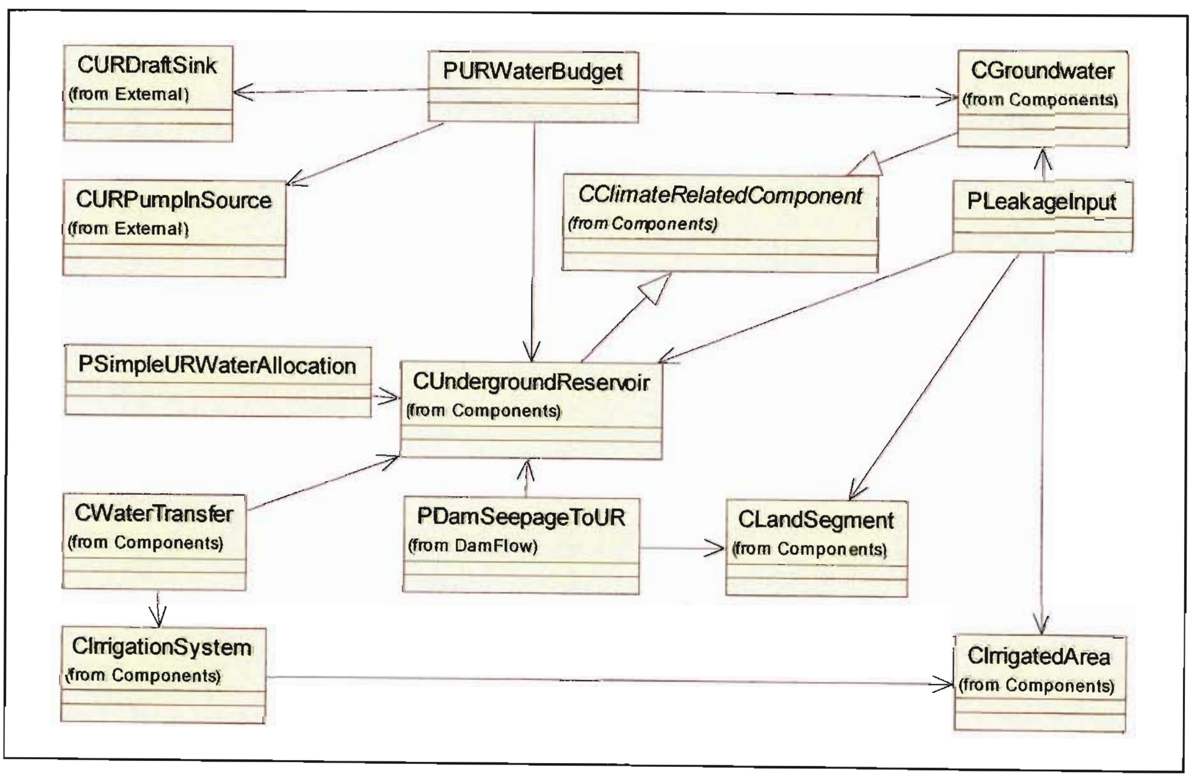


Figure 5.9: Class diagram of *CUndergroundReservoir* object and other Component and Process Classes objects

5.2 Modifications to *ACRUSalinity*

ACRUSalinity is the hydrosalinity module of *ACRU2000*. Presently, the surface reservoir salt budget routine in *ACRUSalinity* does not account for salt load transfers that accompany inter-catchment water transfers into and out of a surface reservoir. The inter-catchment transfer, or water transfer into and out of a surface reservoir, is already represented in *ACRU2000*. Within coal mines, water is usually moved between different water storage facilities (i.e. reservoirs). It is therefore important to take into account the salt loads which accompany such transfers for adequate water and salt balance assessment. The underground reservoir hydrological component is an entirely new addition to *ACRU2000*. Therefore, the budgeting of salt loads associated with it is also a new addition to *ACRUSalinity*. These are discussed in the following sections along with the other modifications carried out.

5.2.1 Surface Reservoir Salt Budgeting

A new Process, *PReservoirComponSalinityOlufemi,* is created in this study to carry out the surface reservoir salt budgeting computations. As in the original process in *ACRUSalinity* which carries out the salt budgeting computations (i.e. *PReservoirComponSalinity* described in Section A.2.2.3, Appendix A), the new process operates in conjunction with the *PSaltStacking* Process to determine the reservoir's current storage salinity and salt load as well as the TDS concentration of the various outflows from a surface reservoir system. However, the new process accounts for inter-catchment salt load transfers as well as the salt loads which accompany controlled releases and seepage out of a surface reservoir.

The average salt concentration of the water flowing into the surface reservoir (inflows) is given by the total load of salts flowing into the reservoir divided by the total volume of water inflow. The total load of salt inflow into the reservoir comprises salt loads from each of the inflow component into the reservoir, i.e. from the runoff flowing into the reservoir from both non-irrigated and irrigated areas, as well as the salt loads from direct rainfall onto the surface of the reservoir and that imported into the reservoir. The salt loads, in mg, are calculated for each inflow component by multiplying the component volume by the component concentration. Therefore, the average salt concentration of water inflow into the reservoir is given by the following equation:

$$Cin_i = \frac{(RUN_{ni} * C_{run\_ni}) + (RUN_{irr} * C_{run\_irr}) + (RFL_{dam} * C_r) + (RUN_{adj\_dam} * C_{run\_adj}) + (TRS_{dam} * C_{trs\_dam})}{I_{dam}} \quad (5.15)$$

where

Cin_i	=	average salt concentration of water flowing into the reservoir (mg/l),
RUN_{ni}	=	runoff flowing into the dam from non-irrigated lands (l),
C_{run_ni}	=	salt concentration of runoff from non-irrigated lands (mg/l),
RUN_{irr}	=	runoff from irrigated areas (l),
C_{run_irr}	=	salt concentration of runoff water from irrigated areas (mg/l),
RFL_{dam}	=	volume of rain falling on the reservoir surface (l),
C_r	=	rainfall salt concentration (mg/l),
RUN_{adj_dam}	=	runoff from adjunct impervious areas into the reservoir (l),
C_{run_adj}	=	salt concentration of runoff from adjunct impervious areas (mg/l),
TRS_{dam}	=	total water imported into the reservoir (l),
C_{trs_dam}	=	salt concentration of water imported into the reservoir (mg/l), and
I_{dam}	=	total water inflow to the reservoir on the day including rain falling on surface of the reservoir (l).

The difference of Equation 6.16 from the original equation, i.e. Equation A.6 in Appendix A, is in the addition to Equation 5.15 of the salt concentration and the total water imported into the surface reservoir from out of the catchment in which the reservoir is located. The salinities of the water imported into a dam are input data and can be entered as a daily time series data. In agreement with the possibility of importing water from six different sources into a surface reservoir, the salinity of each of the six sources can be entered separately as a daily data input. The Data objects created for storing the salinity values are *DMineDamPumpInSalinity (1- 6)* and they are listed and described in Table C3 of Appendix C along with the other Data objects created for surface reservoir salt budgeting. If water is imported into a dam from more than one source, the total salt load imported is determined as the sum of the product of the amount of water and the associated salinity concentration from each source. The salt loads associated with the six possible sources are stored in *DMineDamPumpInSaltLoad (1-6)*.

In terms of total salt outflow, *ACRUSalinity* has been modified to include abstraction salt load, the salt load associated with controlled releases from the surface reservoir and the salt load that may accompany the water movement from a surface reservoir into an underlying underground reservoir. The average outflow concentration value of the surface reservoir, as determined by the *PSaltStacking* Process, is assigned to the reservoir abstraction, as well as to the controlled release and the water outflow to an underground reservoir, with the corresponding salt loads computed as the product of the average outflow concentration of the reservoir and the volumes of abstraction, controlled release and flow into an underground reservoir respectively. To obtain the current reservoir salt load, the salt loads associated with abstractions and controlled releases, along with those associated with normal flow, spillway flow and seepage are subtracted from dam's salt load. However, unlike as was presently structured in *ACRUSalinity* where the seepage salt load can only be transferred to the downstream reach along with normal and spillway flows, in the *PReservoirComponSalinityOlufemi* Process, options have been created to enable the salt associated with seepage from the dam to be transferred either to the downstream reach, the groundwater or to an underground reservoir.

5.2.2 Mine-pit Reservoir Salt Budgeting

Salt budgeting in a mine-pit reservoir is similar to that described above in the surface reservoir. Indeed, the salt budgeting in a mine-pit reservoir and a surface reservoir are carried out by the same Process, *PReservoirComponSalinityOlufemi*. However, in the case of mine-pit reservoirs, salts which accompany the different seepage into a pit, as indicated in Section 5.1.1.2, are taken into consideration in the determination of the total salt inflow into the mine-pit reservoir. In addition, allowance is made for the deterioration of the water quality in a pit reservoir because of the dissolution of salts and oxidation of sulphide-bearing minerals that may be encountered during opencast mining. This is carried out by updating the salinity of the mine-pit reservoir after the *PSaltStacking* process has determined the average TDS concentration of the current storage on the basis of inflows and outflows from the reservoir. The *PMinePitDamSaltUptake* object updates the TDS concentration of water in a mine pit reservoir in the same way in which the salt concentration of the water of each soil layer and the groundwater are updated according to first-rate kinetics proposed by Ferguson *et al.* (1994). This mechanism has been explained in Section A.2.2.1 (Appendix A). The *DUptakeRate* and *DSaltSat*, already created for updating the salinity of water in the soil horizons and groundwater, and which store the rate constant and the equilibrium value respectively, are used in storing the relevant values for the mine-pit reservoir. For reasons of consistency and reality, the salt uptake rate and saturation constant can vary from month to month as with those for the soil layers and groundwater. The class diagram of the *PRervoirCompoSalinityOlufemi* Process for a mine-pit reservoir and the associated Component and Process objects are depicted in Figure 5.10.

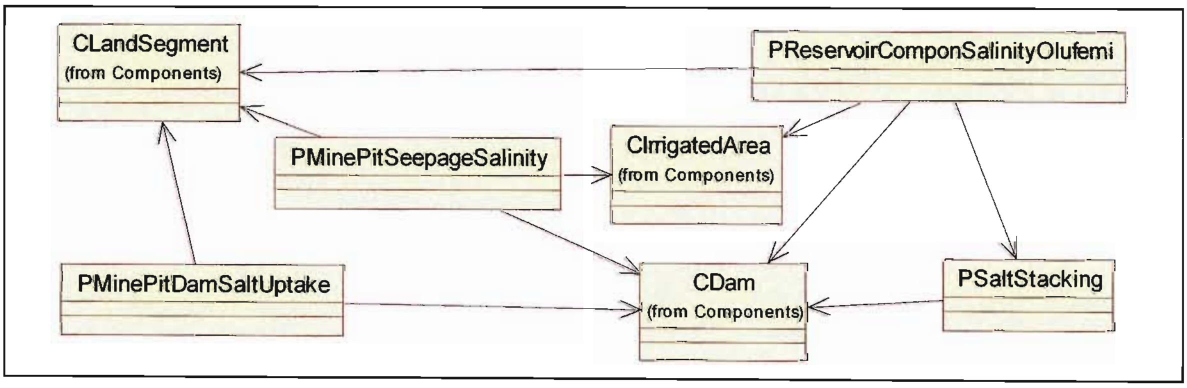


Figure 5.10: Class diagram of the *PRervoirCompoSalinityOlufemi* Process for a mine-pit reservoir and associated Component and Process Classes objects

5.2.3 Spring Discharge Salt Load

The *PSpringFlowSaltTra* Process is designed to represent the transport of the salt load associated with a spring flow in a land segment area. The process assigns the salinity of the groundwater in either an irrigated or non-irrigated area to the volume contributed by spring flow in either of them, as determined in the *PSpringFlow* Process, which has been explained in Section 5.1.3. The salt load is determined as the product of the respective groundwater salinities and the respective volume of spring flow. The process then assigns the salt loads to the destination points specified by the user i.e. either to an internal surface reservoir or to the runoff from the land segment.

5.2.4 Underground Reservoir Salt Budgeting

The underground reservoir salt budgeting computations are carried out by the *PUndergroundReservoirComponSalinity* Process in conjunction with the *PURSaltStacking*, *PURSaltUptake* and *PURSaltDecay* Processes created in this study. The *PUndergroundReservoirComponSalinity* Process and its relationships with other Component and Process objects are depicted in Figure 5.11. The *PUndergroundReservoirComponSalinity* Process supplies the main inputs for *PURSaltStacking*, *PURSaltUptake* and *PURSaltDecay* Processes. These inputs include total volume of water entering the underground reservoir and its salinity, as

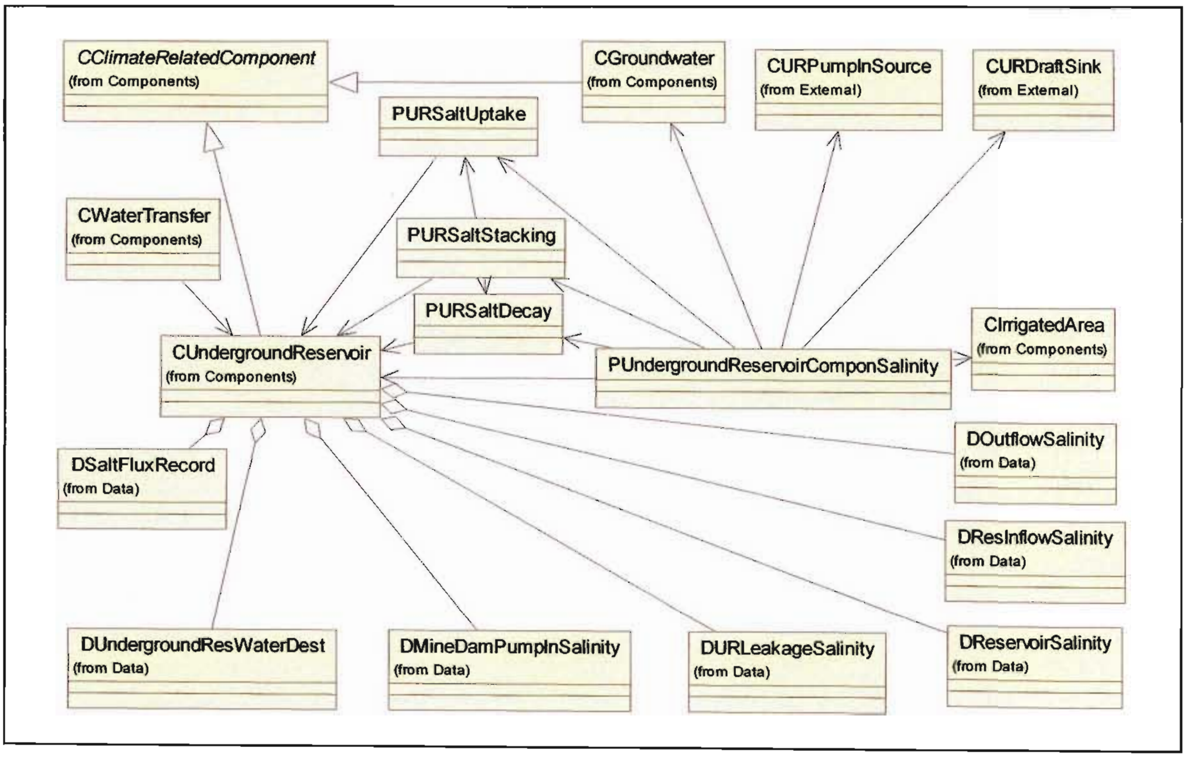


Figure 5.11: Class diagram of the *PUndergroundReservoirComponSalinity* Process and associated Component and Process objects

well as the total volume of water exiting. The total inflow comprises leakage from the overlying aquifers and the volume of water imported into the reservoir from another land segment area. The total outflow comprises the volume of water exported to another land segment from the reservoir, seepage, the amount of controlled release and the amount of overflow. In a case in which a reservoir exists on the ground surface with an underground reservoir occurring underneath it, direct seepage from the surface reservoir into the underground reservoir may occur. The salt load associated with this type of seepage also constitutes part of the total inflow into the underground reservoir. Therefore, the salt load that accompanies water inflow into the underground reservoir depends not only on the amount of groundwater in storage and its salinity, but also on the salinity and the amount of seepage from a surface reservoir existing above the underground reservoir. The average salt concentration of total inflow into an underground reservoir is the sum of salt loads divided by the inflow volumes. The salt loads, in mg, are calculated for each inflow component by multiplying the component volume by the component concentration. Thus, the average salt concentration of the total inflow, as determined on the assumption of thorough instantaneous mixing of the inflow components, is determined by Equation 5.16.

$$C_{in} = \frac{(L_{in} * L_{sal}) + (TR_{in} * TR_{sal}) + (RE_{in} * RE_{sal})}{(L_{in} + TR_{in} + RE_{in})} \quad (5.16)$$

where

C_{in} = average salt concentration of the total inflow into the reservoir (mg/l),

L_{in} = leakage volume into the reservoir (l),

L_{sal} = salt concentration of the leakage into the reservoir (mg/l),

TR_{in} = volume of water imported into the reservoir for the day (l),

TR_{sal} = salt concentration of the water imported into the reservoir (mg/l),

RE_{in} = seepage volume from overlying surface reservoir (l), and

RE_{sal} = salt concentration of seepage from the overlying surface reservoir (mg/l).

The *PURSaltStacking* Process determines average salt concentration of the reservoir for the day and the average salinity of the different outflow components based on the total volume of inflow and its salinity, the updated previous day average salt concentration of the reservoir as well as the total outflow for the day. The *PUndergroundReservoirComponSalinity* Process updates the previous day salt concentration of the reservoir using either the *PURSaltUptake* or *PURSaltDecay* Processes. The *PURSaltUptake* and *PURSaltDecay* Processes imitate the water quality evolution in the underground reservoir as it is based on the premise that the water salinity of the reservoir rises as the reservoir fills up due to pyrite oxidation and salts dissolution from the rocks in contact with the underground reservoir. After the reservoir is fully flooded, the salinity of water decreases in an exponential rate to an asymptotic level, due to the dampening of pyrite oxidation resulting from flushing of the underground reservoir with lower concentration water. The difference between the updated salt load and the salt load of the previous day is added to the salt load of current day along with the total salt load which accompanies the total inflow. The difference therefore represents the amount of salt generated as the reservoir fills up or the amount by which the salt load is dampened as a result of flushing of the underground reservoir after flooding. These mechanisms are explained in details in Sections 5.2.5 and 5.2.6.

The *PUndergroundReservoirComponSalinity* Process calculates the salt loads associated with the various outflow components as the product of the volume of water in the particular outflow component and salinity as determined by the *PURSaltStacking* Process. Thereafter, the current reservoir salt load is updated by subtracting the outflow component salt loads from the current reservoir salt load.

5.2.5 The *PURSaltUptake* and *PURSaltDecay* Process Objects

The water chemistry evolution of an abandoned underground mine is such that the salt concentration increases as the mined voids and the adjoining strata are gradually flooded and the water level rises in the mine, until a peak concentration is reached, after which the concentration decreases exponentially to an asymptotic level due to flushing (see Section 3.6.). Water quality evolution in mined-out areas is complex and is dependent on rock and mineral weathering which in turn are influenced by the complex formation and dissolution of salts; transient water flow conditions, and the kinds of water quantity and quality management strategies in place. Therefore, modelling the processes of water quality evolution in abandoned underground mines can be equally complex and may require the following (Hodgson *et al.*, 1985; Younger, 1995; Wood *et al.*, 1999; Herr *et al.*, 2003):

- A reliable archive of hydrochemical analyses of discharge,

- A knowledge of the local stratigraphy and the mining history,
- The ability to simulate the oxygen concentration in mined-out area since pyrite oxidation depends on the presence of oxygen,
- Specification of the availability of reactive minerals and the geometrics of reactive surfaces in the subsurface environment in order to turn mineral abundance data into reacting quantities,
- A representation of the formation and dissolution of acid-generating salts in the mined-out environments, with particular attention to dissolution and precipitation kinetics, and/or
- The ability to adequately model the inflow of water into the mine workings from overlying and adjacent sediments and also the discharge from it.

The above requirements and the data needed for them are beyond the scope of this research. In this research, a simplified approach to modelling the water quality in underground mine-out areas has been adopted. The approach is essentially based on salt concentration increase during the process of flooding and the decrease after flooding, processes which have been reported in various parts of the world in different underground mines. The Process Objects, *PURSaltUptake* and *PURSaltDecay*, are created in this study as part of the processes responsible for the determination of the salinity and salt load of water in an underground mined-out reservoir.

The *PURSaltUptake* Process addresses the update of the salinity of the water in the underground reservoir during the flooding period when an increase in water salinity occurs as the water level rises. The *PURSaltDecay* Process addresses the update of the salinity either after the mined-out voids are totally flooded or when the current day's volume of water in the mined-out area is the same as the previous day's, both of which cases are attended by a general decrease in the salinity of the reservoir water. The two processes operate using differential rate laws based on the first-order rate kinetics as proposed by Ferguson (1994). However, whereas *PURSaltUptake* has a growth function, *PURSaltDecay* has a decay function. The first-order rate kinetics assumes that the rate of increase in the concentration of a solute over time is proportional to how far the current concentration falls short of its equilibrium value. Consequently, the first-order rate kinetics equations used in *PURSaltUptake* and *PURSaltDecay* assume that the rates of increase or decrease in the concentrations of water in an underground reservoir are proportional to how far the current concentration falls short of an equilibrium value. In *PURSaltUptake*, the equilibrium value represents the peak value of the concentration of water in the underground reservoir at the end of flooding (Figure 5.12), whereas in *PURSaltDecay*, it represents the asymptotic minimum salinity of water in the reservoir after it has been fully flooded (Figure 5.13). Thus, the update of the water salinity by *PURSaltUptake* and *PURSaltDecay* are carried by Equations 5.17 and 5.18 respectively. The difference in two equations is that, whereas the updated salinity is always less than the peak salinity during salt uptake in Equation 5.17, in Equation 5.18, it is always more during the salt decay process. The relationships of the *PURSaltUptake* and *PURSaltDecay* Processes with various Data, Component and Process objects are depicted in Figures 5.14 and 4.15 respectively.

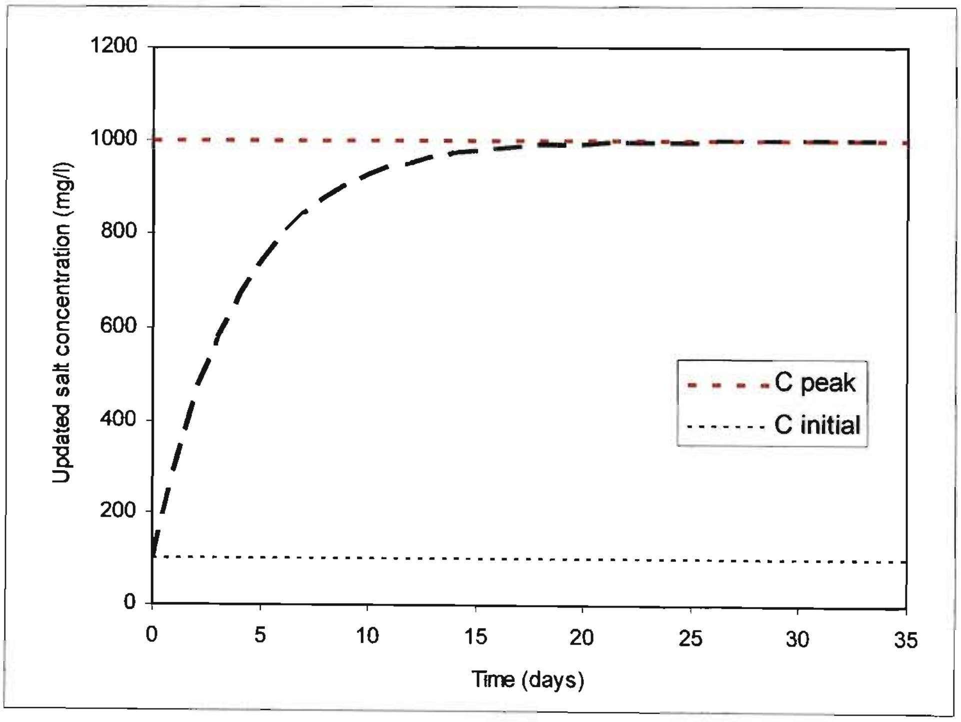


Figure 5.12: Illustration of the increase in the salinity of water in an underground reservoir to a peak as it is filling up, $k_{updated} = 0.25$

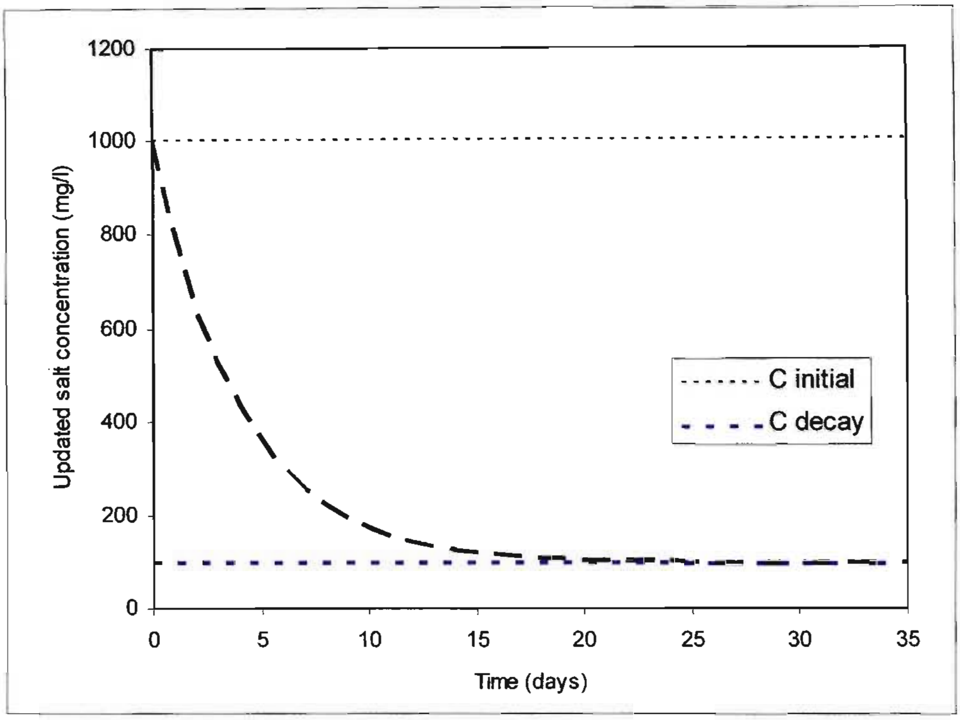


Figure 5.13: Illustration of the decrease in the salinity of water in an underground reservoir to an asymptotic value after the reservoir has been fully flooded, k_{decay}= 0.25

$$C_{updated} = C_{initial} + (C_{peak} - C_{initial})[1 - exp\ (-k_{uptake})] \quad (5.17)$$

$$C_{updated} = C_{initial} + (C_{decay} - C_{initial})[1 - exp\ (-k_{decay})] \quad (5.18)$$

where

$C_{updated}$ = updated salt concentration (mg/l),

$C_{initial}$ = salt concentration before salt generation or salt decay in Equation 5.17 and 5.18 respectively (mg/l),

C_{peak} = the equilibrium value, always more than $C_{initial}$, representing the peak salinity at the end of flooding (mg/l),

C_{decay} = the equilibrium value, always less than $C_{initial}$, representing the minimum asymptotic salinity after the reservoir had been fully flooded and flushed (mg/l),

k_{uptake} = rate constant during the salt uptake process, and

k_{decay} = rate constant during salt decay process

The assumptions under which the first-rate kinetics equations are adopted for the update of the salinity of water in an underground reservoir are the same with those assumed for the update of the TDS concentration of the topsoil, subsoil and the groundwater store as a result of salt generation (see Section A.2.2.1, Appendix A).

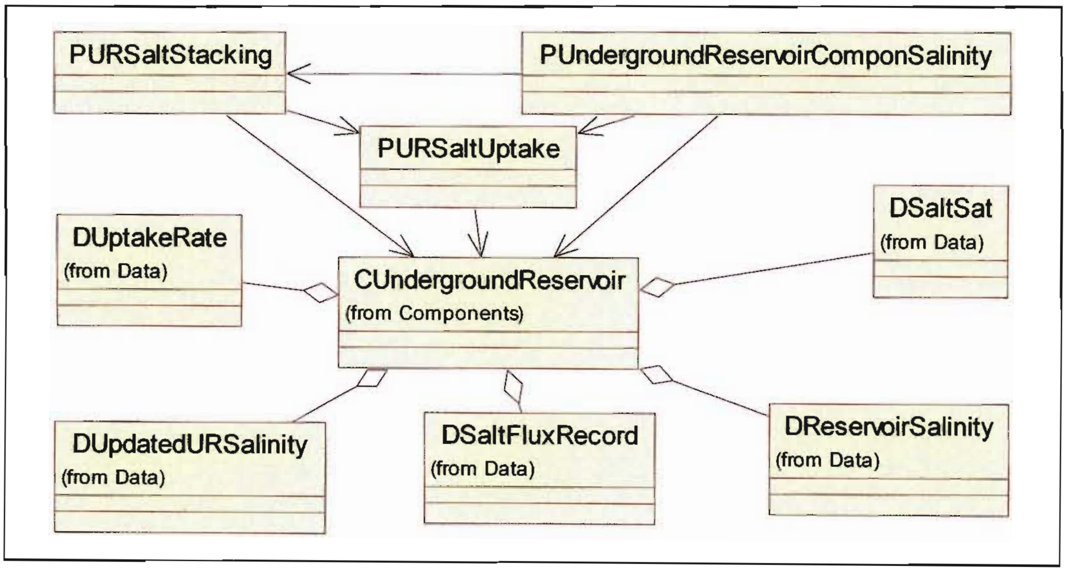


Figure 5.14: Class diagram of *PURSaltUptake* Process and associated Data, Component and Process objects

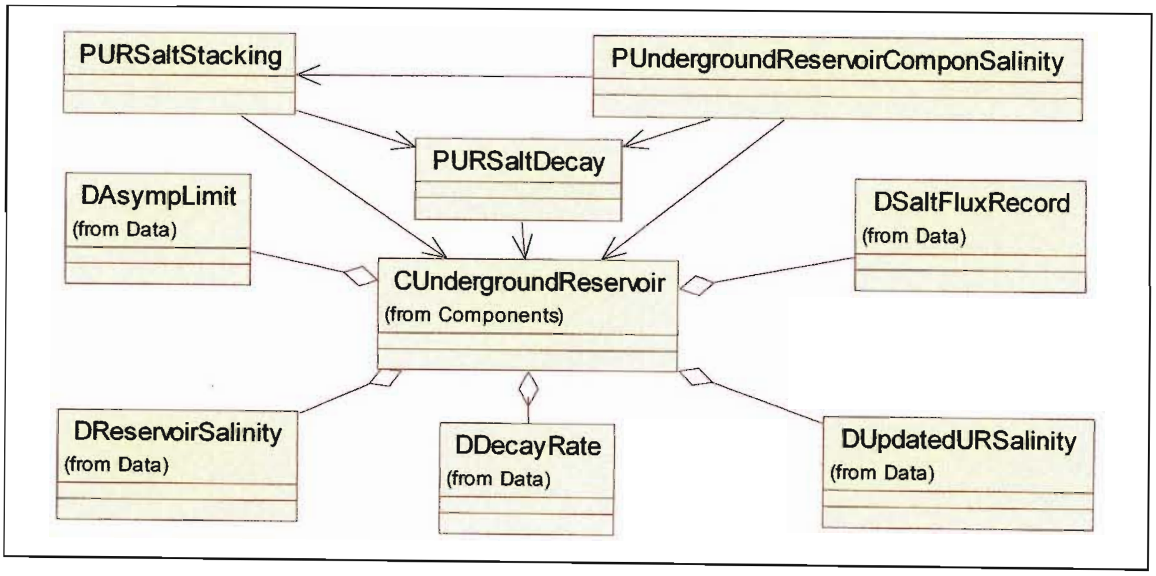


Figure 5.15: Class diagram of *PURSaltDecay* Process and associated Data, Component and Process objects

Which of the two processes is active (i.e. whether a salt increase or decay occurs on a particular day of simulation), depends on the information received from the calling class, which is the *PUndergroundReservoirComponSalinity* Process. When the current volume of water in an underground mine is less than the total volume (capacity) of the mined-out area, two options are considered. The first option is invoked if the current day volume of water in the reservoir is more or less than that for the previous day's. If so, the *PURSaltUptake* Process is invoked, in which case, salt generation takes place and the salinity of the water in the reservoir is updated accordingly using Equation 5.17. This is based on the assumption that as the mine floods, the water salinity increases as a result of the oxidation of pyrite and the dissolution of the oxidised remnants of the pyrite, along with the general weathering of the rocks, which is facilitated by the flooding of the mine. The rate of salt generation is determined by the amount of oxidized mineral being exposed to the flood water (Cairney and Frost, 1975). It has been observed that the rise and fall of the water table in an underground mine, i.e. the change in volume of the water, generally leads to an increase in salt concentration because of the 'flushing out' of further products of pyrite oxidation into the system (Cairney and Frost, 1975; Frost, 1979; Younger, 1997; Wood *et al.*, 1999).

The second option is invoked if the current day volume of water in reservoir is equal to that of the previous day, in which case the *PURSaltDecay* Process is invoked and decay in the water salinity takes place according to Equation 5.18. This is based on the assumption that with the water level in the mine remaining constant, the degree of water mineralisation gradually declines as the oxidised minerals are leached out. The minerals below the flood level are no longer in contact with the mine atmosphere and can undergo no further oxidation. The maintenance of a steady level of water in a 'below drainage' underground mine (underground reservoir in this study) as a management tool for the control/improvement of mine water deterioration has been documented in the literature (Cairney and Frost, 1975; Frost, 1979; Wood *et al.*, 1999). The condition of a steady water level in the mine is similar to when the mined-out area is flooded, i.e. when the mined-out void is completely filled with water. When the volume of water in the reservoir is equal or greater than the volume of the mined-out area therefore, the *PURSaltDecay* is invoked. The flow diagram of the *PURSaltUptake* and *PURSaltDecay* Processes are shown in Figure 5.16

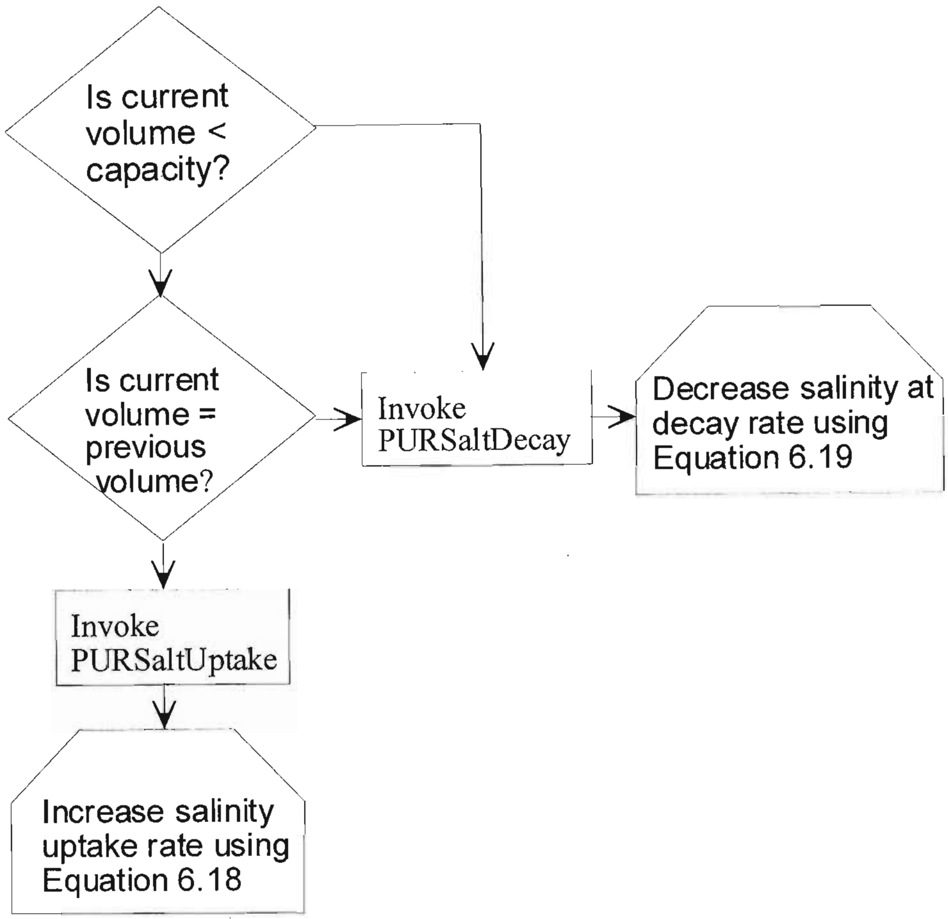


Figure 5.16: Flow diagram of *PURSaltUptake* and *PURSaltDecay* Process

The update of the water salinity in the mine is carried out for the previous day by the *PURSaltStacking* Process. It is the updated value, in addition with the total amount of inflow and outflow from the reservoir for the day, that are employed in the determination of the average current day reservoir water salinity and the salinity of the different components of outflow from the reservoir in the *PURSaltStacking* Process.

5.2.6 The *PURSaltStacking* Process Object

The *PURSaltStacking* Process determines the average salinity of the current storage and of the outflows from the underground reservoir on the basis of the information sent to it by the *PUndergroundReservoirComponSalinity* Process. The information comprises the water storage for the previous day and its updated salinity as determined either by the *PURSaltUptake* or *PURSaltDecay* Process, the total inflow and outflow volumes for the day, average salt concentration of the total inflow as determined by Equation 5.16 and the amount of water in storage for the day. As in the case of the surface reservoir, the salinity of the underground reservoir current storage and outflows are determined through a simplified mixing and routing procedure as employed by Herold (1980). The method is based on the assumption that complete mixing occurs within the time step and that advection is described by means of a cell-to-cell plug-flow model (see Section A.2.2.3, Appendix A). A difference exists, however, between the computation of the average reservoir and outflow salinity as carried out by the *PSaltStacking* Process for a surface reservoir and that carried out by the *PURSaltStacking* Process for an underground reservoir in that the *PURSaltStacking* Process takes into cognizance the increase or decrease of the water salinity in an underground mine when the mine is filling up with water and when it is fully flooded respectively. This is carried out in the *PURSaltStacking* Process by the use of the updated previous day water salinity in the computation of the average salinity of the current storage and the outflows. Thus, when the outflow of water from the underground reservoir on a particular day is less than the storage at the end of the previous day, the salinity of water leaving the reservoir is set equal to the updated reservoir salinity at the end of the previous day and the average reservoir salinity at the end of the day is computed from the mass balance expressed in Equation 5.19, which comprises the total salt inflow into the underground reservoir during the current time step ($Quri_i*Curi_i$) and the salt load left in the reservoir from the previous time, ($Sur_{i-1}*Cur_{i-1}$) after total salt outflow ($Quro_i*Sur_{i-1}$) divided by the total volume of water in the underground reservoir, Sur_i.

$$Cur_i = \frac{Quri_i * Curi_i + Cur_{i-1} * (Sur_{i-1} - Quro_i)}{Sur_i} \qquad (5.19)$$

where

Cur_i = underground reservoir salinity at the end of the current day of simulation (mg/l),

$Quri_i$ = volume of all water inflow into the underground reservoir on the current day of simulation (l),

$Curi_i$ = salt concentration of inflowing water into the underground reservoir on the current day of simulation (mg/l),

Cur_{i-1} = updated underground reservoir salinity at the end of the previous day (mg/l),

Sur_{i-1} = volume of water stored in the underground reservoir at the end of the previous day (l),

$Quro_i$ = volume of water outflow from the underground reservoir for the current day of simulation (l), and

Sur_i = volume of water stored in the underground reservoir at the current day of simulation (l).

When the outflow of water from the underground reservoir is greater than or equal to the storage at the end of the previous day, the average salinity of the outflow from the underground reservoir is computed using Equation 5.20 as the addition of total salt load in the reservoir on the previous day ($Cur_{i-1}*Sur_{i-1}$) to the salt load left after the outflow on the current day ($Curi_i*(Quro_i - Sur_{i-1})$) divided by the total volume of outflow, $Quro_i$. The average underground reservoir salinity at the end of the day (Cur_i) is calculated as volume weighted concentration of total water left in the reservoir at the end of the day (Equation 5.21).

$$Curo_i = \frac{Cur_{i-1} * Sur_{i-1} + Curi_i * (Quro_i - Sur_{i-1})}{Quro_i} \quad (5.20)$$

$$Cur_i = \frac{Curi_i * (Quri_i - (Quro_i - Sur_{i-1}))}{Sur_i} \quad (5.21)$$

where $Curo_i$ is the average salinity of the outflow from the underground reservoir.

In the determination of the average salinity of current storage and outflows as described above, it is assumed that no hydrochemical stratification occurs within the mined-out area. Therefore, the outflow, as computed by the *PURSaltStacking* Process, is assigned to the different outflow components for the computation of the salt load associated with individual components by the *PUndergroundReservoirComponSalinity*. The *PURSaltStacking* Process and its relationship with various Data, Component and Process objects are depicted in Figure 5.17.

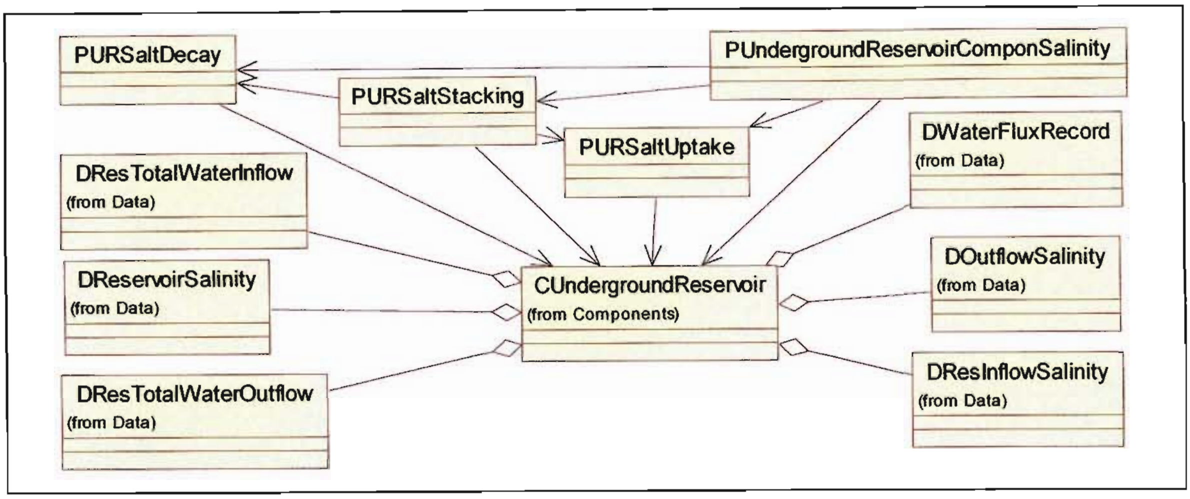


Figure 5.17: Class diagram of the *PURSaltStacking* Process and associated Data, Component and Process objects

5.2.7 The Salt Uptake Rate Constant and Equilibrium Value for the Soil Horizons and Groundwater Store

ACRUSalinity uses a first order rate kinetic to describe the salt generation process (Teweldebrhan, 2003). The salt uptake rate constant (k) and the salt equilibrium value (C_e) are used in the salt generation computations. While k is the rate of salt generation, C_e represents the maximum subsurface water salinity beyond which no salt generation takes place. Presently in *ACRUSalinity*, k and C_e values down the soil profile and within the groundwater store for both irrigated and non-irrigated land are coded to be the same, implying that for each of the parameters the same input values are used for the soil profile and groundwater store in both irrigated and non-irrigated areas. However, in view of significant difference possibly existing in the quality of water applied for irrigation in comparison to that available from rainfall (e.g. if the irrigation water is low-quality mine water), the reality of which may make the rate at which salt is generated in the irrigated and non-irrigated areas significantly different, it is necessary to make the irrigated and non-irrigated areas have separate input values in terms of the two parameters. In recognition of this and in order to enable verification studies that will consider the irrigated and non-irrigated areas of a land segment separately, different data objects were created for k and C_e for the soil profile and the groundwater store in irrigated and non-irrigated areas, thereby making it possible to specify different values of these parameters for the two components of a land segment.

5.2.8 Addition of a Soil Surface Layer

In line with the recent addition of a soil surface layer to the non-irrigated area in *ACRUSalinity* (Thornton-Dibb *et al.*, 2005), a similar addition of a soil surface layer to the irrigated area is developed in this study. In *ACRUSalinity*, originally one of the basic assumption was that the stormflow had the same salinity as that of rainfall. However, stormflow salinity can vary significantly from the rainfall salinity, especially after periods of no rainfall, when the salinity in the soil, mainly near the surface, can increase due to evaporation. When a rainfall event occurs, stormflow comes in contact with the accumulated salts near the surface of the soil and results in a net increase in the salinity of the stormflow than that of rainfall. In order to account for this, a soil surface layer Component (*CSoilSurfaceLayer*) has been added to *ACRUSalinity*. The soil surface layer is conceptualised as a thin soil layer that will drain quickly into the A-Horizon (unless the A-Horizon is already wet) and its addition is meant to model the process of stormflow water picking up salts accumulated near the surface of the soil. It is a type of soil layer (*CSoilLayer*) Component as it is a soil horizon (*CHorizon*), and is represented in Figure 5.18 (Thornton-Dibb *et al.*, 2005).

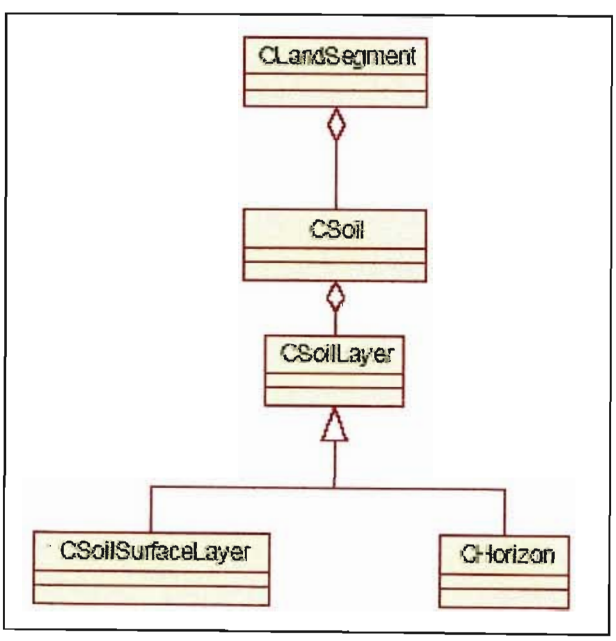


Figure 5.18: Soil layer Component structure in the *ACRU2000* model (after Thornton-Dibb *et al.*, 2005)

A portion of the accumulated salts in the surface layer is dissolved during a rainfall event, based on contact time and the soil characteristics, and the resulting mix is used in calculating the stormflow salinity. Salt precipitation in the surface layer occurs if the salt concentration in it exceeds a maximum value. The salinity processes modelled in the soil surface layer include (Thornton-Dibb *et al.*, 2005):

- Unsaturated upward movement of water and salts from the A-horizon to the soil surface layer driven by the hydraulic gradient induced by evaporation in the soil surface layer;
- Evaporation of water and retention of salts in the soil surface layer;
- Precipitation of salts out of solution in the soil surface layer once the maximum dissolved salt concentration has been reached;
- Dissolving of precipitated salts into stormflow during a rainfall event controlled by rain water/soil water contact time and soil properties;
- Mixing of dissolved salts with rainfall in the soil surface layer during an event;
- Removal of salts in stormflow, proportioned on a daily runoff basis; and
- Redistribution of salts from surface layer into A-Horizon after event.

As a result of the addition of a surface layer to *ACRUSalinity*, some Processes in both *ACRU2000* and *ACRUSalinity* needed to be modified. In this research work, the soil surface layer and corresponding processes were added to the irrigated area in *ACRU2000* and *ACRUSalinity*. The addition of the surface layer to non-irrigated areas is documented in Thornton-Dibb *et al.* (2005). The principle behind the addition of the soil surface layer to both non-irrigated and irrigated areas are the same, except that only a single layer, as conceptualised in the *ACRU2000* model, is present in irrigated areas, while two soil layers (topsoil and subsoil) are present in non-irrigated areas (see Section A1, Appendix A). The following sections summarise the processes added or modified in *ACRU2000* and *ACRUSalinity* in order to accommodate the addition of a soil surface layer in an irrigated area.

5.2.9 Processes Modified or Added to Accommodate Addition of a Soil Surface Layer in *ACRU2000* and *ACRUSalinity*

As a result of the addition of a surface layer to *ACRUSalinity*, some Processes in both *ACRU2000* and *ACRUSalinity* needed to be modified to account for the addition of the surface layer. Modifications were also carried out to maintain a pseudo water balance within a simulation time-step. On each day in *ACRUSalinity*, the water processes are run first after which the salt processes are run. In order to ensure that all the water movement processes have been accounted for in the soil layers and that the appropriate salinity of water in the soil layers is determined for salt load computation and movement, it is necessary to have a mirror of the water movement processes operating while running the salt processes. The pseudo water balance was created for that purpose. It is encapsulated in a Data object, *DAcruSalinityWaterContent*, to which water can be added or subtracted, depending on the movement of water in the soil layers. The pseudo water balance therefore mimics the water movement in *ACRU2000* (in the soil layers) in the sense that it keeps track of how much water is moved to where, and the volume of water movements are used in the appropriate determination of water salinity and salt movements in the soil layers. At the end of the day, a check is run to make sure that the pseudo water balance ties up with the *ACRU2000* water balance, thereby preventing unaccounted-for water and salt movement.

PAcru2000StandardComponents

The Process contains a definition of all components in *ACRU2000* and *ACRUSalinity*. The new soil surface layer, *CSoilSurfaceLayer*, was added to the irrigated area in this Process.

POldIrrigSoilInitialisation

This Process originally sets the initial soil moisture value for the single soil horizon in an irrigated area to wilting point plus 50% of plant available water (PAW). It has been modified to include the soil surface layer.

PInitialseIrrigSaltLoadOlu

This Process was created to replace the original one, *PInitialseIrrigSaltLoad*, which has been modified to include the initialisation of the pseudo water balance. The pseudo water balance was introduced to help keep track of the salinity changes in soil layers and groundwater as earlier explained.

PIrrigSoilWaterEvaporationSaltTrans

This new Process was created to only remove the soil water evaporation from the pseudo water balance, thereby concentrating salts in the soil surface layer.

PIrriLayerTranspirationSaltTrans

This new Process removes water losses by transpiration from the pseudo water balance. Presently the uptake of salts by vegetation is not modelled.

PIrrigRitchieSoilWaterEvapOlu

This Process was created to replace the original one, *PIrrigRitchieSoilWaterEvap*, which has been modified to allow for soil water evaporation from the soil surface layer. In order to use the surface layer processes, EVTR, which in *ACRU* originally was an option for estimating the total evaporation either as an entity or by soil water evaporation and plant transpiration separately, must be set to 2.

PIrrigSoilLayerSaltPrecipitation

This is a new Process, which determines the amount of salt precipitated out of the soil water solution. If the salinity of a soil layer in an irrigated land is greater than the specified maximum concentration in the land segment menu, then the excess salt load is precipitated. The Process also determines the salinity values for soil layers in an irrigated land as well as the groundwater store. The salinity of the surface layer can increase through evapo-concentration, while salt generation from the geology of rock types can lead to salinity increase in the topsoil and groundwater store.

PIrrigStormflowSalinityOlu

This Process was created to replace *PIrrigStormflowSalinity*. In the new Process, stormflow no longer has the same salinity as the rainfall, but simply takes into consideration the prevailing salinity of the soil surface layer from which stormflow is generated. The Process has been modified to take the dissolution of the precipitated salts in the soil surface layer during a rainfall event into consideration. The Process also calculates the stormflow salinity. In *ACRU2000*, stormflow generation from irrigated land is based on the assumption that it occurs only during a rainfall event and irrigation water *per se* does not have a direct contribution to stormflow generation unless when there is over-application of water. It may, however, increase the soil water salinity and results into increased stormflow salinity during a rainfall event. Salt dissolution and the resulting stormflow salinity during rainfall, is based on a simplified empirical model developed by Sharpley *et al.* (1981) to describe the desorption of Phosporous (P) from agricultural soil to rainfall and runoff. The model in its original form describes the release of P as being

- linearly related to the logarithm of contact time,
- linearly related to the logarithm of the water/soil ratio and also, and
- directly proportional to the amount of desorbable P in the soil initially.

In this study, however, the model has been incorporated into *ACRUSalinity* to predict the amount of dissolved salt released from the accumulated salt in the soil surface layer into stormflow during a rainfall event. The model is described by Equation 5.22.

If the net rainfall (*NetRF*L) is greater than zero, then the salt load dissolved from the soil surface layer's precipitated salt store is calculated as follows:

$$DISS1 = k_{diss} * T_{s,i} * (t^{\alpha}) * WR^{\beta} \qquad (5.22)$$

where

$DISS1$ = dissolved precipitated salt (mg),

(If DISS1 > $T_{s,i}$ then DISS1 = $T_{s,i}$),

k_{diss} = salt dissolution constants,

$T_{s,i}$ = the amount of precipitated salt in the surface layer (mg),

t = contact time (min),

α = salt dissolution constant,

β = salt dissolution constant,

WR = (NetRFL + $V_{s,i}$) / $d_{s\ lay}$ (m/m),

$V_{s,I}$ = water content of soil surface layer as a depth (m),

$d_{s\ lay}$ = soil surface layer depth (m),

$NetRFL$ = total rainfall – interception (m),

$$T_{s,i+1} = T_{s,i} - DISS1,$$

where

$T_{s,i+1}$ = the current amount of precipitated salt in the surface layer (mg), and

$T_{s,i}$ = previous day amount of precipitated salt (mg).

The mixed stormflow salinity is calculated using Equation 5.23:

$$MS_{SAL} = (SL_{RFL} + SL_{SSL} + SL_{inflows})/(\theta_{sVol} + RFL_{Vol} + WV_{inflows}) \qquad (5.23)$$

where

MS_{SAL} = mixed stormflow salinity (mg/l),

SL_{RFL} = salt load from rainfall (mg),

SL_{SSL} = salt load in the soil surface layer (mg),

$SL_{inflow\ s}$ = salt load from any other surface inflows (mg) (Currently inflows are from saturated upward flows),

θ_{sVol} = water content of the soil surface layer as a volume (l),

$NetRFL_{Vol}$	=	volume of net rainfall (l), and
$WV_{inflows}$	=	water volume from any other surface inflows (l) (Currently inflows are from saturated upward flows).

PIrrigSubsurfSaltTransportOlu

This new Process replaces the original *PIrrigSubsurfSaltTranport*, which has been modified to provide an option for the combination of the groundwater from an irrigated area with that from a non-irrigated area in a land segment (as described in Section 6.1.2). It has also been modified to make the new pseudo water balance keep track of the water movement in the soil layers as water moves down the profile and thereby ensure correct salt load determination and movement.

PIrrigCheckPseudoWaterBalance

This new Process checks the accuracy of the pseudo water balance (used for tracking the water balance in the soil layers in *ACRU2000* for the appropriate determination of soil water salinity and salt movement) at the end of the day by comparing it with the water balance in *ACRU2000*, thereby ensuring that all the subsurface hydrological water movements have been accounted for by the corresponding salt movement Processes.

PApplyIrrigation

This Process calculates the actual irrigation application amount depending on water availability at the water source and water losses due to conveyance and field application, and then assigns irrigation water from the irrigation system to the irrigated area. The Process has been modified to assign the irrigation water onto the soil surface layer area.

PIrrigAreaSCSRunoff

The Process calculates the stormflow from an irrigated area according to the SCS runoff equation, with the critical depth of the soil from which stormflow can be generated set at 0.3 m for irrigated areas (Lecler and Schulze, 1995). This critical depth lies within the single soil horizon conceptualised for an irrigated area (see Section A.1, Appendix A). The Process has been modified to include the soil surface layer within the critical depth, such that the total depth of 0.3 m is made up of both the soil surface layer and the topsoil. As the surface layer is conceptualise as a thin soil layer (Thornton-Dibb, 2005), the algorithms in the *PIrrigAreaSCSRunoff* Process work out the proportion of critical depth that will be made up of topsoil. With the assumption that the surface layer and the topsoil are made up of the same soil type, the stormflow generation in an irrigated area will not be affected by the inclusion of the surface layer.

PIrrigSaltInput

This Process calculates the quantity of salt load added to an irrigated area based on the volume and salinity of rainfall on the irrigated land. The Process has been modified to enable application of the rainfall salt onto the soil surface layer.

PApplyIrrigationSalt

This Process calculates the quantity of salt added to an irrigated area via irrigation water. The Process has been modified to apply the salts from the irrigation water onto the soil surface layer.

The above modifications were carried out with the following assumptions:

- When using *ACRUSalinity*, a soil surface layer is assumed to exist in the irrigated land,
- The soil surface layer does not contain roots and therefore no transpiration takes place from the soil surface layer, and
- The salt load associated with the intercepted rainfall contributes to the system and is therefore added to the irrigated area. This is based on the assumption that the salt load that is deposited on the vegetation as a result of interception, is washed down the branches and stems of the vegetation onto the surface layer in a subsequent rainfall event. This assumption also

prevents the accumulation of salts on the vegetation because of interception.

The algorithms for the modification carried out in the *ACRU2000* model and the *ACRUSalinity* module were checked for errors by calculating the mass balances of water and salts in the relevant components of the model and comparing them with the output of the overall mass balance. Comparable results were obtained, indicating that there are no errors in the algorithms used for describing the Processes in the model. The checking of the algorithms for the major modifications carried out in the model are presented in Tables D1 – D9 of Appendix D.

In the next chapter, the input data into *ACRU2000* and *ACRUSalinity* for their applications to the three levels of studies in this research are discussed.

6. MODELLING INPUT DATA FOR *ACRU2000* AND *ACRUSalinity*

In this chapter, the hydrological model criteria and parameters used (as well as their sources and relevance), in the application of the *ACRU2000* model and the *ACRUSalinity* module at the three different levels of studies in this research, are described. The procedures adopted in the application of *ACRU2000* and *ACRUSalinity* are described as well.

6.1 Land Segments Delineation

The *ACRU2000* model can operate as a discrete or as a distributed model. For large catchments or areas of complex land uses and soils, *ACRU2000* can be configured as distributed cell-type model (see Appendix A). Considering the complexities in the land uses that usually characterise collieries, *ACRU2000* and *ACRUSalinity* were employed in distributed mode in this study for the mine scale study, with the entire area of the colliery delineated into 29 land segments areas. The delineated land segments are shown in Figure 6.1.

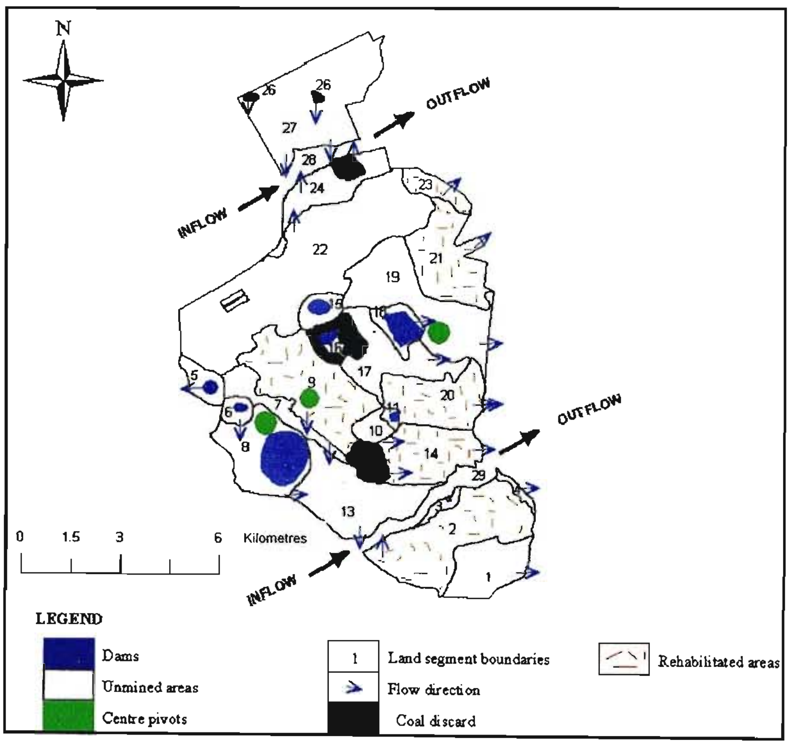


Figure 6.1: Delineated land segments in Kleinkopje Colliery for the mine scale study

The delineation was based on the seven land use types that were recognized in the colliery, and was carried out using 1:10 000 orthophoto and 1:15 000 topographical maps of the colliery. The delineation was first carried out on the 1:15 000 topographical map, then confirmed on the orthophotos and thereafter digitised. The characteristics of the land segments are presented in Table 6.1.

Table 6.1: Land segments in Kleinkopje Colliery and their characteristics

Land Segment	Area (km^2)	Land Use Type	Centre Pivot (Name)	Surface Reservoir (Name)	Underground Reservoir
1	3.08	Unmined			
2	7.03	Rehabilitated			
3	0.38	Unmined		5 West Dam	
4	0.29	Unmined			
5	1.04	Unmined		Dam 5	√
6	0.60	Unmined		Dam 6	√
7	1.89	Unmined			√
8	4.71	Unmined	Fourth Pivot		√
9	6.77	Rehabilitated	Tweefontein Pivot	Tweefontein Pan	
10	0.76	Offices and Plants		Dam 1 and 2	
11	0.21	Unmined		PRW	
12	1.00	Discard Coal Dump			
13	5.34	Unmined			√
14	3.87	Rehabilitated			
15	1.03	Unmined		Berries Pan	√
16	1.58	Coal Discard Dump		Klippan Penstock	√
17	3.60	Unmined		Erikson 1 & 2	√
18	1.37	Unmined		2A Dam	√
19	8.10	Unmined	Major Pivot		√
20	3.92	Rehabilitated			
21	4.54	Rehabilitated			√
22	15.30	Unmined			√
23	1.11	Rehabilitated			
24	2.67	Residential, Low Density			√
25	0.43	Coal Discard Dump			
26	0.13	Coal Discard Dump			
27	8.02	Unmined			√
28	1.39	River course			√
29	2.37	River course			

6.2 Surface Reservoirs

The surface reservoirs occurring in the study area are shown in Figure 7.1. They occur essentially as storage facilities and evaporation pans. The reservoirs were therefore treated as internally draining reservoirs, as no normal (i.e. environmental) flows out of the reservoirs were released. However, abstraction from and pumping into some of the reservoirs were being carried out. Records of transfer into and abstractions from the reservoirs, as well the data on electrical conductivities of water in the reservoirs were extracted from the Kleinkopje data base and formed part of the *ACRU2000* input data for the water and salt budgeting in the reservoirs.

In reservoir water budgeting in *ACRU*, the surface area at full capacity as well as the surface area: storage volume relationship are required for the surface water evaporation computations. When a reservoir has been surveyed, a conventional surface area:storage volume relationship, of the power function type, can be applied in *ACRU*. The area:storage relationship has been stated in Equation 5.7. In this study, however, topographical surveys of the surface reservoirs' basins were not carried out and data were not available on the surface area:storage volume relationship, with the exception of the Tweefontein Pan. A plot of the surface area versus volume of Tweefontein pan (Figure 7.2) obtained from the Kleinkopje Colliery database yielded the equation:

$$A = 1.8447\, F^{0.2743} \qquad (6.1)$$

where 1.8447 and 0.2743 are the constants c and e respectively in Equation 5.7. With the known maximum capacity of the reservoir, the equation was applied to estimate the surface area of Tweefontein Pan at full capacity. The constant and exponent of the equation were input into the land segment menu file as *RESCON* and *RESEXP* respectively for the reservoir water and salt budgeting. The simulations of the Tweefontein Pan carried out in this study did not exceed the bound of the fitted line in Figure 6.2. For the other reservoirs with inadequate available information, the maximum capacities were extracted from the Kleinkopje database and the following relationship was applied (Schulze *et al.*, 1995c):

$$A = 7.2\, F^{0.77} \tag{6.2}$$

where 7.2 and 0.77 are the default constant and exponent of the area:storage volume relationship respectively.

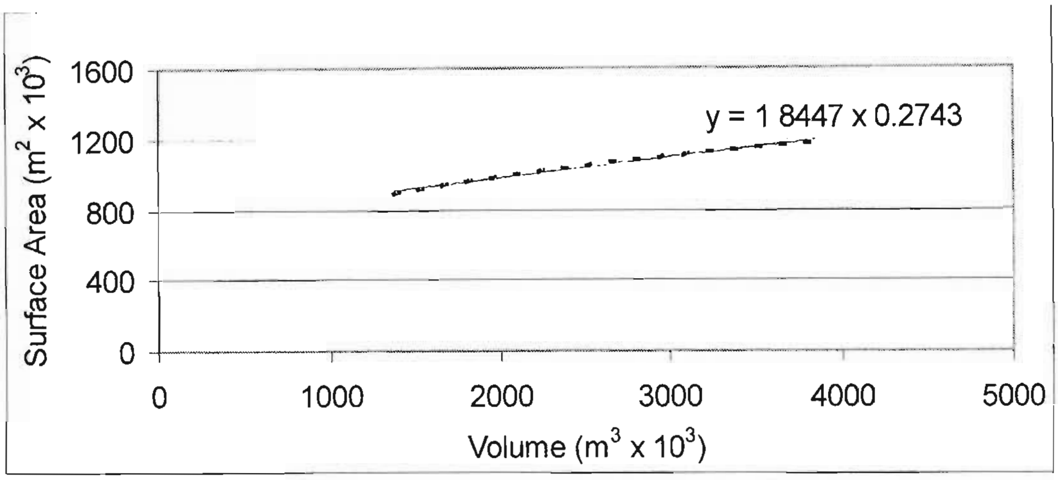


Figure 6.2: Surface area : volume relationship of Tweefontein Pan reservoir

The initial volume of water in the reservoirs was estimated by using the surface areas obtained through digitisation of the reservoirs as they occurred on the 1:10 000 orthophoto map of Kleinkopje Colliery. Table 6.2 contains some characteristics of the surface reservoirs in the colliery used in setting up *ACRU2000* and *ACRUSalinity*.

Table 6.2: Some characteristics of the surface reservoirs in the study area

Name of Dam	Capacity (m^3)	Surface Area at Full Capacity (ha)	Initial Volume (m^3)	Initial Salinity (mg/l)
Tweefontein Pan	4 000 000.00	144.64	3749484.00	2000.00
Plant Return Water Dam	100 000.00	5.10	35512.90	1025.90
2A Dam	4000000.00	73.58	3231717.00	2144.00
Eriksons Dam	300.00	0.06	0.00	2066.56
5 West Dam	36000.00	1.20	10000.00	2080.00
Reservoir 1 and 2	10000.000	0.87	0.00	487.30
Klippan Penstock Dam	1285000.00	36.40	128442.60	2418.60
Berries Dam	878000.00	27.16	439040.00	2511.08
Reservoir 5	7856000.00	24.92	3749484.00	2268.25
Reservoir 6	363600.00	13.80	181797.90	2268.25

6.3 Mine-pit Reservoirs

The mine-pit reservoir represents the water which accumulates in the pit in the window mining area of an opencast system. The reservoir was conceptualised as a surface reservoir in every sense (i.e. with all the inflow and outflow characteristics of a surface reservoir), but with an additional consideration of possible seepage of water from the groundwater store into the mining pit. The description of the mine-pit reservoir as conceptualised in this study has been given in Chapter 5. The potential seepage from the groundwater store into the mining pit depends on the hydraulic gradient of the aquifer and its hydraulic conductivity, as well as the area through which groundwater seeps into the pit. The actual seepage into the pit will depend on the amount of groundwater in storage. A hydraulic gradient of 0.0018, obtained as the average hydraulic gradient between four boreholes located within Kleinkopje, and a hydraulic conductivity of 0.2 m/day, which was the average of the hydraulic conductivities, determined through packer tests of the rock materials that generally overlies the coal deposits occurring in Kleinkopje (Clean Stream Environmental Services, 2004), were used in this study. The seepage area was taken as the product of the length of the mining-pit window (taken to be 100 m for Kleinkopje on the advice of the staff of Kleinkopje) and the average height of water in groundwater storage in the land segments listed as contributing seepage into the pit. Four mine-pit reservoirs existed in the configuration of the Kleinkopje Colliery for *ACRU2000* and *ACRUSalinity* in this study, with each one corresponding to the opencast mining pit in the colliery. The four reservoirs are part of the delineated land segments 2, 9, 20 and 21 in Figure 6.1. The volume and quality of groundwater seepage into the reservoirs from adjacent land segments depended on the volume and quality of the groundwater store in the land segments stipulated as the sources of the seepage. The resident land segments for the reservoirs and the adjacent land segments contributing seepage into them are shown in Table 6.3. The seepage contributing land segments were determined by their proximity to the reservoirs and the direction of groundwater movement, based on topography. It was assumed in this study that seepage out of the mine-pit reservoir downstream were non-existent or insignificant as the water, which may have accumulated in the pit, is usually pumped out into storage facilities for disposal or other uses.

Table 6.3: Land segments contributing seepage into mine-pit reservoirs

Mine-pit Reservoirs Land Segments	Land Segments Contributing to Seepage
2	1, 3, 4, 29
9	5, 7, 15, 16, 22,
20	11, 16, 17, 19, 18,
21	19, 22, 23

6.4 Underground Reservoirs

The underground reservoir is one of the new components added to *ACRU2000*. It was added so that *ACRU2000* could take into consideration the occurrence of water in underground mined-out areas and the interaction of such water with the other components of a hydrological system. The map showing the area of occurrence of underground reservoirs in Kleinkopje is shown in Figure 6.3.

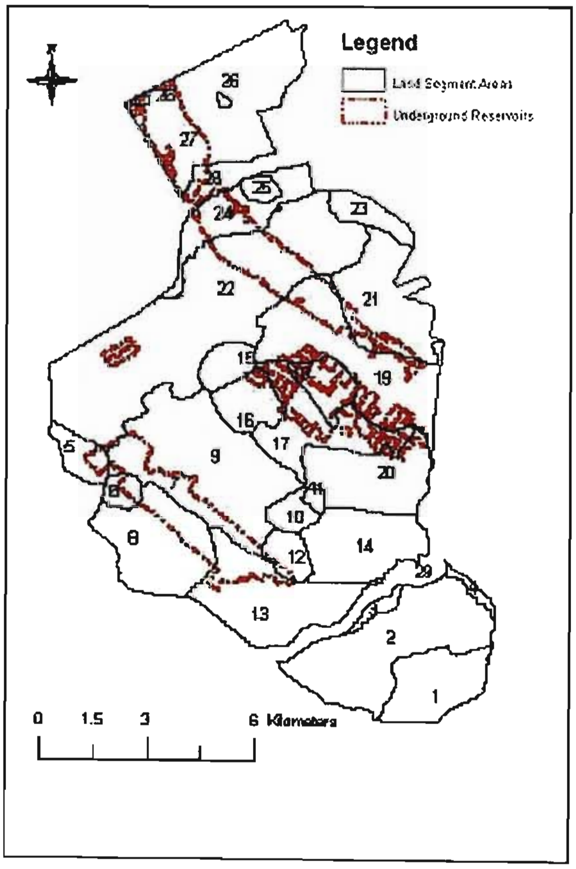


Figure 6.3: Underground water body areas in Kleinkopje Colliery with land segment boundaries

The descriptions of the underground reservoir water and salt budgeting have been described in Section 5.1.5 and 5.2.4 respectively. The land segments in which underground reservoirs are present have been indicated in Table 6.1. The following information was required for the estimation of leakages into an underground reservoir: the hydraulic impedance of the rock material that lie between the aquifer and the underground reservoir, the amount of groundwater in storage and the surface area of the roof of the reservoir. Estimates of these values were obtained by studying the maps showing the areas of occurrence of the underground reservoirs and the water bodies in them, as well as the geologic logs and sections of different areas of Kleinkopje Colliery. Based on the locations in which the reservoirs occur in the colliery, they were categorised into those occurring in 3A and 2A areas. Land segments 5, 6, 7, 8, 9, 10, 12, 13 were located in 3A, while land segments 15, 16, 17, 18, 19, 21, 24, 27 were located in 2A. For the estimation of the hydraulic impedance (i.e. hydraulic conductivity divided by the thickness), a hydraulic conductivity of 0.2 m/day was used as indicated earlier in Section 6.3. From the study of the geological logs and sections, the range and average of the thickness of the rock materials, which generally overlie the underground mine-out areas in 3A areas, were 15.0 – 26.7 m and 20.66 m respectively, with a standard deviation of 4.5 m. In 2A areas, the range and average thickness were 47.8 – 50.7 m and 51.1 m respectively, with a standard deviation of 3.5 m, thereby making the hydraulic impedance values 0.009681/day in 3A and 0.0039/day in 2A.

No continuous data were available on the volume of water in the underground reservoirs. However, estimates of the capacity of the reservoirs, their surface areas and the volume of water in storage at the beginning of simulation were based on the information obtained from the Kleinkopje database. Data on the post-mining affected water bodies for the underground mine-out areas was taken as the final volume of the water bodies expected in the reservoirs. The values were therefore taken as the capacities of the reservoirs. The status of the water in storage in the mined-out areas in 1994 was used as the basis for estimating the volume of water in storage at the beginning of the simulation. Therefore, all recorded abstractions from, and inflow into, the water bodies since 1994 were subtracted and added to the existing water in storage. The leakage into the underground reservoir was assumed to be dependent on rainfall and consequent recharge into the weathered aquifer, which generally overlaid the underground mined-out areas. The surrounding rocks of the reservoir at depth have been described as being completely devoid of water and inhibiting to significant vertical percolation because of stratification and low permeability (Hodgson *et al.*, 2001). Therefore, inflow into the reservoirs was estimated on the basis of an average annual recharge rate of 3% of the total annual rainfall, into the weathered aquifer from which leakage into the underground reservoir was assumed to originate. An average annual recharge rate of 3% has been considered as feasible for the Witbank Dam catchment (Hodgson and Krantz, 1998). The actual amount of leakage into the underground reservoir was estimated as described in Section 5.1.5.

6.5 Vegetative Water Use

The vegetative water use of the land use types in the delineated land segments were dependent essentially on the vegetation identified in each land segment area. These were then associated with the land use categorization and different vegetation characteristics given in Smithers *et al.* (1995) and subsequently modified by BEEH (e.g. Schulze *et al.*, 1996; Summerton, 1996). The land use categories associated with the land segment land use types are given in Table 6.4. From field observations, the vegetation in both virgin and rehabilitated areas that were not under irrigation was similar and categorised as "veld in poor condition", while the irrigated areas in both virgin and rehabilitated areas were taken as being under maize cultivation.

Table 6.4: Land use categorisation in the study area

Land Segment Land Use Type	Categorization used in *ACRU* Model
Virgin (unmined) area	Veld in poor conditions
Rehabilitated area	Veld in poor conditions
Irrigated area (unmined or rehabilitated)	Maize
Coal discard dumps	Mines and Quarries
Residential low density area	Formal Residential Medium Density (Pervious Portion)
River courses	Wetland – grasses
Offices and Plants	Industrial (Pervious portion)

The hydrologically relevant information on the land use categories required as inputs in the *ACRU2000* model include interception loss value, consumptive water use coefficient and the fraction of the plant roots active in extracting moisture from the topsoil. Table 6.5 contains the monthly values of the vegetation characteristics of each land use category used in this study, as available in the *ACRU* model land use information database (Smithers *et al.*, 1995). The monthly values are converted to daily values internally in the *ACRU2000* model by Fourier Analyses.

Another parameter required in *ACRU2000*, and which can change from month to month depending on vegetation, site and management characteristics, is the coefficient of initial abstraction. It is used in the *SCS* stormflow equation to determine the amounts of rainfall that do not contribute to the generation of stormflow because of the process of initial infiltration or temporary surface storage in hollows, before stormflow begins (Schulze, 1995c). The coefficient is typically 0.2. However, immediately after ploughing when surface roughness is high, it can increase to 0.3 or 0.4. Therefore, apart from irrigated areas where ploughing was assumed and 0.3 used, in all the other land uses, the typical value of 0.2 was adopted.

6.6 Rainfall, Potential Evaporation and Temperature

ACRU, being a daily time step model, requires daily rainfall input. The rainfall data used in this study were obtained from the automatic weather stations located within the Kleinkopje Colliery, close to the Tweefontein pivot and within the Syferfontein pivot. Rainfall, when occurring, was recorded every minute with a tipping bucket rain gauge (Texas Instruments) connected to a CR10X data logger (Campbell Scientific Inc., Logan Utah, USA) and then totaled to hourly and daily values. Also required as input into *ACRUSalinity* is the rainfall quality. As no reliable data were available on the study area, a value of 4 mS/m (26 mg/l) was used. The value was the result of chemical analyses of rain water in the Johannesburg city and environs carried out by the Johannesburg City Council (Blight, 1992). Considering that air pollutants disperse quickly on the Transvaal Highveld (Blight, 1992; Blight, 2005), this value may not be significantly different from that of the study area.

Table 6.5: Vegetation characteristics in each land use categorisation (Smithers *et al.*, 1995)

DESCRIPTION	CROPNO	Variable	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Veld in poor condition	2030102	CAY	0.55	0.55	0.55	0.45	0.20	0.20	0.20	0.20	0.30	0.40	0.50	0.55
		INT	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
		ROOTA	0.90	0.90	0.90	0.94	0.94	0.94	0.94	0.94	0.92	0.92	0.90	0.90
Mines and quarries	5310101	CAY	0.45	0.45	0.45	0.35	0.30	0.20	0.20	0.20	0.30	0.35	0.45	0.45
		INT	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
		ROOTA	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Wetland – grasses	4040102	CAY	0.80	0.80	0.80	0.70	0.60	0.50	0.40	0.40	0.40	0.50	0.60	0.70
		INT	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60
		ROOTA	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Industrial (Pervious portion)	1020201	CAY	0.70	0.70	0.70	0.60	0.40	0.40	0.30	0.30	0.50	0.70	0.70	0.70
		INT	1.40	1.40	1.40	1.40	1.20	1.20	1.20	1.20	1.20	1.40	1.40	1.40
		ROOTA	0.90	0.90	0.90	0.94	0.94	0.94	0.94	0.94	0.92	0.92	0.90	0.90
Formal residential medium density (Pervious portion)	103020	CAY	0.80	0.80	0.80	0.70	0.60	0.50	0.50	0.50	0.60	0.70	0.80	0.80
		INT	1.40	1.40	1.30	1.20	1.10	1.00	1.00	1.00	1.10	1.20	1.30	1.40
		ROOTA	0.80	0.80	0.80	0.90	1.00	1.00	1.00	1.00	0.90	0.90	0.80	0.80
Maize (Irrigated)		CAY	0.95	0.43	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.38	0.86	1.09
		INT	1.30	1.17	0.55	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.40	1.07
		ROOTA	0.76	0.88	0.95	1.00	1.00	1.00	1.00	1.00	1.00	0.97	0.40	0.75

CAY - Average monthly crop coefficient for the pervious land cover of a catchment (i.e. the proportion of water "consumed" by a plant under conditions of maximum evaporation in relation to that evaporated by an A-pan (Smithers *et al.*, 1995)

INT - Interception loss value (mm)

ROOTA - Fraction of plant root in topsoil

The determination of the reference potential evaporation in the *ACRU* model is based on the daily United States Weather Bureau Class A evaporation pan amount. However, it can be estimated in *ACRU* using different methods – either directly from pan values or via surrogate equations (Schulze and Kunz, 1995). In this study, the option of the temperature based equation of Linacre (1984) was chosen. Comparative studies of temperature based equations for estimating the reference potential evaporation and lysimeter studies undertaken under diverse climatic conditions for maize, wheat, sugarcane and soybeans indicated that the Linacre (1977) equation was superior to other temperature based ones (Clemence and Schulze, 1982). However, the 1984 Linacre equation has been found to yield better simulations of the reference potential evaporation than the 1977 version when used with the *ACRU* model (Schulze and Kunz, 1995). The daily maximum and minimum temperature inputs into *ACRU2000* for the use of the Linacre (1984) equation were obtained from the automatic weather stations indicated earlier. The temperature was measured with a CS-500 Vaisala temperature probe, recorded every 10 s with a Campbell Scientific CR10X data logger and averaged hourly. In addition, daily maximum and minimum values were logged.

6.7 Soils

Soils regulate the hydrological responses within a catchment because of the roles they play in absorbing, retaining and redistributing water (Schulze *et al.*, 1995b). These roles directly influence the generation of baseflow, stormflow and peak discharges. The soils input requirements for the *ACRU* model include the amounts of soil water content at three critical soil water retentions, *viz.* at total porosity, drained upper limit and permanent wilting point (Schulze *et al.*, 1995b). The soil water retention values have been made to be functions of the soil texture and soil horizon depths in *ACRU*, such that when the soils information is considered inadequate and by choosing a texture and depth class as given in *ACRU*, default values of soil water retention values and soil horizon thickness can be obtained. Six soil depth classes (Table 6.6) and eleven major soil textural classes (Table 6.7) are accommodated in *ACRU*. Owing to inadequate information on the soil retention characteristics, textural class 5 (i.e. sandy loam) and soil depth class of 1 (i.e. very deep) were used in all the land segments delineated within Kleinkopje Colliery, with the exception of the coal discard dump areas and the rehabilitated areas. This was based on a soil survey, which identified the soil type in unmined areas of Kleinkopje Colliery as sandy loam (Claassens, 2000). For the Syferfontein pivot, the clay textural class was used, in accordance with a soil survey, which identified the soil type in the Syferfontein pivot as heavy clay (Claassens, 2001).

Table 6.6: Default values of soil horizon thicknesses as used in *ACRU* when soils information is inadequate (Schulze *et al.*, 1995b)

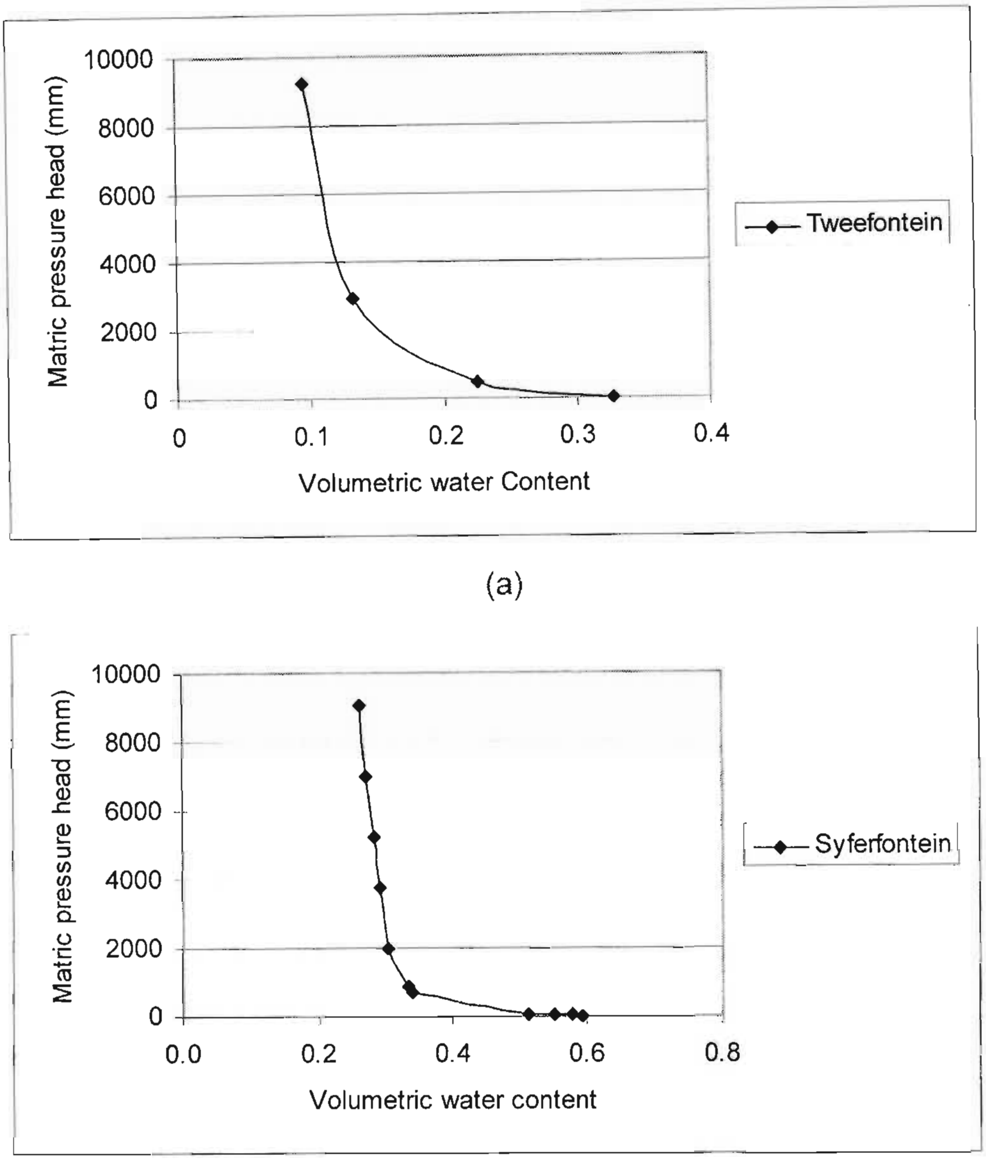
Soil Depth Number	Soil depth Class	Thickness (m) of Horizon	
		Topsoil	Subsoil
1	Very deep	0.30	0.80
2	Deep	0.25	0.50
3	Moderately shallow	0.20	0.20
4	Shallow	0.15	0.15
5	Very shallow	0.10	0.10
6	Impervious (e.g. rock)	0.02	0.02

Table 6.7: Default soil water retention values used in *ACRU* when oils information is inadequate (Schulze *et al.*, 1995b)

Texture Class Number	Texture Class	Permanent Wilting Pont (m/m)	Drained Upper Limit (m.m-1)	Total Porosity (m/m)
1	Clay	0.298	0.416	0.482
2	Loam	0.128	0.251	0.464
3	Sand	0.050	0.112	0.430
4	Loamy sand	0.068	0.143	0.432
5	Sandy loam	0.093	0.189	0.448
6	Silty loam	0.121	0.272	0.495
7	Sandy clay loam	0.159	0.254	0.402
8	Clay loam	0.195	0.312	0.468
9	Silty clay loam	0.190	0.335	0.473
10	Sandy clay	0.228	0.323	0.423
11	Silty clay	0.253	0.390	0.480

In the rehabilitated areas in the Kleinkopje Colliery and the Syferfontein pivot, the soil water retention characteristics obtained from the laboratory analyses of the soil samples collected from the Tweefontein and Syferfontein pivots were used. For the Tweefontein pivot, however, historical data was used (Lorentz and Goba, 1997).

The typical soil water retention characteristics at the Tweefontein and Syferfontein pivots are presented in Figures 6.4.



(b)

Figure 6.4: Soil water retention characteristics for the Tweefontein (a) and Syferfontein (b) pivots at 0.1 m below surface

The soil water retention characteristics of the coal discard dump areas were assumed similar to those considered to be representative of the compacted coal dumps of the Mpumalanga and Natal coalfields in South Africa (Wates and Rykaart, 1999). The wilting point, drained upper limit and porosity values used were 0.03, 0.09 and 0.3 m/m respectively. Figure 6.5 shows the soil-water retention characteristic curve for the compacted coal dumps, from where the soil water retention values were obtained.

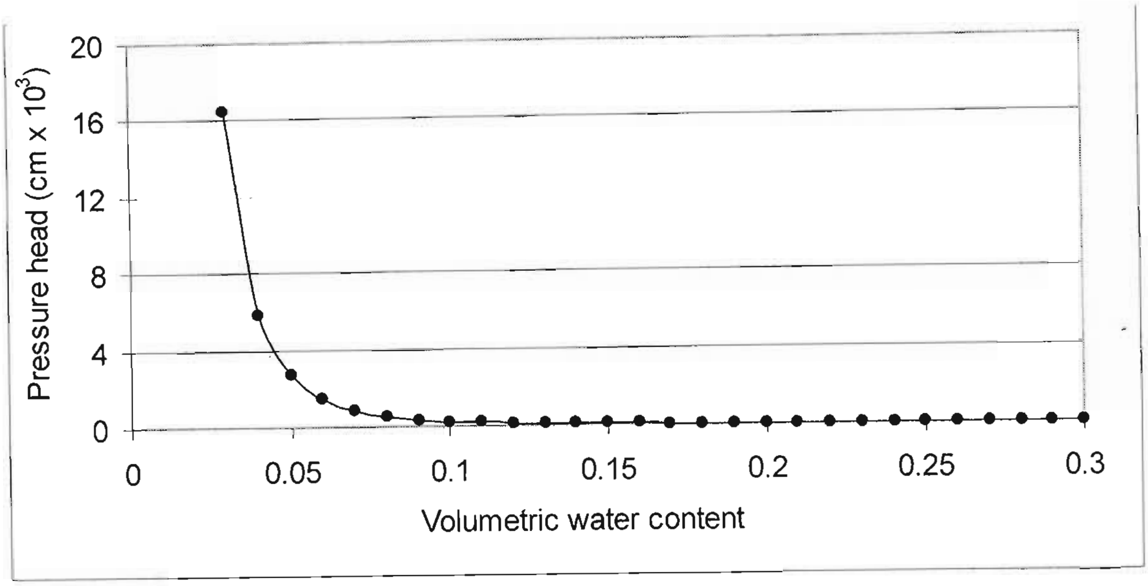


Figure 6.5: Compacted coal discard soil water characteristic curve (Wates and Rykaart, 1999)

In addition to the soil water retention values, the initial salinities of the water in the soil horizons as well as in the groundwater, both in the non-irrigated and irrigated areas are required in *ACRUSalinity*. In the irrigated areas, electrical conductivity values, converted to TDS (in mg/l) by multiplying the EC in *umhos/cm* by 0.64 (Raghunath, 1987; Swatlab, 2004) were used. These data were obtained from the analyses of soil water collected from ceramic cup soil water samplers installed on the centre pivots (at a time corresponding to or closest to the beginning of simulation). The values were 1689.6, 420.0, 1088.0 and 2086.0.0 mg/l for the Tweefontein, Fourth, Major and Syferfontein pivots respectively. The differences in the initial salinities at the pivots may be due to differences in rainfall and duration of irrigation. Annandale *et al.* (2002) have reported the dependence of soil salinity mainly on rainfall and irrigation amounts and quality. Irrigation with mine water commenced in the Tweefontein and Major pivots in 1997, while in the Fourth and Syferfontein pivots, it started in 1999 and 2001 respectively. In the rehabilitated non-irrigated area, the initial soil water salinity at the beginning of simulation was 256 mg/l. These were obtained from the historic records available on the four centre pivots involved in this study. Owing to lack of such data on virgin non-irrigated areas in Kleinkopje, the total dissolved solids of 59 mg/l in a borehole located in an unmined area within Kleinkopje at a time corresponding to the beginning of the simulation period was adopted for an initial soil water concentration. The assumption was that in virgin areas, most of the salts in the soil horizons have been leached, as evidenced by the low salinity of water in the borehole, and that the salinity of soil water was not significantly different from that of the groundwater. In the coal discard dump area, the values used for the soils and groundwater initial salinities was the average TDS of groundwater (1 671 mg/l) in a borehole located in a mine dump within Kleinkopje. The same value was used as the initial groundwater salinity in rehabilitated areas.

6.8 Irrigation

For the pivot scale study, two centre pivots irrigated with mine water, *viz.* the Tweefontein and Syferfontein pivots, were monitored for runoff quantity and quality (see Section 4.3.1). The Tweefontein pivot, located in Kleinkopje Colliery with two other centre pivots, *viz.* the Major and Fourth pivots, form part of the mine scale assessment. Records of daily irrigation water application onto the centre pivots were available and formed part of the data input into the *ACRU2000* model. The areas of each centre pivot and typical qualities of water used for irrigation on each pivot are presented in Table 7.8.

Table 6.8: Characteristics of the centre pivots involved in this study

Centre Pivot	Area (ha)	Irrigation Water Quality (mg/l)	Type of soil
Tweefontein	20.0	1920.0	Rehabilitated
Syferfontein	21.0	2042.0	Virgin
Fourth	30.0	1920.0	Virgin
Major	30.0	1792.0	Virgin

In Kleinkopje Colliery, irrigations were carried out using water from two sources with different water qualities, namely Jaccuzzi and Tweefontein. Jacuzzi was the water from old underground workings (i.e. underground reservoirs) and had a typical salinity of 1 792 mg/l while Tweefontein was the water stored in Tweefontein Pan and had a typical quality of 1 920 mg/l. The higher salinity of the water in Tweefontein Pan in comparison to that in the underground mined-out areas reflects evapo-concentration of salts in the pan resulting from exposure to the atmosphere. In the Syferfontein pivot, the water used for irrigation was from a surface dam and had a typical quality of 2 042 mg/l.

7. RESULTS AND DISCUSSION AT CENTRE PIVOT SCALE

The results of the assessment of irrigation with mine water at the centre pivot scale using *ACRU2000* and *ACRUSalinity* and discussion of the results, are presented in this chapter. Assessments of the Tweefontein Pan catchment and Kleinkopje Colliery as a whole are presented in the next chapter, Chapter 9.

7.1 PIVOT SCALE ASSESSMENT

The centre pivot scale results and assessment are based on the simulations carried out on the Tweefontein and Syferfontein pivots and the monitoring at these pivots. Verification of the simulated results using *ACRU2000* and *ACRUSalinity* are carried out through comparison of the simulated runoff, as well as the simulated runoff salinity and salt load, with the observed data. The simulated results form the basis of the analyses of the total water and salt balances of the two pivots.

7.1.1 The Syferfontein Pivot

The observed and simulated results of the runoffs and runoff salt loads are presented in Figures 7.1 and 7.2 respectively. The runoff volume and salinity were monitored directly, while the salt load of the runoff was determined from the runoff volume and salinity (see Section 4.4.1). A comparison of the salinities of the sampled runoff using the *ISCO* water sampler and the salinities of simulated runoff is presented in Figure 7.3. A high correlation of 0.99 between the simulated and observed runoff salinity indicated that the salt concentration of the runoff from the pivot was simulated accurately. Applying checksums over the time of monitoring of the Syferfontein pivot because of sparseness of the observed data, the totals obtained for the observed and simulated runoff volume are of the same order of magnitude, the difference being 9 %. This indicates that the runoff volume is accurately simulated.

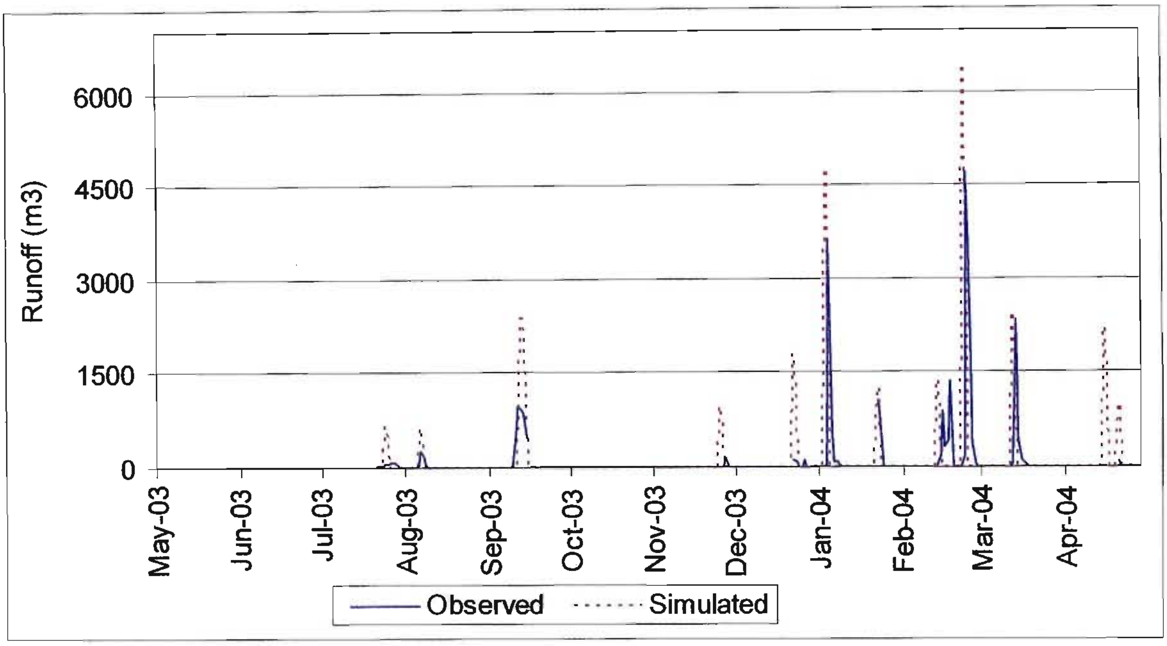


Figure 7.1: Observed and simulated daily runoff from the Syferfontein pivot

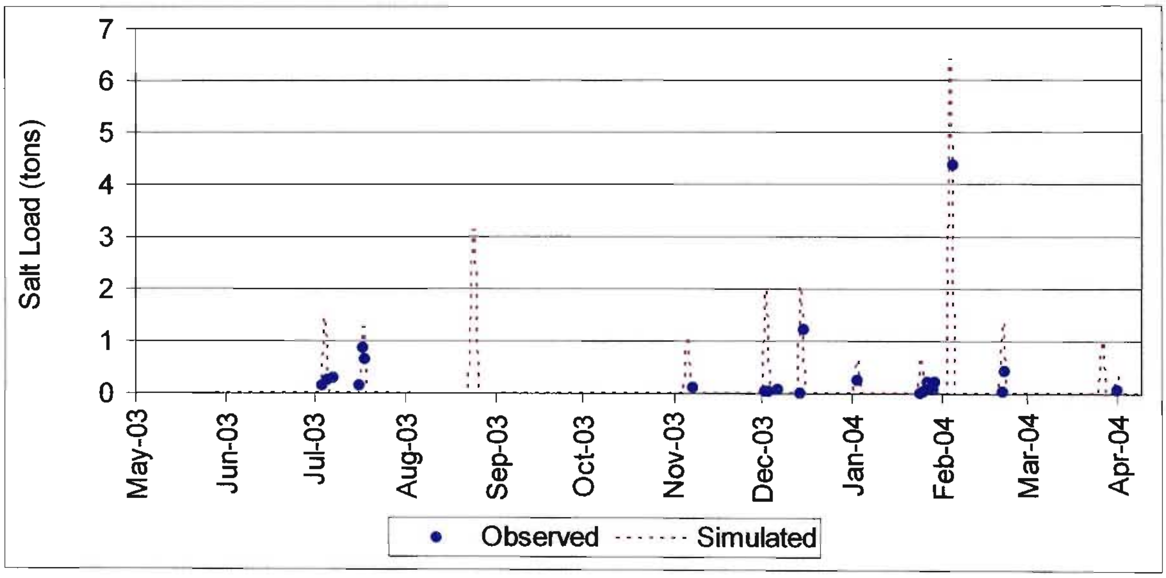


Figure 7.2: Observed and simulated daily salt load associated with runoff from the Syferfontein pivot

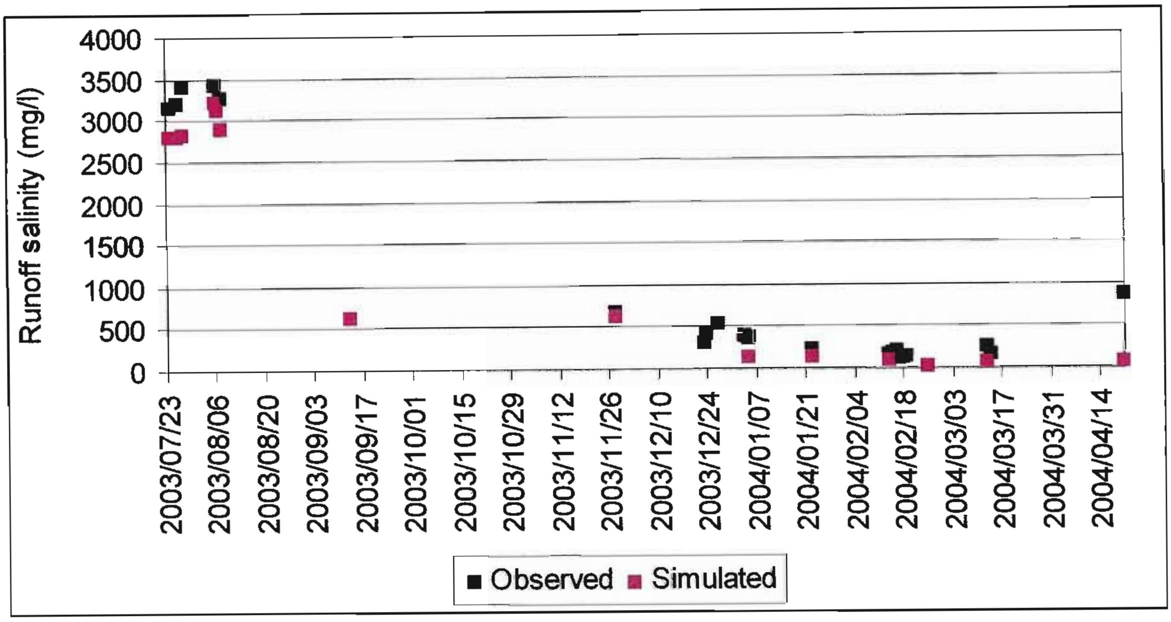


Figure 7.3: Daily salinities of sampled and simulated runoff from the Syferfontein pivot

The total amount of water available at the Syferfontein pivot from both irrigation and rainfall was about 2.19 x 10^5 m^3, representing 1 044 mm of water within the monitoring period of May 2003 to April 2004. The water balance for the period is presented in Table 7.1. Rainfall and irrigation water constituted about 38% (398 mm) and 62% (646 mm) respectively. Most of the water (76%) was lost through evapotranspiration, while about 13% (136 mm) occurred as runoff. About 3% (26 mm) percolated into groundwater storage, while the change in soil moisture content of the soil surface layer and topsoil was very small – 0.05%, effectively representing 0.5 mm of water. Interception loss was about 8%, representing about 88 mm of water. The total amount of salt which accompanied rainfall and irrigation water supplied onto the pivot over the simulation period was about 279 metric tons, with almost all the salts (99%) coming from irrigation. The relative higher TDS of the irrigation water (2 042 mg/l) in comparison to that of rainfall (26 mg/l), as well as the different amount of volume contribution (62% and 38% respectively), were responsible for the higher contribution of salts from irrigation. The total amount of salts generated, which represented salts uptake from the geology of the rocks was 2.19 tons, thereby making the total amount of available salts about 281 tons (Table 7.2). The salt load associated with runoff was about 22 tons, representing about 8% of the total salts available, while the total amount of salts precipitated in the topsoil horizon was about 92 tons (33%). Less than a 1%

of the total salts (1.8 tons) occurred as precipitated salts in the soil surface layer. About 14 tons (2.5%) went into groundwater storage. The salt load associated with the increase in the salinities of the water in the topsoil horizon and the soil surface layer were 147 and 4 tons, representing 52% and 1% respectively.

Table 7.1: Water balance of the Syferfontein pivot

Items	Supplied Water		Water Distribution				
	Rainfall	Irrigation	Runoff	Total Evaporation	Soil Moisture	Drainage To Groundwater	Interception Loss
Volume (m^3)	83559.00	135660.00	28160.00	165819.00	109.87	5397.00	18524.00
Depth (mm)	397.9	646.00	134.10	789.60	0.52	25.70	88.00
Percentage of Total Available Water (%)	38.00	62.00	13.00	76.00	0.05	2.5.0	8.45

Table 7.2: Salt balance of the Syferfontein pivot

Items	Supplied Salts		Generated Salts	Salt Distribution					
	Rainfall	Irrigation		Runoff	Topsoil		Soil Surface Layer		Drainage To Groundwater
					Precipitated Salts	Dissolved Salts	Precipitated Salts	Dissolved Salts	
Mass (tons)	2.17	277.02	2.19	22.48	92.24	147.21	1.84	4.07	13.52
Percentages	0.80	99.20		8.00	33.00	52.00	0.60	1.40	5.00
Total Available Salts (tons)			281.38						

7.1.2 The Tweefontein Pivot

The observed and simulated results of the runoffs and runoff salt loads are presented in Figures 7.4 and 7.5 respectively. A comparison of the salinities of the sampled runoff using the *ISCO* water sampler and simulated runoff is presented in Figure 7.6. A high correlation of 0.9 between the simulated and observed runoff salinity indicated that the salt concentration of the runoff from the pivot was simulated accurately. The difference between the total observed and simulated runoff volume over the simulated period is low (13 %), indicating that the volume of runoff from the Tweefontein pivot is accurately simulated.

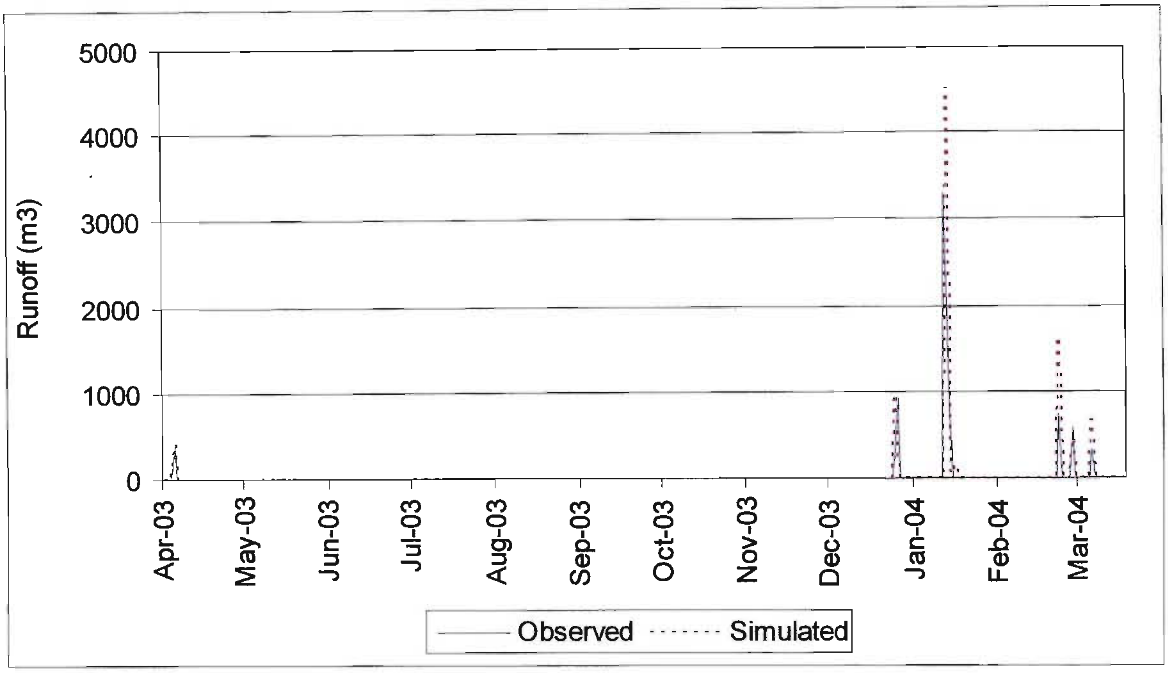


Figure 7.4: Observed and simulated daily runoff from the Tweefontein pivot

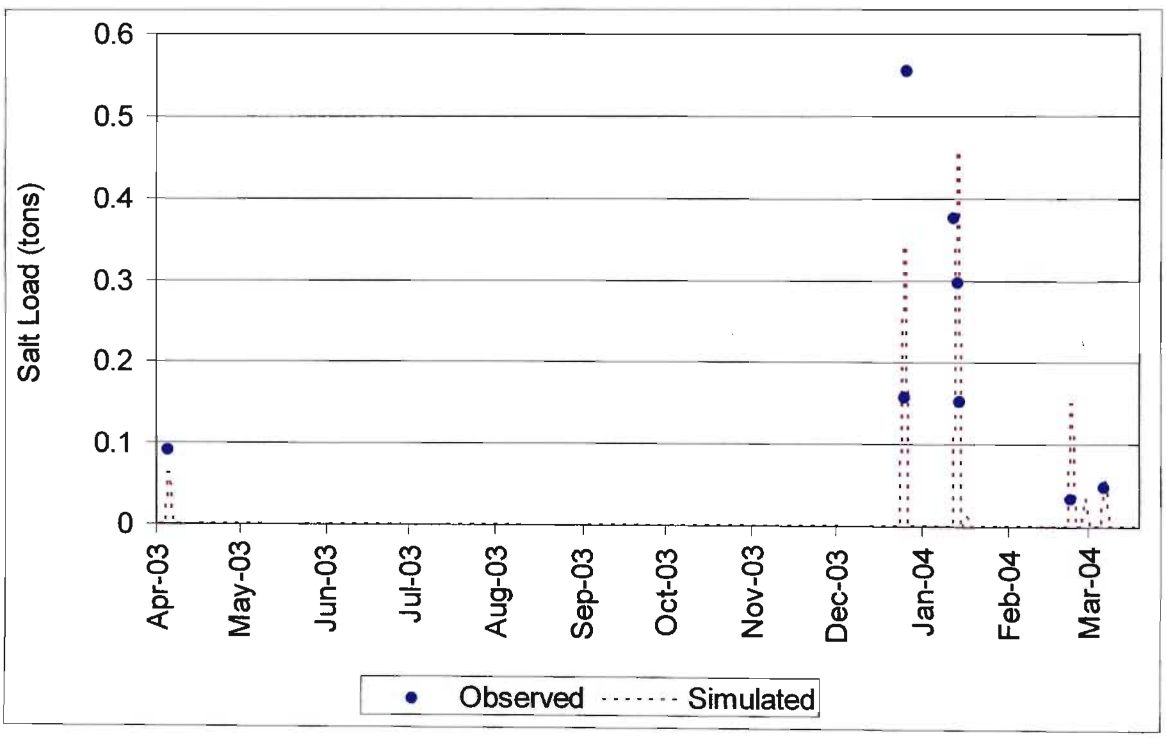


Figure 7.5: Observed and simulated daily salt load associated with runoff from Tweefontein pivot

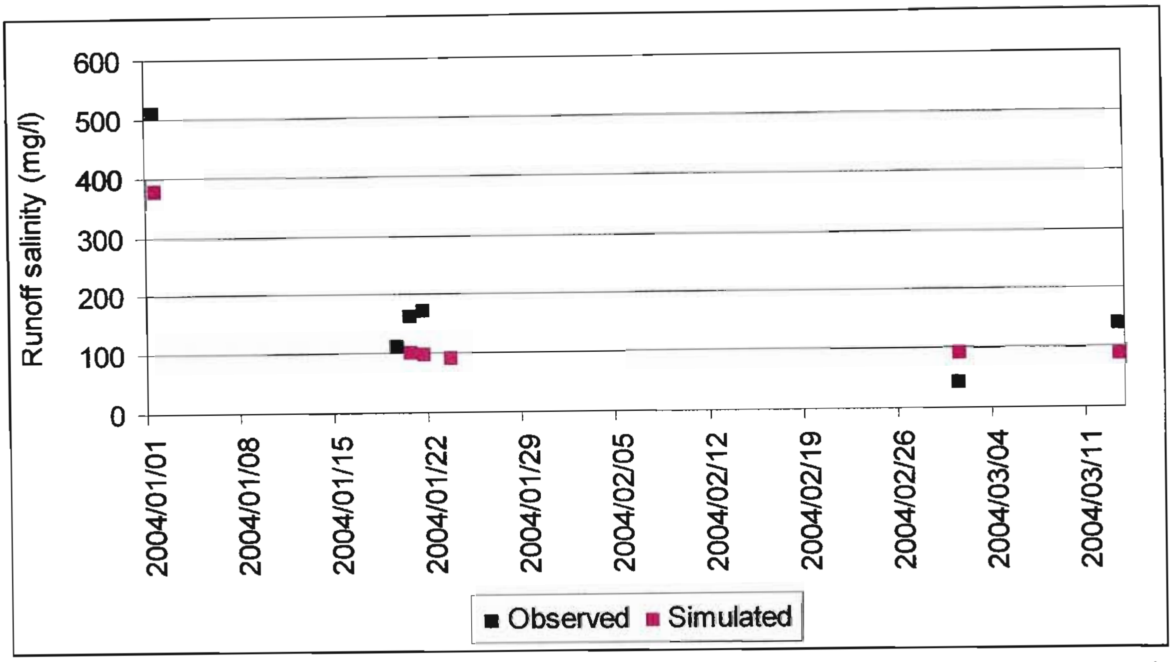


Figure 7.6: Daily salinities of sampled and simulated runoff from the Tweefontein pivot

Table 7.5: Summary of inputs into *ACRU2000* for the Tweefontein pivot
Table 7.6 Summary of inputs into *ACRUSalinity* for the Tweefontein pivot

Of the total amount of water available at the pivot (931.15 mm), irrigation constituted 33% (306 mm), while rainfall constituted 67% (Table 7.3). As in Syferfontein, most of water available at the pivot was lost through evapotranspiration (708 mm, representing 76 %). Runoff was 44 mm (5%). The amount that percolated into groundwater storage was 31 mm (3%), while interception loss was 38 mm (4 %). The total amount of salt, which accompanied the water supplied, was 121 tons (Table 7.4). Salts from irrigation water constituted 97% (i.e. 117.4 metric tons), while that from rainfall was 3% (i.e. 3.3 metric tons). The geologically generated salt was less than a ton (0.3 tons), making the total available salts about 121 tons. The amount of salts that was lost in runoff was about 1% of the total available salt, while 19% (about 23 tons) accompanied drainage water into the groundwater store. About 49% of the salt, (60 tons), was precipitated in the top soil horizons, while the salt load associated with the increase in the salinity of water in the topsoil was about 31% (38 tons). An insignificant amount of salts (21 g) occurred as precipitated salts on the soil surface layer. A net decrease in the salinity of the water in the surface layer occurred from 3 611 mg/l at the beginning of simulation to about 450 mg/l at the end of simulation, thereby making the increase in salt load zero. The insignificant amount of precipitated salts and decrease in soil water salinity in the surface layer were due to dilution of salts by rainfall, loss of salts in runoff and salt redistribution to the A-horizon.

Table 7.3 Water balance of the Tweefontein pivot

Items	**Supplied Water**		**Distribution**				
	Rainfall	Irrigation	Runoff	Total Evaporation	Soil Moisture	Drainage To Groundwater	Interception Loss
Volume (m^3)	125100.00	61130.00	8879.04	141594.46	23218.00	6097.8.00	7616.00
Depth (mm)	625.50	305.65	44.40	707.97	116.09	30.49	38.08
Percentage of Total Available Water (%)	67.00	33.00	5.00	76.00	12.00	3.00	4.00

Table 7.4 Salt balance of the Tweefontein pivot

Items	**Supplied Salts**		**Generated Salts**	**Distribution**					
	Rainfall	Irrigation		Runoff	Topsoil		Soil Surface Layer		Drainage To Groundwater
					Precipitated Salts	Dissolved Salts	Precipitated Salts	Dissolved Salts	
Mass (tons)	3.25	117.37	0.30	1.13	59.79	37.85	0.00	-1.35	23.25
Percentages	3.00	97.00		1.00	49.0	31.00	0.00	0.00	19.00
Total Available Salts (tons)			120.92						

7.1.3 Comparison of Results Between the Tweefontein and Syferfontein Pivots

The verifications of simulations presented in Figures 7.1 - 7.6 for both the Syferfontein and Tweefontein pivots, were constrained by the non-continuity of the records of the monitoring of the runoff from the pivots. This can be observed in the figures. This was due to logistical reasons associated with the downloading of data from the data loggers and the collection of water samples from the *ISCO* samplers. Inability to collect the water samples from the *ISCO* samplers immediately after they were filled, and restock the sampler with empty bottles meant that flows could pass unsampled. Similarly, once the storage capacity of the data logger was full, the earlier collected data on runoff was overwritten, thereby making the retrieval of such data impossible.

Comparisons of water and salt balances at both the Syferfontein and Tweefontein pivots are presented in Figures 7.7 and 7.8. The differences in the characteristics of the water and salt distribution for the two pivots were due to differences in the soil types at the pivots, the crops for which the simulation were carried out and the differences in the amounts and salt loads of the water supplied onto the pivots. While the soil at the Tweefontein pivot is sandy loam, that of Syferfontein is clay. Typical water retention characteristics of the soils at the Syferfontein and Tweefontein pivots at 0.1 m have been presented in Figure 6.4 (see Section 6.7). Although the porosity and the residual water of clay at the Syferfontein pivot were relatively higher in comparison to those of the sandy loam in the Tweefontein pivot (0.8 and 0.25 against 0.3 and 0.09 respectively), in general, clay is relatively impermeable and drains poorly. This is reflected in the higher percentage of the volume of water that occurred as runoff of the total available water in Syferfontein. As a result of the higher percentage of runoff in Syferfontein, the percentage of the volume of water that percolates into groundwater storage was lower than in the Tweefontein pivot (Figure 7.7). Unlike at the Tweefontein pivot, salt precipitation and increase in the soil water salinity occurred in the soil surface layer at the Syferfontein pivot. This may have been caused by water logging (ponding) and eventual evaporation (with the deposition of the salts) resulting from the clayey nature of the soil at Syferfontein, coupled with the fact that more saline irrigation water than rainfall was used at Syferfontein. Although ponding of water also occurred at Tweefontein (see Figure 7.9), the irrigation water contribution to water logging must have been more in Syferfontein than in Tweefontein. The reason for this is that the water and salt inputs from irrigation onto the Syferfontein pivot were more than that from rainfall, whereas at the Tweefontein pivot, rainfall onto the pivot was more than double that from irrigation water.

The assessment of water and salt balances on both the Syferfontein and Tweefontein pivots indicated that a significant part of the water loss from the pivots occurred as evaporation and transpiration from plants, i.e. total evaporation. Total evaporation constituted not less than 75% at both pivots (Tables 7.1 and 7.3).

Salts input onto both pivots were from rainfall and irrigation water. Irrigation water contributed almost all the salts, and it was about 97% and 99.5% respectively of the total available salts at the Tweefontein and Syferfontein pivots.

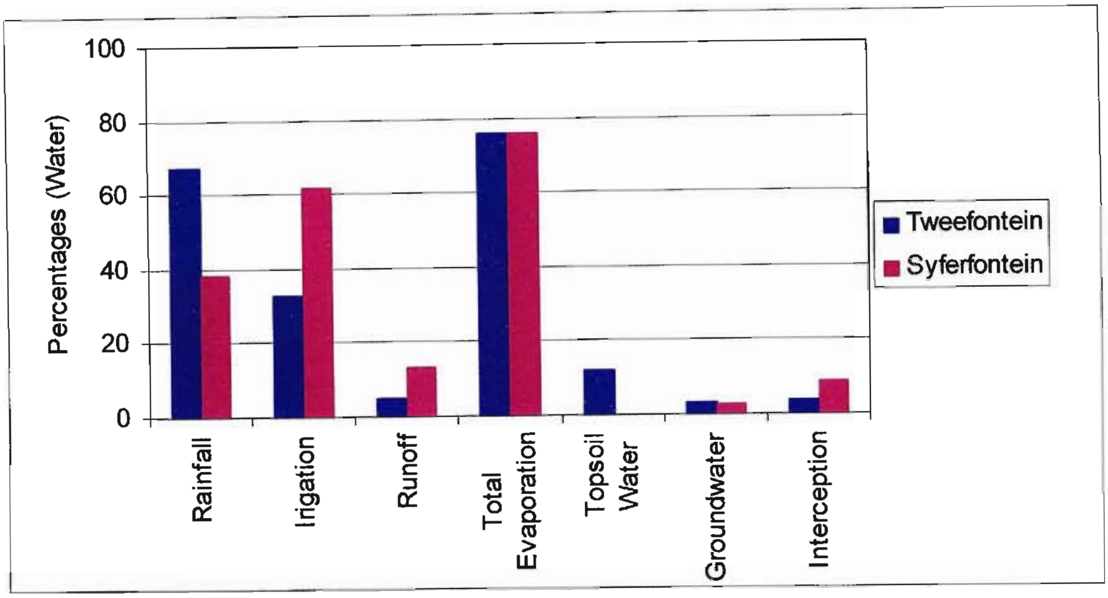


Figure 7.7: Comparison of available water distribution as a percentage of total water applied through irrigation and rainfall at the Tweefontein and Syferfontein pivots

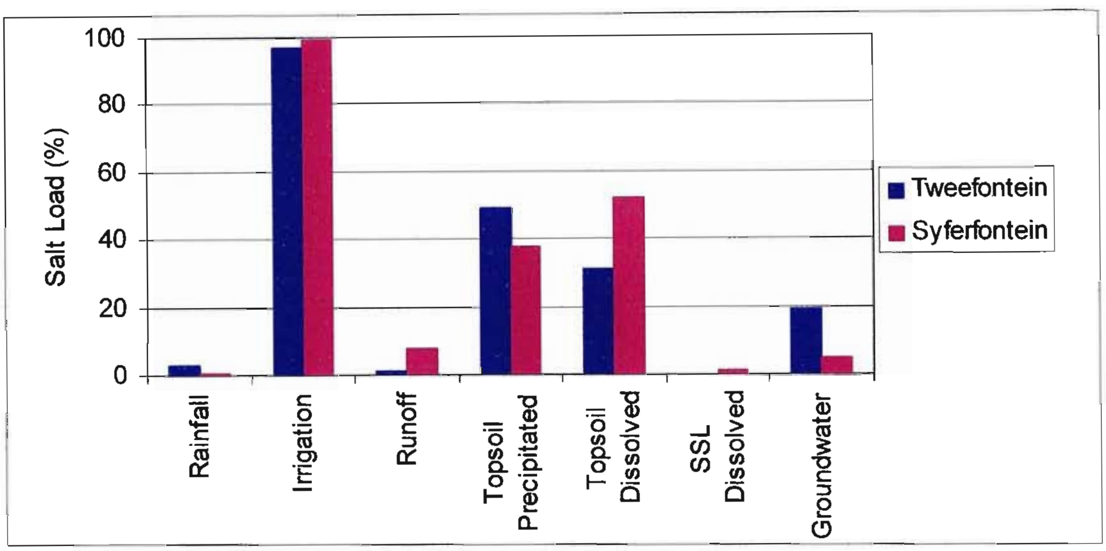


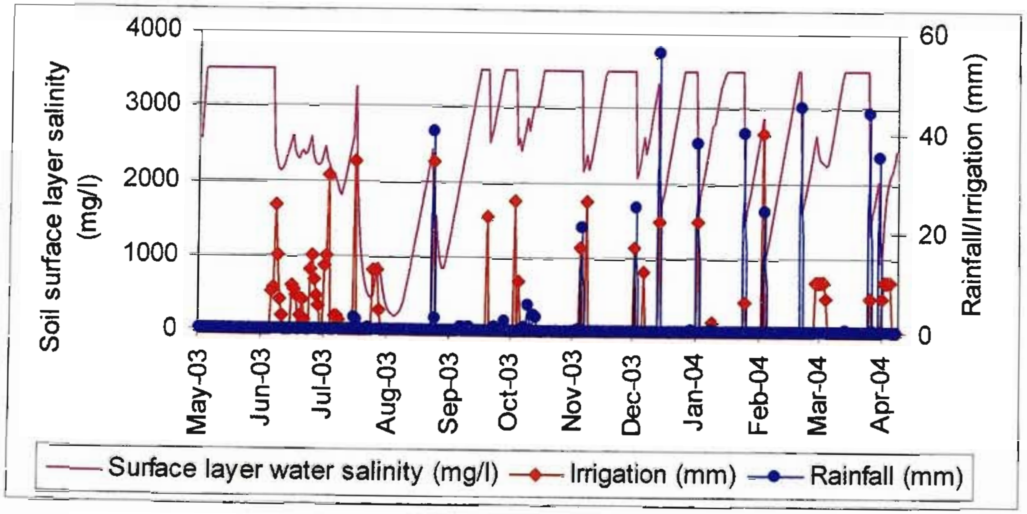
Figure 7.8: Comparison of salt load distribution as a percentage of the total salt load applied through irrigation and rainfall at the Tweefontein and Syferfontein pivots

A significant proportion of the salts supplied to the pivots and generated within the system, were either precipitated within the root zone or associated with the soil water in the topsoil (i.e. about 90 tons in Syferfontein and 80 tons in Tweefontein). Therefore, by irrigating with a saline mine water, a significant proportion of the salts associated with the saline mine water can be removed from the water system as precipitated salts, thereby reducing the possibility of off-site salt export and environmental pollution.

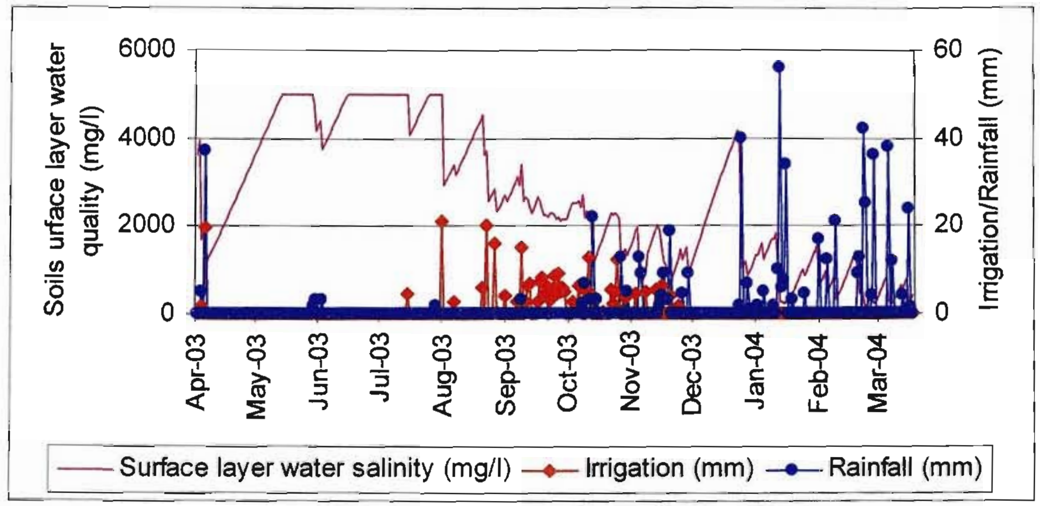
Figure 7.9: A picture showing examples of ponding of water at the Tweefontein pivot (photo by O. Idowu 27/06/2005)

The maximum root depth and the soil depth to which majority of soil water extraction takes place for a fully-grown irrigated crop (Smithers *et al*., 1995) at the Tweefontein pivot are taken to be 2 m and 1 m respectively for maize, while at the Syferfontein pivot, they are 1.2 m and 0.6 m respectively for grasses. The salinities of the soil surface layer (taken to 0.1 m for the simulations) at both pivots were dependent on rainfall. During an event, the salinity of the surface layer drops as result of dilution effect of rainfall (Figure 7.10). The larger the event, therefore, the more the dilution effect. Between rainfall events, the increase in salinity occurs as a result of evapo-concentration until the salt saturation limit is reached and salts are subsequently precipitated. In the topsoil, salinity fluctuated less rapidly than in the surface layer because of the muted influence of the dilution effect of rainfall. When a large event or continuous days of rainfall occur, significant amount of water can then drain into the topsoil and reduce the soil water salinity appreciably by dilution. This is evident at the Tweefontein pivot between February and March 2004 (Figure 7.10d), when continuous days of rainfall led to a significant drop in the topsoil salinity from 4 300 mg/l to 2 800 mg/l.

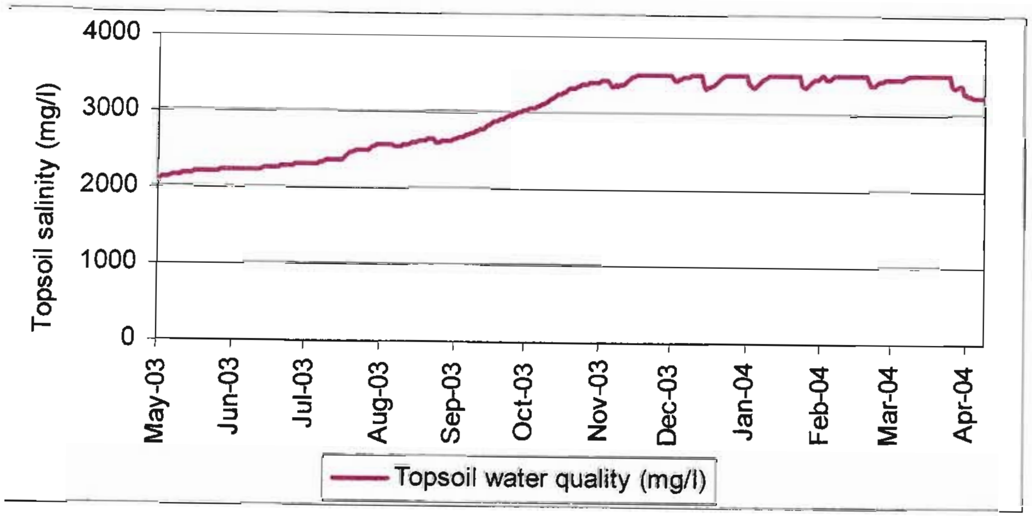
The precipitation of salts in the soil horizons means that salts could accumulate in the soil to damaging concentrations that could reduce crop yields (Ayers and Westcot, 1994). Yield reductions occur when the salts accumulate in the root zone to such an extent that the crop is no longer able to extract sufficient water from the salty soil solution, resulting in a water stress for a significant period. If water uptake is reduced appreciably, the plant slows its rate of growth. According to Rhoades *et* al. (1992), the hypothesis that best fits the observations is that excessive salinity reduces plant growth primarily because it increases the energy that must be expended to acquire water from the soil of the root zone and to make the biochemical adjustments necessary to survive under stress. This energy is diverted from the processes which lead to growth and yield. This effect is primarily related to the total electrolyte concentration and is largely independent of specific solute composition (Rhoades *et al.*, 1992). All plants do not respond to salinity in a similar manner; some crops can produce acceptable yields at much greater soil salinity than others. The reason for this is that some are better able to make the needed osmotic adjustments enabling them to extract more water from a saline soil. Considering the salinity increase that may attend irrigation with mine water, the ability of the crop planted to adjust to salinity can therefore be very important. Table 7.5 shows the crop tolerance and yield potential of selected crops as influenced by irrigation water and soil salinity. The salt saturation values, which represent the maximum subsurface water quality beyond which no salt generation takes place and at which precipitation of salts occurs, were 5 000 mg/l (≈ 7.8 dS/m) and 3 500 mg/l (≈ 5.5 dS/m) at the Tweefontein and Syferfontein pivots respectively. The salinities of the irrigation water used at the Tweefontein and Syferfontein pivots were 1 920 mg/l (≈ 3 dS/m) and 2 042 mg/l (≈ 3.2 dS/m) respectively (Table 6.8). Comparisons of these values with Table 7.5 indicate that many crops can tolerate the salt saturation values and irrigation water salinities at both pivots.



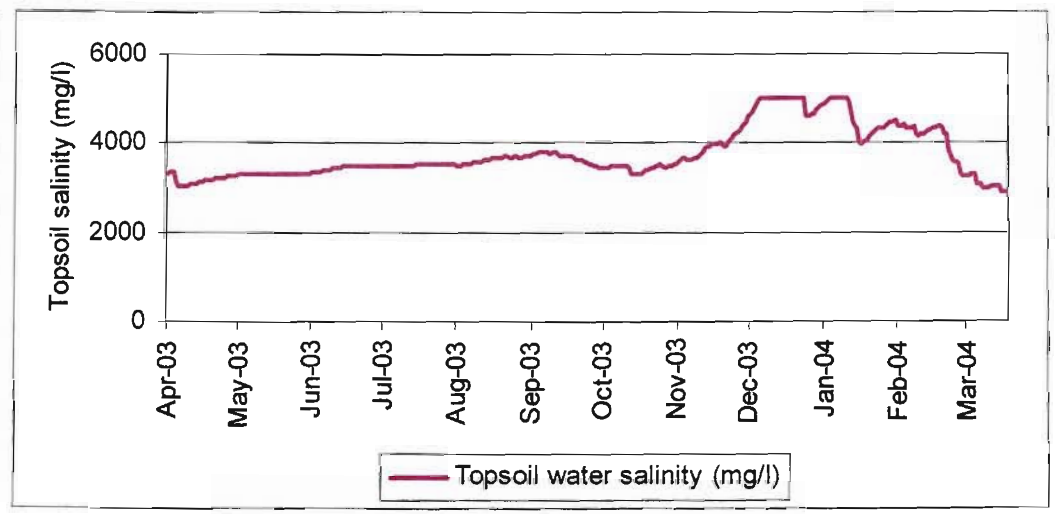
(a)



(c)



(b)



(d)

ig 7.10: Soil surface layer and topsoil salinities (a) and (b) – at the Syferfontein pivot, (c) and (d) – at the Tweefontein pivc

Table 7.5: Crop tolerance and yield potential of selected crops as influenced by irrigation water salinity (EC_w) and soil salinity (EC_e) (Ayers and Westcot, 1994)

CROPS	YIELD POTENTIAL									
	100%		90%		75%		50%		0% maximum	
	EC_e	EC_w	EC_e	EC_w	EC_e	EC_w	EC_e	EC_w	EC_e	EC_w
FIELD CROPS										
Barley *(Hordeum vulgare)*	8.0	5.3	10	6.7	13	8.7	18	12	28	19
Cotton *(Gossypium hirsutum)*	7.7	5.1	9.6	6.4	13	8.4	17	12	27	18
Sugarbeet *(Beta vulgaris)*	7.0	4.7	8.7	5.8	11	7.5	15	10	24	16
Sorghum *(Sorghum bicolor)*	6.8	4.5	7.4	5.0	8.4	5.6	9.9	6.7	13	8.7
Wheat *(Triticum aestivum*	6.0	4.0	7.4	4.9	9.5	6.3	13	8.7	20	13
Wheat, durum *(Triticum turgidum)*	5.7	3.8	7.6	5.0	10	6.9	15	10	24	16
Soybean *(Glycine max)*	5.0	3.3	5.5	3.7	6.3	4.2	7.5	5.0	10	6.7
Cowpea *(Vigna unguiculata)*	4.9	3.3	5.7	3.8	7.0	4.7	9.1	6.0	13	8.8
Groundnut (Peanut) *(Arachis hypogaea)*	3.2	2.1	3.5	2.4	4.1	2.7	4.9	3.3	6.6	4.4
Rice (paddy) *(Oriza sativa)*	3.0	2.0	3.8	2.6	5.1	3.4	7.2	4.8	11	7.6
Sugarcane *(Saccharum officinarum)*	1.7	1.1	3.4	2.3	5.9	4.0	10	6.8	19	12
Corn (maize) *(Zea mays)*	1.7	1.1	2.5	1.7	3.8	2.5	5.9	3.9	10	6.7
Flax *(Linum usitatissimum)*	1.7	1.1	2.5	1.7	3.8	2.5	5.9	3.9	10	6.7
Broadbean *(Vicia faba)*	1.5	1.1	2.6	1.8	4.2	2.0	6.8	4.5	12	8.0
Bean *(Phaseolus vulgaris)*	1.0	0.7	1.5	1.0	2.3	1.5	3.6	2.4	6.3	4.2
VEGETABLE CROPS										
Squash, zucchini (courgette) *(Cucurbita pepo melopepo)*	4.7	3.1	5.8	3.8	7.4	4.9	10	6.7	15	10
Beet, red *(Beta vulgaris)*	4.0	2.7	5.1	3.4	6.8	4.5	9.6	6.4	15	10
Squash, scallop *(Cucurbita pepo melopepo)*	3.2	2.1	3.8	2.6	4.8	3.2	6.3	4.2	9.4	6.3
Broccoli *(Brassica oleracea botrytis)*	2.8	1.9	3.9	2.6	5.5	3.7	8.2	5.5	14	9.1
Tomato *(Lycopersicon esculentum)*	2.5	1.7	3.5	2.3	5.0	3.4	7.6	5.0	13	8.4
Cucumber *(Cucumis sativus)*	2.5	1.7	3.3	2.2	4.4	2.9	6.3	4.2	10	6.8
Spinach *(Spinacia oleracea)*	2.0	1.3	3.3	2.2	5.3	3.5	8.6	5.7	15	10
Celery *(Apium graveolens)*	1.8	1.2	3.4	2.3	5.8	3.9	9.9	6.6	18	12
Cabbage *(Brassica oleracea capitata)*	1.8	1.2	2.8	1.9	4.4	2.9	7.0	4.6	12	8.1
Potato *(Solanum tuberosum)*	1.7	1.1	2.5	1.7	3.8	2.5	5.9	3.9	10	6.7
Corn, sweet (maize) *(Zea mays)*	1.7	1.1	2.5	1.7	3.8	2.5	5.9	3.9	10	6.7
Sweet potato *(Ipomoea batatas)*	1.5	1.0	2.4	1.6	3.8	2.5	6.0	4.0	11	7.1
Pepper *(Capsicum annuum)*	1.5	1.0	2.2	1.5	3.3	2.2	5.1	3.4	8.6	5.8
Lettuce *(Lactuca sativa)*	1.3	0.9	2.1	1.4	3.2	2.1	5.1	3.4	9.0	6.0
Radish *(Raphanus sativus)*	1.2	0.8	2.0	1.3	3.1	2.1	5.0	3.4	8.9	5.9
Onion *(Allium cepa)*	1.2	0.8	1.8	1.2	2.8	1.8	4.3	2.9	7.4	5.0
Carrot *(Daucus carota)*	1.0	0.7	1.7	1.1	2.8	1.9	4.6	3.0	8.1	5.4
Bean *(Phaseolus vulgaris)*	1.0	0.7	1.5	1.0	2.3	1.5	3.6	2.4	6.3	4.2
Turnip *(Brassica rapa)*	0.9	0.6	2.0	1.3	3.7	2.5	6.5	4.3	12	8.0
Wheatgrass, tall *(Agropyron elongatum)*	7.5	5.0	9.9	6.6	13	9.0	19	13	31	21
Wheatgrass, fairway crested *(Agropyron cristatum)*	7.5	5.0	9.0	6.0	11	7.4	15	9.8	22	15

Table 7.5 contd.

CROPS	YIELD POTENTIAL									
	100%		90%		75%		50%		0% maximum	
	EC_e	EC_w	EC_e	EC_w	EC_e	EC_w	EC_e	EC_w	EC_e	EC_w
Bermuda grass *(Cynodon dactylon)*	6.9	4.6	8.5	5.6	11	7.2	15	9.8	23	15
Barley (forage) *(Hordeum vulgare)*	6.0	4.0	7.4	4.9	9.5	6.4	13	8.7	20	13
Ryegrass, perennial *(Lolium perenne)*	5.6	3.7	6.9	4.6	8.9	5.9	12	8.1	19	13
Trefoil, narrowleaf birdsfoot *(Lotus corniculatus tenuifolium)*	5.0	3.3	6.0	4.0	7.5	5.0	10	6.7	15	10
Harding grass *(Phalaris tuberosa)*	4.6	3.1	5.9	3.9	7.9	5.3	11	7.4	18	12
Fescue, tall *(Festuca elatior)*	3.9	2.6	5.5	3.6	7.8	5.2	12	7.8	20	13
Wheatgrass, standard crested *(Agropyron sibiricum)*	3.5	2.3	6.0	4.0	9.8	6.5	16	11	28	19
Vetch, common *(Vicia angustifolia)*	3.0	2.0	3.9	2.6	5.3	3.5	7.6	5.0	12	8.1
Sudan grass *(Sorghum sudanense)*	2.8	1.9	5.1	3.4	8.6	5.7	14	9.6	26	17
Wildrye, beardless *(Elymus triticoides)*	2.7	1.8	4.4	2.9	6.9	4.6	11	7.4	19	13
Cowpea (forage) *(Vigna unguiculata)*	2.5	1.7	3.4	2.3	4.8	3.2	7.1	4.8	12	7.8
Trefoil, big *(Lotus uliginosus)*	2.3	1.5	2.8	1.9	3.6	2.4	4.9	3.3	7.6	5.0
Sesbania *(Sesbania exaltata)*	2.3	1.5	3.7	2.5	5.9	3.9	9.4	6.3	17	11
Sphaerophysa *(Sphaerophysa salsula)*	2.2	1.5	3.6	2.4	5.8	3.8	9.3	6.2	16	11
Alfalfa *(Medicago sativa)*	2.0	1.3	3.4	2.2	5.4	3.6	8.8	5.9	16	10
Lovegrass *(Eragrostis sp.)*	2.0	1.3	3.2	2.1	5.0	3.3	8.0	5.3	14	9.3
Corn (forage) (maize) *(Zea mays)*	1.8	1.2	3.2	2.1	5.2	3.5	8.6	5.7	15	10
Clover, berseem *(Trifolium alexandrinum)*	1.5	1.0	3.2	2.2	5.9	3.9	10	6.8	19	13
Orchard grass *(Dactylis glomerata)*	1.5	1.0	3.1	2.1	5.5	3.7	9.6	6.4	18	12
Foxtail, meadow *(Alopecurus pratensis)*	1.5	1.0	2.5	1.7	4.1	2.7	6.7	4.5	12	7.9
Clover, red *(Trifolium pratense)*	1.5	1.0	2.3	1.6	3.6	2.4	5.7	3.8	9.8	6.6
Clover, alsike *(Trifolium hybridum)*	1.5	1.0	2.3	1.6	3.6	2.4	5.7	3.8	9.8	6.6
Clover, ladino *(Trifolium repens)*	1.5	1.0	2.3	1.6	3.6	2.4	5.7	3.8	9.8	6.6
Clover, strawberry *(Trifolium fragiferum)*	1.5	1.0	2.3	1.6	3.6	2.4	5.7	3.8	9.8	6.6
FRUIT CROPS										
Date palm *(phoenix dactylifera)*	4.0	2.7	6.8	4.5	11	7.3	18	12	32	21
Grapefruit *(Citrus paradisi)*	1.8	1.2	2.4	1.6	3.4	2.2	4.9	3.3	8.0	5.4
Orange *(Citrus sinensis)*	1.7	1.1	2.3	1.6	3.3	2.2	4.8	3.2	8.0	5.3
Peach *(Prunus persica)*	1.7	1.1	2.2	1.5	2.9	1.9	4.1	2.7	6.5	4.3
Apricot *(Prunus armeniaca)*	1.6	1.1	2.0	1.3	2.6	1.8	3.7	2.5	5.8	3.8
Grape *(Vitus sp.)*	1.5	1.0	2.5	1.7	4.1	2.7	6.7	4.5	12	7.9
Almond *(Prunus dulcis)*	1.5	1.0	2.0	1.4	2.8	1.9	4.1	2.8	6.8	4.5
Plum, prune *(Prunus domestica)*	1.5	1.0	2.1	1.4	2.9	1.9	4.3	2.9	7.1	4.7
Blackberry *(Rubus sp.)*	1.5	1.0	2.0	1.3	2.6	1.8	3.8	2.5	6.0	4.0
Boysenberry *(Rubus ursinus)*	1.5	1.0	2.0	1.3	2.6	1.8	3.8	2.5	6.0	4.0
Strawberry *(Fragaria sp.)*	1.0	0.7	1.3	0.9	1.8	1.2	2.5	1.7	4	2.7

EC_e means average root zone salinity as measured by electrical conductivity of the saturation extract of the soil, reported in deciSiemens per metre (dS/m) at 25°C., while EC_w means electrical conductivity of the irrigation water in deciSiemens per metre (dS/m). The zero yield potential or maximum EC_e indicates the theoretical soil salinity (EC_e) at which crop growth ceases.

7.1.4 Two Dimensional Electrical Resistivity Survey

The interpretation of the 2D electrical resistivity survey carried at the Tweefontein, Syferfontein and Major pivots, as well as a comparison of the results, are presented in the sections that follow.

7.1.4.1 The Syferfontein Pivot

The pseudo-section of the 2D model interpretation of the electrical resistivity investigation to a depth of about 10 m along the line of survey is shown in the Figures 7.11. The line of survey was about 700 m long in a N-S direction (Figure F1, Appendix F). The general range of resistivities of the subsurface soil materials was 4.98 -164 ohm-m. This is indicative of unconsolidated or weathered materials with soil water and/or dissolved ions present. The resistivities generally increase with depth, indicating a general decrease in the water content or dissolved ions, with depth. From field observation, the lithologic profile to a depth of about 2 m in a pit close to the line of investigation consists of black clay, underlain by a dolerite dyke or sill, which in turn is underlain by yellowish clay. The dolerite is thoroughly weathered and fractured at the top and the degree of weathering decreases with depth. The rock types across the pivot area appear to vary over short distances and include clays, dolerites, sandstones and shales, based on the lithologic logs of five boreholes located around the pivot area (Figure F2, Appendix F).

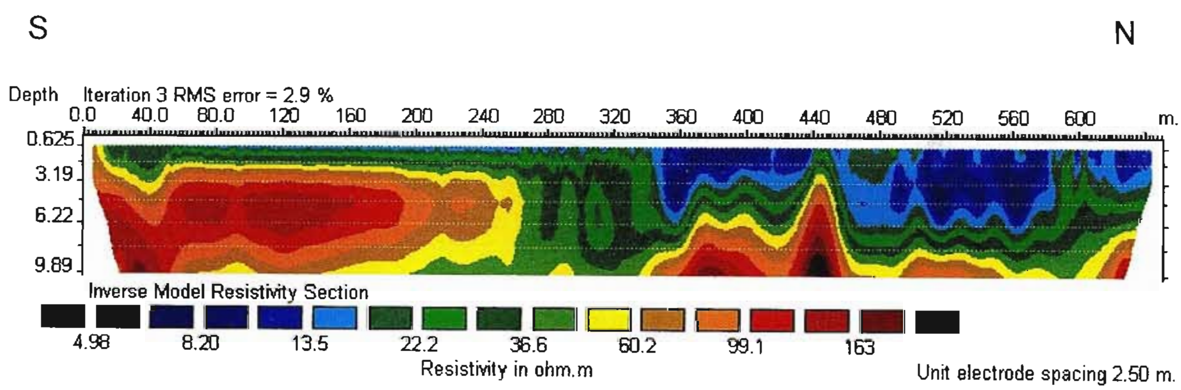


Figure 7.11: Pseudo-section of the 2D model interpretation of electrical resistivity for the Syferfontein pivot

The general increase in resistivities with depth and the lateral variation of resistivity values indicates the varying nature of the lithologies as well as the amount and quality of water in the subsurface of the pivot area. The black clay, which is the topmost layer in the pivot area, has the lowest resistivity and is represented by the shades of blue in the Figure 8.12. The layer appears to have been categorised as "soil" in the borehole lithologic logs in Figure F2 (Appendix F). The layer appears generally to be about 1 m thick in the southern half of the line of investigation (i.e. from station 0 – 340), whereas it appears thicker in the northern half (i.e. from station 340 – 600) with a thickness of up to 6 m in some places. This may be the nature of occurrence of the layer in the investigation area. However, it is also possible that the variation is a reflection of the distribution of salt or water in the subsurface layer, such that the salt associated with the mine water used for irrigation influenced the subsurface more in the direction of the surface and near surface flow of soil water, down the slope and towards the outlet of the pivot. The pivot slopes in a northerly direction and the line of survey was actually close to the flume used for monitoring the runoff leaving the pivot area. The horizons in various shades of green may be representative of the subsurface soil materials in different degrees of weathering and varying amount of water and salt content, with the degree of weathering and amount of water and salt content decreasing with depth. The yellow areas probably represent the dolerite occurring in the area. As it is fractured and weathered, it may have a lower bulk density and therefore may have a much lower resistivity than a fresh dolerite.

7.1.4.2 The Tweefontein Pivot

The result of the 2D interpretation of the electrical resistivity survey at the Tweefontein pivot is presented in the Figure 7.12, while the aerial photograph of the pivot, with the line of investigation, is shown in Figure F3 (Appendix F). In comparison to the resistivity values for Syferfontein, which ranged from 4.98 -164 ohm-m, the resistivity values for Tweefontein range from 15.5 - 679 ohm-m, indicating a more resistive subsurface. The pseudo-section of the 2D interpretation shows a general increase of resistivity with depth which probably indicates the decreasing influence of the mine water used for irrigation with depth. At the beginning and end of the survey line, the subsurface resistivities were high. These areas lie outside the pivot area irrigated with mine water. The lower resistivity values which occur within the pivot areas in comparison to the areas that lie outside the pivot area, reflect the influence of the mine water used for irrigation. The greater supply of water and the associated salts in the pivot area has made the subsurface more conductive, hence the lower resistivity values. Similar to Syferfontein, the areas with the lowest resistivity values increase in the direction of the outlet of the pivot area.

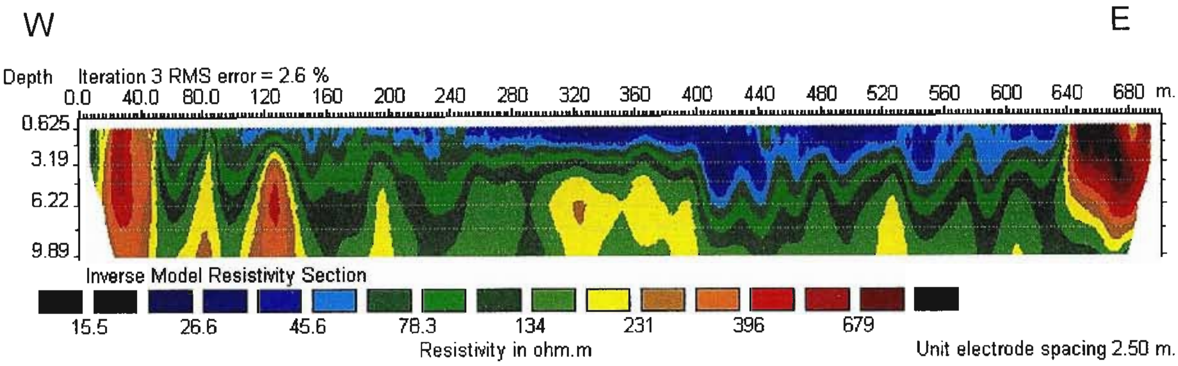


Figure 7.12: Pseudo-section of the 2D model interpretation of electrical resistivity for the Tweefontein pivot

The pseudo-section of the 2D interpretation of the subsurface shows areas of contrasting and isolated resistivities, which reflects the uneven nature of the spoil materials underlying the topsoil at Tweefontein. The picture could be a reflection of the high degree of variability of the sizes and composition of the spoil materials. Cracks and voids in the topsoil and spoil, caused by settling and weathering of the spoil materials, allow irrigation water to percolate and cause areas of varying resistivities in the subsurface. The rehabilitated nature of the Tweefontein pivot is reflected in the 2D interpretation of its subsurface, which contrasts sharply with that at the Major pivot (Figure 7.13), which is within the same mine but located in an unmined area, and where a generally consistent increase in resistivity with depth, apart from the areas outside the pivot at the beginning and end of the survey line, occurs. The 2D interpretation at Major pivot is consistent with the lithologic log of a borehole located within the pivot (Figure F4, Appendix F), where a clayey soil layer of about 5 m, which is more sandy at the bottom, is underlain by sandstone, which is thoroughly weathered at the top (up to 10-12 m). The shades of blue and green up to 6 m in the figure probably represent the clayey soil layer, with the influence of the saline irrigation water. No borehole log is available for the Tweefontein pivot.

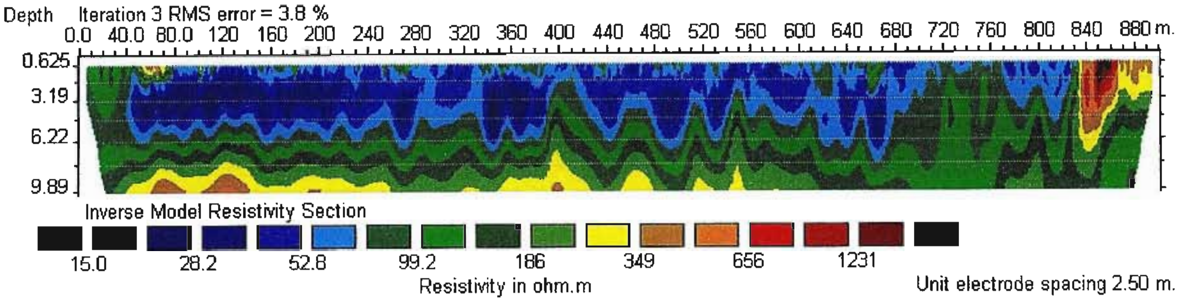


Figure 7.13: Pseudo-section of 2D model interpretation of electrical resistivity for the Major pivot

From the 2D resistivity surveys at Syferfontein and Tweefontein, indications of the influence that irrigating with mine water may have on the subsurface are shown. The resistivities are lower in areas irrigated with the mine water, thereby reflecting the greater amount of water and dissolved salts supply to the pivot areas. A general increase in resistivities with depth in the pivot areas can be taken as a reflection of the decreasing influence of the mine water used for irrigation with depth. The occurrence of a thicker topmost layer towards the exit of the pivot areas may be a reflection of the distribution of water and salt content such that the mine water used for irrigation influences the subsurface more in the direction of surface and near surface flow of soil water, towards the outlet of the pivot areas.

7.2 Conclusions

The applications of the modified *ACRU2000* model and the *ACRUSalinity* module to the Tweefontein and Syferfontein pivots have enabled the impact assessment of irrigation with low quality mine water on the water resources of the Tweefontein and Syferfontein pivots. The verifications undertaken in the applications of the model under field conditions, and through the comparison of the simulated results against the observed data, have yielded good results, taking into account the constraints of the observed data. By determining the water and salt balances at the pivot scale, the inputs necessary for application of the model to the Tweefontein Pan catchment and the Kleinkopje Colliery were calibrated. The results from the 2D electrical resistivity have given indications of the distribution of the salts in the soil water at the centre pivots and, therefore, complemented the results obtained from the application of the *ACRU2000* model and the *ACRUSalinity* module.

In the next chapter, the results obtained from the application of the modified *ACRU2000* and the *ACRUSalinity* module to the Tweefontein Pan catchment and the Kleinkopje Colliery, are presented and discussed.

8. RESULTS AND DISCUSSION AT CATCHMENT AND MINE SCALES

The catchment scale study comprised the assessment of the Tweefontein Pan catchment under current irrigation and different scenarios of widespread irrigation with gypsiferous mine water from the Tweefontein reservoir. The mine scale assessment involved the evaluation of the discharge from Kleinkopje Colliery into Witbank Dam under the current land use conditions and different scenarios of widespread irrigation with available mine water in the colliery. The assessments and discussions on both the Tweefontein Pan catchment and the Kleinkopje Colliery are presented in the following sections.

8.1 Tweefontein Pan Catchment

The simulated scenarios carried out on the Tweefontein Pan catchment and the available data for verification have been described in Tables 4.1 and 4.2 respectively. The scenarios simulated include baseline condition, irrigation with alternative source of mine water from the underground reservoir and widespread irrigation on both virgin and rehabilitated soils.

8.1.1 Baseline Simulation

In simulating the Tweefontein catchment, the available data on the amount and quality of water in storage in the Tweefontein Pan reservoir, as well as the salinity of soil water in the soil surface layer of the Fourth pivot were used for verification. Water pumped into the pan from the Plant Return Water Dam and the opencast mining area outside the catchment, as well as the water abstracted for irrigating two centre pivots (Fourth and Tweefontein pivots) were entered in the input data file, and were therefore taken into consideration in the reservoir water budgeting. As the Tweefontein pivot was outside of the catchment, there was no return flow from the pivot into the pan; return flow was only from the Fourth pivot. Considering that the irrigated area (Fourth pivot) was on an unmined soil, the same porosity, drained upper limits and wilting point values (for sandy loam) were used for the irrigated and non-irrigated areas. Widespread irrigation on virgin soils with mine water from Tweefontein Pan and its impact was investigated, as was the impact of irrigating rehabilitated soils in the catchment with mine water. The possibility of sourcing the irrigation water for the Fourth pivot from an alternative source in the catchment (i.e. from the underground reservoir), as well as the impact such a possibility may have, were also investigated.

The baseline condition used in the assessment of the Tweefontein Pan catchment comprises the current scenario of an unmined irrigated area of 30 ha with maize (Fourth pivot), a rehabilitated irrigated area of 20 ha (Tweefontein pivot, which lies outside the catchment) with maize, a non-irrigated area of 2 964 ha with veld in poor conditions, a surface reservoir (Tweefontein Pan) with a capacity and surface area at full capacity of 4 000Ml and 1.5 km^2 respectively, and an underground reservoir with a capacity of about 2 000 Ml. The amount of water in storage in the surface and underground reservoirs at the beginning of the simulation were observed as 3 750 Ml and 1 443 Ml respectively. The amount of seepage from Tweefontein Pan into underground workings used was 2 400 m^3/day as this reflected the water balances in the simulation of the Tweefontein Pan catchment. The seepage compares well with an estimate of 2 000 m^3/day by the Kleinkopje Management (Clean Stream Environmental Services, 2004). The observed and simulated volume, as well as the observed and simulated salinity of water in storage in the Tweefontein Pan for the baseline conditions are presented in Figures 8.1 and 8.2. With a correlation coefficients of 0.96 and 0.76 respectively between the observed and the simulated volume and salinity of water in the Pan, the amount and quality of water in the Pan are simulated adequately. The decline in water storage in the reservoir is due to evaporation, abstraction of water for irrigation at the Fourth and Tweefontein pivots, coupled with inconsistent pumping of water into the reservoir. The generally increasing trend in the salinity of water in the reservoir reflects the declining volume of water in the reservoir and the effect of concentration of salts in the reservoir by evaporation. The sharp drop in the salinity of water in the reservoir towards the end of simulation (i.e. between January – July 2004) is due to the dilution effect of the increased rainfall which occurred during the period. The amount of rainfall that occurred during the period

(505 mm) was about four times more than the amount of rainfall for the same period (125.4 mm) in the previous year.

Limited observed data were available on the soil water quality at Fourth pivot due to difficulties encountered in extracting soil water with the ceramic soil water samplers, particularly under dry conditions. Figure 8.3 shows the comparison of the simulated and observed salinities of water in the irrigated soil at the Fourth pivot at 0.1 m, while Figure 8.4 shows the amount and quality of return flow from the irrigated area into the reservoir. Figure 8.5 shows the runoff from the non-irrigated area into the reservoir. Runoff was not monitored at the Fourth pivot, but the simulated runoff was in agreement with the Tweefontein and Syferfontein pivots results. An inverse relationship can be observed between the volumes and salinities of runoff from the irrigated and non-irrigated area into the reservoir. This is a direct consequence of the dilution effect of rainfall. When a significant event occurs that leads to high runoff, the dilution effect is high and the runoff salinity is consequently low. The opposite is the case during low rainfall events. When there is no rainfall, evaporation of soil water leads to a concentration of salts until the saturation level is reached and salts are precipitated. It can be concluded therefore, that the soil surface layer is strongly influenced by the occurrence of rainfall. The results of water and salt assessment of the irrigated area, presented in Tables 8.1 and 8.2, are similar to those obtained in the pivot scale studies, with most of the water lost through evapotranspiration, and the salts, either precipitated within the root zone or associated with the soil water in the topsoil. Similar assessments for the non-irrigated areas are presented in Table 8.3 and 8.4. The simulated results obtained for the Fourth pivot is similar to that reported for the same pivot by Annandale *et al.*, (2002) using Soil Water Balance (SWB), which is a mechanistic, daily time step, soil water-salt balance generic crop growth model (Annandale *et al.*, 2002). The results, summarised in Table 8.5, were based on a study covering a crop season in 1999/00 when the pivot was planted to maize. The total evaporation (soil water evaporation and crop transpiration) and interception loss reported are 71% and 4% of the total available water respectively, while 75% and 4% were obtained in this study. As the runoff is assumed to be zero by Annandale *et al.* (2002), the high drainage reported is explainable, in that part of the simulated drainage would have formed part of runoff.

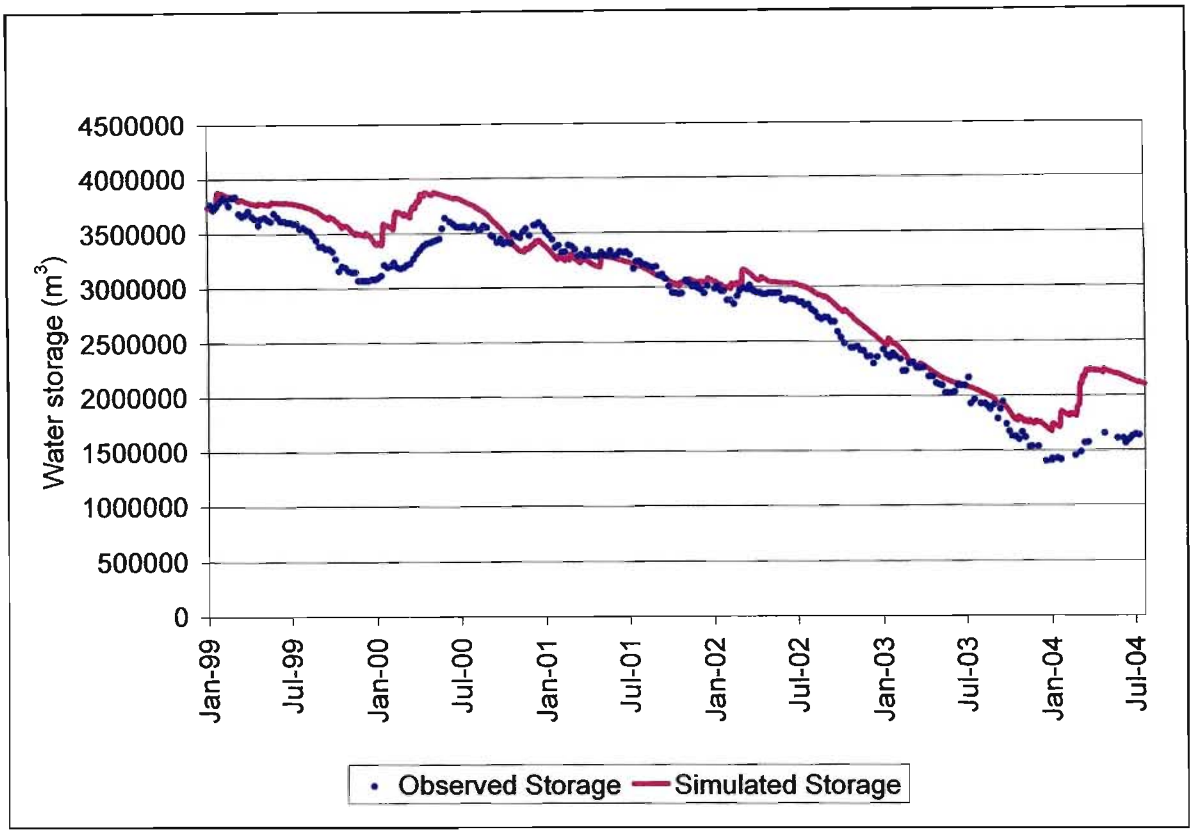


Figure 8.1: Simulated and observed daily water storage in the Tweefontein Pan

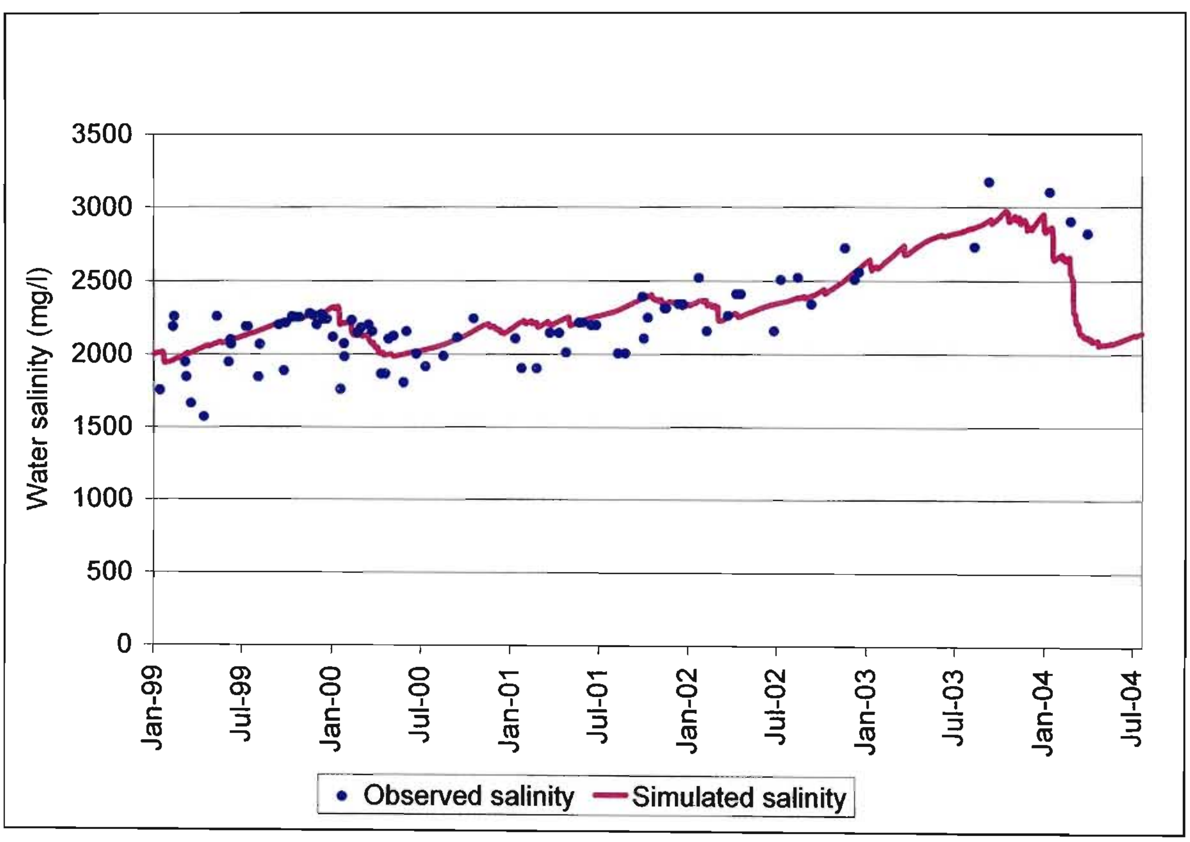


Figure 8.2: Observed and simulated quality of water in storage in the Tweefontein Pan

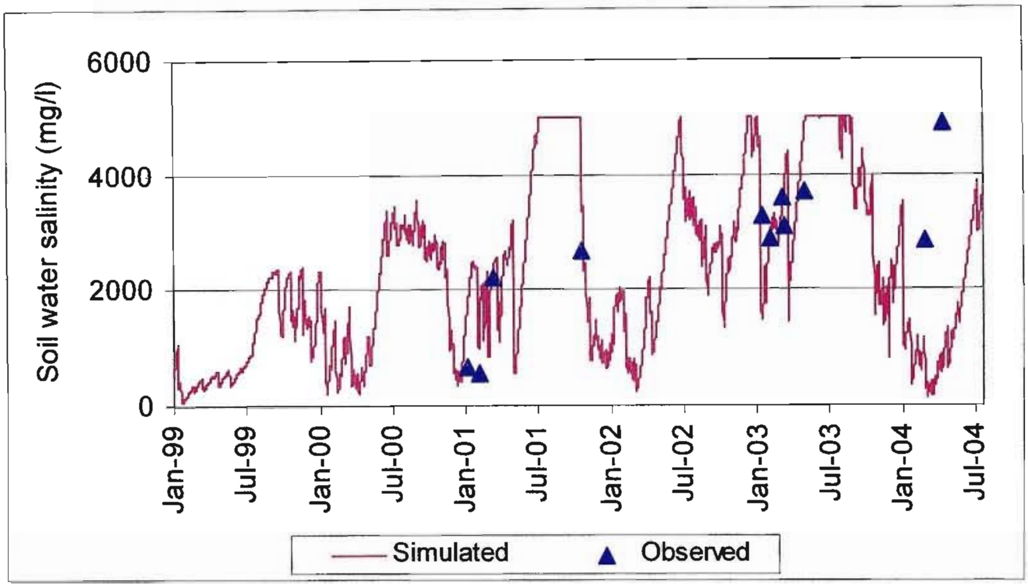


Figure 8.3: Observed and simulated daily salinities of soil water at 0.1 m in the irrigated area of the Fourth pivot

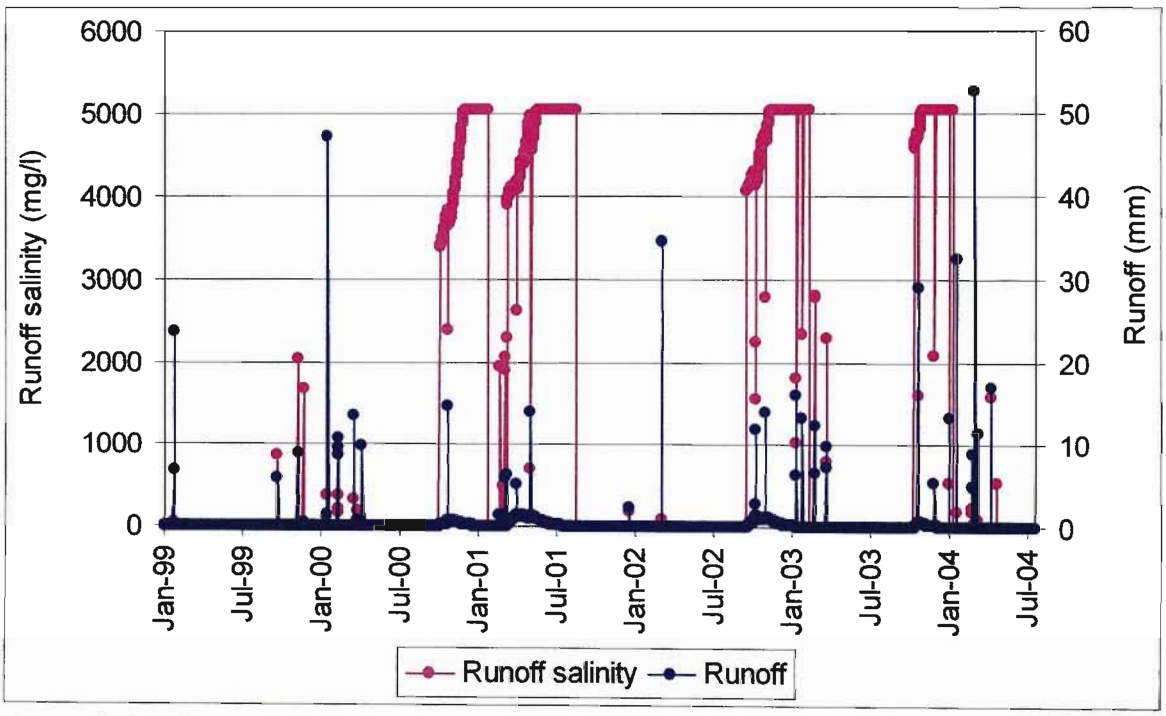


Figure 8.4: The simulated volume and salinity of daily runoff from the irrigated area (Fourth pivot) into the Tweefontein Pan

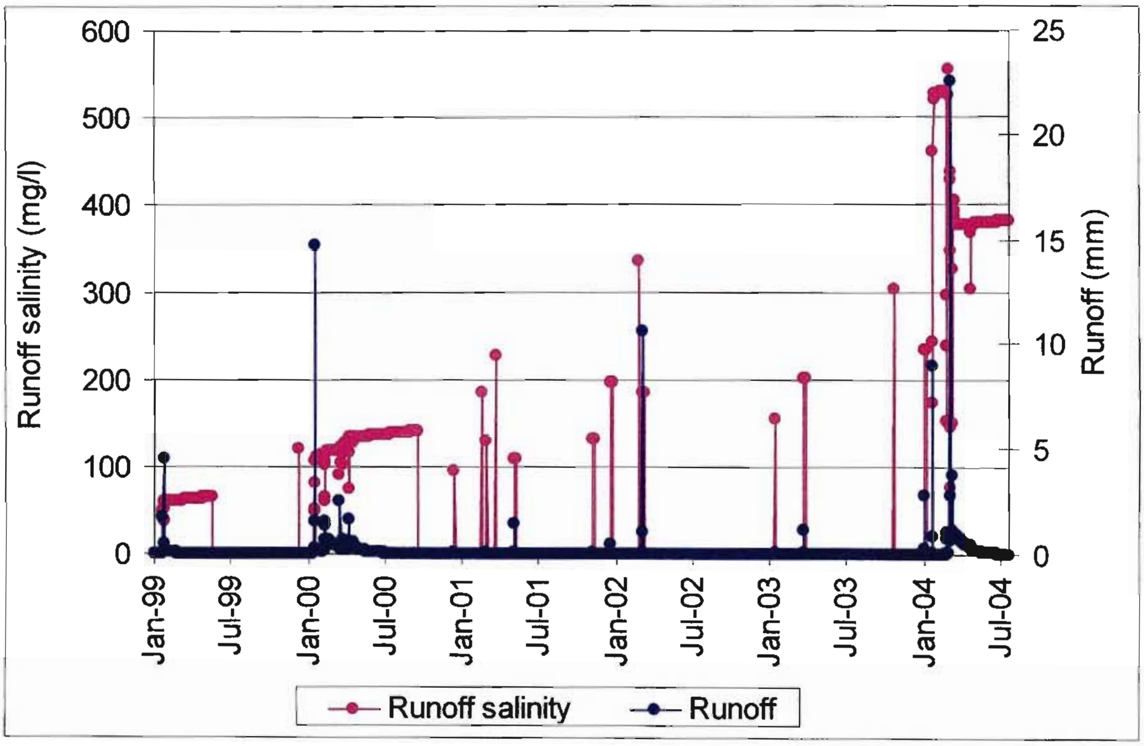


Figure 8.5: The simulated volume and salinity of daily runoff from the non-irrigated area into the Tweefontein Pan

Table 8.1: Water balance of the irrigated area (Fourth pivot) in the Tweefontein Pan catchment

Items	**Supplied Water**		**Distribution**				
	Rainfall	Irrigation	Total Evaporation	Stormflow	Groundwater Drainage	Soil Moisture	Interception Loss
Volume (mm)	2 498.0	2 208.0	3 598.0	501.0	374.0	19.0	220.0
Percentage of Total Water (%)	53.1	46.9	76.4	10.6	7.9	0.4	4.7

Table 8.2: Salt balance of the irrigated area (Fourth pivot) in the Tweefontein Pan catchment

Items	**Supplied Salts**		**Generated Salts**	**Distribution**					
				Stormflow	Topsoil		Soil Surface Layer		Groundwater Drainage
	Rainfall	Irrigation			Precipitated Salts	Dissolved Salts	Precipitated Salts	Dissolved Salts	
Amount (tons)	19.5	1 601.4	2.7	126.8	757.4	290.5	0	21.8	427.1
Percentages	1.0	99.0		7.8	46.7	17.9	0	1.3	26.3
Total Available Salts (tons)			1 623.6						

Table 8.3: Water balance of the non-irrigated area in the Tweefontein Pan Catchment

Items	Supplied Water		Distribution				
	Rainfall	Irrigation	Total Evaporation	Stormflow	Groundwater Drainage	Soil Moisture	Interception Loss
Volume (mm)	2 498.0	0.0	2 020.0	89.0	145.0	6.0	217.0
Percentage of Total Water (%)	100.0	0.0	80.9	4.4	5.8	0.2	8.7

Table 8.4: Salt balance of the non-irrigated area in the Tweefontein Pan Catchment

Items	Supplied Salts		Generated Salts	Distribution				
	Rainfall	Irrigation		Stormflow	Topsoil	Subsoil	Soil Surface Layer	Groundwater Drainage
					Dissolved Salts	Dissolved Salts	Dissolved Salts	
Amount (tons)	192.4	0.0	2.4	27.8	12.4	28.2	19.0	106.8
Percentages	100.0	0.0		15.0	6.0	15.0	10.0	55.0
Total Available Salts (tons)			194.8					

Table 8.5: Simulated values of the soil water balance for maize for the1999/00 season at the Fourth pivot using SWB (Annandale *et al.*, 2002)

Item	Total water		Total Evaporation		Drainage	Canopy interception	Runoff	Change in soil water storage
	Rainfall	Irrigation	Soil evaporation	Crop transpiration				
Amount (mm)	666.0	30.0	248.0	225.0	205.0	30.0	0.0	-12.0
Percentage of Total Water	96.0	4.0	39.0	32.0	30.0	4.0	0.0	-2.0

A comparison of the results from the irrigated and non-irrigated areas indicates that because of the availability of more salts and water in the irrigated area than in the non-irrigated areas, higher volumes of stormflow, drainage to groundwater, soil moisture in the soil horizons, and the salt loads associated with them, occurred in the irrigated area than in the non-irrigated area. Whereas the average salinity of the runoff and the drainage to groundwater in the irrigated area are 4 480 mg/l and 3 824 mg/l respectively, in the non-irrigated areas, the corresponding values are 556 mg/l and 242 mg/l respectively.

The underground reservoir in the Tweefontein Pan catchment is configured to permit seepage from it into adjacent underground reservoirs. This is done in order to avoid decanting or spillage of water from the reservoir, which was not occurring for the period that this study covered. Kleinkopje Colliery has only one decant point from Landau 1 and II workings into Landauspruit (Clean Stream Environmental Services, 2004). This corresponds with the underground reservoirs associated with land segments 24 and 27 (see Figure 6.3). The seepage from the underground reservoir was assumed to be equivalent to 0.35% of the water in storage in the reservoir. The assumed seepage of water from the underground reservoir in the Tweefontein Pan catchment represents the functioning of the underground water because, in some parts of the Kleinkopje Colliery, water is pumped out from the underground workings and stored in surface reservoirs (Clean Stream Environmental Services, 2004). Movement of water from the other parts of the underground mine workings, through the walls separating underground mine-out areas, in the direction of decreasing head and towards the pumping well could therefore occur. The salinity of water in the underground reservoir is determined by the changes in the volume of water in storage (as detailed in Chapter 6). Hence, at the initial stage, when the rate of change of water in storage is rapid, the rate of increase in the salinity is rapid as well. After some time, the rate of change of salinity becomes less rapid, in response to the changes in the amount of water in storage in the reservoir (Figure 8.6). The limited available observed salinity, in comparison to the simulated (Figure 9.6), indicates that the salinity of water in the underground reservoir is simulated reasonably realistically. The little variability in the simulated salinity, which does not exactly mirror the day to day values of the observed data, are due to the

- little changes in the daily volume of water going into the underground reservoir, which determines the salinity of the water in the reservoir, and
- the fact that the observed data represent a observation at just one point through the sampling of water pumped out from the reservoir from a borehole, whereas the simulated results represent the whole water body.

Lack of relevant data prevented the verification of the variability of volume of water in storage.

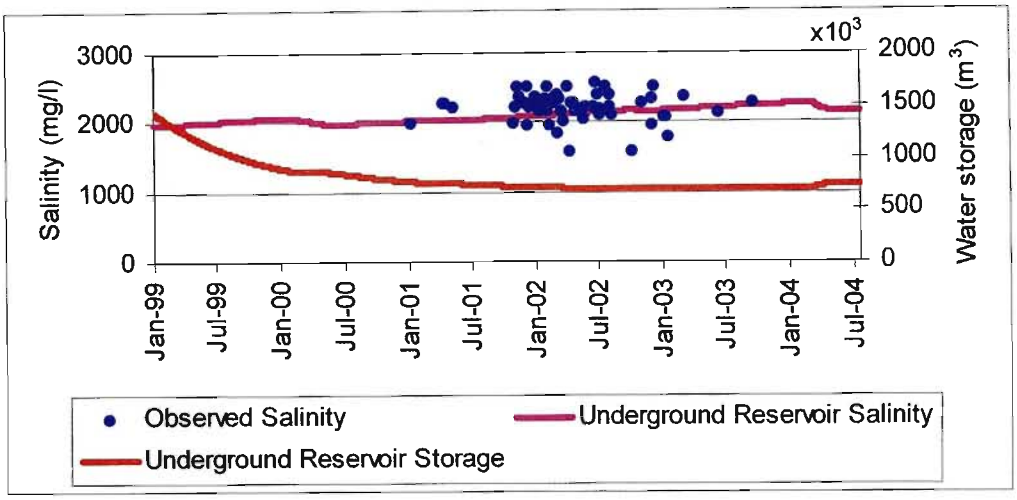


Figure 8.6: Observed salinity, and simulated daily water storage and salinity, in the underground reservoir

8.1.2 Irrigation with an Alternative Source of Mine Water

The impact of irrigation with an alternative source of mine water other than that from Tweefontein Pan was investigated in the Tweefontein catchment by sourcing the irrigation water for the centre pivot located in the catchment from the mine water occurring in the underground reservoir within the catchment. The comparison of the impacts of sourcing the irrigation water from Tweefontein Pan and the underground reservoir are presented in Figures 8.7 – 8.10 and Table 8.6. A general increase in the daily amount of water in storage in the Tweefontein Pan would occur if the source of irrigation water were from the underground reservoir and not from the pan (Figure 8.7). The calculated increase would be about 9% in the mean daily volume of water in storage (Table 8.6). The comparison of the salinity of water in the pan if irrigation water was from either the pan or underground reservoir shows that the salinity would be slightly higher if the irrigation water was from the underground reservoir (Figure 8.8). The difference is less than 0.5% (Table 8.6). The slight increase may be due to the additional salt load provided by the return flow from the irrigated area (as the irrigation water was not abstracted from the Pan) and the effect of evapo-concentration. The total salt load from runoff into the pan will be more by about 25 tons (representing a difference of about 6%) if the irrigation water was from the pan than if it was from the underground reservoir (Figure 8.9 and Table 8.6). Similarly, the amount of the precipitated salt in the soils, the average salinity and the total salt load of the drainage to groundwater will also be higher for the Tweefontein Pan abstraction (Table 8.6). This reflects the fact that the salinity of water in the pan is higher than in the underground reservoir (Figures 8.2 and 8.6). The average salinity of water in Tweefontein Pan and the underground reservoir over the simulation period are 2 333 mg/l and 2 100 mg/l respectively. The facts that a little more salt will be dissolved in the soil surface layer and the topsoil if the irrigation water was from the underground reservoir are reasonable, as more of the salts will be precipitated in soils and transported with runoff if the irrigation water was from the pan. The runoff remained the same in both cases (Figure 8.10).

The comparison of the impact of irrigation with different kinds of mine water indicates that the impacts of irrigation with low quality mine water on water resources will not only be dependent on the soil type of the irrigated area and the type of irrigation management practices (crop cultivated, amount of irrigation water applied) employed (as shown in Chapter 7), but also on the characteristics of the mine water used for irrigation.

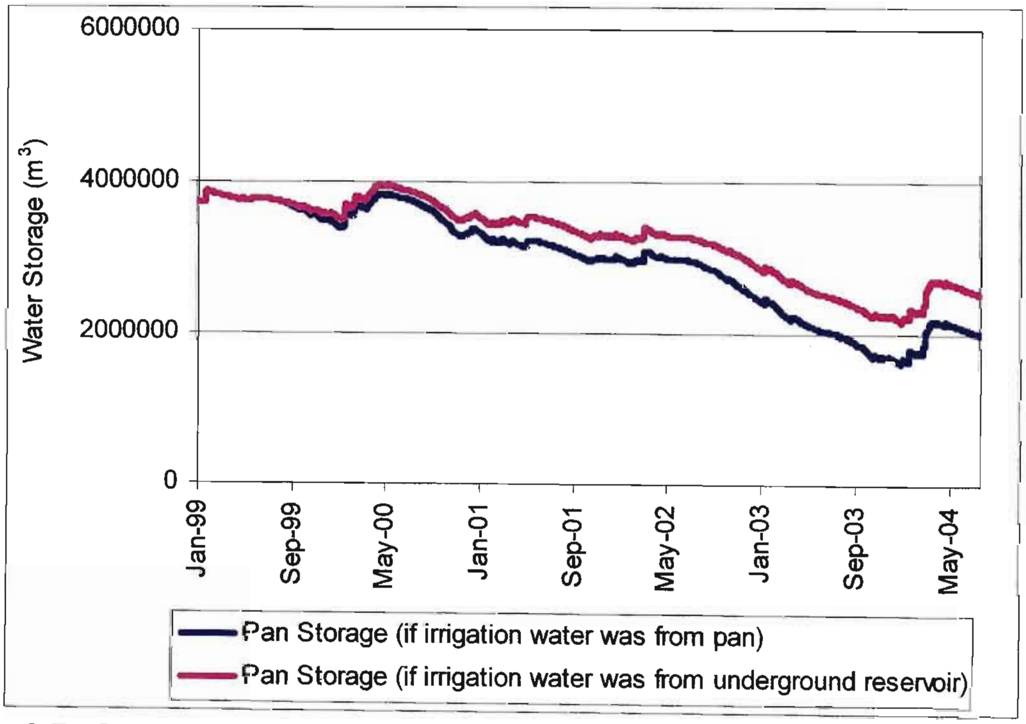


Figure 8.7: Comparison of the impact on the Tweefontein Pan water storage of sourcing irrigation water from either the Tweefontein Pan or the underground reservoir

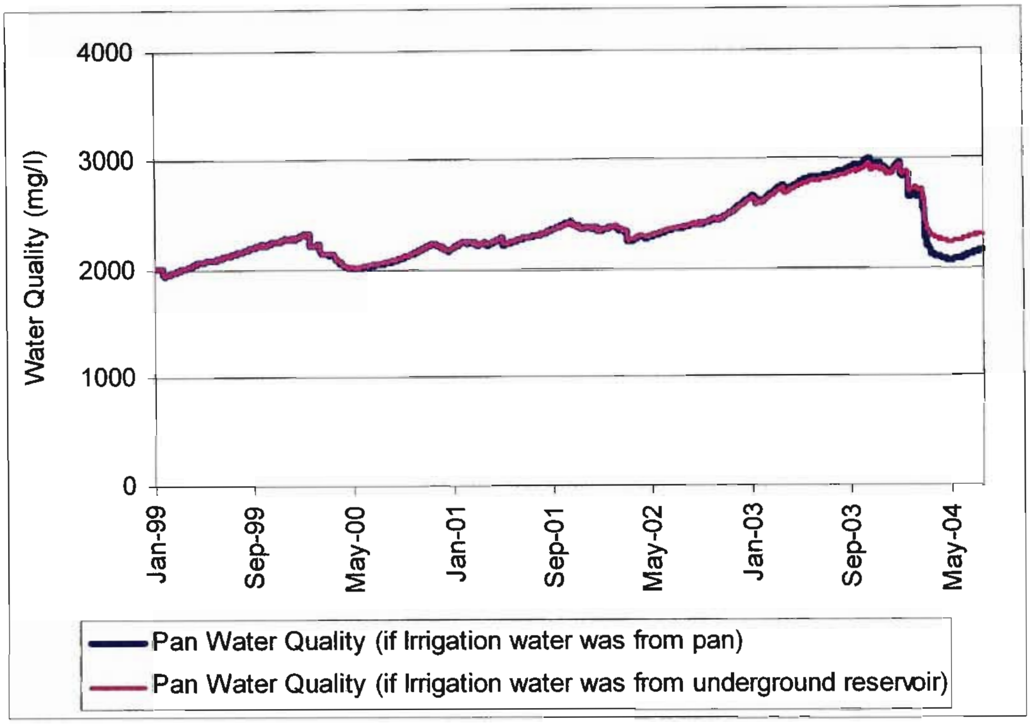


Figure 8.8: Comparison of the impact on the Tweefontein Pan water quality of sourcing irrigation water from either the Tweefontein Pan or the underground reservoir

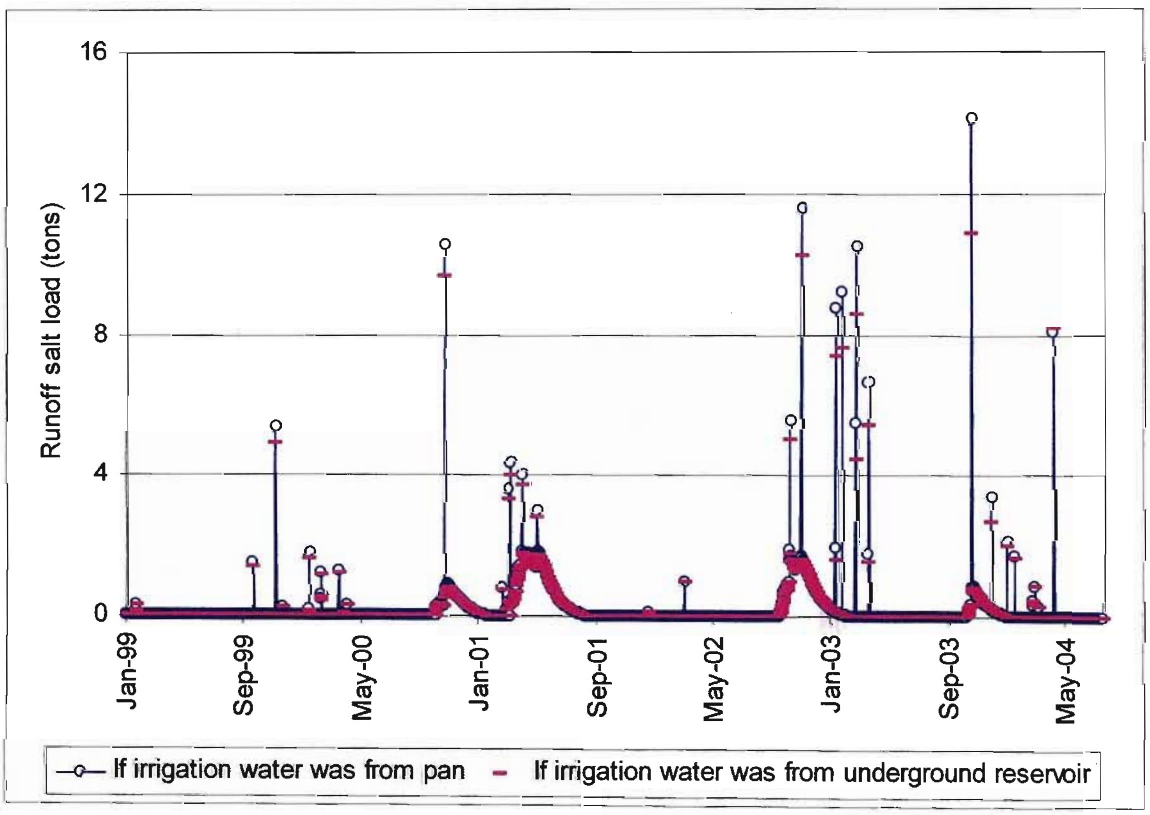


Figure 8.9: Comparison of daily runoff salt load from the irrigated area if irrigation water was from either the Tweefontein Pan or the underground reservoir

Table 8.6: Comparison of impact of different irrigation water sources on Tweefontein Pan

Characteristics	Irrigation Water Sources		Difference (%)
	Tweefontein Pan	Underground Reservoir	
Average daily water storage in Tweefontein Pan (m^3)	2959335.0	3240956.0	8.6
Average salinity of water in Tweefontein Pan (mg/l)	2348.0	2358.0	0.4
Average runoff salinity to Tweefontein Pan (mg/l)	4480.0	4392.0	2.0
Total runoff salt load to Tweefontein Pan (tons)	430.8	405.7	5.8
Dissolved salt in soil surface layer (tons)	21.75	21.81	0.3
Dissolved salt in topsoil (tons)	290.5	290.7	0.07
Precipitated salt in topsoil (tons)	757.4	581.0	23.3
Average salinity of drainage to groundwater (mg/l)	3825.0	3649.0	4.6
Total salt drainage to groundwater (tons)	427.1	408.0	4.5

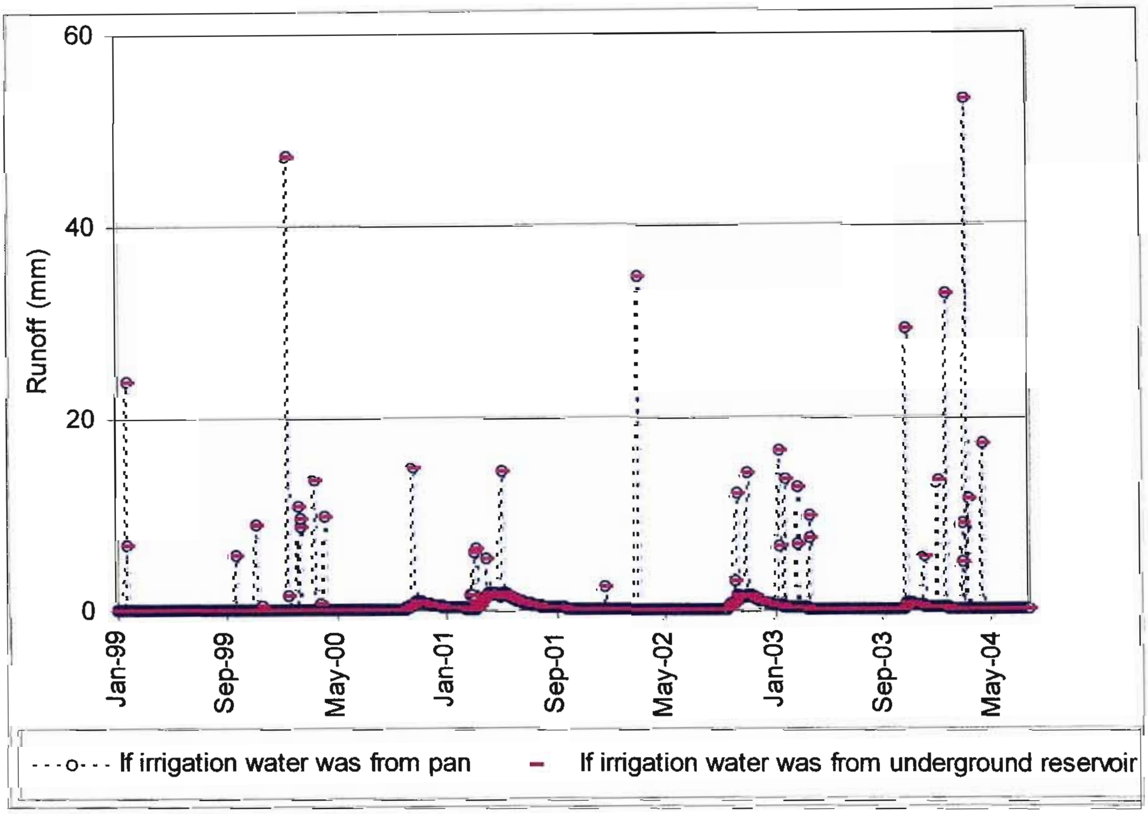


Figure 8.10: Comparison of daily runoff from irrigated area if irrigation water was from either the Tweefontein Pan or the underground reservoir

The comparison of the impact of irrigation with different kinds of mine water indicates that the impacts of irrigation with low quality mine water on water resources will not only be dependent on the soil type of the irrigated area and the type of irrigation management practices (crop cultivated, amount of irrigation water applied) employed (as shown in Chapter 8), but also on the characteristics of the mine water used for irrigation.

8.1.3 Widespread Irrigation with Mine Water

In addition to the irrigation of a rehabilitated area of 20 ha at the Tweefontein pivot with the water from the Tweefontein Pan, a virgin area of 160 Ha, representing an additional 8 centre pivots of 20 ha each, could still be sustained with irrigation water from pan without it becoming empty. Figures 8.11 and 8.12 show the effects of optimum use of the available areas for irrigation on the amount and quality of water in Tweefontein Pan. The sudden change in the quality of water in the reservoir in comparison to the baseline condition from around October 2003 is due to the increased dilution effect of rainfall with the diminishing water in storage. What is demonstrated with the results in Figure 8.11 is that, in making decisions on widespread irrigation with mine water, it is very important that sustainability, in terms of the availability of adequate mine water for widespread application, be assessed.

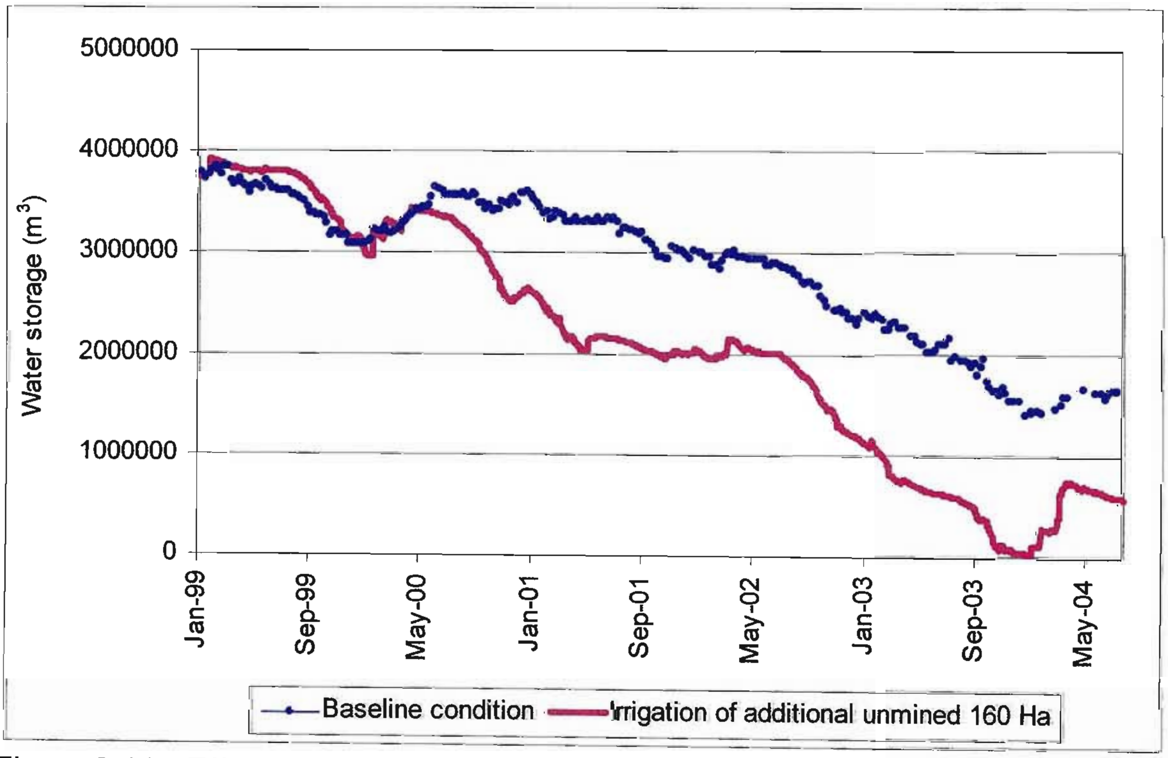


Figure 8.11: Effect of widespread irrigation of 160 ha in the Tweefontein Pan catchment on the water storage in the Tweefontein Pan

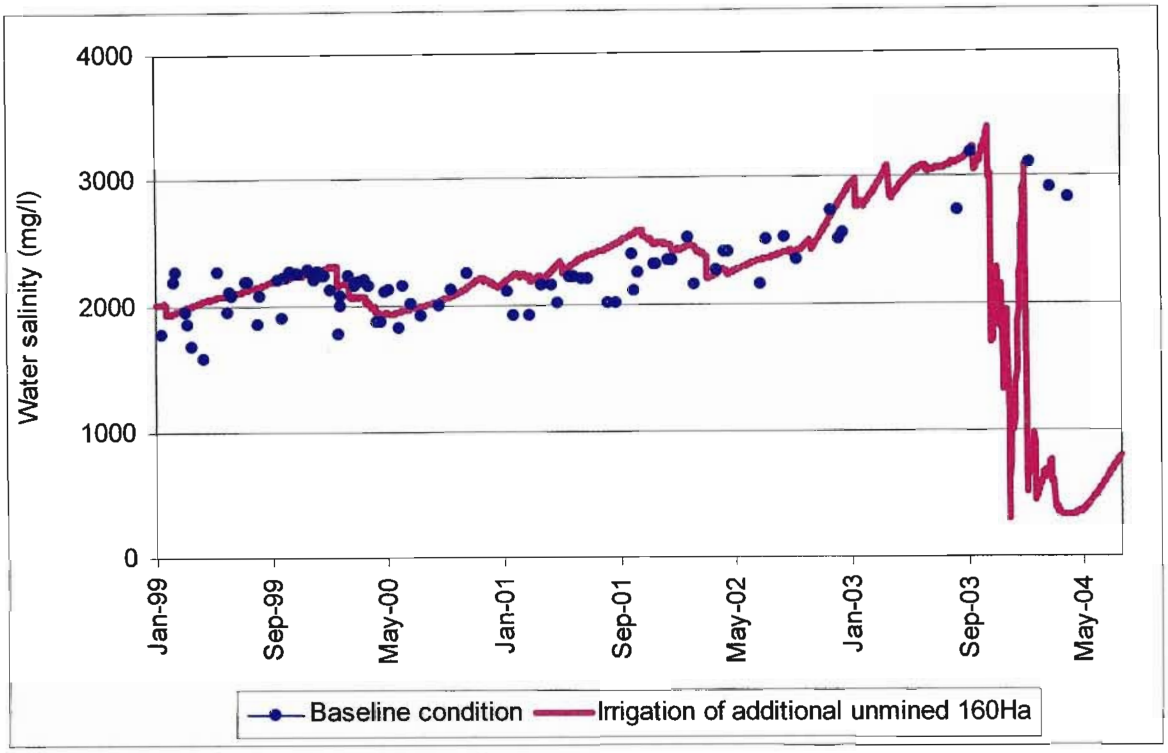


Figure 8.12: Effect of widespread irrigation of 160 ha in the Tweefontein Pan catchment on the water quality in the Tweefontein Pan

Apart from investigating the impact of widespread irrigation on virgin soils in the Tweefontein Pan catchment, widespread irrigation in the catchment, if it is mined-out and subsequently rehabilitated, was also investigated. In investigating the impacts of widespread irrigation with mine water on rehabilitated soils, a distinction is made between a rehabilitated irrigated area before and after the re-establishment of the regional water table. Opencast mining leads to dewatering of aquifers and the lowering of the water table, which may form a depression cone not usually extending more than 40 m in the Upper Olifants (Hodgson and Krantz, 1998). The dewatering cone extends over short distances into the adjacent sediments because of shallow mining depths, low hydraulic conductivities and the stratified nature of the Karoo sediments that constitute the aquifers (Hodgson and Krantz, 1998). In the rehab void, water level recovery may occur, with the water level rising to the lowest rehabilitated surface elevation and then decanting, thereby establishing a new equilibrium. Prior to the re-establishment of a new equilibrium however, percolating water will gradually accumulate in depressions at the bottom of the mined-out area, with the water table gradually rising until a decanting level is reached and a regional water table re-established. Consequently, contribution of baseflow to runoff may be insignificant, unlike after the re-establishment of equilibrium in the water table, when groundwater will flow in the direction of the hydraulic gradient and contributes to runoff. Taking these into consideration, during the simulations of rehabilitated areas prior to the re-establishment of the water table, the contribution of baseflow to runoff was set at zero, whereas during the simulations representing post-water table re-establishment, the default value of 0.02% of the amount of groundwater in storage was used.

If Tweefontein Pan catchment is mined out, rehabilitated and the water table has not been re-established (i.e. the mine is still active), only a maximum of 120 ha can be adequately irrigated with mine water from the pan, indicating that the area that can be sustained by irrigation with water from the Tweefontein Pan will be less than if the catchment is virgin. A comparison of this scenario on the volume and salinity of water in Tweefontein Pan with the two other scenarios of irrigating a virgin area and a rehabilitated area, post water table re-establishment (i.e. after cessation of mining) are presented in Figures 8.13 - 8.17 and Table 8.7.

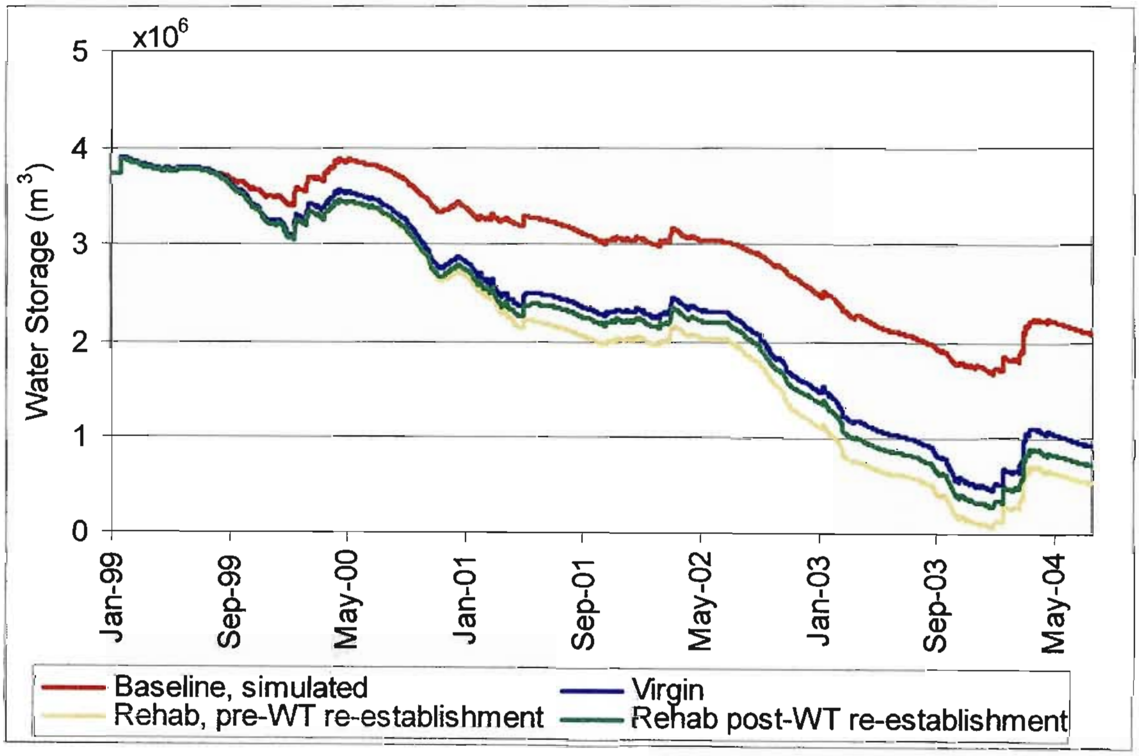


Figure 8.13: Comparison of the effect of widespread irrigation on the Tweefontein Pan water storage depending on whether the irrigated area of 120 ha is virgin or rehabilitated

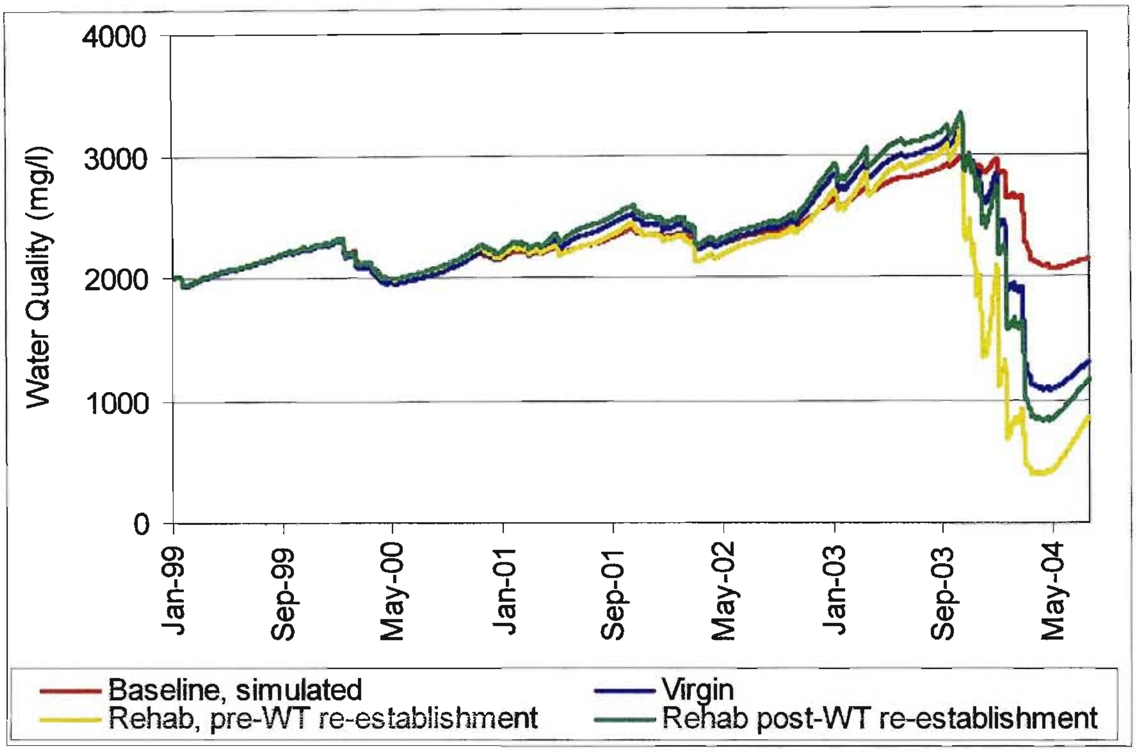


Figure 8.14: Comparison of the effect of widespread irrigation on the Tweefontein Pan water quality depending on whether the irrigated area of 120 ha is virgin or rehabilitated

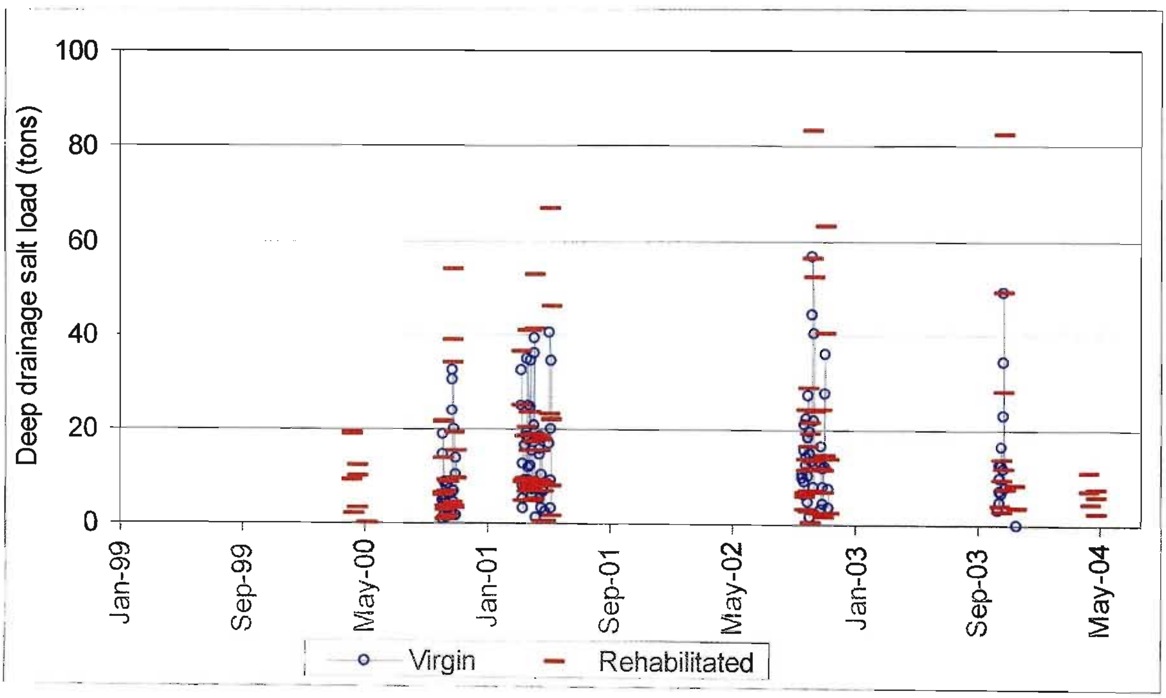


Figure 8.15: Comparison of salt load from deep drainage depending on whether the irrigated area of 120 ha is virgin or rehabilitated

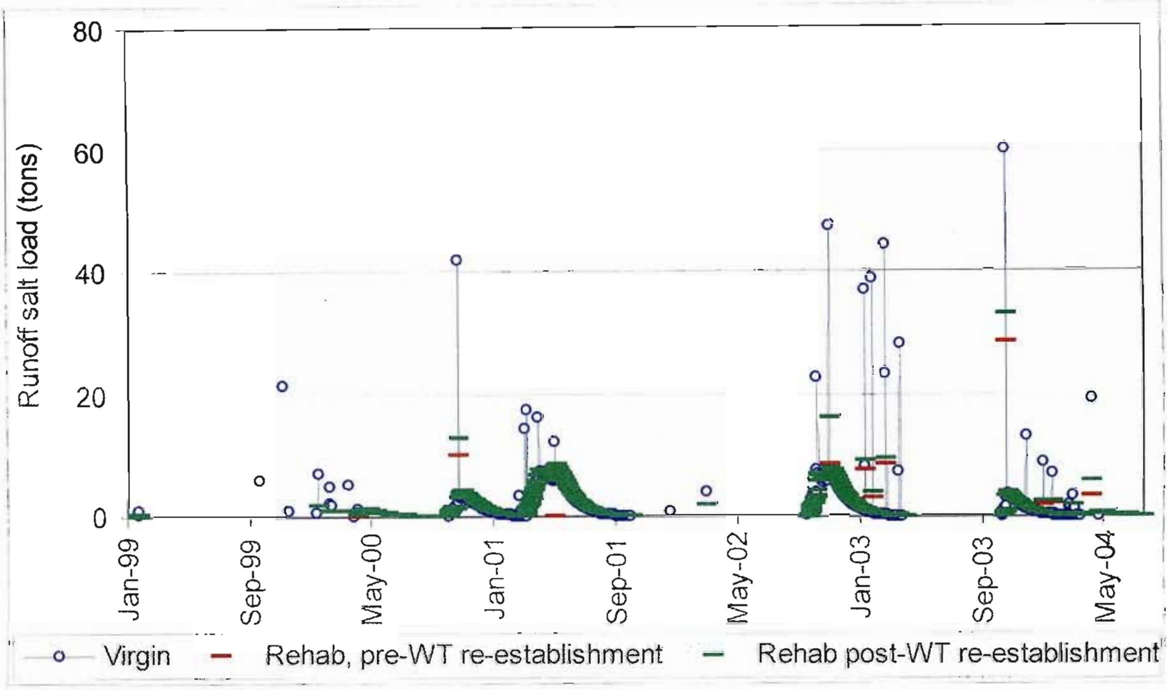


Figure 8.16: Comparison of daily runoff salt load depending on whether the irrigated area of 120 ha is virgin or rehabilitated

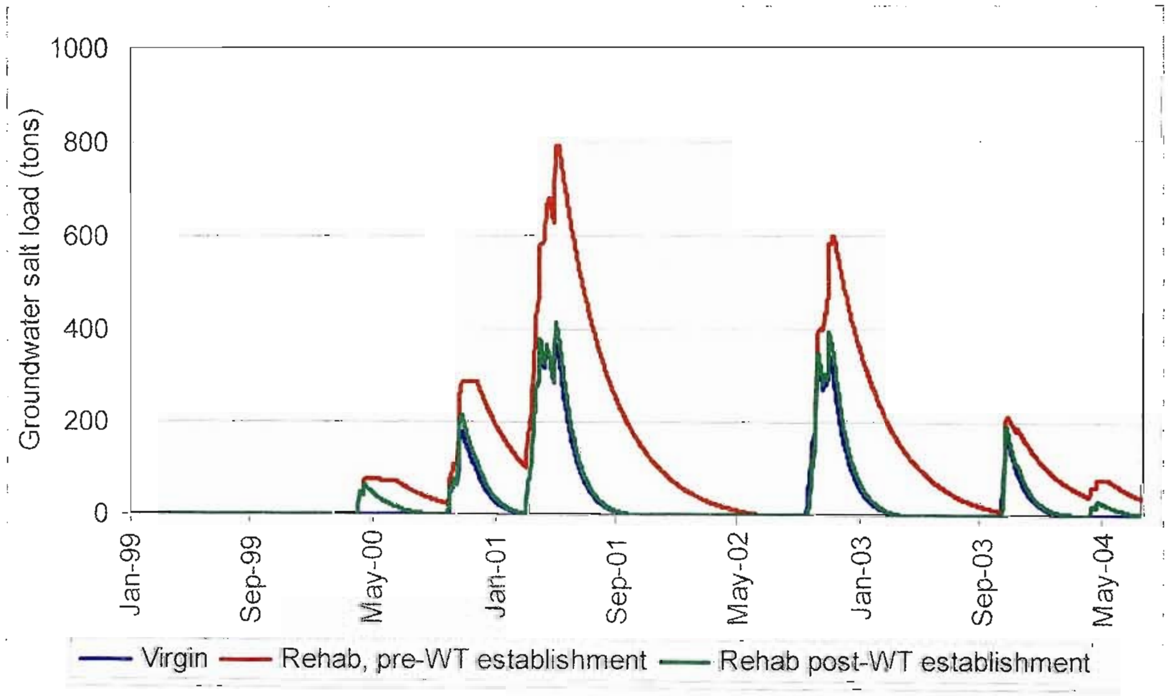


Figure 8.17: Comparison of groundwater salt load depending on whether the irrigated area of 120 ha is virgin or rehabilitated

Table 8.7: Comparison of scenario results from widespread irrigation of 120 ha in the Tweefontein Pan catchment

Parameters	Virgin	Rehab Pre-Water Table Establishment	Rehab Post-Water Table Establishment
Runoff (mm)	744.0	195.0	490.0
Runoff Salt Load (tons)	1856.0	81.0	1678.0
Drainage to Groundwater (mm)	374.0	454.0	454.0
Drainage to Groundwater Salt load (tons)	1709.0	1982.0	1982.0
Baseflow (mm)	243.0	0.0	295.0
Baseflow Salt Load (tons)	1352.0	0.0	1590.0
Average Pan Salinity (mg/l)	2285.0	2143.0	2302.0

Irrigating a rehabilitated area of 120 ha in Tweefontein Pan catchment (either pre- or post- water table re-establishment) will deplete the water in the pan more rapidly than irrigating a virgin area of 120 ha (Figure 8.13). The reason for this would be that, the runoff (and runoff salt load) from the rehabilitated area would be lower and the amount of water and salt that would drain into groundwater storage would be more when the irrigated area is rehabilitated than when it is unmined (Figures 8.15 and 8.16). Lower runoff (i.e. lower return flow into the pan) means quicker depletion of water in the reservoir. The runoff from the rehabilitated area will be lower pre- than post water table re-establishment because no contribution from baseflow to runoff will occur prior to water table re-establishment. The salinity of water in the pan will be slightly higher when the irrigated area comprises rehabilitated post water table establishment than when it comprises virgin or rehabilitated pre water table establishment. The volume of groundwater and the accompanying salt load in storage is highest when the irrigated area is rehabilitated prior to water table re-establishment (Figure 8.17) as it was assumed that discharge from the groundwater store in terms of baseflow did not occur. In typical rehabilitated soils in an operational opencast mining system, some water that drains into the groundwater storage may seep into the mining window area to form part of the water available in the opencast pit (see Section 5.1.1.2).

8.2 Kleinkopje Colliery

The area of Kleinkopje Colliery catchment in this study is 92 km^2. This area includes the entire Tweefontein Pan catchment, part of which lies outside the boundary of the Kleinkopje Colliery. The locations and areas of the other delineated land segments that constituted Kleinkopje as configured in this study, have been presented in Table 6.1 and Figure 6.1. The simulations and analyses carried out are for baseline conditions of the colliery and on widespread irrigation with mine water on virgin and rehabilitated soils. The baseline conditions have been described in Sections 6.5. The description of the simulated scenarios and the data available for verification studies have been presented in Tables 4.1 and 4.2 respectively. The focus of the simulations and analyses are on the determination of the contribution of total water and salt outflow from the colliery to Witbank Dam, which is their eventual destination. Quantification and characterisation of different water sources and usages within the colliery does not form part of this study.

The soils, hydrological and salinity response units used in setting up the *ACRU2000* model and the *ACRUSalinity* module for modelling the delineated land segment areas are based on pivot and catchment scales studies. Consequently, the response units calibrated for the Tweefontein pivot, which is located in a rehabilitated area, are used for all delineated rehabilitated land segment areas, while those employed in the Tweefontein Pan catchment, which is virgin, are used for all unmined land segment areas, with the exception of coal discard dump areas, which is discussed separately in the next section because of its special nature. Extrapolation of the input parameters from the Tweefontein pivot and Tweefontein Pan catchment studies in this manner for the simulation of the entire Kleinkopje Colliery was necessitated by availability of limited data coupled with limitation of resources, both financial and time, as well as logistical difficulties that had to do with access, investigation and monitoring of different parts of the colliery.

The flow configuration used in setting up *ACRU2000* and *ACRUSalinity* is shown in Figure 6.1. It is based on the topography of the colliery. According to the flow configuration, three drainage outlets carry runoff from Kleinkopje into the Witbank Dam. They are the Tweefonteinspruit-Olifants River combination, Landauspruit and Northeastspruit. Tweefonteinspruit and Landauspruit flow through the colliery. Tweefonteinspruit does not flow directly into Witbank Dam, but joins the Olifants at about 1 km south of Wolkerans, which is adjacent to the colliery. Northeastspruit is a small stream adjacent to the colliery in the northeast and only Land Segment 21, which was adjacent to it, is assumed to contribute runoff to it. In order to determine the impact of the outflow from the Kleinkopje on Witbank Dam, the composite runoff from the three outlets and the fraction contributed from groundwater storage (both in quantity and salt load) are determined and compared with the volume of water and salt load in Witbank Dam. The effects of changes in the land use pattern on the runoff and contributions to groundwater storage are determined by comparing the results obtained from a particular scenario with the baseline condition results. The scenarios simulated and compared with the baseline condition included the widespread irrigation with mine water on virgin and rehabilitated soils in the colliery. The results obtained from the simulation of the baseline condition and the other scenarios are presented after Section 8.2.1, in which the coal discard dumps, identified as one of the land use categories in this study, is discussed.

8.2.1 Coal Discard Dump

In Kleinkopje Colliery, the coal discards are deposited on virgin lands. Therefore, like the rehabilitated areas in Kleinkopje, the discard dump areas can be taken to be disturbed. Unlike the rehabilitated areas, however, they were neither top-soiled nor re-vegetated and the discards were compacted in layers. In order to model the discard dump areas using *ACRU2000* and *ACRUSalinity*, the soil water retention characteristics of the coal discard dump areas were assumed to be similar to those which have been considered as representative of the compacted coal dumps of the Mpumalanga and Natal coalfields in South Africa (Wates and Rykaart, 1999). The soil-water characteristic curve for the compacted coal dumps has been presented in Section 6.7. The vegetative requirement used is that categorised for mine and quarries (see Table 6.11). In order to further ensure reliable simulation of the discard dump areas, a land segment comprising coal discards (Land Segment 12, which is referred to as the KK discard dump), is simulated using the soil water retention values and vegetative water requirements for the period 1999 - 2004. The results are then compared with similar results reported for mine dumps in other parts of South Africa and the world. The results indicate that 71% of the total rainfall occurred as total evaporation, while 7%, 15% and 1% occurred as stormflow, drainage into groundwater storage and change in the subsoil water content respectively (Table 8.8). No net change occurred in the surface layer water content, while the change in the water content of the topsoil layer was negative. The salt load associated with stormflow was 4% of total available salt (including that added by rainfall), while those associated with deep drainage into groundwater storage, change in subsoil water salinity, and precipitated soil in the subsoil were 77%, 8% and 1% respectively (Table 8.9). The generated salt in the groundwater store was 10%.

Table 8.8: Distribution of water as % of total rainfall in the KK discard dump

Parameters	**Water balance as % of rainfall**
Total Evaporation	71.0
Stormflow	7.0
Deep Drainage	15.0
Change in Subsoil Water	1.0
Interception Loss	6.0

Table 8.9: Distribution of salts as % of total salt in the KK discard dump

Parameters	**Salt load in % Total Available**
Stormflow	4
Deep Drainage Salt Load	77
Subsoil Water Salt Load	8
Subsoil Precipitated Salt	1
Generated Salt Load in Groundwater	10

In an experiment on the outflow from compacted coal discard dumps in Northern KwaZulu-Natal, Vermaak *et al.* (2004) reported a recharge rate of between 13.4 % and 41% as percentage of rainfall, with an average of 21%, while in a waste rock pile in Mine Doyon, Quebec, Canada, a recharge value of 24% of the average precipitation was reported (Sracek *et al.*, 2004). The results obtained in this study are reasonable in comparison to those reported. Northern KwaZulu-Natal receives more rainfall than the Mpumalanga highveld region. Therefore, one would expect the recharge rates to be lower in the Mpumalanga region than in the Northern KwaZulu-Natal. Apart from climate, the physical and geochemical properties of the coal discard as well as the slope distance and angle of dump do affect the distribution of water in a coal discard dump. The coal discard used in the reported experiment of Vermaak *et al.* (2004) was fine and homogenous. Typically, coal discard is heterogeneous, ranging from large boulders to fines. In comparison to poorly sorted (heterogeneous) deposits, well-sorted (homogenous) deposits have higher porosity (Todd and Mays, 2005). This may also be responsible for the higher drainage reported by Vermaak *et al.* (2004). With respect to salinity, leachate salinity will depend on the various geohydrological, geochemical and biological processes taking place in the coal discard. Figures 8.18 and 8.19 show the salinity of the drainage into groundwater storage and that of runoff from Land Segment 12. A generally increasing trend can be observed, although dilution of salinity occurs during rainfall periods (Figure 8.19). The red dots are the limited observed data on the quality of runoff from the KK discard dump. A generally increasing trend in the salinity of leachates from uncovered, compacted and unvegetated discard material has also been reported by Vermaak *et al.* (2004). The salinity of the drainage reported for the coal discard in Vermaak *et al.* (2004) experiment, however, is higher than that obtained for the KK discard dump. The range, mean and standard deviation for KK discard dump are 1 070 -2 305 mg/l, 1 660 mg/l and 292 mg/l respectively, whereas the respective values for the coal discard in Vermaak *et al.* (2004) are 1 939 – 4 461 mg/l, 3 005 mg/l and 322 mg/l. The relatively high ash content of the selected coal discards in the Vermaak *et al.* (2004) experiment than is typical may be responsible for the higher values.

The results obtained for the KK discard dump demonstrate the fate of most of the salts in the system as water moves through the discard into groundwater storage or seepage from the toe of the pile. The soil, hydrological and salt response units used in the simulation of Land Segment 12 are applied to other areas in Kleinkopje identified as coal discard dump areas i.e. Land Segments 16, 25 and 26 (see Figure 6.1).

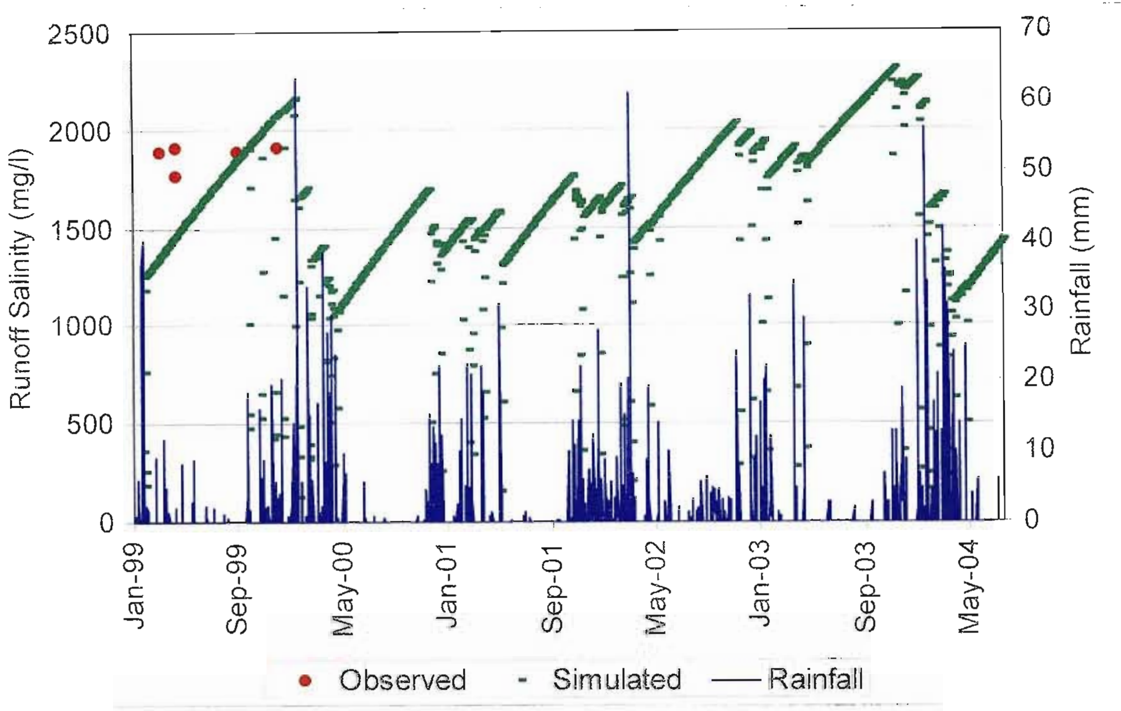


Figure 8.18: Daily runoff salinity from a coal discard dump (Land Segment 12)

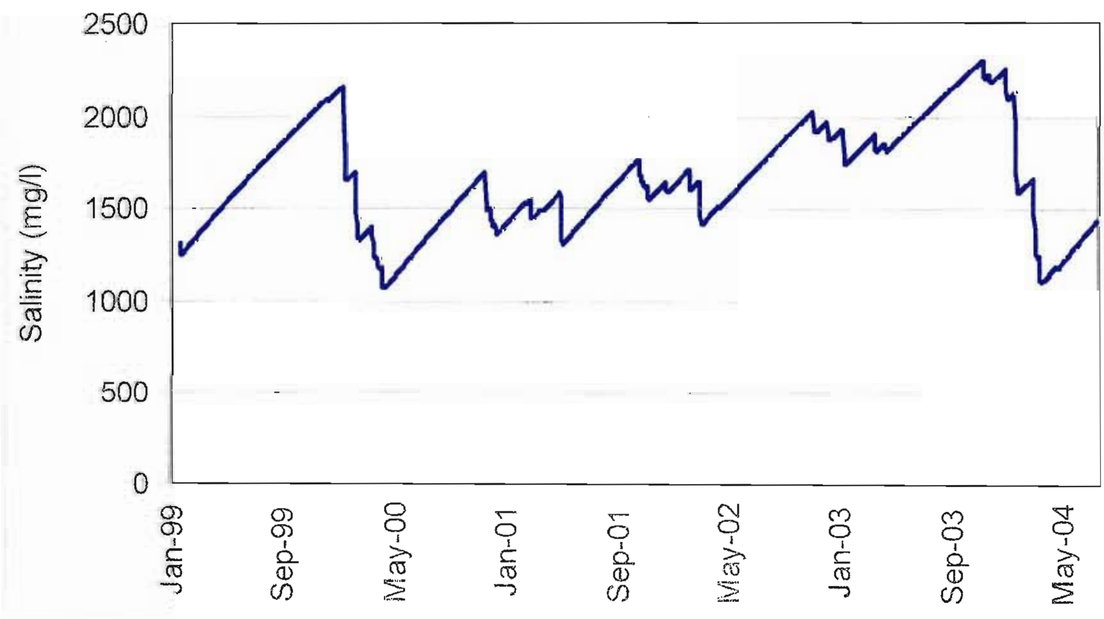


Figure 8.19: Salinity of daily drainage into groundwater storage below a coal discard dump (Land Segment 12)

8.2.2 Baseline Conditions

A comparison of some results from the simulation of the baseline conditions of the study area with the available observed data for some of the different hydrological components of the land segments modelled are presented in Figures 8.20 to 8.24. The available observed data comprised the quality of water in some surface reservoirs in the colliery and the salinities of the seepage from the Landau underground reservoir into Landauspruit. The comparisons demonstrate that the model output reflects the signals from the observed quality of water in the reservoirs in the study area. The variability of the observed data, when compared against the smoothness of fit of the simulated results, is due to the fact that the simulation is for the entire water body while the observed data are measurements at a single point. The salinity of the seepage from Landau underground reservoir into Landauspruit is remarkable in that a general decline can be observed (Figure 8.24), suggesting that there may be a long-term equilibrium state with respect to the salinity of the water seeping out from the underground reservoir into Landauspruit. Similar observations have been reported for the closed underground mines in the Pittsburgh Coal Basin, USA (Donovan *et al.*, 2003) and for mines in the UK (Woods *et al.*, 1999; Demchak *et al.*, 2004) where the salinities of water discharge from flooded underground mines approached equilibrium between one and two decades and after 40 years of continued discharge respectively.

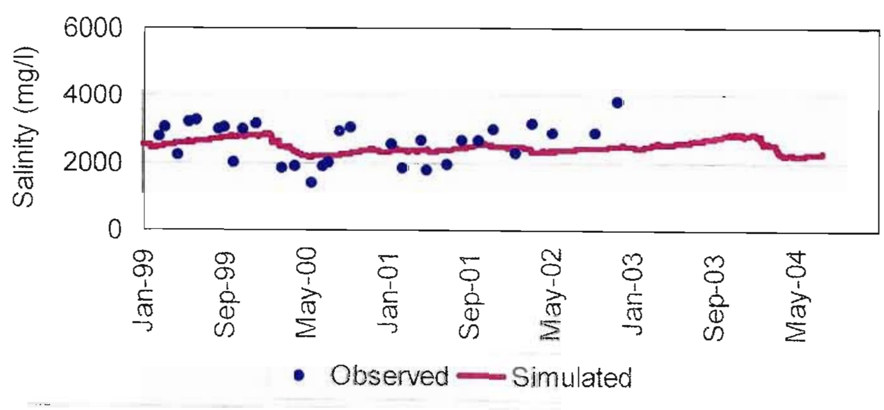


Figure 8.20: Comparison of observed and simulated daily salinity for Berries Pan

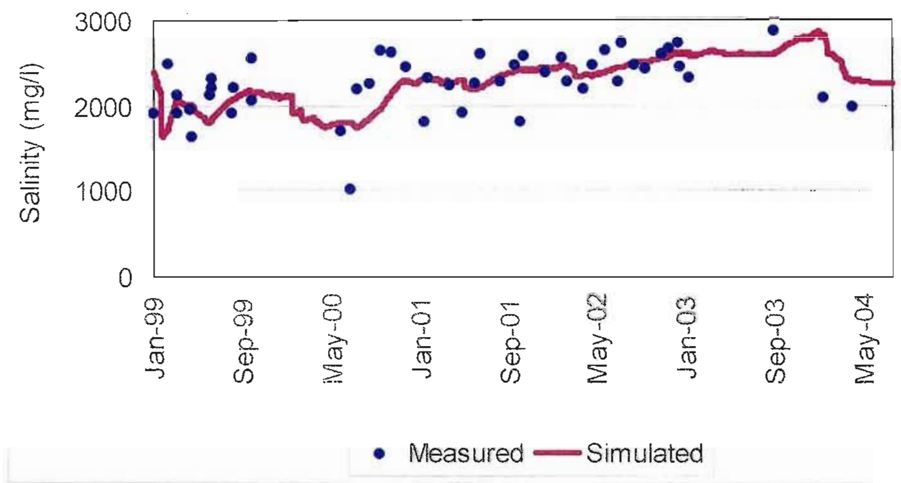


Figure 8.21: Comparison of observed and simulated daily salinity for Klippan Penstock reservoir

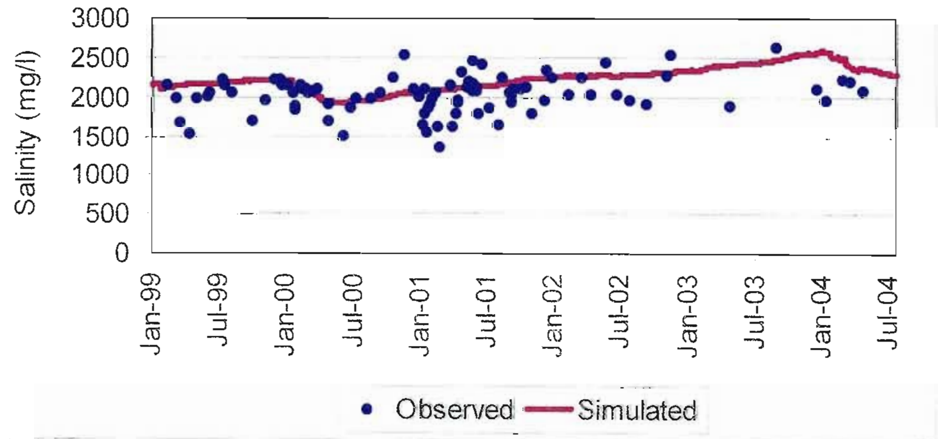


Figure 8.22: Comparison of observed and simulated daily salinity for 2A dam

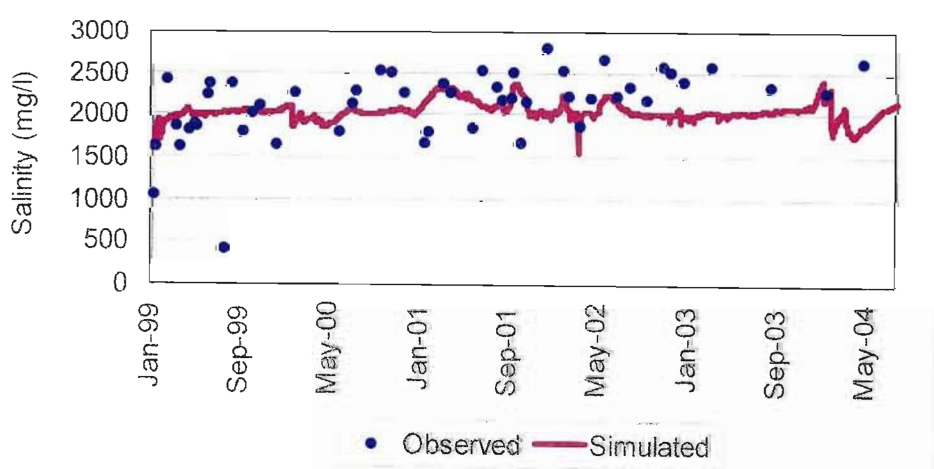


Figure 8.23: Comparison of observed and simulated daily salinity for the Plant Return Water Dam

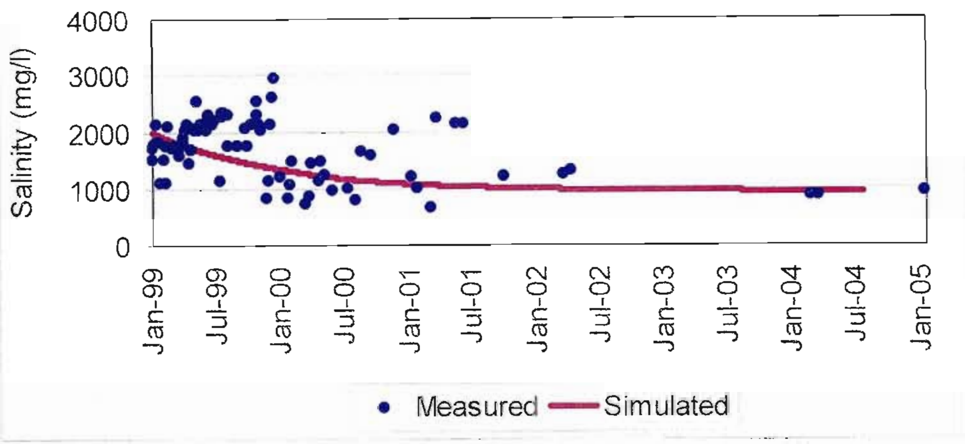


Figure 8.24: Comparison of observed and simulated daily salinity of seepage from the Landau underground reservoir

The simulated total daily water inflow (runoff) and salt load contributions from the study area into Witbank Dam, under baseline conditions, and over a period of about 5½, are 11.2 x 10^3 Ml and 2 208 tons respectively, amounting to a mean annual runoff (MAR) and salt load contributions of 2 x 10^3 Ml and 392 tons respectively. The total daily water inflow and accompanying salt load into Witbank Dam in comparison to the daily water storage and salt load in the Dam, are shown in Figures 8.25 and 8.26. The contribution of the MAR from the study area is 2.7% of the mean annual water storage in Witbank Dam while the MAR salt load contribution is 1.4% of the mean annual salt load in the dam. The inflow and salt load included seepage and the accompanying salt load from Landau underground reservoir into Landauspruit. The seepage, which were about 168 Ml and 183 tons with respect to the total volume and salt load respectively, were considered as part of the groundwater contributions to the total runoff. About 44% of the total water inflow and 65% of the total salt load contribution from the study area into Witbank Dam came from groundwater storage.

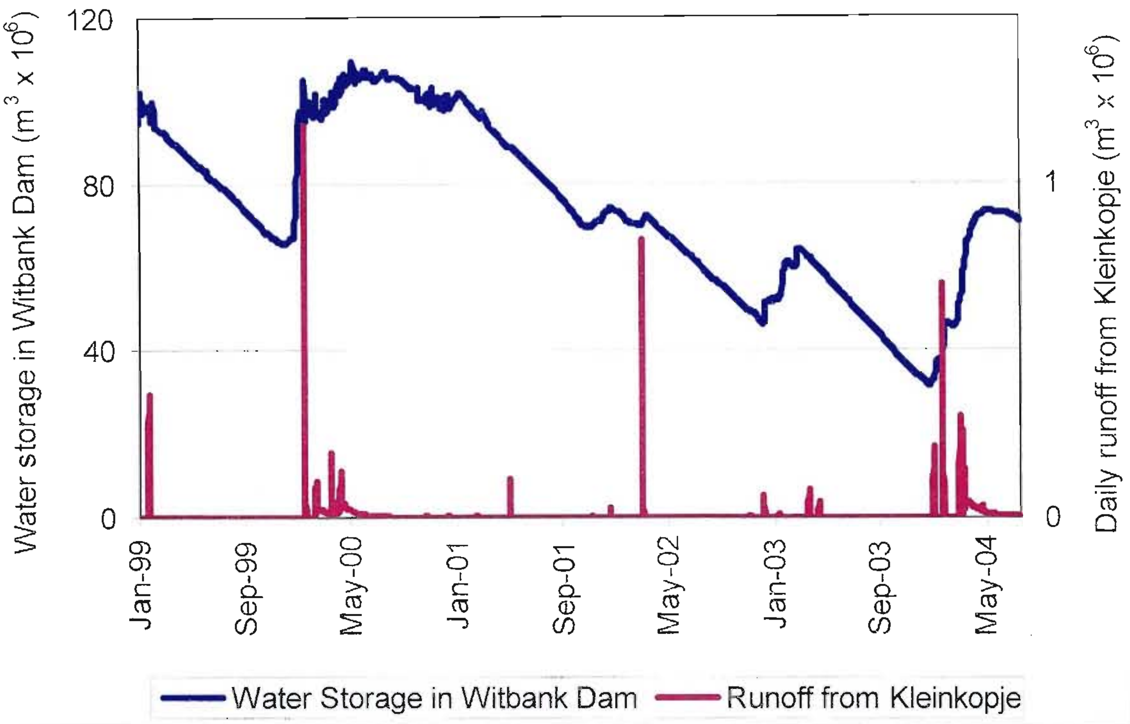


Figure 8.25: A comparison of simulated daily runoff from the Kleinkopje Colliery into the Witbank Dam under baseline conditions with the water storage in the dam

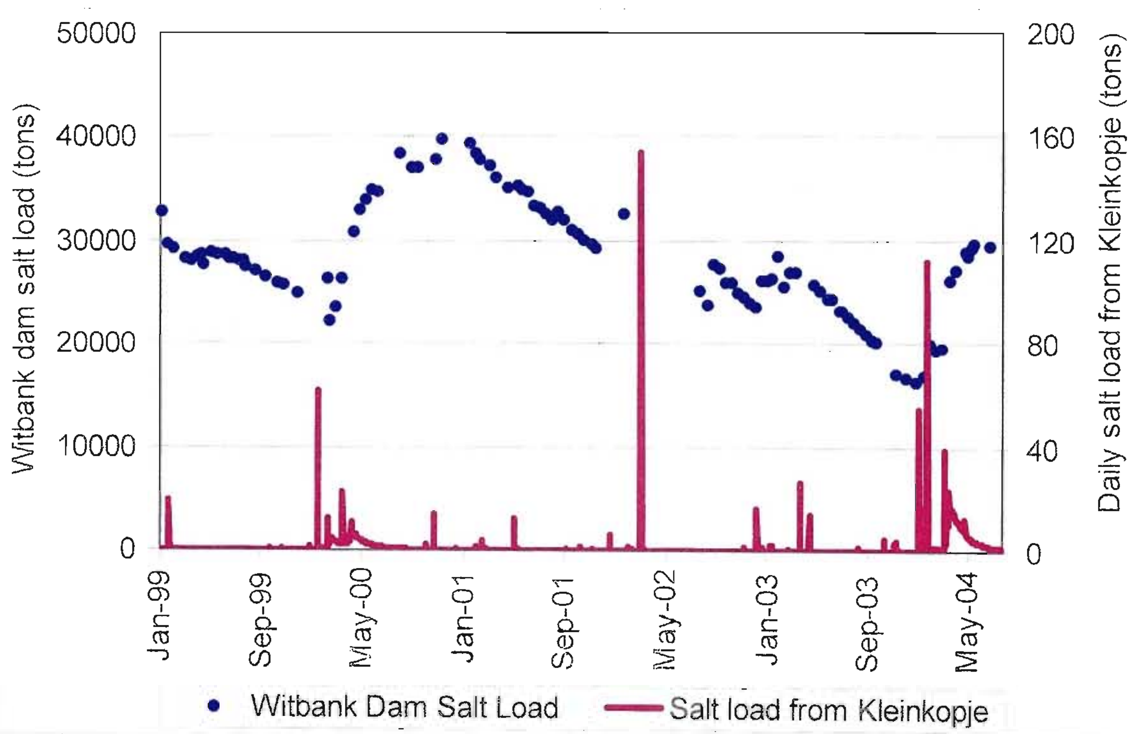


Figure 8.26: A comparison of simulated daily salt load accompanying runoff from the Kleinkopje Colliery into Witbank Dam under baseline conditions with the salt load in the dam

Plots of the daily volume of water and salt load from groundwater storage in comparison to the daily total water and salt contribution to Witbank Dam are presented in Figures 8.27 and 8.28 respectively. The lag in the peaks of the groundwater contribution to runoff, observable in Figure 8.27, reflects the lag effects of rainfall on groundwater storage by the time it takes for percolation of recharge and discharge of groundwater to the runoff channel. The non-response of the groundwater contribution to the peak runoff in March 2002 is due to the occurrence of an intense rainfall of 61 mm in a day and the consequent increase in the runoff, with very little or no contribution from groundwater. In the baseline condition, it was assumed that the process of water table re-establishment was still ongoing as the mine was still very active and at such, the contribution of groundwater flow to runoff in the rehabilitated areas was assumed insignificant.

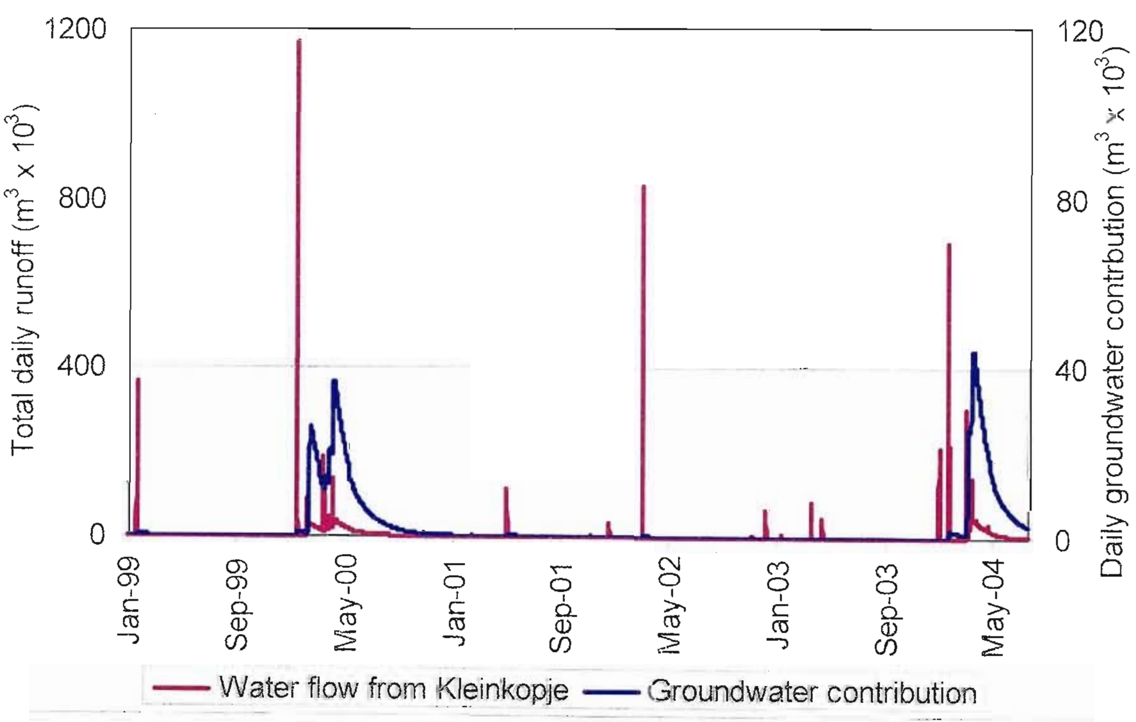


Figure 8.27: Simulated total daily runoff from the Kleinkopje Colliery flowing into the Witbank Dam and the groundwater contribution

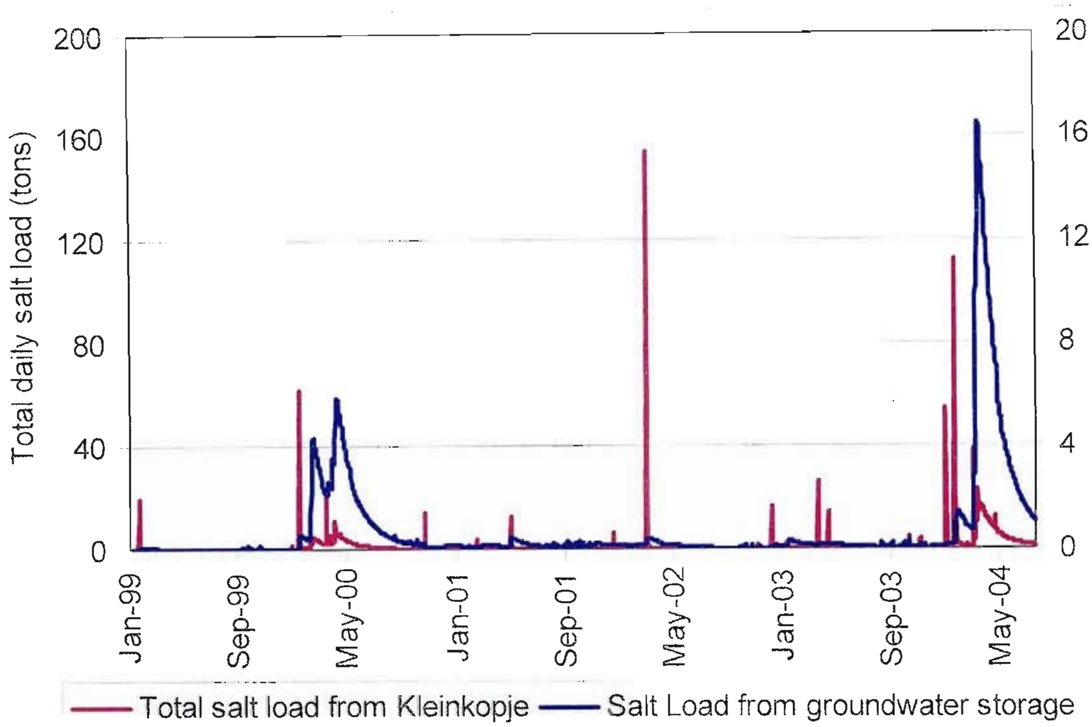


Figure 8.28: Total daily salt load from the Kleinkopje Colliery flowing into the Witbank Dam and daily salt load contribution from groundwater

The contribution from groundwater storage is expected to increase with the re-establishment of the water table and regional groundwater flow in the mined-out and rehabilitated areas. The total rehabilitated area in the baseline condition is 27.3 km^2, which represents about 30% of the total area simulated. In order to simulate and compare the contributions to Witbank Dam of water and salts from the study area after the re-establishment of the water table with the baseline condition, a default value of 0.02 is assumed as the coefficient of baseflow response in the land segments identified as rehabilitated areas. Table 8.10 shows the comparison, which indicates an increase in the runoff and salt load of 13% and 28% respectively, while increases of 37% and 47% respectively are observed for the contribution of groundwater to total runoff and its salt load. The comparison of water and salt contributions from the study area into Witbank Dam after water table re-establishment are shown in Figures 8.29 and 8.30 respectively, while the contribution of groundwater flow to the total runoff and its salt load are shown in Figures 8.31 and 8.32.

Table 8.10: Comparison of water and salt contributions from the study area to Witbank Dam under baseline conditions, for both pre- and post water table establishment

Parameters	Pre-Water Table Establishment	Post-Water Table Establishment	% Increase
Total daily runoff to Witbank Dam (Ml)	11.2 x 10^3	12.7 x 10^3	13.0
Mean annual runoff (MAR) to Witbank Dam (Ml)	2.0 x 10^3	2.3 x 10^3	15.0
% of MAR contribution to Witbank Dam (%)	2.7	3.1	
Total daily runoff salt load to Witbank Dam (tons)	2208.0	2820.0	28.0
MAR salt load to Witbank Dam (tons)	392.0	500.0	28.0
% of MAR salt load contribution to Witbank Dam (%)	1.4	1.4	
Total daily groundwater contribution to total runoff (Ml)	4.9 x 10^3	6.7 x 10^3	37.0
% total groundwater contribution to total runoff (%)	44.0	53.0	
Total daily salt load from groundwater to total runoff salt load (tons)	1445.0	2120.0	47.0
% of total salt load from groundwater to total runoff salt load (%)	65.0	75.0	

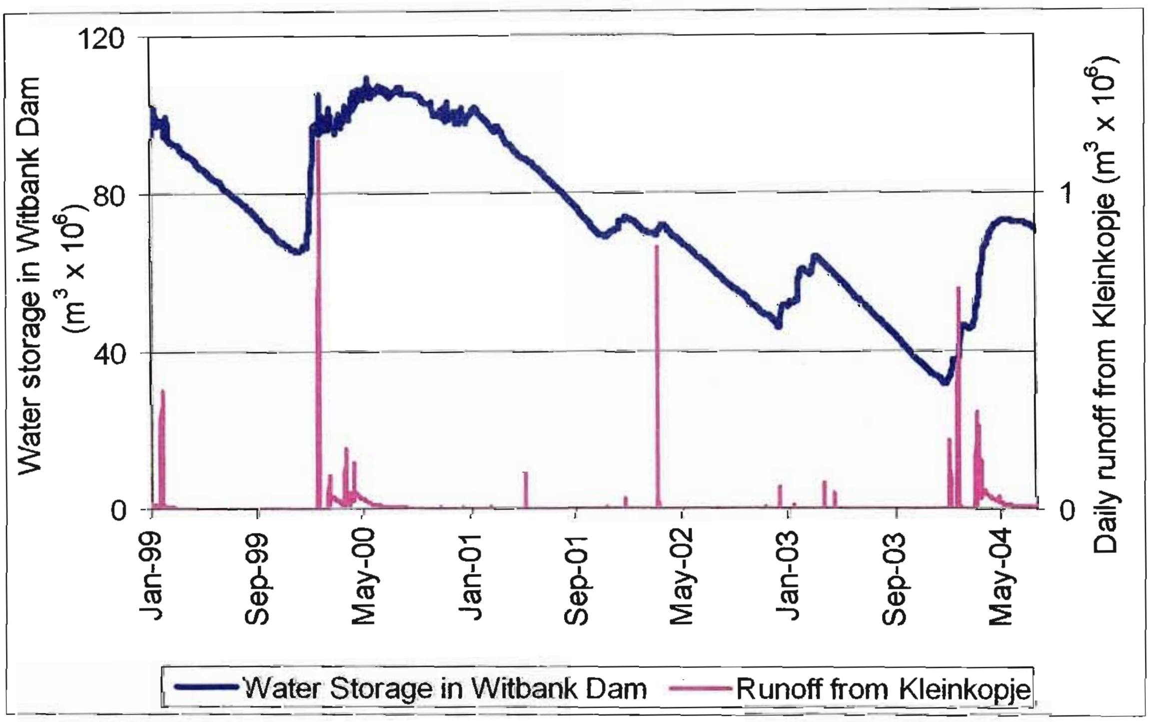


Figure 8.29: A comparison of simulated daily runoff from Kleinkopje Colliery into the Witbank Dam after water table re-establishment with the measured water storage in the dam

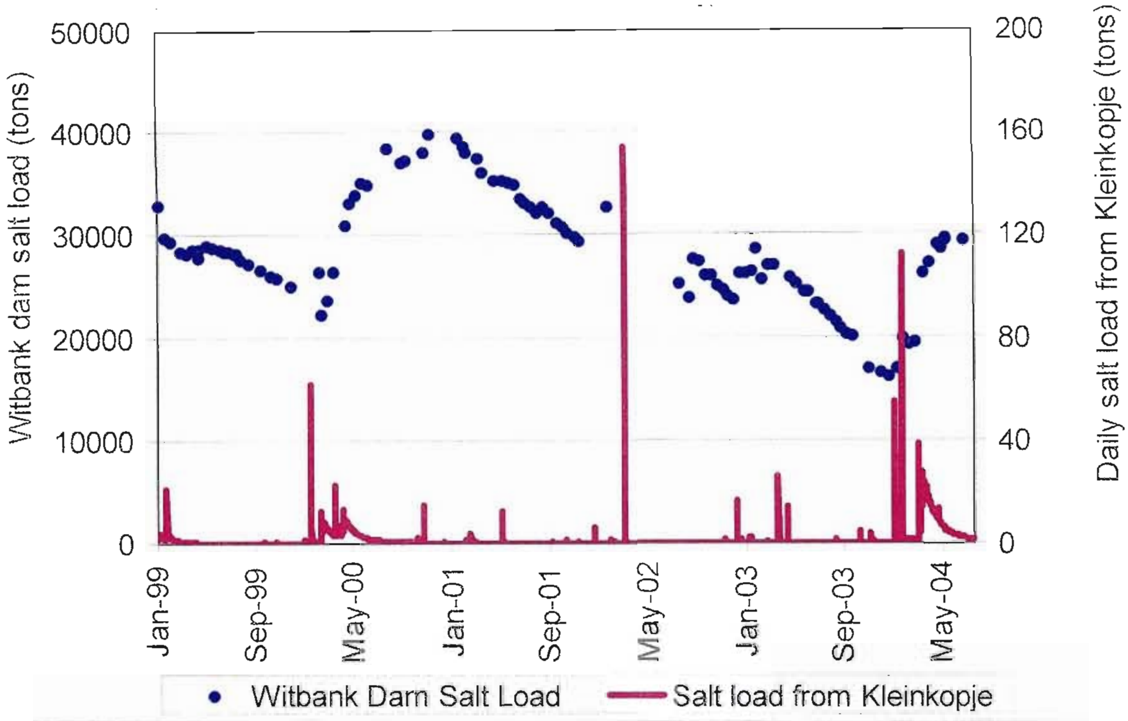


Figure 8.30: A comparison of simulated daily salt load accompanying runoff from the Kleinkopje Colliery into the Witbank Dam after water table re-establishment with the measured salt load in the dam

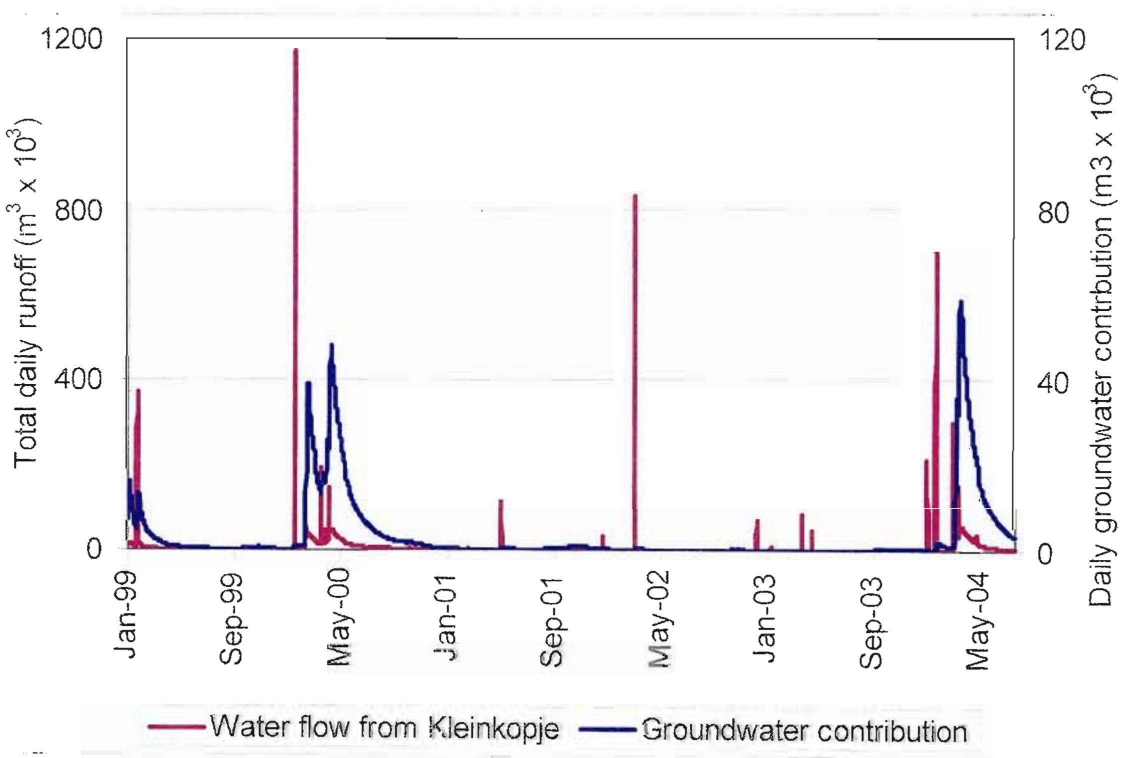


Figure 8.31: Simulated total daily runoff from the Kleinkopje Colliery into the Witbank Dam and the groundwater contribution after water table re-establishment

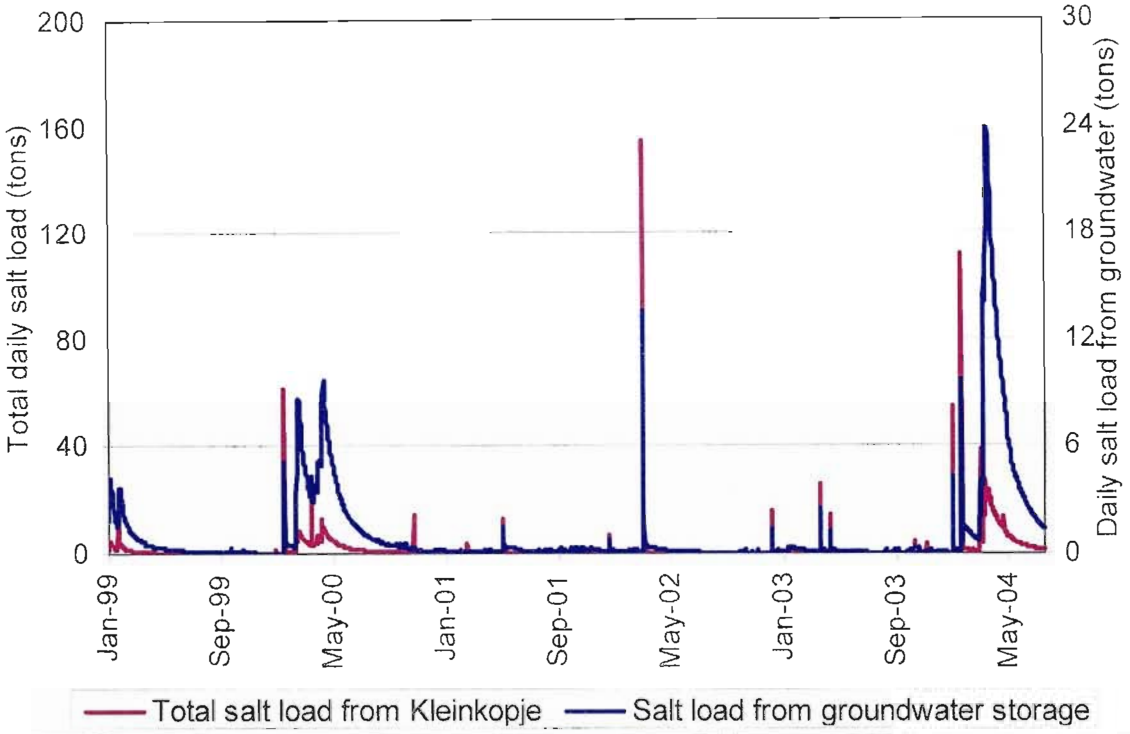


Figure 8.32: Total daily salt load from the Kleinkopje Colliery flowing into the Witbank Dam and the daily salt load contribution from the groundwater after water table re-establishment

Lack of streamflow data prevented the evaluation and verification of the simulated salt loads discharged into the streams that passed through the study area. However, the available data on salinity of Tweefonteinspruit indicated a general increase in salinity as the stream passes through the mine area. Figure 8.33 shows the comparison of the measured salinities of Tweefonteinspruit as it enters and exits the study area. Based on the available data, the average salinity of the stream as it entered and exited the study area are 672 mg/l and 842 mg/l respectively.

The salt loading of Tweefonteinspruit from the study area, according to the configuration of the study area for this study, comes from four land segments, *viz.* land segments 2, 3, 13 and 14 (Figure 6.1). The composite simulated daily salt loading of the stream is presented in Figure 8.34. The salt loading may be expected to increase after the mine has closed down and the local water table has been re-established.

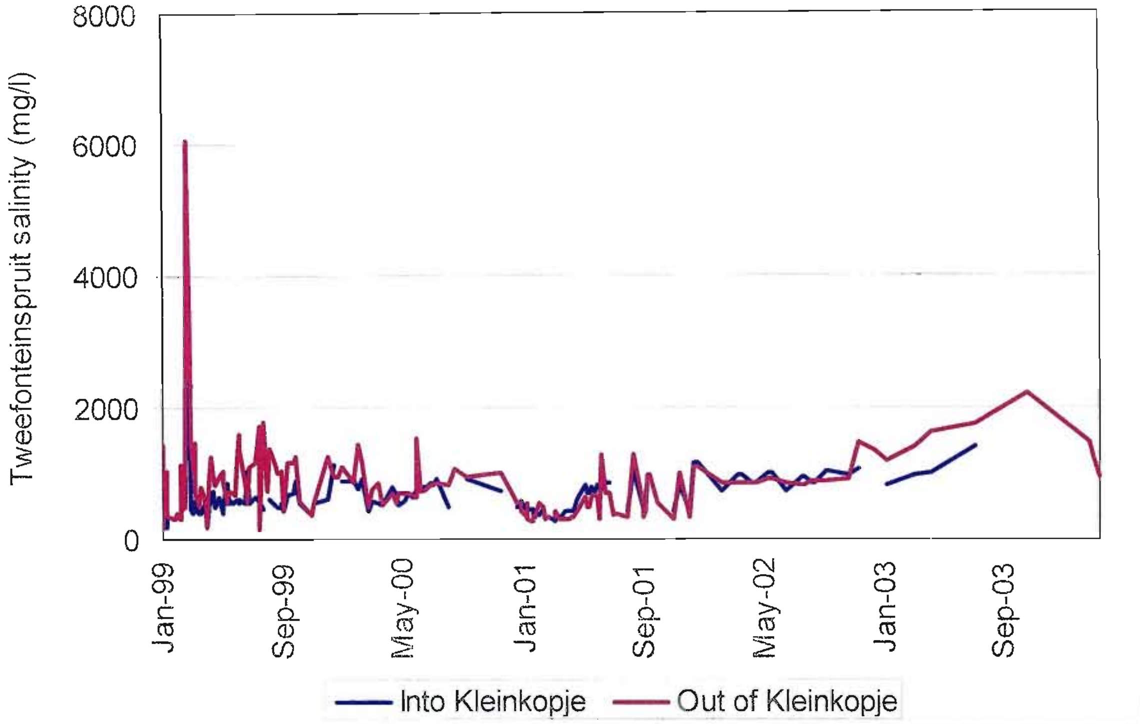


Figure 8.33: Measured daily salinity of Tweefonteinspruit as it enters and exits the Kleinkopje Colliery

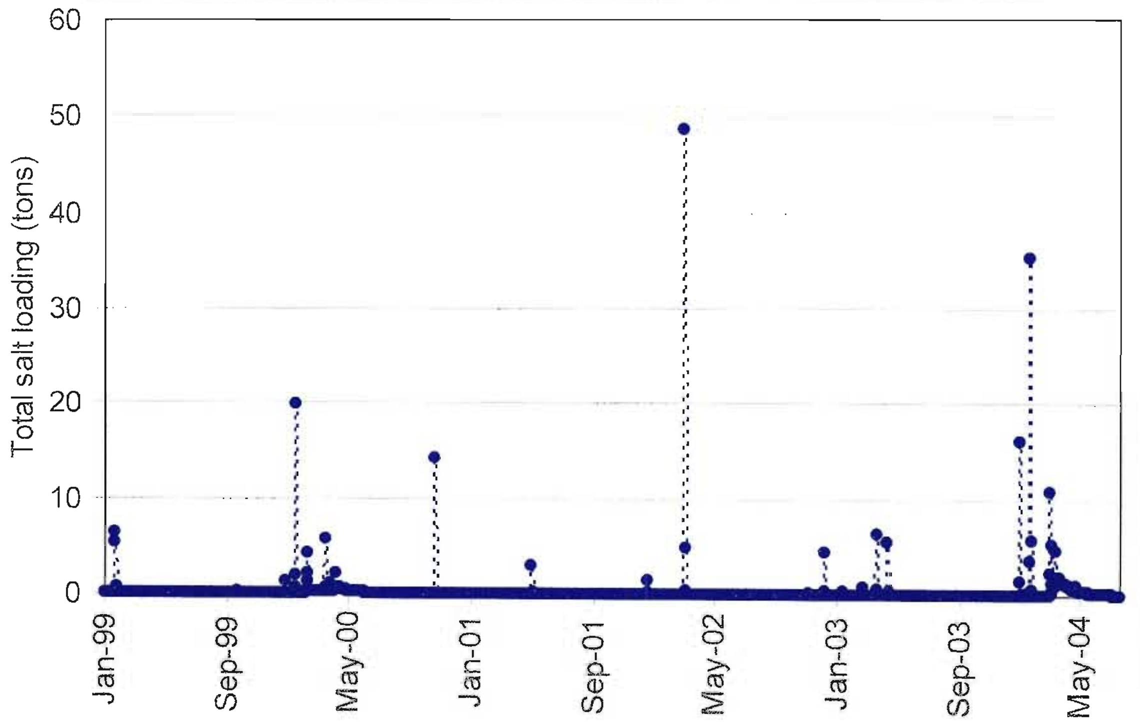


Figure 8.34: Simulated daily salt loading of Tweefonteinspruit from the Kleinkopje Colliery

8.2.3 Scenario Simulations

The simulated scenarios are focused on widespread irrigation with mine water in the study area. As a way of demonstrating the impacts of widespread irrigation if more areas than the baseline condition had been irrigated with mine water, the land areas under irrigation with mine water were increased and the results compared with the baseline scenario and its impact on Witbank Dam. The baseline condition had an irrigated area of 80 ha. The outflow from the study area and its impact on Witbank Dam with widespread irrigation was assessed by irrigating an additional area of 600 ha, representing a percentage increase of about 88% in the extent of the irrigated area. This is equivalent to a total of an additional 30 centre pivots of 20 ha each. A comparison was made between a scenario in which the additional 30 centre pivots were all typical of the Fourth pivot on virgin soils and a scenario in which they were all typical of the Tweefontein pivot on rehabilitated soils. For irrigation on rehabilitated soils, a distinction was again made between the time prior to and after water table re-establishment. Table 8.12 and Figures 8.35 – 8.38 show the volume of runoff and groundwater contributions to Witbank Dam from the study area under widespread irrigation. Increases in the runoff and its salt load of 45% and 607% respectively would have occurred if an additional area of 600 ha had been irrigated with mine water on virgin soils only. However, with widespread irrigation on rehabilitated soils, the impact will be dependent on whether the water table has re-established or not. Prior to the establishment of the water table, the increase in water salt load that would emanate from the study area is 5% and 22% respectively. Much more water and salts contribution (39% and 230% increases respectively) to Witbank Dam would take place after the re-establishment of the water table. The amount of water and salt load contributions will depend on the extent of the area being irrigated. It is therefore imperative that the possible downstream consequences of the drainage from areas meant for irrigation with mine water is carried out on the basis of other stakeholders and ecological requirements. Conversely, these requirements could be used to determine the tolerable amount of drainage, which may in turn, inform the extent of irrigation permissible. Considering that the least of outflow would occur when rehabilitated soils are irrigated with mine water before the re-establishment of the regional water table, it may therefore be a better mine water management strategy in an active opencast mining environment if irrigation of agricultural crops were carried out on rehabilitated soils instead of on virgin soils. The rate and degree of water table re-establishment are related to site-specific factors, which have to do mainly with the areal extent and depth of the mine site, the local hydrological conditions and sources of recharge, and the changes in local hydrogeology owing to excavation and backfilling (Reed and Singh, 1986).

Table 8.11: Comparison of runoff and baseflow outflows from the study area under widespread irrigation of extra 600 ha

Parameters	Virgin	Rehabilitated (pre WT re-establishment)	Rehabilitated (post WT re-establishment)
Total daily runoff to Witbank Dam (Ml)	16175.0	11802.0	15532.0
Mean annual runoff (MAR) to Witbank Dam (Ml)	2871.0	2095.0	2757.0
% of MAR contribution to Witbank Dam (%)	3.90	2.8.0	3.8
Total daily runoff salt load to Witbank Dam (tons)	15625.0	2695.0	7286.0
MAR salt load to Witbank Dam (tons)	2773.0	478.0	1293.0
% of MAR salt load contribution to Witbank Dam (%)	0.10	0.02.0	0.05
Total daily groundwater contribution to total runoff (Ml)	7733.0	5152.0	8894.0
% total groundwater contribution to total runoff (%)	48.0	44.0	57.0
Total daily salt load from groundwater to total runoff salt load (tons)	12847.0	1445.0	5994.0
% of total salt load from groundwater to total runoff salt load (%)	82.0	54.0	82.0

WT = Water table

8.3 Conclusions

The modified *ACRU2000* model and the *ACRUSalinity* module have been realistically applied in the hydrological modelling of the Tweefontein Pan catchment and the Kleinkopje Colliery, and they give a good assessment of the impact of widespread irrigation with gypsiferous mine water on the surface water and the groundwater resources of the catchment and the colliery. The simulations carried out demonstrate the necessity for adequate integrated assessment of the water resources in a watershed and in a colliery in order to predict and manage the volume of water and the mass of salt in the different components of the hydrological cycle, as well as the likely impact of irrigation on the quantity and quality of the source of irrigation water supply. The modified *ACRU2000* and *ACRUSalinity* can therefore be used, not only in assessing the impact of irrigation with low quality mine water, but also in the management of water resources in a coal-mining environment.

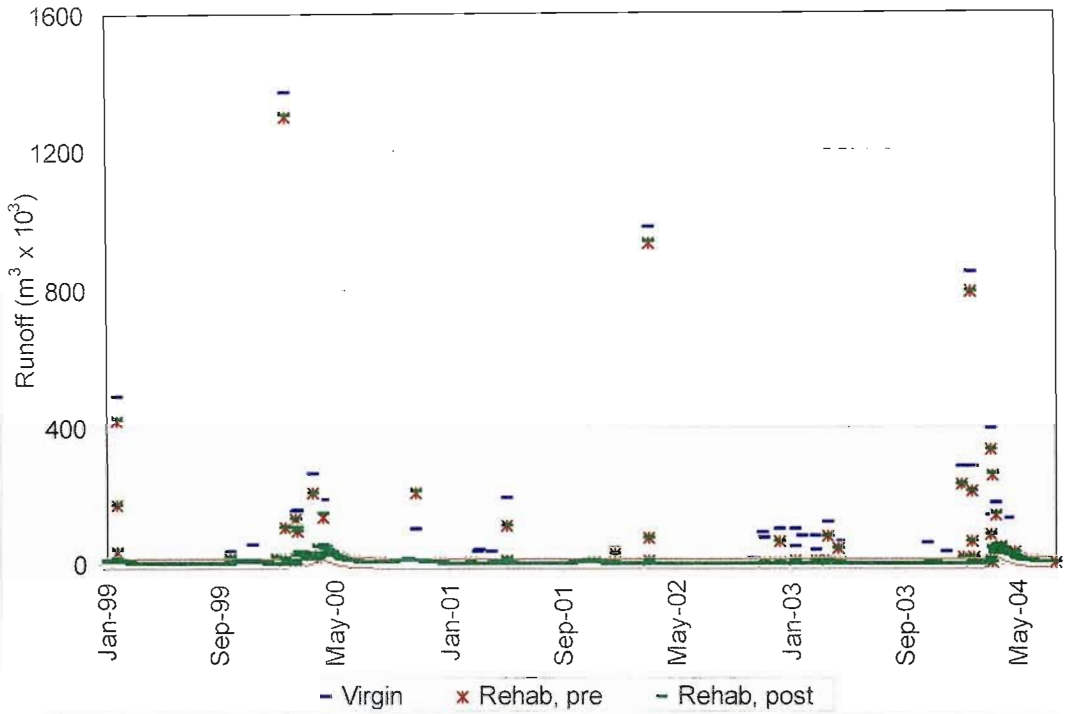


Figure 8.35: Total simulated daily runoff from the study area under different scenarios

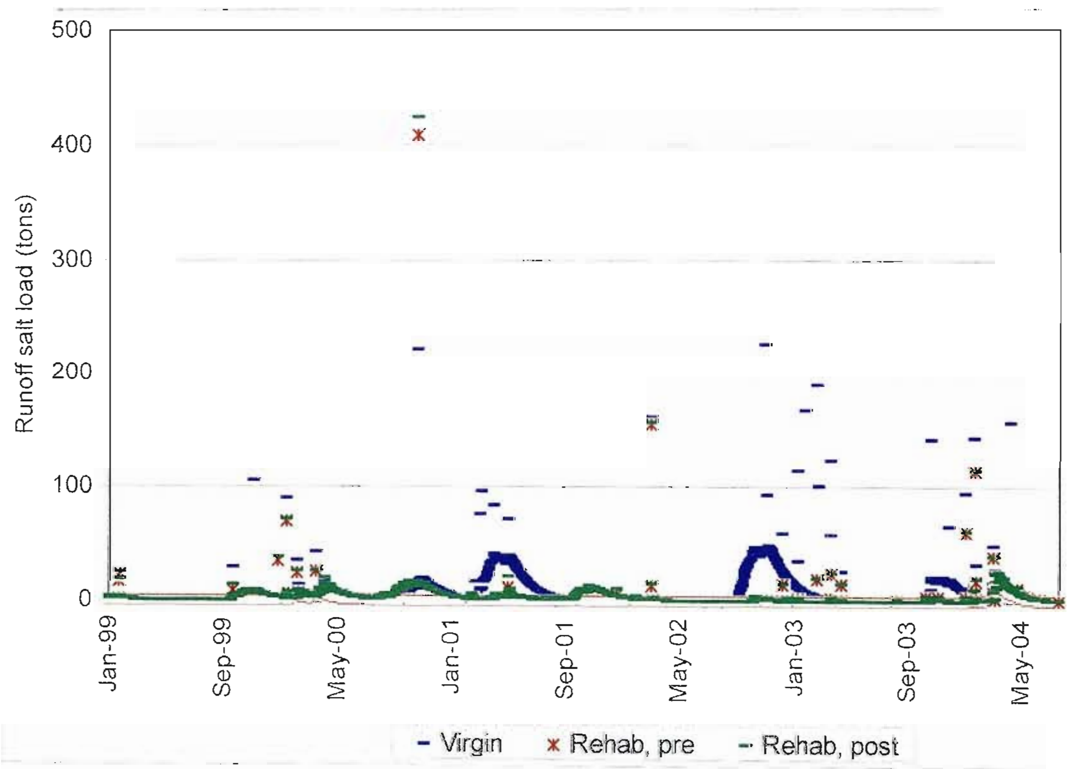


Figure 8.36: Simulated daily salt load from the runoff under different scenarios

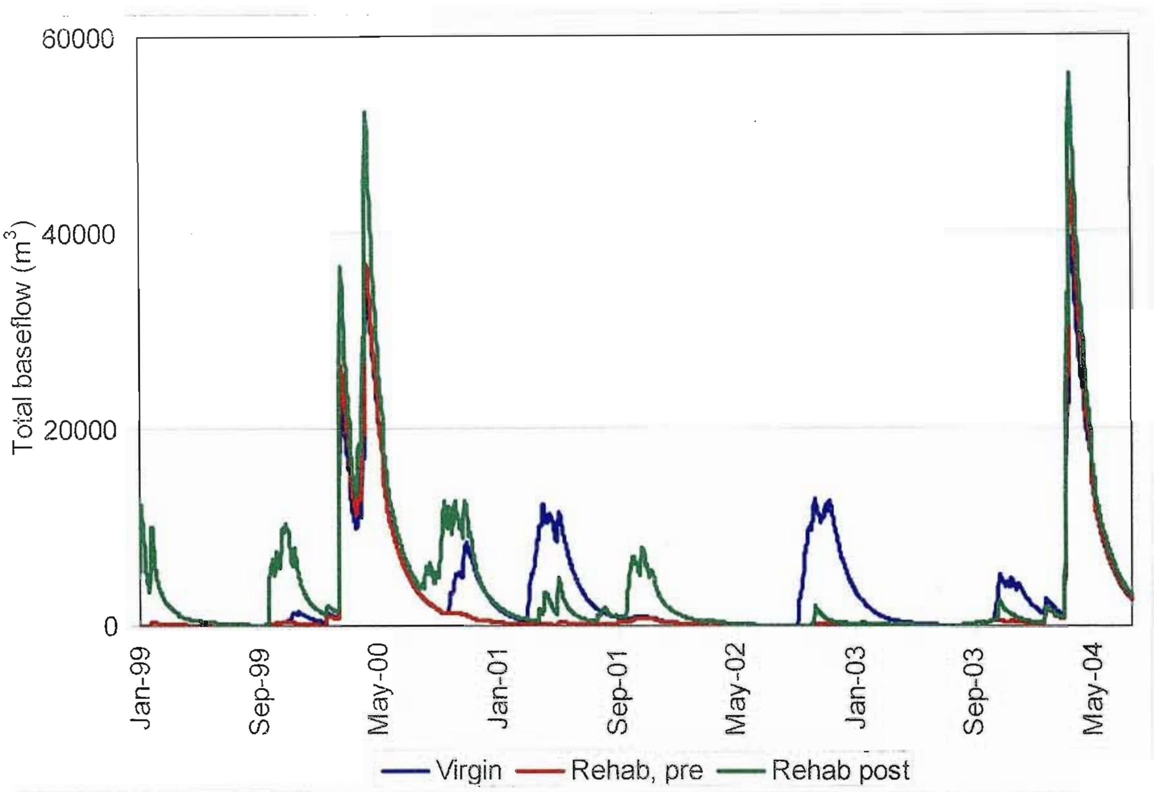


Figure 8.37: Simulated daily groundwater contribution to runoff under different scenarios

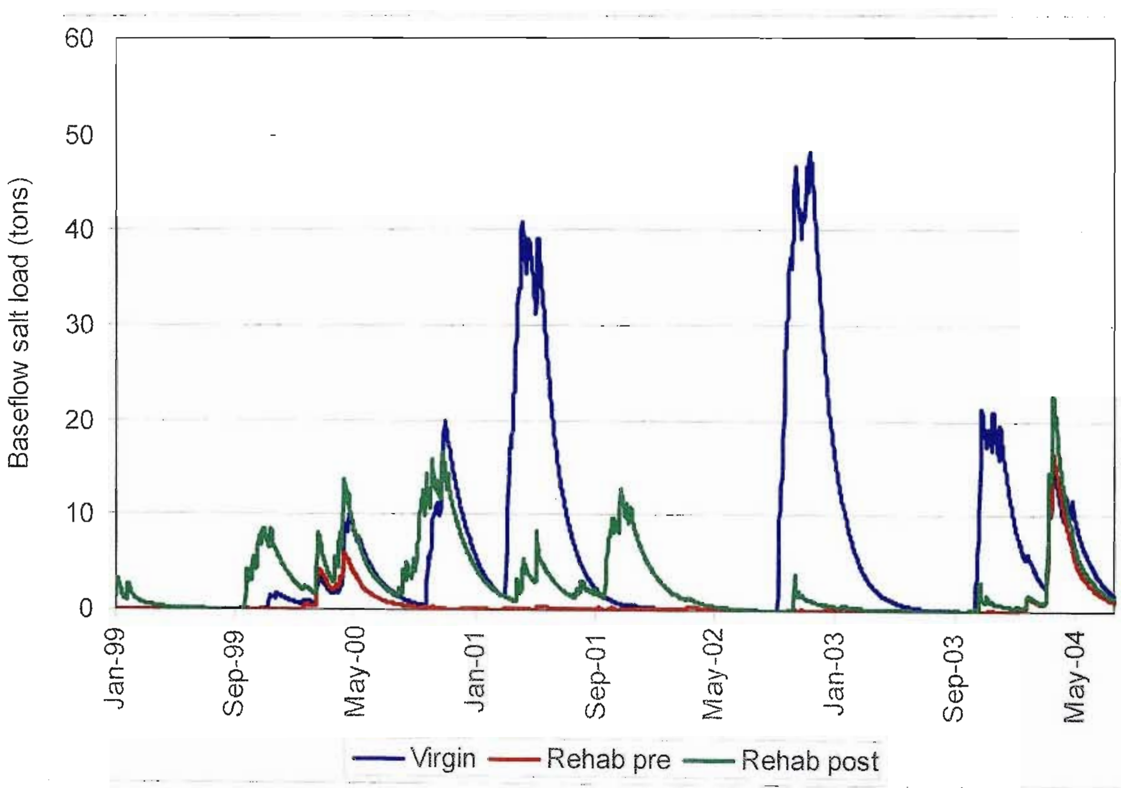


Figure 8.38: Simulated daily salt loading from the groundwater contribution under different scenarios

In the next chapter are conclusions from this research work, as well as recommendations for future research and successful application of the modified *ACRU2000* and *ACRUSalinity* module for the assessment of the impact of irrigation with low quality mine water on water resources. A general thesis conclusion, highlighting the uniqueness of this study, completes the chapter.

9. CONCLUSIONS AND RECOMMENDATIONS

9.1 Conclusions

Modifications were carried out in this study to both the *ACRU2000* model and the *ACRUSalinity* module that will enable their application for the assessment of the impact of irrigation with saline water on both the surface water and groundwater. In this study, the modified *ACRU2000* model and the *ACRUSalinity* module were employed to assess the impacts of widespread irrigation of agricultural crops with saline mine water in a coal-mining environment.

The impacts that irrigation of agricultural crops with saline mine water may have on both the surface water and groundwater are dependent on many factors. In parts of the Upper Olifants basin, and on the basis of the three scales of study (i.e. at centre pivot, catchment and mine scales) carried out in this research work using the modified *ACRU2000* and *ACRUSalinity* module, the following factors may affect the magnitude of impacts that irrigation of agricultural crops with low quality mine water may have on water resources:

- The soil type of the irrigated area,
- Whether the irrigated area is on a virgin (i.e. unmined) or rehabilitated profile,
- Whether a regional water table has been re-established or not in a rehabilitated mining system,
- The characteristics and the volume of the mine water applied as irrigation water,
- The type of crops under irrigation, and
- The climate under which the agricultural crop is irrigated, especially in regard to of rainfall and temperature.

A significant proportion of the water input onto an irrigated area, both as rainfall and irrigation water, may be lost through evaporation and plant transpiration i.e. total evaporation. No less than 76% of the water applied onto the irrigated areas on both virgin and rehabilitated profiles assessed in this study was lost to total evaporation. Soil types may not have much influence on the amount of total evaporation on an area irrigated with mine water, as a simulated value of 76% was obtained for an irrigated area located on clay as well as one located on sandy loam. However, textural characteristics of the soils may be expected to influence the volume of runoff, drainage to groundwater and the volume of water retained in the soils. In a permeable soil such as sandy loam, for example, the runoff from the irrigated area may not be as high as in a less permeable soil such as clay, whereas the volume of drainage beyond the root zone may be expected to be higher. Depending on the salinity of the irrigation water therefore, the soil textural characteristics may be expected to be a controlling factor in the amount of salt exports from the irrigated area.

In comparison to the salt input onto an irrigated area from rainfall, the salt input from the irrigation water sourced from the mine is significant. The salt load contribution from the irrigation water applied onto the three centre pivots studied in details in this research work are 99% for both the Fourth and Syferfontein pivots, and 97% for the Tweefontein pivot. Therefore, the application of mine water for irrigation can be expected to lead to an increase in the soil water salinity of the irrigated area and in the drainage to the groundwater store. However, extreme rainfall events may be instrumental in moving salts deeper into the profile and in washing salts from the surface layer. The changes from the initial conditions are dependent on the salinity of the irrigation water. However, a significant proportion of the salt input, both from rainfall and irrigation water, will either be precipitated within the root zone in the soil horizons or dissolved in the soil water of the soil horizons. A general increase in the resistivities of the soil materials with depth in the irrigated area can be taken as a reflection of the decreasing influence of the mine water used for irrigation with depth. Therefore, by irrigating with a saline mine water, a significant proportion of the salts can be removed from the water system as precipitated salts within the root zone, thereby reducing the possibility of off-site salt export and environmental pollution. On-site salt precipitation, however, may require efficient cropping strategies and the cultivation of salt tolerance crops. The salinities of water used for irrigation in this study, which ranged between 1 920 mg/l and 2 042 mg/l, as well as the salt saturation values obtained in both the rehabilitated and virgin profiles (3 500 mg/l and 5 000 mg/l respectively), indicate that many crops can be successfully cultivated with the type of irrigation water used. Such crops include barley, wheat, soyabean, maize, tomatoes and potato.

The salinity of the runoff from irrigated areas as well as the salinity of the soil water in the soil surface layer are influenced by the volume and frequency of rainfall. An inverse relationship between the volumes and salinities of runoff is a reflection of the dilution effect of rainfall. During a large rainfall event, the dilution effect is high and the runoff salinity consequently low. The opposite will be the case during a low rainfall event.

Irrigation of agricultural crops with mine water, especially in a mining environment, occurs on virgin and rehabilitated profiles. However, the impact on water resources may be different for each of these profiles. In this study, a comparative assessment of irrigation with mine water on virgin and rehabilitated profiles indicates that increased drainage beyond the root zone into a groundwater store and lower runoff occur from a rehabilitated profile. The same conditions apply to salt loads associated with runoff and drainage to groundwater. The kinds of response in a rehabilitated profile, however, may be expected to vary depending on the kinds and methods of rehabilitation, e.g. the depth of the topsoil overlying the spoils, the degree of spoil compaction before placement of topsoil and the slope of the rehabilitated land. In a rehabilitated area, a distinction can be made between the impact of irrigation with the mine water prior to the re-establishment of the regional water table and after. Prior to the re-establishment of the water table, the contribution of groundwater to runoff as baseflow may be insignificant as water moves through the soils and spoils and accumulates in depressions at the bottom of the spoils. The rate and degree of water table re-establishment will depend on the areal extent and depth of the opencast mining, the rate and sources of recharge, and the changes in local hydrogeology owing to excavations and backfilling. After the cessation of mining and re-establishment of the water table, an appreciable contribution of baseflow to runoff can be expected. Therefore, the off-site impact of irrigation with mine water on rehabilitated profile prior to the re-establishment of the water table may not be as much as that of the impact of irrigation on virgin and rehabilitated soils after the re-establishment of the water table. Because of opencast mining activities and the attendant drawdown towards the opencast pit, the re-establishment of the water table may not occur until after the closure of an opencast mine.

The application of *ACRU2000* model and the *ACRUSalinity* module, as modified in this study, to Kleinkopje Colliery enabled the estimation of both the water and salt export from the colliery under different conditions of widespread irrigation with mine water on virgin and rehabilitated soils. The simulated total water and salt load contribution to Witbank Dam from the Colliery for a simulation period of 1999 - 2004 were estimated to be 11.2 x 10^3 Ml and 2 208 tons respectively, amounting to a mean annual runoff and salt load of 2 x 10^3 Ml and 392 tons respectively. The mean annual runoff and its salt load contributions to Witbank Dam represented an average of 2.7% and 1.4% of the average annual water and salt storages in the dam respectively. From the assessment, the least salt export would occur when widespread irrigation is carried out in rehabilitated areas before the re-establishment of the water table. It may, therefore, be a sound water management strategy in active collieries if irrigation with mine water were carried out on rehabilitated soils.

9.2 Recommendations

This study has shown that irrigating with saline mine water will lead to increases in the salinities of the soil water, runoff and drainage to groundwater. Therefore, regular monitoring of the groundwater and surface water, not only in the irrigated area, but also in the surrounding areas, should form part of the irrigation project in which mine water use is being planned. The monitoring should not only provide insight into the changes taking place in the irrigated area as a result of the increased supply of saline water, but should also form a good quantitative basis for verification of simulated results, as well as for assessing and predicting downstream consequences and regional hydrological effects of large scale irrigation with mine water. The monitoring network should include the monitoring of groundwater levels and qualities, rainfall and applied irrigation water volumes and qualities, soil water content and salinities, surface water flows and qualities emanating from the irrigated areas and the qualities and flows of streams in close proximity to the irrigated areas.

In *ACRUSalinity*, it is currently assumed that there is no salt build up from fertilizer application and that the crops will take up the salt input onto an irrigated area from fertilizer application. However, where the application of fertilisers is part of the irrigation strategy, salts releases from the applied fertilisers could further increase the salinities of the soil water, runoff and drainage into groundwater storage. It may be necessary, therefore, to accommodate the release of salts from the applied fertilisers into *ACRUSalinity* for adequate salt balance computation. In this regard, crop uptake of salts from fertiliser application may need to be accommodated as well.

Sustainability, in regard to the availability of an adequate amount of irrigation water and long-term salt build up in the profile, is very important for widespread application of mine water for irrigation to be successful. In this study, the limitation to the area that can be successfully irrigated with saline mine water, based on the volume of available mine water and the duration of irrigation, were shown. Consequently, it is necessary that before widespread application of a mine water source for irrigation is commenced, a thorough assessment of the extent of the irrigated area that can be adequately supported by a mine water source and for how long, be carried out. Such an assessment should include the level of salt export likely to occur from the proposed irrigated area and the possible downstream consequences.

The decision to irrigate with mine water must be attended to by adequate plans for land preparation that will prevent water logging and facilitate effective drainage water management. In rehabilitated soils especially, where subsidence and occurrence of micro-depressions at the interface between the surface of the spoil and the topsoil may cause ponding and secondary salinisation, construction of drainage outlets may be necessary. Depending on the type of irrigation water, the area of irrigation and the expected drainage salinity, a decision may have to be taken on whether to include the regional drainage network in the drainage system of the irrigated area or to isolate the field drainage to permit re-cycling and re-use.

In the determination of seepage from groundwater into an opencast pit and leakages into underground mined-out areas, Darcian flows were assumed. In a highly fractured rock in which groundwater flows in irregularly spaced cracks and openings, a non-Darcian flow regime may be more applicable. Therefore, a non-Darcian flow regime, in regard to seepage of groundwater in opencast pits and leakages into underground reservoirs, may need to be accommodated in *ACRU2000* for the purpose of modelling seepage from groundwater in a highly fractured rock.

Opencast mining operations not only depress the water table, they also disrupt the unworked rock strata and significantly change the hydraulic properties of the original rock. In addition, if the excavated void is not fully restored or if differential settlements of backfill materials occur, the restored surface levels can be altered, leading to the creation of ponds over the restored sites and the consequent change in the local surface water and groundwater flow systems. Although re-establishment of the water table in a rehabilitated profile is assumed after mine closure in this study, the rate and degree of groundwater recovery vary widely and are site specific, depending on the areal extent and depth of mining, sources of recharge and changes in local hydrogeology owing to excavation and backfilling. The rates and degree of groundwater recovery not only affect the surface and subsurface water movement, but also the development of surface water and groundwater quantity and quality. It is therefore recommended that in cases where the rehabilitated profile is targeted for irrigation with mine water, prediction studies of the groundwater recovery rates and magnitudes be carried out. Such studies will enable adequate representation of the baseflow contribution to runoff when using the modified *ACRU2000* model for the simulation of rehabilitated areas.

9.3 Contributions of Thesis

In conclusion, this research work has shown that successful irrigation of some (salt tolerance) crops with low quality mine water could be done, although increases in the soil water salinity of the irrigated area, runoff from the irrigated area and drainage to the groundwater store would occur. Through the modifications carried out in the *ACRU2000* model and the *ACRUSalinity* module in this research work, a tool has been developed, not only for application in the integrated assessment of impact of irrigation with mine water on water resources, but also for the integrated assessment and management of water resources in coal-mining environments in South Africa.

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11. APPENDICES

APPENDIX A Concepts and Structure Development of *ACRU20000* and *ACRUSalinity*

A.1 *ACRU* Modelling System

The *ACRU* is a multi-purpose, physical conceptual model, which integrates the various water budgeting and runoff producing components of the terrestrial hydrological system (Schulze *et al.*, 1995a). It is conceptual in that it simulates a system in which important processes are idealised and it is physical in that physical processes are represented in the model explicitly (Schulze *et al.*, 1995a). In order to capture relevant processes, the model uses daily time steps and thus, for example, uses daily rainfall as primary inputs. *ACRU* operates on a daily multi-layered soil water budget and it is structured to be highly sensitive to land cover/use and climate changes on the hydrological system of an area, with its water budget responsive to supplementary watering by irrigation, inflows and abstractions. The model also provides multiple options in many of its routines that can be used, depending on the level of input data available or the detail of output required. It can operate either as a lumped small catchment model, or as a distributed cell-type model for larger catchments, or in areas of complex land use and soils. Although *ACRU* has been applied internationally, it was developed with the southern African hydrological conditions in mind and is therefore linked to appropriate local land use, soils and climate databases. A schematic diagram of the manner in which multi-layer soil water budgeting by partitioning and redistribution of soil water is accounted for in *ACRU* is depicted in Figure A.1.

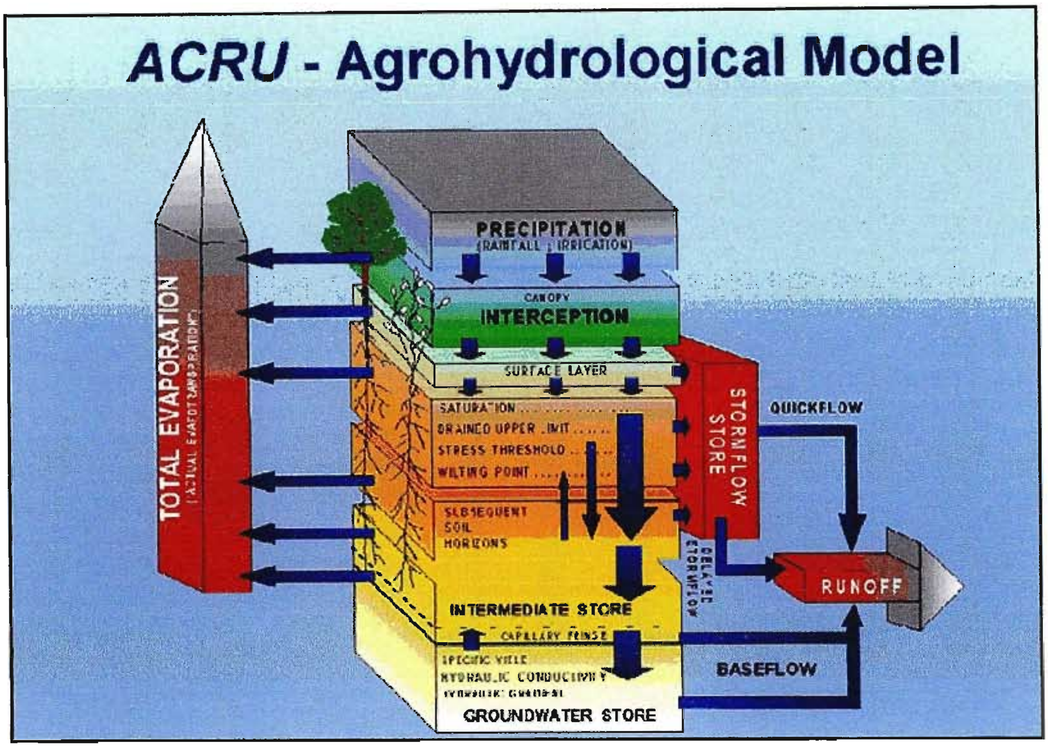

Figure A.1: General structure of the *ACRU* agrohydrological model (after Schulze *et al.*, 1995a)

Water input into the hydrological system occurs as precipitation or irrigation. Vegetative or impervious land covers may intercept part or all of the water input. The rainfall and/or irrigation not abstracted as interception or as stormflow (either rapid response or delayed) first enters through the surface layer and resides in the topsoil (A) horizon. When the drained upper limit of the topsoil is reached, excess water percolates into the subsoil (B) horizon as saturated drainage at a rate dependent on respective horizon soil textural characteristics, wetness and the other drainage related properties. Saturated and unsaturated soil water redistribution may take place between soil horizons. However, saturated soil water movement downwards from the lower (B) soil horizon drains into the groundwater store, from where baseflow may be generated. Unlike in the non-irrigated area where the subsurface soil water redistribution takes place between two soil horizons (A and B), in the irrigated area, it takes place in only one soil horizon. In *ACRU*, the soil horizon in the irrigated area is assumed to be a tilled soil. It is the zone in which the majority of roots occur, and therefore where the amount of water available in the total soil profile is regulated (Lecler and Schulze, 1995). Owing to repeated tillage, this zone is assumed homogenous and differentiation into horizons A and B is considered unnecessary (Lecler and Schulze, 1995; Horan, 2006.). The depth of this zone can be stipulated by the user of *ACRU*. Evaporation takes place from the intercepted water and from the various soil horizons, in which case, it is either split into separate components of soil water evaporation and plant transpiration, or combined as total evaporation. Plant transpiration takes place from all root active soil horizons. A detailed explanation on the background, concepts and applications of *ACRU* is given in the Schulze (1995a). However, further description will be provided in the way in which *ACRU* has been restructured and employed for the present study.

A.1.1 Restructuring of *ACRU*

The *ACRU* model was initially written in FORTRAN 77. Numerous additions and enhancements were made to the model by a number of model collaborators such that the model structure became complex to the point where, in some instances, changes to the model were becoming difficult to effect due to its structure and the limitations of the FORTRAN 77 programming language (Clark *et al.*, 2001). In order to overcome the difficulties and accommodate future model additions, the model was written in an object-oriented framework, using Java programming language (Kiker and Clark, 2001). Although FORTRAN 77 programming language has many merits in terms of computational efficiency, it also has limitations in developing a modular, easily expandable program design (Campbell *et al.*, 2001), which otherwise could be achieved by any object-oriented programming language, such as Java. The new object-oriented version of *ACRU* is named *ACRU2000*. The *ACRU* model prior to the development of the object-oriented version is referred to as *ACRU 300 Series*.

A.1.1.1 Object-oriented programming and *ACRU2000*

Object-oriented programming is relatively new and represents the real world using computer codes. It is an intuitive way of modelling real world systems, such as a hydrological system, in a conceptual manner without being distracted by implementation details (Clark *et al.*, 2001). Silvert (1993) describes object-orientation as being based on the idea that a model should represent the interaction between abstract representations of real objects rather than the linear sequence of calculations commonly associated with procedural programming. From a modelling perspective, Quatrani (1998) defines an Object as: "... a representation of an entity, either real-world or conceptual". Objects have three basic characteristics: identity, state (or variable) and behaviour (or method) and they can be composed of several types of objects (Kjell, 2003). As objects are a representation of an entity, either real world or conceptual, there is always an interaction between objects. A Class is a description of a group of object and therefore has an object-like nature. For example, the word "channel" may be used to describe a class of objects that may include river, stream and canal. Thus, river, stream and canal objects may have the same set of attributes (length and flow rate) and behaviour (flow), but the actual values attached to the attributes and the actual behaviour may be different. The concept of classes is important in object-orientation, not only as a means of grouping similar objects, but also in relation to inheritance as explained below.

The development of the *ACRU2000* model comprises two consecutive steps, namely object design (including analysis) and the subsequent code development (Campell *et al.*, 2001). The Unified Modelling Language (UML) forms the graphical design language for objects in the *ACRU2000* model (Kiker and Clark, 2001). The UML was developed as a solution to consolidate conflicting methods in the symbols and nomenclature of the object-oriented designs formulated at the early stages of object-orientation programming (Quatrani, 1998). It has been recognised as providing a robust support for the conceptualization, visualization and documentation of model structure and design (Object Management Group, 2004). The second step, code development, was implemented using the Java object-oriented programming language by translating the initial concepts drafted and finalised in UML into Java source code files and then into classes through a compiler. The classes are then translated into various operating systems (Windows or Unix) through the Java Virtual Machine resident in most operating systems. In order to provide a basic understanding of the structure of the *ACRU2000* model, the relationships that can exist between objects and the basic *ACRU2000* structure are described next.

A.1.1.2 Objects relationships and basic *ACRU2000* structure

There are three main relationships used in the *ACRU2000* model to describe the interactions between objects or classes, *viz*. inheritance, aggregation and association relationships (Clark *et al*., 2001). Inheritance relationships are "type of" relationship; a river is a type of channel. Aggregation or "part of" relationships allow an object to contain other objects, for example, a catchment object may contain a river object, a dam object and several land segment objects. Association relationships indicate interaction between objects. For example, an irrigated field may be associated with a dam, where the dam plays the role of water source and the irrigated field plays the role of water user. UML representations of the interactions in the *ACRU2000* model is presented in **Figure** A.2. Classes are represented by rectangular boxes, each with a list of attributes and operations. Inheritance relationships are represented by lines with a closed triangular arrowhead at one head, while aggregation relationships are represented by lines with a diamond shape at one end. Thus, a river is a type of channel while a dam is part of a catchment. Association relationships are represented by plain lines or lines with open arrowheads at one end and can be unidirectional or bi-directional. The choice of objects and the relationships between them depends on the system or the situation being modelled.

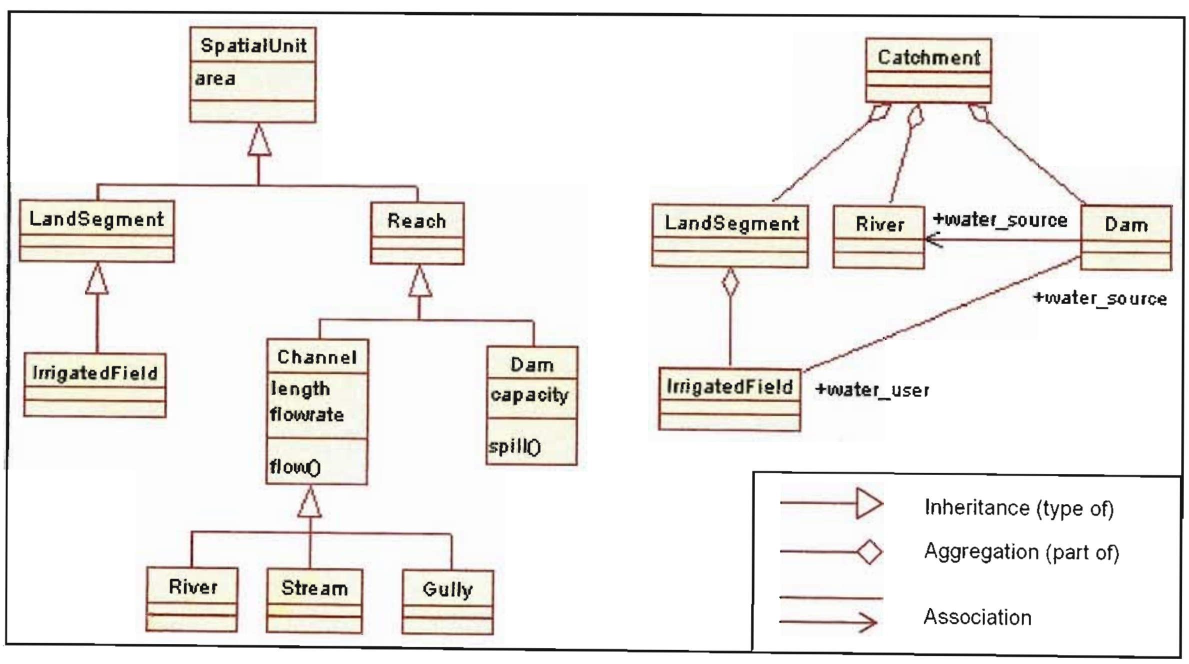

Figure A.2: Class diagram showing inheritance, aggregate and association relationships (after Clark *et al*., 2001) names start with lower case letters. Class, method and variable names are written in italics, make use of uppercase letters after the first letter to highlight the start of words within the name, and may not contain spaces.

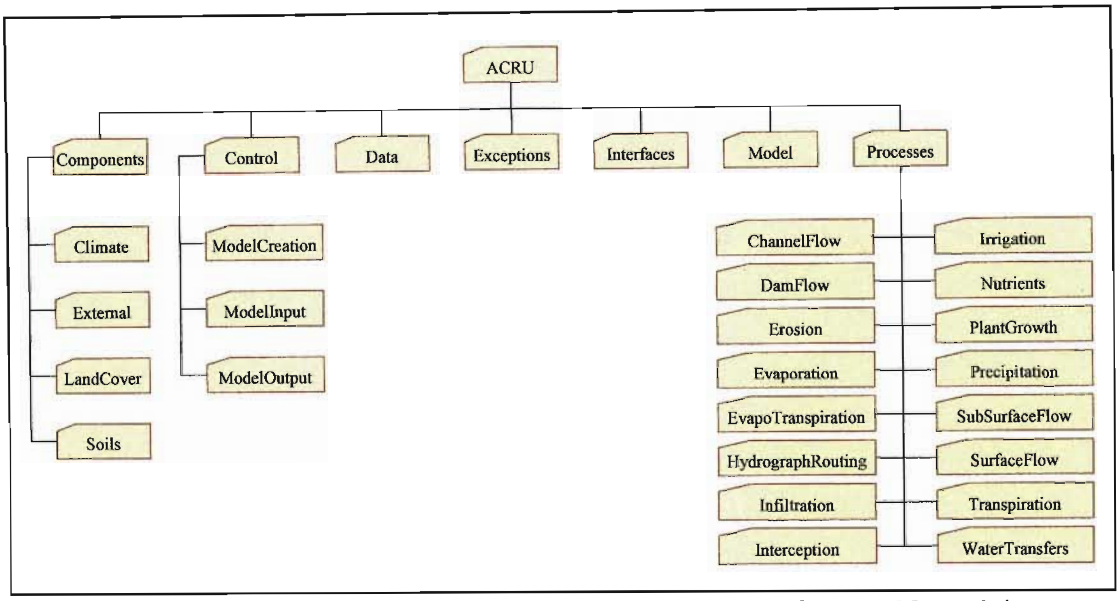

Figure A.3: Structure of the packages belonging to the *ACRU2000* model (after Clark *et al.*, 2001)

The Models, Control, Interfaces and Exceptions objects operate mainly out of sight to the programmer and are only changed at rare intervals or not at all (Clark *et al.*, 2001b). The Model Object creates the starting point for model simulation in *ACRU2000*, while the Control Object is used for reading and writing files. The Interface Object is used to group similar processes for reference by other objects while the Exception Object is used to handle various errors and unexpected errors that may occur. Both the Interface and Exception Objects are constructed from the Java programming language and are used as inherited Objects from Java objects. According to Clark *et al.* (2001b), the three most important class types, as far as modelling hydrology is concerned, are: Components, Processes and Data objects. Therefore, a little more explanation is given on them than the previously mentioned four Objects, though detailed explanation exists in Kiker and Clark (2001), Clark *et al.* (2001a), Clark *et al.* (2001b) and Campbell *et al.* (2001).

Component Object

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Component Object

The Component classes or objects represent the physical components of the hydrological system being modelled and form the building blocks of the *ACRU2000* model. The main Component classes in the model are shown in Figure A.4. Most Components fall into one of two categories, those representing surface features as would be seen on a topographic map and those representing various vertical layers. The surface features objects belong to the *CSpatialUnit* class and include features such as land segments, dams, rivers, and urban areas represented as *CLandSegment*, *CDam*, *CRiver* and *CUrbanArea* respectively. The concept of land segments is adopted in *ACRU2000* to replace the term sub-catchment in *ACRU 300 Series* in order to demonstrate the flexibility of the model in configuring simulations as surface or spatial components independent of each other. In this way, an area need not be self-contained hydrologically, but could be created from a digital elevation grid. Conceptually, there are three main vertical layers: land cover, soil and groundwater store. Each is represented by *CLandCover*, *CSoil* and *CGroundwater* respectively. Climatic parameters constitute important parts of hydrological simulation. The *ACRU2000* model defines a *CClimate* Component with each *CSpatialUnit* type object, with the sub-components of the same *CSpatialUnit* having an association type relationship with the *CClimate* object.

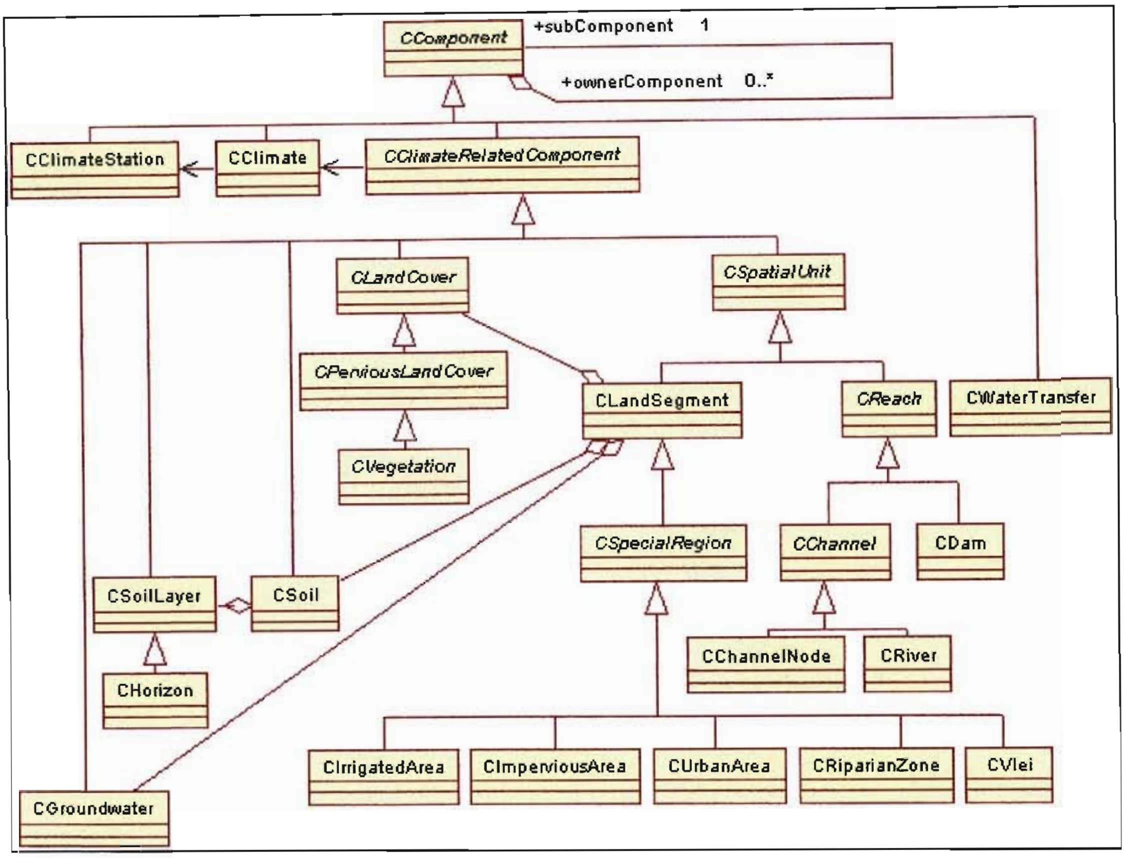

Figure A.4: Class diagram showing the main *ACRU2000* Component classes and their relationships (after Clark *et al.*, 2001)

Data Object

All Data classes in *ACRU200*0 are sub-classes of the *DData* class and are contained in the Data package. Figure A.5 shows the main *ACRU2000* Data classes. The Data classes or objects represent Component attributes. For example, Component attributes such as *Darea*, *Dtemperature* and *DwiltingPoint* represent area, temperature and wilting point respectively. Clark *et al.* (2001a) gave two reasons for representing Components attributes as Data objects:

- the ability of Data objects to perform additional functions, such as range checking, specification of data units and metadata storage, than just being a simple variable and
- the ability to make the model easily extensible, which means that a model developer who wants to add a new Data object to the model simply creates the Data object and specifies to which Component object it belongs to, instead of changing the code of the Component class itself.

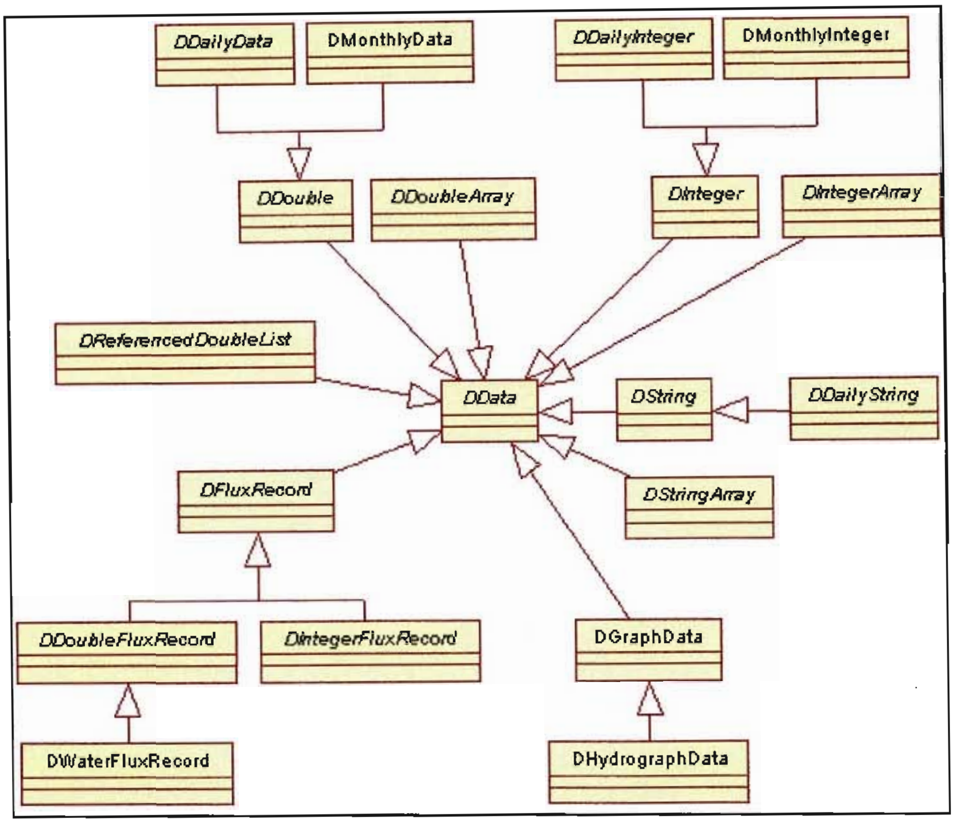

Figure A.5: Class diagram showing the main *ACRU2000* Data classes (after Clark *et al.*, 2001)

Two main characteristics relate to the data to be stored in a Data object: what type of data (integer, decimal, Boolean, or alphanumeric), and the temporal aspect, which may range from constant values to daily or monthly values. In the *ACRU2000* model, resources such as water, sediments and nutrients are not modelled as Component objects, but as quantities using *DfluxRecord* type Data objects such as *DwaterFluxRecord*, which records not only how much water is stored in a particular Component, but also where water flowed in from or out to and who owns the water.

Process Object

The Process classes represent the various processes that take place in a hydrological system, such as interception, infiltration and subsurface water flow. All Process classes are sub-classes of the *Pprocess* (Figure A.6) and are contained in the Processes package.

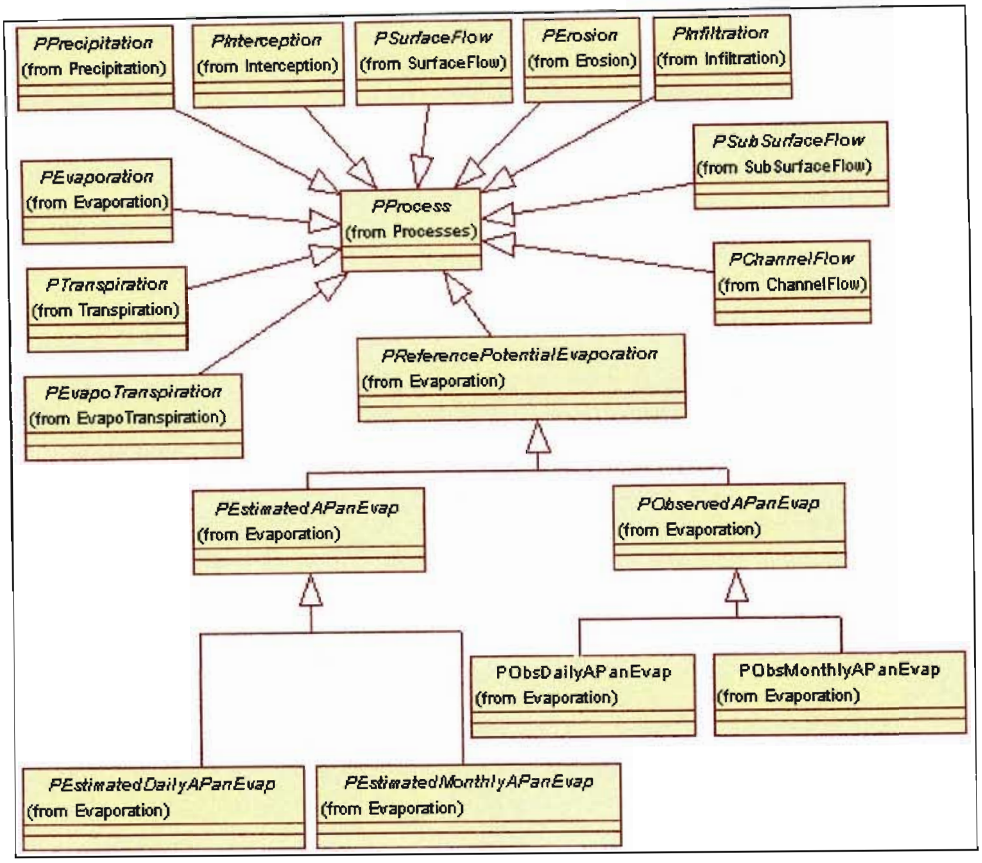

Figure A.6: Class diagram showing the main abstract Process classes in *ACRU2000* (after Clark *et al.*, 2001)

As shown in Figure A.3, the Process package contains several sub- packages used to group related or similar Process classes together. Each Process object has one or more Component objects on which it acts and for each of these, it specifies which Data objects are required.

A.2 *ACRUSalinity*

ACRUSalinity is the hydrosalinity module of *ACRU2000*. The term "module" in the *ACRU2000* model is defined as groups of objects with a common overall purpose (Kiker and Clark, 2001). The *ACRUSalinity* module was developed in the restructured version of *ACRU* model, *viz. ACRU2000*. Therefore, it inherits the basic structure and objects of the model and involves the interaction of hydrological processes, as determined by the hydrological modules of *ACRU2000* and salinity related processes (Teweldebrhan, 2003). In order to be useful in cases where availability of data is a problem, the module is designed to require minimum input information in the readily available unit of mg/l and yet provide as output, adequate information relevant to the planning, design and management of land and water resources in terms of salinisation. The internal computations of hydrosalinity processes in the module involve salt load (mg) in terms of the Total Dissolved Solids (TDS). Therefore, in the *ACRUSalinity* module, the conservative salt load in different components of a hydrological system is determined and not the different solute species concentrations.

The *ACRUSalinity* module enables the assessment of the conservative salt load transport in subsurface components, i.e. from rainfall and irrigation water salt input, through soil horizons to the groundwater store and runoff, as well as the allocation of the runoff salt load to various destination components within a sub-catchment and to downstream reaches. It could therefore deal with the salt load transport in dryland and irrigated conditions, in reservoirs and channel reaches and for upward and downward subsurface salt. Some of the identified potential applications of the *ACRUSalinity* module included (Teweldebrhan, 2003):

- the impact of changes in future climatic and hydrological changes on TDS concentration and salt loading;
- the impact of forest plantations or clearing of forests on dryland salinity;
- the on-site and off-site impacts of irrigation on surface and subsurface water salinity as well as its impact on downstream TDS concentrations in streamflow and salt loading;
- the impact of water resources developments, such as a reservoirs, on downstream TDS concentration; and
- the impact of different management options on reservoir TDS concentration and salt loading.

As already stated, the *ACRUSalinity* module inherits the structure and objects of the *ACRU2000* model. Therefore, the subsequent sections will present the three basic objects as they occur in the module, followed by the modelling approaches taken in the development of the module.

A.2.1 Basic Objects in *ACRUSalinity*

As in the *ACRU2000* model on which its development was based, the *ACRUSalinity* module is based on the interaction between three objects, *viz.* Components, Data and Processes. In *ACRUSalinity*, no new component was created in addition to those in *ACRU2000*.

A number of Data objects were created in the module that served a similar purpose as in the *ACRU2000* model, *viz.* to store and describe hydrosalinity attributes belonging to Component objects. Thus, *DReservoirSalinity*, *DGroundwaterSalinity* and *DTopsoilSalinity* store data on *CDam*, *CGroundwater* and *Csoil* respectively. However, apart from Data objects that store and describe attributes of Component objects, some Data objects also hold information about certain processes. For example, *DReservoirSalinityOption* stores information on whether the reservoir salt budget routine is to be executed in a particular simulation or not and *DSaltFluxRecord* serves not only to store the salt load of a particular component, but also to conduct internal salt balance computations with the help of its parent classes (Teweldebrhan, 2003).

The Process objects in the *ACRUSalinity* module are designed to describe the salt input, balance and movement taking place on the surface and subsurface components, including reservoirs and channels, on the basis of water flow sequence as determined by the hydrological modules of the *ACRU2000* model. Consequently, on each day of simulation, the Processes for the land segment on the headwaters of the simulated catchments are executed first, followed by land segments in progression towards catchment's discharge point (Clark *et al.*, 2001). Thereafter, Processes for each *CReach* type Component (which may represent channel and dam water bodies), are executed, starting with the headwaters of the flow network and moving progressively downstream. Six groups of objects exist in the module for implementing the various processes of hydrosalinity dynamics (Teweldebrhan, 2003). These are:

1. Initialising salt load

The main aim of the salt load initialization object is to set the initial salt load through mass balance computations, based on the initial salt concentration and volumetric water content of the soil layers in irrigated and non-irrigated lands. The object also sets the initial salt load of reservoirs based on the initial reservoir water storage and its associated total dissolved solids (TDS) concentration.

2. Salt Input

The objects in the salt input group are responsible for salt load input from rainfall and irrigation water to the topsoil horizon of irrigated and non-irrigated lands, as well as to reservoirs. The processes, which represent the salt input mechanism to irrigated land, non-irrigated land and a reservoir, are *PIrrigSaltInput*, *PLandSegSaltInput* and *PReservoirSaltInput*, respectively.

3. Surface Salt Movement

The objects in surface salt movement group describe stormflow and runoff salinity, as well as the distribution of salt load from irrigated, non-irrigated and impervious areas, and from reservoirs, to an appropriate destination component. Some of the process classes contained in this group include *PStormflowSalinity,* which is responsible for determining the quickflow salinity and salt load in non-irrigated areas; *PIrrigAreaSaltMovement*, which is responsible for determining the runoff salinity and salt load in an irrigated area; and *PLandSegmentSaltMovement*, which distributes runoff salt load from a land segment to appropriate outflow components, such as channel and dam reaches.

4. Subsurface Salt Movement

The subsurface salt movement processes are responsible for the movement of salt in the subsurface components i.e. from the topsoil through the subsoil into the groundwater store. Also included here, are the salt generation processes in each of the soil horizons and groundwater store, as well as the upward movement of salt load from the bottom horizon to stormflow through the overlying horizons. *PIrrigUpwardSaltTransport*, *PSubsurfaceSaltMovement* and *PSaltUptake* are some of the process examples of this object. The *PIrrigUpwardSaltTransport* process transports salt carried along with the percolating water from one horizon to another and finally to groundwater, as well as conducts subsurface salt balance computations in an irrigated area, while the *PSubsurfaceSaltMovement* process does the same thing in a non-irrigated area. The *PSaltUptake* determines the updated salinity level of a soil layer or groundwater after salt uptake has taken place, according to first order rate kinetics (see Section A.2.2.1).

5. Reservoir Salt Budget

The processes in the reservoir salt budget describe the reservoir salt budget by determining the reservoir storage salinity and the salt concentration of various outflows from the reservoir, such as seepage and overflow. The main classes in this object are *PReservoirComponSalinity* and *PSaltStacking*, which conducts general reservoir water salt budgeting and determines current reservoir storage salinity and outflow salinity respectively (see Section A.2.2.3).

6. Channel Salt Movement

The channel salt movement object contains classes that describe the salt balance at the channel outlet of a particular land segment i.e. sub catchment. This object also performs the transfer of salt load from one land segment to the relevant downstream land segment, in the case of distributed hydrosalinity modelling. The main process classes contained in this object are *PCatchmentSalinity* and *PChannelReachSaltInput*. The former process calculates the salt load and salinity of the water flowing out of a particular channel, while the later determines the daily salt load which is input at a particular channel reach from outside the system being simulated and transports that quantity of salt from the external reach to the channel.

A.2.2 Modelling Approach

This section provides a brief description of the approaches employed in *ACRUSalinity* for salt movement and balances in the subsurface and surface flows, runoff, and reservoirs. The detailed description of the modelling approach in *ACRUSalinity* exists in Teweldebrhan (2003). Some of the approaches have been challenged and modified in this study. The modifications are provided in Chapter 5. The sections that follow provide enough background information for the appreciation of the modifications carried out in this study.

ACRUSalinity is based on two sources of salt input into the soil solution, other than that from the primary source due to *in situ* weathering processes. These are solute input from rainfall (wet atmospheric deposition) and irrigation water (for irrigated areas). Owing to the usual difficulty of obtaining a time series of rainfall water salinity, the salt concentrations of water supplied from a rainfall source are assumed to be constant in value. The appropriate value can be taken as the average of the observed rainfall salinity concentrations at a site. The salt concentration of irrigation water is input either as a monthly value or computed internally as a daily simulated salinity value for the irrigation water source (which can be a reservoir or a river), in order to account for the variation that may occur. The salt load, either from rainfall or irrigation water, is added to the topsoil only and is calculated as the product of the volume of effective rainfall and its salt concentration, or the product of the actual applied irrigation water and its average concentration.

A.2.2.1 Subsurface Salt Movement and Balance

Subsurface salt movement can either be in a downwards or upwards directions, depending on the direction of soil moisture movement. In *ACRUSalinity*, downward salt movement from a soil layer takes place only when the drained upper limit from that soil layer is exceeded. In this way, salt is transported from the topsoil to the underlying horizon and finally to the groundwater store, depending on the amount of percolating water and its salinity. The percolating water has the same salt concentration as that of the soil water in the layer from which percolation is taking place. The salt load of each soil horizon and the groundwater store depends on the amount of salt input. In the topsoil, the salt load is replenished from rainfall (and from irrigation water in the case of irrigated areas), as well as from the salt internally generated as a result as weathering processes. In the subsoil and the groundwater store, the salt load is replenished not only from the percolating water overlying the layers, but also from the salt internally generated as a result of weathering processes within the subsoil and the aquifer in which the groundwater is stored. The salt load in each soil horizon and in the groundwater store, therefore, depend on the amount internally generated, the amount of replenishment, the amount percolating into the groundwater store (in the case of subsoil) and the amount of baseflow release (in the case of groundwater). For irrigated lands, only a single horizon and groundwater store are considered, as *ACRU2000* includes only two subsurface stores in irrigated areas.

Internal generation of salt in the topsoil, subsoil and groundwater store in *ACRUSalinity* is based on the first order rate kinetics equation of Ferguson *et al.* (1994), which assumes that the rate of increase at a specific time (in the concentration of a solute) is proportional to how far the current concentration falls short of its equilibrium value. This is illustrated in Figure A.7 and Equation A.1, which describe an initially rapid, but progressively slower salt generation such that the concentration asymptotically approaches the equilibrium, which represents the maximum value.

$$C_{upd\_i} = C_i + (C_{sat} - C_i)[1 - \exp(-k)] \qquad \text{(A.1)}$$

where

C_{upd_i} = updated salt concentration of the i-th horizon or groundwater store on current day (mg/l),

C_i = salt concentration of the i-th horizon or groundwater store on previous day, which represents initial value (mg/l),

C_{sat} = the saturation value, which represents the maximum salt concentration (mg/l), and

k = salt uptake rate constant.

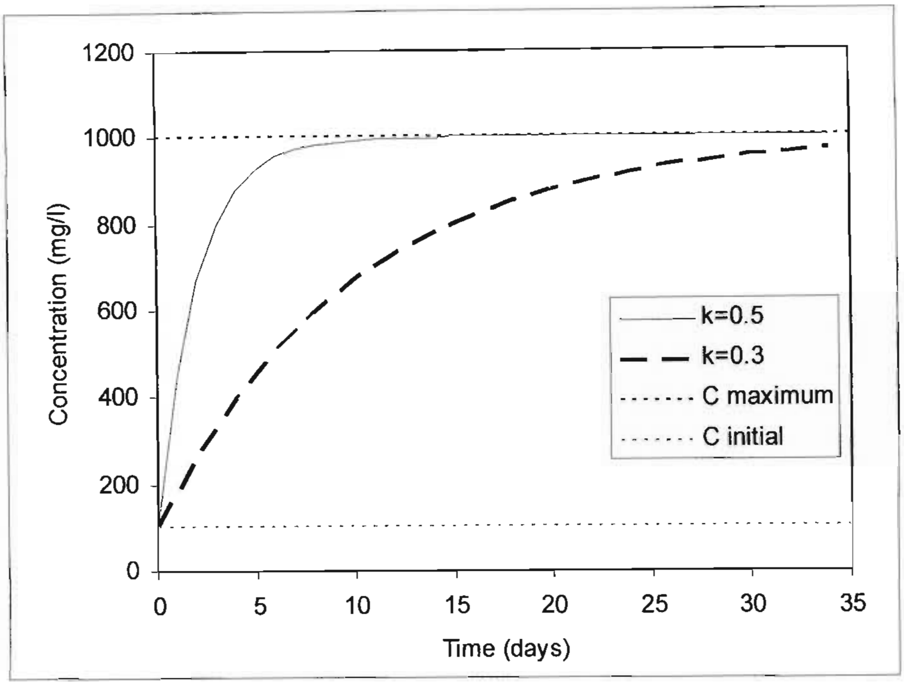

Figure A.7: An illustration of the increase in subsurface TDS concentration with time, based on first order rate kinetics with k=0.3 and k=0.5 (after Teweldebrhan, 2003)

The first order rate kinetics equation was adopted in *ACRUSalinity* with some assumptions. Originally, the equation was proposed for use in estimating solute enrichment of the soil solution due to soil water uptake of individual solute species. However, in *ACRUSalinity*, the equation is used for estimating the increased total dissolved solutes (TDS) value. This is based on the assumption that the quantity of total dissolved solutes, which is the salinity of a given layer, is the sum total of the major individual solute species in the soil solution. Thus, the increase in total dissolved solute concentration follows a trend similar to that of the individual solute species and so can be described by a similar equation. The time parameter (t) in the original equation which would be multiplied to the rate constant, *k*, is omitted in Equation A.1, since in this case, the time step between successive salt generation computations is fixed to a single day. Hence, its value is unity.

Upward salt movement in *ACRUSalinity* occurs only under saturated conditions and is therefore dependent on the moisture status and drainage of a particular soil layer. It occurs if the rate of water movement to a layer exceeds the rate of water loss from that particular layer. If the upward salt movement originates from the subsoil, the salt load entering into the overlying soil layer is expressed as the product of the volume of water entering the overlying layer and the current salt concentration of the subsoil layer. Where the origin of the upward water movement is the topsoil (i.e. when the soil moisture content of the topsoil exceeds its porosity), the salt load associated with water movement is added to the quickflow salt load and subsequently updated. As only one soil horizon is conceptualized for irrigated areas in *ACRU*, upward salt movement can only take place from the topsoil to quickflow.

A.2.2.2 Surface Water Salt Balance

This section describes stormflow and runoff salinity, as well as their salt loads. Schulze (1995c) describes stormflow as the water which is generated on or near the surface of a (sub)catchment from a rainfall event and which contributes to flow in the streams within that (sub)catchment, while runoff is described as the water yield from a given (sub)catchment consisting of stormflow and baseflow as well as any normal flow and overflow from any reservoirs within the (sub)catchment. Baseflow consists of water from previous rainfall events that has percolated through the soil horizons into groundwater store and then contributes as a delayed flow to the streams within a (sub)catchment, whereas, quickflow is the stormflow released into the stream on the same day as the rainfall event. Applied irrigation water, unless when over-application occurs, is assumed not to contribute to stormflow. Therefore, stormflow in irrigated areas may be generated during rainfall events and when over-application of irrigation water occurs. In *ACRUSalinity* however, the stormflow generated on a particular day is assumed to have the same salinity as the average rainfall TDS concentration for the area. Possible salt load contribution, arising from enrichment from soil surface is ignored in *ACRUSalinity*, just as in most hydrosalinity models (Teweldebrhan, 2003). It is assumed that the leaching edge of the water flowing over the soil infiltrates into the soil and carries the soluble salt with it (Rhoades *et al.*, 1997). The salt is not expected to diffuse upwards significantly when the water is percolating downwards. Therefore, one would not expect to find a significant increase in the salinity of stormflow compared to that of the applied water, other than that which might be derived from the desorption of solutes from suspended sediments during erosion (Teweldebrhan, 2003). In this study however, this concept is challenged and due consideration is given to the possible difference in the stormflow salinity from the applied water, especially after periods of no rainfall, when the salinity of soil water near the surface can increase due to evaporation.

Stormflow salinity depends not only on the current rainfall event's salinity, but also on the salt concentration of delayed stormflow. In the *ACRU2000* model, delayed stormflow is the fraction of the event generated total stormflow but released over several days due to interflow retardation. This is determined by a stormflow response coefficient, which controls the "lag" of the delayed component of stormflow by discharging only a specified fraction of stormflow on the day of event. The remaining stormflow is retained to the following day when again the same fraction is applied to the remaining stormflow to generate discharged. Quickflow salinity, taking into consideration the salt concentration of the delayed stormflow, is determined by assuming a simple mixing of the fraction of the delayed stormflow and the fraction of generated stormflow leaving an area on a particular day. Quickflow salinity is determined by volume weighted concentration of quickflow and delayed stormflow from Equation A.2.

$$C_{qf} = \frac{(QF_a * C_{sf}) + (SF_d * C_{dsf})}{QF_a + SF_d} \tag{A.2}$$

where

C_{qf}	=	quickflow salinity (mg/l),
QF_a	=	actual quickflow, i.e. fraction of the stormflow leaving the land on the day of the event (l),
C_{sf}	=	stormflow salinity (= rainfall average salinity) (mg/l),
SF_d	=	fraction of delayed stormflow contributing to quickflow (l), and
C_{dsf}	=	salt concentration of delayed stormflow (mg/l).

After the determination of the quickflow salinity, the salt load associated with quickflow is determined as the product of the quickflow volume and its salinity from Equation A.3.

$$SL_{qf} = QF * C_{qf} \tag{A.3}$$

where

SL_{qf} = salt load associated with the total quickflow volume for the day (mg), and

QF = total quickflow volume, i.e. $QFa + SF_d$ (l).

Runoff salinity and salt load in both non-irrigated and irrigated areas are determined by assuming simple instantaneous mixing of the baseflow and quickflow. Runoff salinity is determined from the flow weighted concentration of baseflow and quickflow using Equation A.4, while the associated salt load is subsequently calculated using Equation A.5.

$$C_{run} = \frac{(BF * C_{bf}) + (QF * C_{qf})}{QF + BF} \tag{A.4}$$

$$SL_{run} = C_{run} * (BF + QF) \tag{A.5}$$

where

C_{run} = salt concentration of runoff water (mg/l),

SL_{run} = the salt load associated with runoff water (mg),

BF = baseflow volume (l), and

C_{bf} = baseflow concentration (mg/l).

The salt loads associated with runoff water from dryland, irrigated lands and impervious areas are distributed according to the direction of water flow as configured by the user of the model. The runoff salts end up in a channel reach and/or a reservoir. In impervious areas, runoff does not include baseflow. Therefore, the runoff salinity from impervious areas is assumed to have the same salinity as that of quickflow, which in turn is assumed to have the same TDS concentration as the rain falling on that area.

A.2.2.3 Reservoir Salt Budget

The reservoir salt budgeting computations in the *ACRUSalinity* module are carried out by the *PReservoirComponSalinty* Process. This process operates in conjunction with the *PSaltStacking* Process to determine the reservoir's current storage salinity and salt load as well as TDS concentration of the various outflows from the reservoir system. The *PReservoirComponSalinty* Process prepares the main data input requirements for the *PSaltStacking* Process. These inputs include total volume of water flowing into the reservoir and its salinity, as well as total volume of water flowing out from the reservoir, excluding evaporation losses. The total volume of water flowing into the reservoir system, which comprises runoff from irrigated and non-irrigated lands, adjunct impervious areas as well as rain falling on the surface of the reservoir, is obtained from the daily total water influx record of the reservoir, as determined by the hydrological modules of *ACRU*. However, the salt load associated with the various inflow sources varies depending on the flow volume and salinity of each source. Hence, the required data for these flow components are also retrieved from the relevant individual data objects, as shown in Figure A.8. The average TDS concentration of the total inflow from the various sources is determined as the volume weighted concentration of all inflows using Equation A.6. Instantaneous mixing of the different inflows is assumed.

$$Cin_i = \frac{(RUN_{ni} * C_{run\_ni}) + (RUN_{irr} * C_{run\_irr}) + (RFL_{dam} * C_r) + (RUN_{adj\_dam} * C_{run\_adj})}{I_{dam}} \qquad (A.6)$$

where

Cin_i = average salt concentration of water flowing into the reservoir (mg/l),
RUN_{ni} = runoff flowing into the reservoir from non-irrigated lands (l),
C_{run_ni} = salt concentration of runoff from non-irrigated lands (mg/l),
RUN_{irr} = runoff from irrigated areas (l),
C_{run_irr} = salt concentration of runoff water from irrigated areas (mg/l),
RFL_{dam} = volume of rain falling on the reservoir surface (l),
C_r = rainfall salt concentration (mg/l),
RUN_{adj_dam} = runoff from adjunct impervious areas inflowing to the reservoir (l),

C_{run_adj} = salt concentration of runoff from adjunct impervious areas (mg/l), and

I_{dam} = total water inflow to the dam on the day including rain falling on surface of the reservoir (l).

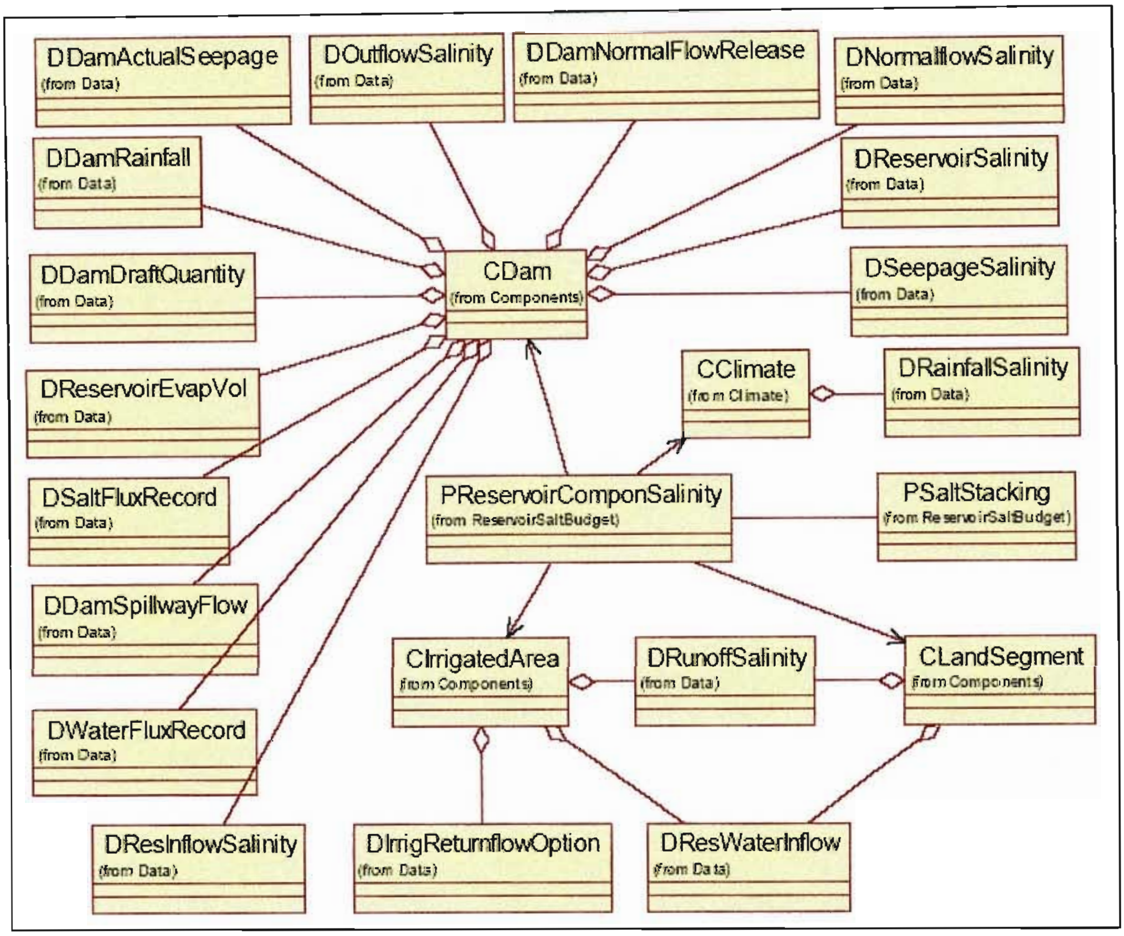

Figure A.8: Class diagram of *PReservoirComponSalinity* Process and associated data and component objects (Teweldebrhan, 2003)

The salinity level of reservoir inflows is computed for use in the reservoir salt budgeting and for predicting the average salt concentration of reservoir inflows under different combinations of hydrological, climatic and catchment conditions, including upstream land use practices. Therefore, the average TDS concentration and salt load of the total reservoir inflow are stored in the *DResInflowSalinity* and *DInflowSaltLoad* data objects respectively for use in other computations and as outputs at the end of the day.

The total outflow from the reservoir system that comprises so-called normal flow (i.e. environmental) releases, abstractions from the reservoir, spillway overflow, seepage and evaporation from reservoir surface is obtained from the total outflux record of the reservoir, as determined by the hydrological processes of *ACRU*. This record includes evaporation from the reservoir surface. However, this process assumes that evaporation losses from the reservoir system have a salt concentrating effect by leaving the salts behind. Therefore, in order to accommodate this assumption, the total water outflow from the reservoir, which influences the salt load released from the system, is reduced as described by the following equation:

Total water outflow = total water outflux record – reservoir evaporation (A.7)

One of the basic assumptions in the reservoir salt budget computations is a complete mixing of the reservoir at the end of each time step. Thus, no stratification in salt concentration is assumed to occur throughout the depth of the reservoir. The *PReservoirComponSalinty* and its relationship with the various components, data and process objects is depicted in Figure A.8.

The TDS concentration at the current storage of the reservoir is computed in the *PSaltStacking* Process based on the information sent from *PReservoirComponSalinity* Process on total inflow and outflow volumes, as well as the average salt concentration of the total inflow to the reservoir, as described by Equation A.6. The outflow components are assigned an average TDS concentration value and the corresponding salt load associated with the various outflow components is calculated as the product of the volume of water in the particular outflow component and the average outflow TDS concentration. The salinity of a reservoir's current storage and average outflow TDS concentration are accomplished by using a simplified mixing and routing procedure as employed by Herold (1980). The method is based on the assumption that complete mixing occurs within the time step and advection is described by means of a two-cell plug-flow model (Figure A.9).

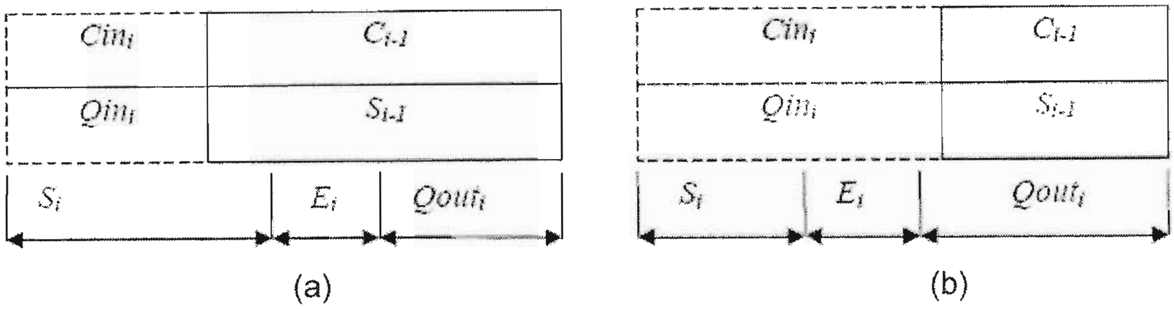

Figure A.9: Plug-flow cells for the cases (a) when outflow is less than storage and (b) when outflow is greater or equal to storage (after Herold, 1980)

The first cell contains the mixed contents of the reservoir at the end of the previous day, while the second cell comprises all the inflows to the reservoir during the day being simulated. The algorithm in the *PSaltStacking* Process considers two outcomes. The first (a in Figure A.9) arises when outflow of water from the reservoir during the current time step is less than the storage at the end of previous time step. In this outcome, the salinity of water leaving the reservoir is set equal to the reservoir salinity at the end of the previous time step (C_{i-1}) and the reservoir salinity at the end of the current time step is calculated from the mass balance expressed in Equation A.8. The mass balance comprises the addition of the total salt inflow during the current time step (Qin_i*Cin_i in Equation A.8) to the salt load left in the reservoir from the previous time, ($S_{i-1}*C_{i-1}$) after total salt outflow ($Qout_i*C_{i-1}$) divided by the total volume of water in the reservoir, S_i.

$$C_{ir} = \frac{Qin_i * Cin_i + C_{i-1} * (S_{i-1} - Qout_i)}{S_i} \qquad \text{(A.8)}$$

where

C_{ir} = reservoir salinity at the end of the current time step of simulation (mg/l),

Qin_i = all water inflow to the reservoir on the current time step (l),

Cin_i = salt concentration of inflowing water on the current time step (mg/l),

C_{i-1} = reservoir salinity at the end of the previous time step (mg/l),

S_{i-1} = volume of water stored in the reservoir at the end of the previous time step (l),

$Qout_i$ = water outflow from the reservoir for the current time step (excluding evaporation loss) (l), and

S_i = volume of water stored in the reservoir at the current time step (I).

The second case (b in the Figure A.9) arises when outflow of water from the dam is greater or equal to the storage at the end of the previous day. In this outcome, the average TDS concentration of an outflow from the reservoir ($Cout_i$) is determined by the mass balance expressed in Equation A.9 as the addition of total salt load in the reservoir on the previous day ($C_{i-1}*S_{i-1}$) to the salt load left after the outflow on the current day ($Cin_i*(Qout_i - S_{i-1})$ divided by the total volume of outflow, $Qout_i$. The reservoir salinity at the end of the day (C_i) is calculated as volume weighted concentration of total water left in the reservoir at the end of the day (Equation A.10).

$$Qout_i = \frac{C_{i-1} * S_{i-1} + Cin_i * (Qout_i - S_{i-1})}{Qout_i} \qquad (A.9)$$

$$C_i = \frac{Cin_i * (Qin_i - (Qout_i - S_{i-1}))}{S_i} \qquad (A.10)$$

Whichever is applicable of the two cases above, the average TDS concentration of the outflow is assigned to the different outflow components and the corresponding salt loads associated with the various outflow components are determined as the product of the volume of water in the particular outflow component and the average outflow salinity.

A major shortcoming of *ACRUSalinity* is that it does not account for salt transfer from the reservoir system through water abstraction or salt transfer through pumping of water out of or into the reservoir. This shortcoming is addressed in the modifications carried out in this study.

APPENDIX B New Data Objects added to *ACRU2000*

Table B1 Definitions of general data objects

Class Name	Abbreviation	Definition	Remark
DCombinedGWOption	CGWOPTION	An option to combine the groundwater from an irrigated area with that from non-irrigated area	Input
DOlufemisOption	OLUFEMI	A general switch to turn on the modifications and addition to *ACRU* and *ACRUSalinity*	Input

Table B2 Definitions of data objects that belong to non-irrigated areas

Class Name	Abbreviation	Definition	Remark
DActualSpringFlow	ASPRGFL	The amount of spring flow (in depth) which is abstracted from the groundwater storage	Internal (m)
DActualSpringFlowVol	ASPRGFLOW	The daily volume of spring flow abstracted from the groundwater storage	Input (m^3)
DBaseflowVolToMinePitDam	BFLOVMPD	The volume of groundwater that flows directly into an internal mine pit dam	Output (m^3)
DPorosity	AQPOROSITY	The porosity of the geologic material through which seepage flows into a mine-pit reservoir	Input
DRespectiveSeepToMinePitDam	SEEPFGW	The seepage from a land segment area into a mine-pit reservoir	Output (m^3)
DSeepFraction	GWFRACTN	The fraction of groundwater in a land segment that flows into a mine-pit reservoir located in it	Input
DSeepFromSameLandSegToMineDam	SEEPSAMELS	Volume of seepage from the groundwater of a land segment into a mine-pit reservoir located in it	Output (m^3)

Table B2 Continued

Class Name	Abbreviation	Definition	Remark
DSeepToMinePitDam	SEEPTOPIT	Total seepage from groundwater into a mine-pit reservoir	Output (m^3)
DSeepToMinePitDamCoeff	SEEPPITCOEF	A coefficient of groundwater seepage into a mine-pit reservoir	Input
DSpringFlow	SPRGFLOW	The observed daily spring flow	Input (m^3)
DSpringFlowOption	SPRGFLOPTION	The option to include spring flow simulation	Input
DSurfToURSeepOption	SURTOUROPTION	The option whether to include direct seepage form a surface reservoir into an underground reservoir	Input
DUpperNetLandSegArea	UPAREADAM	The area of part of a land segment whose runoff flows directly into an internal reservoir	Internal (m^2)
DURLeakage	LEAKAGE	Leakage into underground reservoir from non- irrigated area	Output (m^3)

Table B3 Definitions of data objects that belong to irrigated areas

Class Name	Abbreviation	Definition	Remark
DActualIrrigVol	F_APIRVOL	The volume of actual irrigation water applied	Output (m^3)
DActualSpringFlow	ASPRGFL	The amount of spring flow (in depth) which is abstracted from the groundwater storage	Internal (m)
DActualSpringFlowVol	ASPRGFLOW	The daily volume of spring flow abstracted from the groundwater storage	Input (m^3)
DCoefBaseflowResp	IRRCOFRU	The coefficient of baseflow response for an irrigated area	Input
DDepth	IRDEPSS	The soil surface layer depth in the irrigated area	Input (m)

Table B3 Continued

Class Name	Abbreviation	Definition	Remark
DEvapoTranspiration	AETSS	The total evaporation from the soil surface layer of an irrigated area	Output (mm)
DFieldCapacity	IRFCSS	The soil water content at drained upper limit for the soil surface layer in the irrigated area	Input ($m.m^{-1}$)
DPorosity	IRPOSS	The soil water content at saturation for the soil surface layer of an irrigated area	Input ($m.m^{-1}$)
DRespectiveSeepToMinePitDam	SEEPFGW	The seepage from an irrigated area into a mine-pit reservoir	Output (m^3)
DSeepFromSameLandSegToMineDam	SEEPSAMELS	The volume of seepage from the groundwater of a land segment into a mine-pit reservoir located in it	Output (m^3)
DSoilLayerResponse	IRSARESP	The fraction of soil water in the soil surface layer of an irrigated area above the drained upper limit to be redistributed daily from the surface layer into the topsoil.	Input
DSoilWaterEvaporation	ASSEV	The amount of evaporation from the surface layer of an irrigated area	Output (mm)
DSaturatedFlow	SURS	The saturated water flow form the soil surface layer of the irrigated area	Output (m)
DURLeakage	LEAKAGE	Leakage into underground reservoir from the irrigated area	Output (m^3)
DWaterFluxRecord	IRSMSINI	The initial value of soil water content in the soil surface layer of an irrigated area	Input (m)
DWiltingPoint	IRWPSS	The soil water content at the permanent wilting point for the surface layer of an irrigated area	Input ($m.m^{-1}$)

Table B4 Definitions of data objects that belong to surface reservoir component

Class Name	Abbreviation	Definition	Remark
DDamControlledRelease	DAMREL	The volume of controlled realise form a surface reservoir	Input (m^3)
DDamSeepageOlufemi	SEEPTOUR	The amount of direct seepage form a surface reservoir into an underground reservoir	Input (m^3)
DDepthCapillaryFringe	CAPDEPTH	The depth of the capillary fringe below the bottom of a surface reservoir	Input (m)
DDirectFlowToInternalDam	DFLOINTDAM	The runoff which flows directly into a surface reservoir from its catchment area	Output (m^3)
DDischargeToDam	DTDAM	The discharge from groundwater into a surface reservoir	Output (m^3)
DHydraulicConductivity	HYDRAULICOND	The hydraulic conductivity of the geologic material through which seepage flows into a mine-pit reservoir	Input (m/day)
DHydraulicGradient	HYDRAULIGRAD	The hydraulic gradient of the geologic material through which seepage flows into a mine-pit reservoir	Input
DHydraulicImpedance	HYDIMP	The hydraulic impedance of the geologic material through which seepage flows from a surface reservoir into groundwater	Input (day^{-1})
DMineDamDraftQuantity	MDRAFT	The daily amount of water abstracted from a surface reservoir	Input (m^3)
DMineDamPumpInQuantity1	MPUMPIN1	The volume of water pumped into a surface reservoir from a first source	Input (m^3)
DMineDamPumpInQuantity2	MPUMPIN2	The volume of water pumped into a surface reservoir from a second source	Input (m^3)
DMineDamPumpInQuantity3	MPUMPIN3	The volume of water pumped into a surface reservoir from a third source	Input (m^3)

Table B4 Continued

Class Name	Abbreviation	Definition	Remark
DMineDamPumpInQuantity4	MPUMPIN4	The volume of water pumped into a surface reservoir from a fourth source	Input (m^3)
DMineDamPumpInQuantity5	MPUMPIN5	The volume of water pumped into a surface reservoir from a fifth source	Input (m^3)
DMineDamPumpInQuantity6	MPUMPIN6	The volume of water pumped into a surface reservoir from a sixth source	Input (m^3)
DMineDamWaterTransferOption	MDWTOPTION	The option to switch on multiple water salt transfers to a surface reservoir	Input
DMinePitDamSeepLandSegList	MDSLSLIST	The list of land segment areas contributing seepage into a mine-pit reservoir	Input
DMinePitSeepageWindowLength	WINDOWLENGTH	The length of the window area through which groundwater can seep into an opencast mining pit	Input (m)
DMinePitSeepOption	MPITOPTION	The option to switch on water budgeting in a mine-pit reservoir	Input
DMineTotalPumpIn	DAMPUMPIN	The total amount of water pumped into a surface reservoir from multiple sources	Input (m^3)
DOlufemisSeepageOption	SEEPOPTION	The option to estimate seepage to groundwater based on reservoir storage volume	Input
DResTotalWaterInflow	DAMTIN	The total amount of water inflow into a surface reservoir	Output (m^3)
DResTotalWaterOutflow	DAMTOUT	The total amount of water outflow form a surface reservoir	Output (m^3)
DSurfaceReservoirDepth	SRVDEP	The depth to the bottom of a surface reservoir	Input (m)

Table B5 Definitions of data objects that belong to the underground reservoir component

Class Name	Abbreviation	Definition	Remark
DArea	URAREA	The area covered by an underground reservoir	Input (m^2)
DDamControlledRelease	URREL	The volume of controlled release from a surface reservoir	Input (m^3)
DDamFullCapacity	URCAP	The capacity of an underground reservoir	Input (m^3)
DDamSeepage	URSEEP	The seepage from an underground reservoir	Output (m^3)
DDamSpillwayFlow	URSPIL	The spillage from an underground reservoir	Output (m^3)
DHydraulicImpedance	URHYIMP	The hydraulic impedance of the geologic material through which leakage flows into an underground reservoir	Input (day^{-1})
DMineDamDraftQuantity	URDRAFT	The daily volume of water abstracted from an underground reservoir	Input (m^3)
DMineDamPumpInQuantity	URPUMPIN	The volume of water pumped into an underground reservoir	Input (m^3)
DResTotalWaterInflow	URTIN	Total water inflow into an underground reservoir	Output (m^3)
DResTotalWaterOutflow	URTOUT	Total water outflow from an underground reservoir	Output (m^3)
DUndergroundReservoirID	URID	The underground reservoir identity	Input
DUndergroundReservoirOption	URESERVOIR	The option to include simulation of an underground reservoir or not	Input
DUndergroundReservoirSeepageCoeff	URSCO	The coefficient of seepage from an underground reservoir	Input
DUndergroundResWaterDest	URWATERDEST	The destination Component of outflow form an underground reservoir	Input
DWaterFluxRecord	URSTO	The amount of water in storage in an underground reservoir	Output (m^3)

APPENDIX C New Data Objects added to *ACRUSalinity*

Table C1 Definitions of data objects that belong to non-irrigated areas

Class Name	Abbreviation	Definition	Remark
DBaseflowSaltToMinePitDam	BFLOSLMPD	The amount of salt from the groundwater that flows directly into an internal mine pit dam	Output (mg)
DMixedSaltAdded	MSALTADDED	The salt load added to the soil surface layer of a non-irrigated area after rainfall and thorough mixing of salts in a soil surface layer	Output (mg)
DPrecipitatedSaltFluxRecord	GWPRSALT	The precipitated salt in the groundwater store of a non-irrigated area	Output (mg)
DResSeepToMinePitDamSaltLoad	SEEPFGWSL	The salt load associated with seepage into a mine-pit dam from the non-irrigated area of an adjacent land segment	Output (mg)
DSeepSaltFromSameLandSeg	SEEPSAMESL	The salt load associated with the seepage, from the groundwater of a non-irrigated area in a land segment, into a mine-pit reservoir located in it	Output (mg)
DSeepToMinePitDamSaltLoad	SEEPPITSL	The total salt load associated with the seepage into a mine-pit reservoir from adjacent land segments	Output (mg)
DSoilWaterEvapSaltLoad	EVAP1SL	The salt load moved into the soil surface layer from the A-Horizon because of evaporation.	Output (mg)
DSoilWaterEvapSaltLoad	EVAP2SL	The salt load moved into the A-Horizon from the B-Horizon because of evaporation.	Output (mg)
DSpringFlowSaltLoad	ASPRGFLSL	The salt load associated with the groundwater of the non-irrigated area occurring a spring flow	Output (mg)
DURLeakageSalinity	URLSA	The salinity of the leakage into and underground reservoir from a non-irrigated area	Output (mg/l)
DURLeakageSaltLoad	LEAKAGESL	The salt load associated with water leakage from a non-irrigated area into an underground reservoir	Output (mg)
DIntialSoilSurfaceLayerPrecipSalt	TOPSINIPRSALT	The initial amount of precipitated salt in the topsoil layer of a non-irrigated area	Input (mg/g)

Table C2 Definitions of data objects that belong to irrigated areas

Class Name	Abbreviation	Definition	Remark
DIntialSoilSurfaceLayerPrecipSalt	SUBSINIPRSALT	The initial amount of precipitated salt in the subsoil layer of a non-irrigated area	Input (mg/g)
DAcruSalinityWaterContent		The water content for a pseudo water balance in the soil surface layer	Internal (m^3)
DGeneratedSaltLoad	GENSLSS	The salt load generated in the soil surface layer of an irrigated area	Output (mg)
DDissolvedPrecipitatedSalts	SSDISPRSALT	The salt dissolved from the precipitated store in the soil surface layer of an irrigated area	
DInitialSalinity	IRINISSLSA	The initial salinity of the soil surface layer in an irrigated area	Input (mg/l)
DInitialSaltLoad	INISSLSL	The initial saat load of the soil surface layer of an irrigated area	Output (mg)
DIntialSoilSurfaceLayerPrecipSalt	IRSSINIPRSALT	The initial mount of salt precipitated in the soil surface layer of an irrigated area	Output (mg/g)
DIntialSoilSurfaceLayerPrecipSalt	IRTSINIPRSALT	The initial mount of salt precipitated in the topsoil of an irrigated area	Output (mg/g)
DMixedSaltAdded	MSALTADDED	The salt load added to the soil surface layer of an irrigated area after rainfall and thorough mixing of salts in the soil surface layer	Output (mg)
DPrecipitatedSaltFluxRecord	GWPRSALT	The precipitated salt in the groundwater store of an irrigated area	Output (mg)
DPrecipitatedSaltFluxRecord	SSPRSALT	The precipitated salt in the soil surface layer of an irrigated area	Output (mg)
DPrecipitatedSaltFluxRecord	TSPRSALT	The precipitated salt in the topsoil of an irrigated area	Output (mg)
DResSeepToMinePitDamSaltLoad	SEEPFGWSL	The salt load associated with seepage into a mine-pit dam from the irrigated area of an adjacent land segment	Output (mg)
DSaltDissolutionConstant	IRSALTDISCNST	The dissolution constant based on the soil characteristics of the soil surface of an irrigated area	Input
DSaltDissolutionConstantAlpha	IRSALTDISALFA	The dissolution constant of the soil surface layer	Input

Table C2 Continued

Class Name	Abbreviation	Definition	Remark
DSaltDissolutionConstantBeta	IRSALTDISBETA	Dissolution constant of a soil surface layer	Input
DSaltFluxRecord	SSSL	The salt load associated with the soil water in the soil surface layer of an irrigated area	Output (mg)
DSaltRunoffEventContactTime	IRSALTCTIME	The runoff event contact time	Input (minutes)
DSaltSat	IRSALTSATSS	The saturation level of salt in the soil surface layer of an irrigated area	Input (mg)
DSaturatedFlowSaltConc	SURSSA	The TDS of the saturated water flow from the soil surface layer of an irrigated area	Output (mg/l)
DSaturatedFlowSaltLoad	SURSSL	The salt load associated with the saturated water flow from the soil surface layer of an irrigated area	Output (mg)
DSeepSaltFromSameLandSeg	SEEPSAMESL	The salt load associated with the seepage, from the groundwater of an irrigated area in a land segment, into a mine-pit reservoir located in it	Output (mg)
DSoilLayerSalinity	SSSA	The TDS of the soil surface layer at the end of the day	Output (mg/l)
DSoilWaterEvapSaltLoad	EVAP1SL	The salt load moved into the soil surface layer from A-Horizon of and irrigated area because of evaporation.	Output (mg)
DSpringFlowSaltLoad	ASPRGFLSL	The salt load associated with the groundwater of the irrigated area occurring a spring flow	Output (mg)
DIntialSoilSurfaceLayerPrecipSalt	IRSSINIPRSALT	The initial amount of precipitated salt in the soil surface layer of an irrigated area	Input (mg/g)
DIntialSoilSurfaceLayerPrecipSalt	IRTSINIPRSALT	The initial amount of precipitated salt in the topsoil layer of an irrigated area	Input (mg/g)
DUptakeRate	IRSALTUPTSS	The salt uptake rate of water in a soil surface layer of an irrigated area	Input
DURLeakageSaltLoad	LEAKAGESL	The salt load associated with water leakage from an irrigated area into an underground reservoir	Output (mg)

Table C3 Definitions of data objects that belong to surface reservoir component

Class Name	Abbreviation	Definition	Remark
DControlledReleaseSaltLoad	DAMRELSL	The salt load associated with the controlled release from a surface reservoir	Output (mg)
DDamDraftSalinity	DAMDFTSA	The TDS of water abstracted from a surface reservoir	Output (mg/l)
DDamDraftSaltLoad	DAMDFTSL	The salt load associated with the abstracted water from a surface reservoir	Output (mg)
DDamSpillwayFlowSalinity	DSPILLSA	The TDS of overflow water from a surface reservoir	Output (mg/l)
DDamSpillwayFlowSaltLoad	DSPILLSL	The salt load associated with the overflow water from a surface reservoir	Output (mg/l)
DDirectSaltFlowToInternalDam	DFLOINTDMSL	The salt load associated with the direct runoff into an internal surface reservoir	Output (mg)
DDischargeToDamSalinity	DTDAMSA	The TDS of water discharged into a surface reservoir from groundwater	Output (mg/l)
DDischargeToDamSaltLoad	DTDAMSL	The salt load associated with the water discharged from groundwater into a surface reservoir	Output (mg)
DMineDamPumpInSalinity1	MPUMPINSA1	The TDS of the water pumped into a surface reservoir from a first source	Input (mg/l)
DMineDamPumpInSalinity2	MPUMPINSA2	The TDS of the water pumped into a surface reservoir from a second source	Input (mg/l)
DMineDamPumpInSalinity3	MPUMPINSA3	The TDS of the water pumped into a surface reservoir from a third source	Input (mg/l)
DMineDamPumpInSalinity4	MPUMPINSA4	The TDS of the water pumped into a surface reservoir from a fourth source	Input (mg/l)
DMineDamPumpInSalinity5	MPUMPINSA5	The TDS of the water pumped into a surface reservoir from a fifth source	Input (mg/l)

Table C3 Continued

Class Name	Abbreviation	Definition	Remark
DMineDamPumpInSalinity6	MPUMPINSA6	The TDS of the water pumped into a surface reservoir from a sixth source	Input (mg/l)
DMineDamPumpInSaltLoad1	MPUMPINSL1	The salt load associated with the water pumped into a surface reservoir from the first source	Output (mg)
DMineDamPumpInSaltLoad2	MPUMPINSL2	The salt load associated with the water pumped into a surface reservoir from the second source	Output (mg)
DMineDamPumpInSaltLoad3	MPUMPINSL3	The salt load associated with the water pumped into a surface reservoir from the third source	Output (mg)
DMineDamPumpInSaltLoad4	MPUMPINSL4	The salt load associated with the water pumped into a surface reservoir from the fourth source	Output (mg)
DMineDamPumpInSaltLoad5	MPUMPINSL5	The salt load associated with the water pumped into a surface reservoir from the fifth source	Output (mg)
DMineDamPumpInSaltLoad6	MPUMPINSL6	The salt load associated with the water pumped into a surface reservoir from the sixth source	Output (mg)
DReservoirSaltUptakeOption	SUFRESSALTUPTAKE	An option to include salt uptake in the surface reservoir salt budgeting	
DSeepFromSurDamToURSaltLoad	DAMTOURSL	The salt load associated with direct seepage from a surface reservoir into an underground reservoir	Output (mg)
DTotalMineDamPumpInSaltLoad	DAMPUMPINSL	The total salt load associated with the water pumped into a reservoir from all the possible 6 sources.	Output (mg)
DUptakeRate	RESALTUPT	The salt uptake rate of water in a surface reservoir	Input (day^{-1})
DSaltSat	RESALTSAT	The salt saturation level of water in a surface reservoir if reservoir salt uptake process is switched on	Input (mg/l)

Table C4 Definitions of data objects that belong to the underground reservoir component

Class Name	Abbreviation	Definition	Remark
DAsympLimit	ASYMPLIM	The asymptotic limit of underground reservoir salinity after flooding.	Input (mg/l)
DControlledReleaseSaltLoad	URRELSL	The salt load associated with a controlled release from an underground reservoir	Output (mg/l)
DDamDraftSalinity	URDFTSA	The TDS of water abstracted from an underground reservoir	Output (mg/l)
DDamDraftSaltLoad	URDFTSL	The salt load associated with the abstracted water from an underground reservoir	Output (mg)
DDecayRate	DECAYRATE	The rate of salt decay in an underground reservoir after flooding	Input (day^{-1})
DGeneratedSaltLoad	URGENSL	The salt load generated in an underground reservoir	Output (mg)
DResInflowSalinity	URISA	The average TDS of the total inflow to an underground reservoir	Output (mg/l)
DInflowSaltLoad	URISL	The salt load associated with the total inflow to an underground reservoir	Output(mg)
DInitialSalinity	URINISA	The initial salinity of water in an underground reservoir	Input (mg/l)
DInitialSaltLoad	URINISL	The salt load of the water stored in an underground reservoir at the beginning of simulation	Output (mg)
DMineDamPumpInSalinity	URPUMPINSA	The TDS of the water pumped into an underground reservoir	Input (mg/l)
DOutflowSalinity	UROUTSA	The average TDS of the total outflow from an underground reservoir	Output (mg/l)
DOutflowSaltLoad	UROUTSL	The salt load associated with the total outflow from an underground reservoir	Output (mg)
DPumpInSaltLoad	URPUMPSL	The salt load associated with the water pumped into an underground reservoir	Output (mg)

Table C4 Continued

Class Name	Abbreviation	Definition	Remark
DReservoirSalinity	URSA	The salinity of water in an underground reservoir at the end of the day	Input (mg/l)
DSaltSat	URSALTSAT	The salt saturation level of water in an underground reservoir	Input (mg)
DSaltFluxRecord	URSTOSL	The salt load associated with the water stored in an underground reservoir	Output (mg)
DSaltStackGeneratedSaltLoad	URGENSTACK	The salt load generated in an underground reservoir as a result of stacking of salts	Output (mg)
DSeepageSalinity	URSEEPSA	The TDS of seepage from an underground reservoir	Output (mg)
DSeepageSaltLoad	URSEEPSL	The salt load associated with the seepage from an underground reservoir	Output (mg)
DSpillwayflowSalinity	URSPILSA	The TDS of overflow from an underground reservoir	Output (mg)
DSpillwayflowSaltLoad	URSPILSL	The salt load associated with the overflow from an underground reservoir	Output (mg)
DUndergroundReservoirSalinityOption	URSALINITY	An option to include simulation of underground reservoir salt budget or not.	1
DOutflowSalinity	UROUTSA	TDS of the outflow water from an underground reservoir	Output (mg/l)
DUptakeRate	URRATEC	The salt uptake rate for the water in an underground reservoir	Input

APPENDIX D Code Validation of Major Modifications to *ACRU2000* and *ACRUSalinity*

Table D1 Mass balance of the code validation of the underground reservoir water budgeting processes

Properties		Date				
		24/01/1999	25/01/1999	26/01/1999	27/01/1999	28/01/1999
Water inflow (m^3)	leakage	167.26	187.66	191.14	186.50	181.45
	seepage into	2400.00	2400.00	2400.00	2400.00	2400.00
Water outflow (m^3)	seepage from	4843.33	4835.44	4827.58	4819.74	4811.91
Previous day storage(m^3)		1383642.72	1381366.64	1379118.86	1376882.41	1374649.17
Calculated water storage (m^3)		1381366.64	1379118.86	1376882.41	1374649.17	1374649.17
Simulated water storage (m^3)		1381366.64	1379118.86	1376882.41	1374649.17	1372418.70
Error %		0.00E+00	7.25E-11	0.00E+00	-7.27E-11	7.29E-11

Table D2 Mass balance of the code validation of the underground reservoir salt budgeting processes

Properties		Date				
		24/01/1999	25/01/1999	26/01/1999	27/01/1999	28/01/1999
Salt inflow (mg)	leakage	9879563.31	11100295.70	11320683.50	11055573.59	10765128.34
	seepage into	4668840672.79	4660729429.10	4663765880.98	4666567759.40	4669150233.87
	salt uptake	415941169.34	415257756.96	414578508.72	413899408.85	413220253.06
	salt release	109196866.58	108003092.93	116129948.29	113153002.73	110428176.71
Salt outflow (mg)	seepage from	9608332367.22	9592860257.92	9577440934.38	9562072660.68	9546755229.97
Previous day salt load (mg)		2735094469239.27	2730689995144.06	2726292225460.83	2721920579547.94	2717563182631.83
Calculated salt load (mg)		2730689995144.06	2726292225460.83	2721920579547.94	2717563182631.84	2713219991193.84
Simulated salt load (mg)		2730689995144.06	2726292225460.83	2721920579547.94	2717563182631.83	2713219991193.85
Error %		-1.79E-14	5.37E-14	3.59E-14	-2.34E-13	2.16E-13

Table D3 Mass balance of the code validation for the mine-pit reservoir water budgeting processes

Properties		Date				
		08/04/1999	09/04/1999	10/04/1999	11/04/1999	12/04/1999
Water inflow (m^3)	rainfall	1418.88	0.00	0.00	0.00	0.00
	seepage*	0.00	0.00	0.00	0.00	0.00
	pump in	0.00	0.00	0.00	0.00	0.00
	direct inflow	716.50	804.33	813.37	780.44	729.35
	seepage**	10174.25	10306.94	9891.63	9244.06	8512.72
Water outflow (m^3)	evaporation	500.76	524.55	509.32	493.67	529.33
	abstraction	0.00	0.00	0.00	0.00	0.00
Previous day storage(m^3)		265830.39	277639.26	288225.99	298421.66	307952.49
Calculated water storage (m^3)		277639.26	288225.99	298421.66	307952.49	316665.22
Simulated water storage (m^3)		277639.26	288225.99	298421.66	307952.49	316665.22
Error %		0.00E+00	0.00E+00	-3.35E-10	-3.25E-10	0.00E+00

Table D4 Mass balance of the code validation for the mine-pit reservoir salt budgeting processes

Properties		Date				
		08/04/1999	09/04/1999	10/04/1999	11/04/1999	12/04/1999
Salt inflow (mg)	rainfall	36890880.00	0.00	0.00	0.00	0.00
	Seepage*	0.01	0.02	0.02	0.02	0.02
	pump in	0.00	0.00	0.00	0.00	0.00
	direct inflow	200758875.94	229671237.54	234273947.29	226904241.30	214255169.46
	seepage**	2899379420.11	2947486295.87	2849509709.53	2687610039.81	2500723670.08
Salt outflow (mg)	abstraction	0.00	0.00	0.00	0.00	0.00
Previous day salt (mg)		150838688056.19	153975717232.26	157152874765.69	160236658422.53	163151172703.65
Calculated salt load (mg)		153975717232.26	157152874765.69	160236658422.53	163151172703.65	165866151543.21
Simulated salt load (mg)		153975717232.26	157152874765.69	160236658422.53	163151172703.65	165866151543.21
Error %		3.57E-13	-2.33E-13	-7.62E-14	2.06E-13	-9.20E-14

seepage*: seepage from the adjacent land segment areas
seepage**: seepage from the rehabilitated areas of the same land segment in which the mine-pit reservoir is located.

Table D5 Mass balance of the code validation for surface reservoir water budgeting processes

Properties		Date				
		24/01/1999	25/01/1999	26/01/1999	27/01/1999	28/01/1999
Water inflow (m^3)	rainfall	9256.64	0.00	0.00	0.00	0.00
	pump in	3884.44	3831.93	3847.72	3875.18	3849.40
	non-irrigated	414.37	329.00	322.88	313.76	305.27
	irrigated	0.00	0.00	0.00	0.00	0.00
	spring flow	30.00	30.00	30.00	30.00	30.00
Water outflow (m^3)	irrigation	0.00	0.00	0.00	0.00	40.00
	seepage	2400.00	2400.00	2400.00	2400.00	2400.00
	evaporation	3463.12	3510.13	3310.98	3124.17	3269.41
Previous day storage(m^3)		3877048.40	3884740.74	3882991.54	3881451.17	3880115.95
Calculated water storage (m^3)		3884770.74	3883021.55	3881481.17	3880145.95	3878591.21
Simulated water storage (m^3)		3884770.74	3882991.54	3881481.17	3880145.95	3878591.21
Error %		7.72E-04	7.73E-04	7.73E-04	7.73E-04	7.73E-04

Table D6 Mass balance of the code validation for surface reservoir salt budgeting processes

Properties		Date				
		24/01/1999	25/01/1999	26/01/1999	27/01/1999	28/01/1999
Salt inflow (mg)	rainfall	240672640.00	0.00	0.00	0.00	0.00
	spring flow	1772056.02	1774556.38	1776851.86	1776851.86	1778415.18
	pump in	6239970525.14	6155617897.29	6180985168.52	6225095286.84	6183677988.08
	non-irrigated	21520833.65	19164449.36	19093989.93	18599725.60	18111868.82
	irrigated	0.00	0.00	0.00	0.00	0.00
Salt outflow (mg)	irrigation	0.00	0.00	0.00	0.00	77819170.56
	seepage	4668840672.79	4660729429.10	4663765880.98	4666567759.40	4669150233.87
Previous day salt (mg)		7542217195295.89	7544052290677.93	7545568118151.86	7547106208281.19	7547106208281.19
Calculated salt load (mg)		7544052290677.92	7545568118151.87	7547106208281.19	7548685113949.41	7550141714299.27
Simulated salt load (mg)		7544052290677.93	7545568118151.86	7547106208281.19	7548685113949.42	7550141714299.27
Error %		-1.29E-13	6.47E-14	3.88E-14	-1.03E-13	6.47E-14

Table D7 Mass balance of code validation of the subsurface salt movement in the soil horizons of the non-irrigated area

Components	Date	Previous Salt (mg)	Salt Input (mg)	Generated Salt (mg)	Moved Salt (mg)	Drained Salt (mg)	Diss Salt (mg)	Precp Salt (mg)	Calculated Salt Load (mg)	Simulated Salt Load (mg)	Error (%)
Surface Layer	1999/01/24	2110032694.11	493151360.00	0.00	524171317.09	192729282.51	0.00	0.00	2934626088.69	2934626088.69	-4.9E-14
	1999/01/25	2934626088.69	0.00	0.00	25407639.62	0.00	0.00	0.00	2960033728.31	2960033728.31	3.2E-14
	1999/01/26	2960033728.31	0.00	0.00	434341559.77	0.00	0.00	0.00	3394375288.08	3394375288.08	-2.8E-14
	1999/01/27	3394375288.08	0.00	0.00	434079938.48	0.00	0.00	0.00	3828455226.55	3828455226.55	-1.1E-13
	1999/01/28	3828455226.55	0.00	0.00	405530493.57	0.00	0.00	0.00	4233985720.13	4233985720.13	-6.8E-14
Topsoil	1999/01/24	9385240416.28	192729282.51	857664.82	0.00	138550163.04	0.00	0.00	8916105883.48	8916105883.48	-4.3E-14
	1999/01/25	8916105883.48	0.00	810081.55	0.00	0.00	0.00	0.00	8891508325.41	8891508325.41	2.1E-14
	1999/01/26	8891508325.41	0.00	733006.22	0.00	0.00	0.00	0.00	8457899771.87	8457899771.87	5.6E-14
	1999/01/27	8457899771.87	0.00	659803.32	0.00	0.00	0.00	0.00	8024479636.71	8024479636.71	1.2E-14
	1999/01/28	8024479636.71	0.00	590292.77	0.00	0.00	0.00	0.00	7619539435.91	7619539435.91	-1.0E-13
Subsoil	1999/01/24	7167215120.20	138550163.04	612210.89	0.00	350195968.13	0.00	0.00	6956181526.00	6956181526.00	9.6E-14
	1999/01/25	6956181526.00	0.00	579379.05	0.00	155462699.72	0.00	0.00	6801298205.34	6801298205.34	-1.4E-14
	1999/01/26	6801298205.34	0.00	562313.91	0.00	53696553.36	0.00	0.00	6748163965.90	6748163965.90	-8.5E-14
	1999/01/27	6748163965.90	0.00	553936.81	0.00	3342563.31	0.00	0.00	6745375339.40	6745375339.40	9.9E-14
	1999/01/28	6745375339.40	0.00	549503.12	0.00	0.00	0.00	0.00	6745924842.52	6745924842.52	1.4E-14

Table D8 Mass balance for code validation of subsurface salt movement processes in the groundwater of the non-irrigated area

Properties		Date				
		1999/01/24	1999/01/25	1999/01/26	1999/01/27	1999/01/28
Salt inflow (mg)	drainage	350195968.13	155462699.72	53696553.36	3342563.31	0.00
	generated	869111.50	974924.02	992952.59	968873.38	942665.47
Salt ouflow (mg)	baseflow	16624196.75	18674785.67	19045023.56	18599725.60	18111868.82
	leakage	9879563.31	11100295.70	11320683.50	11055573.59	10765128.34
	seepage	0.01	0.02	0.02	0.02	0.02
	spring	1772056.02	1774556.38	1776851.86	1778415.18	1779897.39
Previous day salt (mg)		687947217.06	1010736480.60	1135624466.58	1158171413.59	1131049135.89
Calculated salt load (mg)		1010736480.60	1135624466.58	1158171413.59	1131049135.89	1101334906.79
Simulated salt load (mg)		1010736480.60	1135624466.58	1158171413.59	1131049135.89	1101334906.79
Error %		7.90E-13	-6.09E-13	4.94E-13	1.90E-13	0.00E+00

Table D9 Mass balance of code validation of the subsurface salt movement in the soil horizons of the irrigated area

Components	Date	Previous Salt (mg)	Salt Input (mg)	Generated Salt (mg)	Moved Salt (mg)	Drained Salt (mg)	Diss. Salt (mg)	Precp. Salt (mg)	Calculated Salt Load (mg)	Simulated Salt Load (mg)	Error (%)
Surface Layer	1999/01/24	421737753.69	291752327.63	424027.99	35596487.23	89594226.92	0.00	0.00	659916369.62	659916369.62	1.3E-13
	1999/01/25	659916369.62	0.00	337413.41	35653741.54	71114144.50	0.00	0.00	624793380.08	624793380.08	0.0E+00
	1999/01/26	624793380.08	0.00	302264.32	35692434.00	31379031.25	0.00	0.00	629409047.15	629409047.15	-1.7E-13
	1999/01/27	629409047.15	0.00	287256.62	35691316.23	13623693.65	0.00	0.00	651763926.35	651763926.35	3.7E-14
	1999/01/28	651763926.35	0.00	280727.66	35672405.32	5672630.01	0.00	0.00	682044429.32	682044429.32	-1.7E-14
Topsoil	1999/01/24	35596487232.77	89594226.92	3256566.68	0.00	0.00	0.00	0.00	35653741539.14	35653741539.14	-4.3E-14
	1999/01/25	35653741539.14	71114144.50	3232053.63	0.00	0.00	0.00	0.00	35692433995.73	35692433995.73	-4.3E-14
	1999/01/26	35692433995.73	31379031.25	3195633.46	0.00	0.00	0.00	0.00	35691316226.44	35691316226.44	8.6E-14
	1999/01/27	35691316226.44	13623693.65	3156719.00	0.00	0.00	0.00	0.00	35672405322.86	35672405322.86	-1.1E-13
	1999/01/28	35672405322.86	5672630.01	3119446.53	0.00	0.00	0.00	0.00	35645524994.07	35645524994.07	0.0E+00

APPENDIX E Observed Daily Runoff Volume and Salinity from the Tweefontein and Syferfontein Pivots

Table E1: Observed daily runoff volume from the Tweefontein pivot

Date	Runoff (m^3)	Date	Runoff (m^3)	Date	Runoff (m^3)	Date	Runoff (m^3)	Date	Runoff (m^3)	Runoff (m^3)	Runoff (m^3)	Runoff (m^3)	Runoff (m^3)
03/04/08	0.0	03/05/28	0.0	03/07/17	0.0	03/09/05	0.0	03/10/25	0.0	03/12/14	0.0	04/02/02	0.0
03/04/09	0.0	03/05/29	0.0	03/07/18	0.0	03/09/06	0.0	03/10/26	0.0	03/12/15	0.0	04/02/03	0.0
03/04/10	0.0	03/05/30	0.0	03/07/19	0.0	03/09/07	0.0	03/10/27	0.0	03/12/16	0.0	04/02/04	0.0
03/04/11	0.0	03/05/31	0.0	03/07/20	0.0	03/09/08	M	03/10/28	0.0	03/12/17	0.0	04/02/05	0.0
03/04/12	391.3	03/06/01	0.0	03/07/21	0.0	03/09/09	M	03/10/29	0.0	03/12/18	0.0	04/02/06	0.0
03/04/13	42.5	03/06/02	0.0	03/07/22	0.0	03/09/10	M	03/10/30	0.0	03/12/19	0.0	04/02/07	0.0
03/04/14	0.0	03/06/03	0.0	03/07/23	0.0	03/09/11	M	03/10/31	0.0	03/12/20	0.0	04/02/08	0.0
03/04/15	0.0	03/06/04	0.0	03/07/24	0.0	03/09/12	M	03/11/01	0.0	03/12/21	0.0	04/02/09	0.0
03/04/16	0.0	03/06/05	0.0	03/07/25	0.0	03/09/13	M	03/11/02	0.0	03/12/22	0.0	04/02/10	0.0
03/04/17	0.0	03/06/06	0.0	03/07/26	0.0	03/09/14	M	03/11/03	0.0	03/12/23	0.0	04/02/11	0.0
03/04/18	0.0	03/06/07	0.0	03/07/27	0.0	03/09/15	M	03/11/04	0.0	03/12/24	0.0	04/02/12	0.0
03/04/19	0.0	03/06/08	0.0	03/07/28	0.0	03/09/16	M	03/11/05	0.0	03/12/25	0.0	04/02/13	0.0
03/04/20	0.0	03/06/09	0.0	03/07/29	0.0	03/09/17	M	03/11/06	0.0	03/12/26	0.0	04/02/14	0.0
03/04/21	0.0	03/06/10	0.0	03/07/30	0.0	03/09/18	M	03/11/07	0.0	03/12/27	0.0	04/02/15	0.0
03/04/22	0.0	03/06/11	0.0	03/07/31	0.0	03/09/19	M	03/11/08	0.0	03/12/28	0.0	04/02/16	0.0
03/04/23	0.0	03/06/12	0.0	03/08/01	0.0	03/09/20	M	03/11/09	0.0	03/12/29	0.0	04/02/17	0.0
03/04/24	0.0	03/06/13	0.0	03/08/02	0.0	03/09/21	M	03/11/10	0.0	03/12/30	0.0	04/02/18	0.0
03/04/25	0.0	03/06/14	0.0	03/08/03	0.0	03/09/22	M	03/11/11	0.0	03/12/31	0.0	04/02/19	0.0
03/04/26	0.0	03/06/15	0.0	03/08/04	0.0	03/09/23	M	03/11/12	0.0	04/01/01	306.9	04/02/20	0.0
03/04/27	0.0	03/06/16	0.0	03/08/05	0.0	03/09/24	M	03/11/13	0.0	04/01/02	930.6	04/02/21	0.0
03/04/28	0.0	03/06/17	0.0	03/08/06	0.0	03/09/25	M	03/11/14	0.0	04/01/03	0.0	04/02/22	0.0
03/04/29	0.0	03/06/18	0.0	03/08/07	0.0	03/09/26	M	03/11/15	0.0	04/01/04	0.0	04/02/23	0.0
03/04/30	0.0	03/06/19	0.0	03/08/08	0.0	03/09/27	M	03/11/16	0.0	04/01/05	0.0	04/02/24	0.0
03/05/01	0.0	03/06/20	0.0	03/08/09	0.0	03/09/28	M	03/11/17	0.0	04/01/06	0.0	04/02/25	0.0
03/05/02	0.0	03/06/21	0.0	03/08/10	0.0	03/09/29	M	03/11/18	0.0	04/01/07	0.0	04/02/26	0.0
03/05/03	0.0	03/06/22	0.0	03/08/11	0.0	03/09/30	M	03/11/19	0.0	04/01/08	0.0	04/02/27	0.0
03/05/04	0.0	03/06/23	0.0	03/08/12	0.0	03/10/01	0.0	03/11/20	0.0	04/01/09	0.0	04/02/28	0.0
03/05/05	0.0	03/06/24	0.0	03/08/13	0.0	03/10/02	0.0	03/11/21	0.0	04/01/10	0.0	04/02/29	0.0
03/05/06	0.0	03/06/25	0.0	03/08/14	0.0	03/10/03	0.0	03/11/22	0.0	04/01/11	0.0	04/03/01	744.3
03/05/07	0.0	03/06/26	0.0	03/08/15	0.0	03/10/04	0.0	03/11/23	0.0	04/01/12	0.0	04/03/02	0.5
03/05/08	0.0	03/06/27	0.0	03/08/16	0.0	03/10/05	0.0	03/11/24	0.0	04/01/13	0.0	04/03/03	0.0
03/05/09	0.0	03/06/28	0.0	03/08/17	0.0	03/10/06	M	03/11/25	0.0	04/01/14	0.0	04/03/04	0.0
03/05/10	0.0	03/06/29	0.0	03/08/18	M	03/10/07	M	03/11/26	0.0	04/01/15	0.0	04/03/05	0.0
03/05/11	0.0	03/06/30	0.0	03/08/19	M	03/10/08	M	03/11/27	0.0	04/01/16	0.0	04/03/06	585.1
03/05/12	0.0	03/07/01	0.0	03/08/20	0.0	03/10/09	M	03/11/28	0.0	04/01/17	0.0	04/03/07	11.8
03/05/13	0.0	03/07/02	0.0	03/08/21	0.0	03/10/10	M	03/11/29	0.0	04/01/18	0.0	04/03/08	0.0
03/05/14	0.0	03/07/03	0.0	03/08/22	0.0	03/10/11	M	03/11/30	0.0	04/01/19	3309.3	04/03/09	0.0
03/05/15	0.0	03/07/04	0.0	03/08/23	0.0	03/10/12	M	03/12/01	0.0	04/01/20	1788.3	04/03/10	0.0
03/05/16	0.0	03/07/05	0.0	03/08/24	0.0	03/10/13	M	03/12/02	0.0	04/01/21	859.5	04/03/11	0.0
03/05/17	0.0	03/07/06	0.0	03/08/25	0.0	03/10/14	M	03/12/03	0.0	04/01/22	0.0	04/03/12	0.0
03/05/18	0.0	03/07/07	0.0	03/08/26	0.0	03/10/15	M	03/12/04	0.0	04/01/23	0.0	04/03/13	339.4
03/05/19	0.0	03/07/08	0.0	03/08/27	0.0	03/10/16	M	03/12/05	0.0	04/01/24	0.0	04/03/14	40.0
03/05/20	0.0	03/07/09	0.0	03/08/28	0.0	03/10/17	0.0	03/12/06	0.0	04/01/25	0.0	04/03/15	0.0
03/05/21	0.0	03/07/10	0.0	03/08/29	0.0	03/10/18	0.0	03/12/07	0.0	04/01/26	0.0	04/03/16	0.0
03/05/22	0.0	03/07/11	0.0	03/08/30	0.0	03/10/19	0.0	03/12/08	0.0	04/01/27	0.0	04/03/17	0.0
03/05/23	0.0	03/07/12	0.0	03/08/31	0.0	03/10/20	0.0	03/12/09	0.0	04/01/28	0.0	04/03/18	0.0
03/05/24	0.0	03/07/13	0.0	03/09/01	0.0	03/10/21	0.0	03/12/10	0.0	04/01/29	0.0	04/03/19	0.0
03/05/25	0.0	03/07/14	0.0	03/09/02	0.0	03/10/22	0.0	03/12/11	0.0	04/01/30	0.0	04/03/20	0.0
03/05/26	0.0	03/07/15	0.0	03/09/03	0.0	03/10/23	0.0	03/12/12	0.0	04/01/31	0.0	04/03/21	0.0
03/05/27	0.0	03/07/16	0.0	03/09/04	0.0	03/10/24	0.0	03/12/13	0.0	04/02/01	0.0	04/03/22	0.0

M – Missing data

Table E2: Observed daily salinity of runoff from the Tweefontein pivot

Date	Salinity (mg/l)
04/01/01	512.0
04/01/19	113.3
04/01/20	165.4
04/01/21	176.7
04/03/01	44.2
04/03/13	141.9

Table E3: Observed daily runoff volume for the Syferfontein pivot

Date	Runoff (m^3)	Date	Runoff (m^3)	Date	Runoff (m^3)	Date	Runoff (m^3)	Date	Runoff (m^3)	Runoff (m^3)	Runoff (m^3)	Runoff (m^3)	Runoff (m^3)
03/05/21	0.0	03/07/10	0.0	03/08/29	0.0	03/10/18	0.0	03/12/07	0.0	04/01/26	0.0	04/03/16	86.4
03/05/22	0.0	03/07/11	0.0	03/08/30	0.0	03/10/19	0.0	03/12/08	0.0	04/01/27	0.0	04/03/17	24.4
03/05/23	0.0	03/07/12	0.0	03/08/31	0.0	03/10/20	0.0	03/12/09	0.0	04/01/28	0.0	04/03/18	0.0
03/05/24	0.0	03/07/13	0.0	03/09/01	0.0	03/10/21	0.0	03/12/10	0.0	04/01/29	0.0	04/03/19	0.0
03/05/25	0.0	03/07/14	0.0	03/09/02	0.0	03/10/22	0.0	03/12/11	0.0	04/01/30	M	04/03/20	0.4
03/05/26	0.0	03/07/15	0.0	03/09/03	0.0	03/10/23	0.0	03/12/12	0.0	04/01/31	M	04/03/21	M
03/05/27	0.0	03/07/16	0.0	03/09/04	0.0	03/10/24	0.0	03/12/13	0.0	04/02/01	M	04/03/22	M
03/05/28	0.0	03/07/17	0.0	03/09/05	0.0	03/10/25	0.0	03/12/14	0.0	04/02/02	M	04/03/23	M
03/05/29	0.0	03/07/18	0.0	03/09/06	0.0	03/10/26	0.0	03/12/15	0.0	04/02/03	M	04/03/24	M
03/05/30	0.0	03/07/19	0.0	03/09/07	0.0	03/10/27	0.0	03/12/16	0.0	04/02/04	M	04/03/25	M
03/05/31	0.0	03/07/20	0.0	03/09/08	0.0	03/10/28	0.0	03/12/17	0.0	04/02/05	M	04/03/26	M
03/06/01	0.0	03/07/21	28.8	03/09/09	0.0	03/10/29	0.0	03/12/18	0.0	04/02/06	M	04/03/27	M
03/06/02	0.0	03/07/22	42.3	03/09/10	524.7	03/10/30	0.0	03/12/19	0.0	04/02/07	M	04/03/28	M
03/06/03	0.0	03/07/23	42.3	03/09/11	974.7	03/10/31	0.0	03/12/20	M	04/02/08	M	04/03/29	M
03/06/04	0.0	03/07/24	46.8	03/09/12	917.1	03/11/01	0.0	03/12/21	M	04/02/09	M	04/03/30	M
03/06/05	0.0	03/07/25	72.9	03/09/13	851.4	03/11/02	0.0	03/12/22	130.7	04/02/10	M	04/03/31	M
03/06/06	0.0	03/07/26	80.1	03/09/14	477.9	03/11/03	0.0	03/12/23	88.0	04/02/11	M	04/04/01	M
03/06/07	0.0	03/07/27	79.2	03/09/15	M	03/11/04	0.0	03/12/24	0.0	04/02/12	M	04/04/02	1.9
03/06/08	0.0	03/07/28	72.0	03/09/16	M	03/11/05	0.0	03/12/25	0.0	04/02/13	29.0	04/04/03	M
03/06/09	0.0	03/07/29	0.0	03/09/17	M	03/11/06	0.0	03/12/26	130.4	04/02/14	184.8	04/04/04	M
03/06/10	0.0	03/07/30	0.0	03/09/18	M	03/11/07	0.0	03/12/27	0.0	04/02/15	895.3	04/04/05	M
03/06/11	0.0	03/07/31	0.0	03/09/19	M	03/11/08	0.0	03/12/28	0.0	04/02/16	331.7	04/04/06	M
03/06/12	0.0	03/08/01	0.0	03/09/20	M	03/11/09	0.0	03/12/29	0.0	04/02/17	404.2	04/04/07	M
03/06/13	0.0	03/08/02	0.0	03/09/21	M	03/11/10	0.0	03/12/30	0.0	04/02/18	1359.5	04/04/08	M
03/06/14	0.0	03/08/03	0.0	03/09/22	M	03/11/11	0.0	03/12/31	M	04/02/19	0.0	04/04/09	M
03/06/15	0.0	03/08/04	0.0	03/09/23	M	03/11/12	0.0	04/01/01	M	04/02/20	0.0	04/04/10	M
03/06/16	0.0	03/08/05	36.9	03/09/24	M	03/11/13	0.0	04/01/02	M	04/02/21	0.0	04/04/11	M
03/06/17	0.0	03/08/06	258.3	03/09/25	M	03/11/14	M	04/01/03	29.6	04/02/22	0.0	04/04/12	M
03/06/18	0.0	03/08/07	192.6	03/09/26	M	03/11/15	M	04/01/04	3616.1	04/02/23	181.6	04/04/13	M
03/06/19	0.0	03/08/08	25.2	03/09/27	M	03/11/16	M	04/01/05	559.3	04/02/24	4724.2	04/04/14	M
03/06/20	0.0	03/08/09	0.0	03/09/28	M	03/11/17	M	04/01/06	86.4	04/02/25	2405.8	04/04/15	M
03/06/21	0.0	03/08/10	0.0	03/09/29	0.0	03/11/18	M	04/01/07	86.4	04/02/26	400.1	04/04/16	M
03/06/22	0.0	03/08/11	0.0	03/09/30	0.0	03/11/19	M	04/01/08	26.8	04/02/27	60.4	04/04/17	M
03/06/23	0.0	03/08/12	0.0	03/10/01	0.0	03/11/20	M	04/01/09	0.0	04/02/28	0.0	04/04/18	M
03/06/24	0.0	03/08/13	0.0	03/10/02	0.0	03/11/21	M	04/01/10	0.0	04/02/29	0.0	04/04/19	M
03/06/25	0.0	03/08/14	0.0	03/10/03	0.0	03/11/22	M	04/01/11	0.0	04/03/01	0.0	04/04/20	97.6
03/06/26	0.0	03/08/15	0.0	03/10/04	0.0	03/11/23	M	04/01/12	0.0	04/03/02	0.0	04/04/21	0.0
03/06/27	0.0	03/08/16	0.0	03/10/05	0.0	03/11/24	M	04/01/13	0.0	04/03/03	M	04/04/22	0.0
03/06/28	0.0	03/08/17	0.0	03/10/06	0.0	03/11/25	M0.0	04/01/14	0.0	04/03/04	M	04/04/23	0.0
03/06/29	0.0	03/08/18	0.0	03/10/07	0.0	03/11/26	0.0	04/01/15	0.0	04/03/05	M	04/04/24	0.0
03/06/30	0.0	03/08/19	0.0	03/10/08	0.0	03/11/27	142.2	04/01/16	0.0	04/03/06	M	04/04/25	0.0
03/07/01	0.0	03/08/20	0.0	03/10/09	0.0	03/11/28	0.0	04/01/17	M	04/03/07	M	04/04/26	0.0
03/07/02	0.0	03/08/21	0.0	03/10/10	0.0	03/11/29	0.0	04/01/18	M	04/03/08	0.0	04/04/27	0.0
03/07/03	0.0	03/08/22	0.0	03/10/11	0.0	03/11/30	0.0	04/01/19	M	04/03/09	0.0	04/04/28	0.0
03/07/04	0.0	03/08/23	0.0	03/10/12	0.0	03/12/01	0.0	04/01/20	M	04/03/10	0.0	04/03/16	86.4
03/07/05	0.0	03/08/24	0.0	03/10/13	0.0	03/12/02	0.0	04/01/21	M	04/03/11	0.0	04/03/17	24.4
03/07/06	0.0	03/08/25	0.0	03/10/14	0.0	03/12/03	0.0	04/01/22	1074.6	04/03/12	74.0	04/03/18	0.0
03/07/07	0.0	03/08/26	0.0	03/10/15	0.0	03/12/04	0.0	04/01/23	761.5	04/03/13	2340.1	04/03/19	0.0
03/07/08	0.0	03/08/27	0.0	03/10/16	0.0	03/12/05	0.0	04/01/24	0.0	04/03/14	457.9	04/03/20	0.4
03/07/09	0.0	03/08/28	0.0	03/10/17	0.0	03/12/06	0.0	04/01/25	0.0	04/03/15	115.9	04/03/21	M

M – Missing data

Table E4: Observed daily salinity of runoff from the Syferfontein pivot

Date	Salinity (mg/l)	Date	Salinity (mg/l)
03/07/23	3168.0	04/01/04	397.1
03/07/25	3219.2	04/01/22	247.5
03/07/27	3411.2	04/02/13	185.6
03/08/05	3436.8	04/02/14	203.0
03/08/06	3155.2	04/02/15	234.7
03/08/07	3280.0	04/02/17	148.8
03/11/27	684.8	04/02/18	156.3
03/12/22	332.8	04/03/12	275.2
03/12/23	444.8	04/03/13	176.0
03/12/26	565.8	04/04/20	881.6
04/01/03	422.4		

APPENDIX F Centre Pivots and Borehole Lithologic Logs

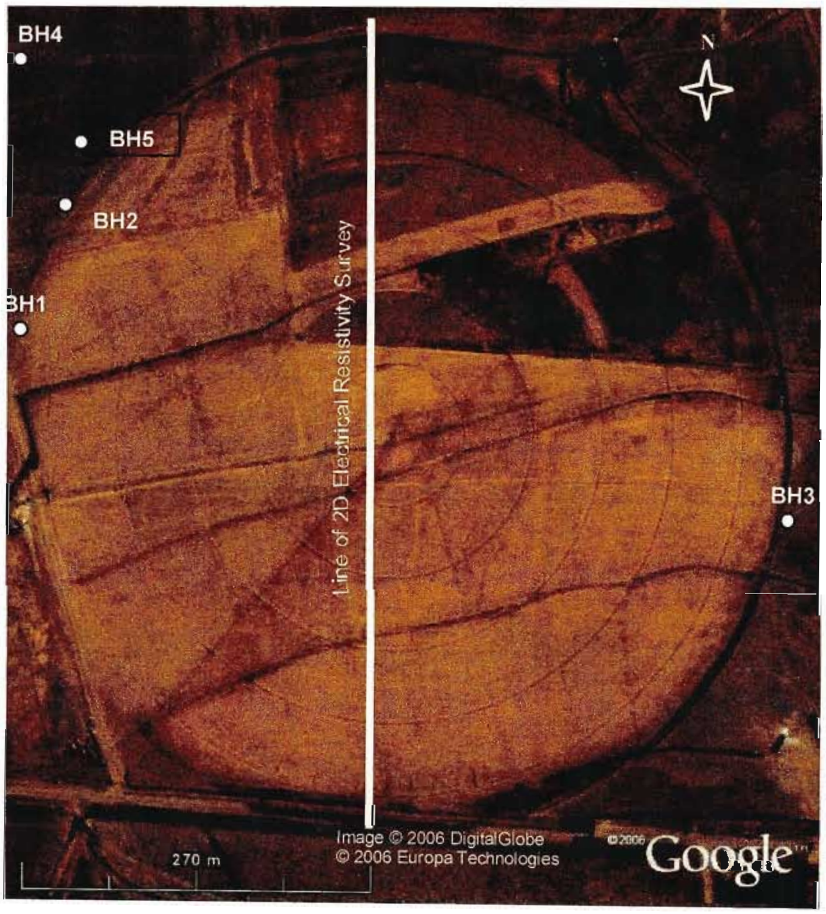

Figure F1: Aerial photograph of the Syferfontein pivot (Google, 2006) showing the transect of 2D electrical resistivity survey

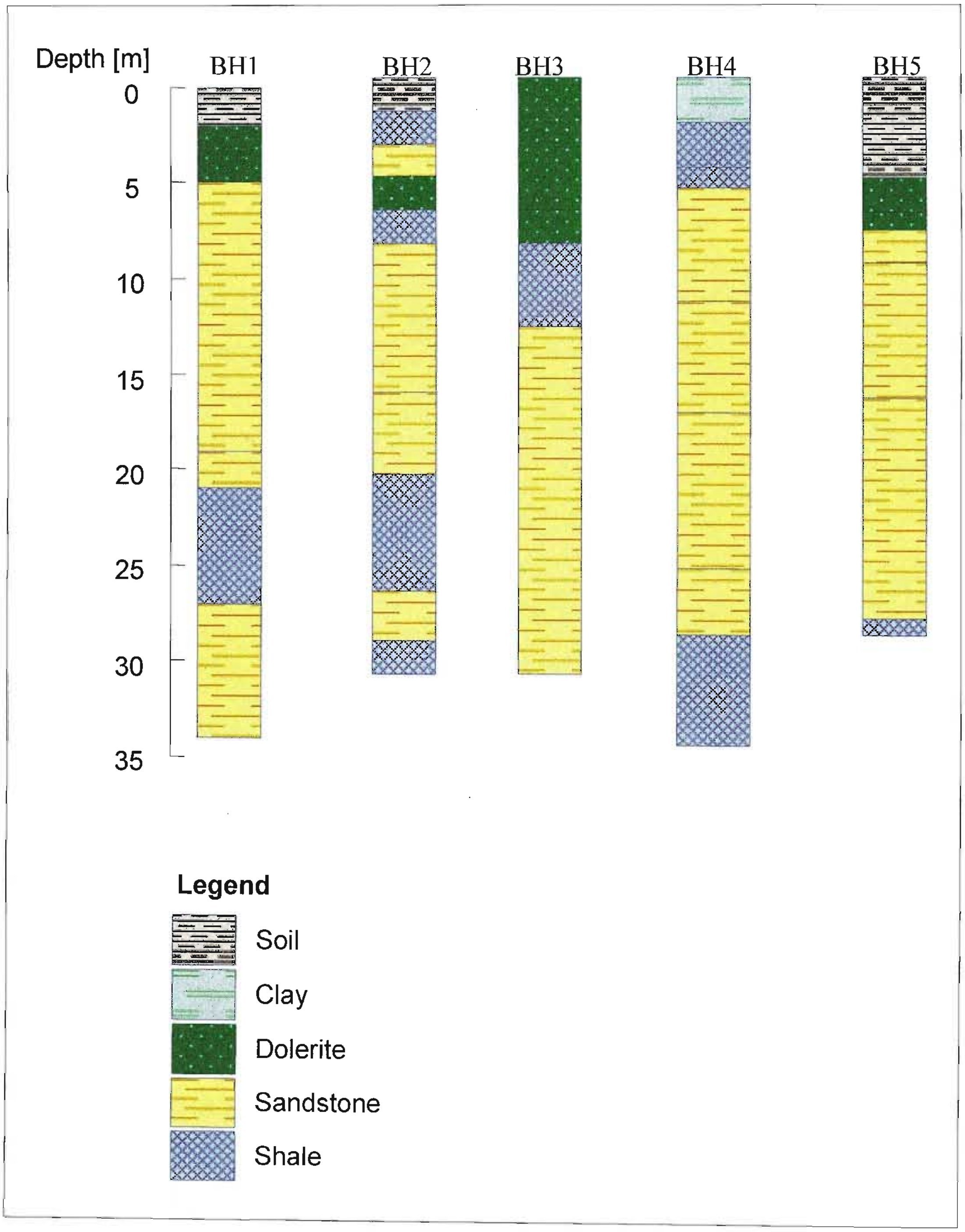

Figure F2: Borehole logs showing rock types in and around the Syferfontein pivot (Usher and Hough, 2002a)

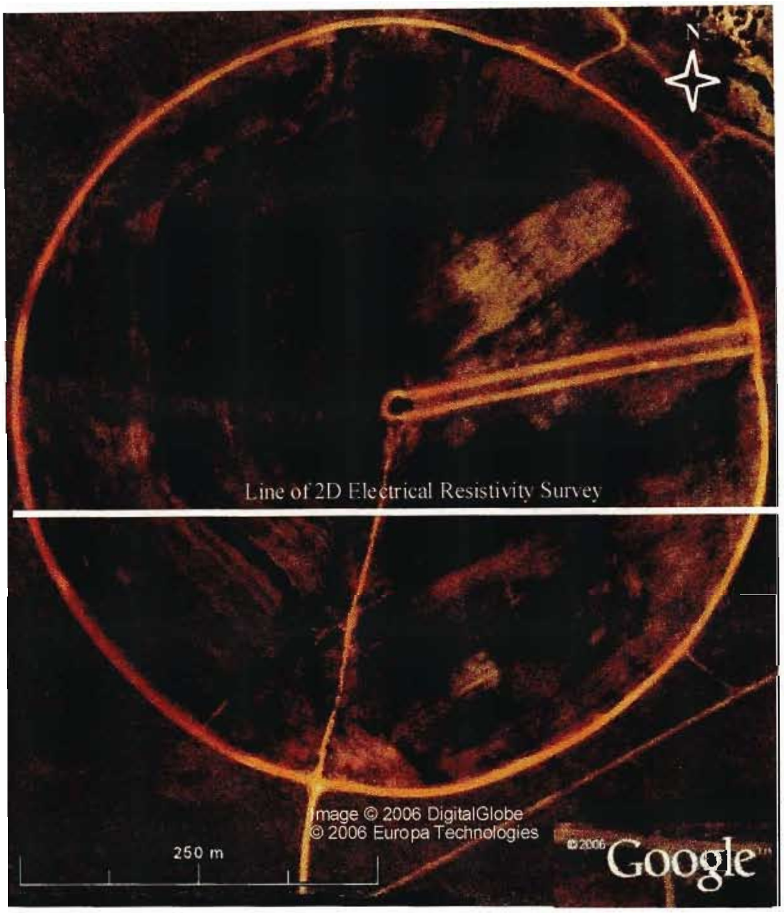

Figure F3: Aerial photograph of the Tweefontein pivot (Google, 2006) showing the transect of 2D electrical resistivity survey

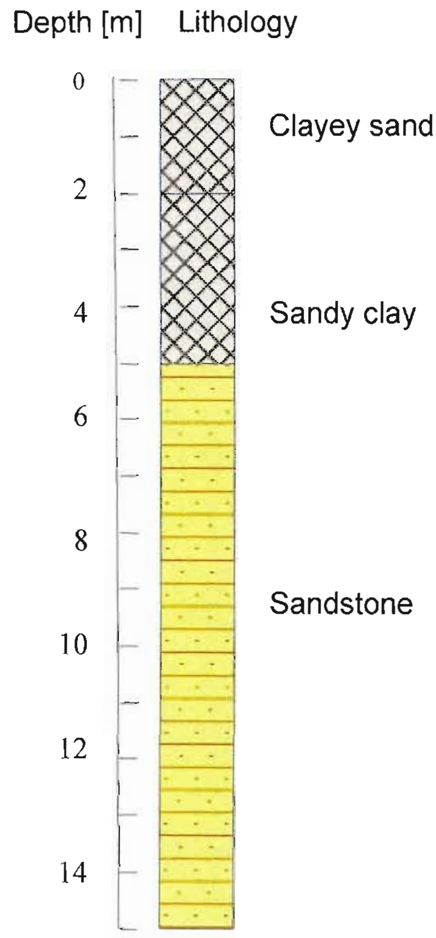

Figure F4: Typical borehole lithologic log in the Fourth pivot area (Usher and Hough, 2002b)