DRYLAND SALINITY IMPACTS ON WESTERN CAPE RIVERS

MV Fey • WP de Clercq

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Water Research Commission

RESEARCH ON BERG RIVER WATER
MANAGEMENT

DRYLAND SALINITY IMPACTS ON WESTERN CAPE RIVERS

by

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Final report on WRC Project No K5/1342 entitled "ESTIMATION OF THE CONTRIBUTION FROM DRYLAND SALINITY TO WATER QUALITY IN THE BERG RIVER CATCHMENT - A PILOT STUDY"

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EXECUTIVE SUMMARY

Introduction

This 18-month pilot study was undertaken to assess whether a more detailed investigation is needed of dryland (i.e. non-irrigated) agricultural impacts on river salinity, similar to those being researched intensively in Australia. The Berg River basin was targeted because of its strategic importance to rural and industrial development in the Western Cape and its history of water quality research.

Objectives

- To obtain a preliminary estimate of the quantity of salts stored in the regolith of the Berg River catchment.
- To calculate the current potential for decantation of these salts into the river.
- To calculate, retrospectively and prognostically, the rate of change of salt discharge in response to changes in land use practices.
- To make a preliminary assessment of the applicability of the results to other major river systems in the region (e.g. the Breede River) based on existing information on soil properties and the history of catchment land use practices.

Research approach

The approach adopted was fourfold, involving: (i) field work and sampling for salinity assessment at selected sites, (ii) correlation of remote sensing imagery with salinity, (iii) calculation of likely salt discharge in response to change in land use, and (iv) synthesis of existing data to produce a picture of likely influences on salt flux the catchment.

Methods

Key areas in the basin were sampled intensively and soils were analysed for salinity and related properties. An EM 38 salinity sensor was calibrated against soil analyses as a means of obtaining a rapid field index of soil salinity and its spatial variability. Geostatistical analysis was performed to assess the possibilities of extrapolation based on topography and land use features gleaned from remote imagery. Bare patches identified in wheat fields by aerial photography were ground-truthed by soil sampling and analysis. Spectral analysis of remote images (colour ortho-photos) was used to establish whether these images could also be used to delineate saline soils in the landscape. Geological, groundwater, surface water and climatic data were collected and correlated to establish possible origins of salts within the catchment. The influence of land use changes, in particular the replacement of natural renosterveld by wheat, on water and salt balance at selected sites in the catchment was modelled using the ACRU model.

Results

This pilot study has confirmed the original assertion that dryland salinity is extensive and is likely to have a significant impact on water quality in the river. It has also provided the justification and the basis sought for planning a concerted study aimed at fully understanding and quantifying the problem. The main results and conclusions are as follows:

- Remote sensing through aerial photography indicates that there is widespread patchiness in croplands, especially in wheat fields that dominate land use in the catchment.
- Ground truthing by soil sampling and analysis of transects through the barren patches (*kiewietkolle*) at several locations has consistently confirmed that they are associated with soil salinity which is of sufficient magnitude to explain the poor wheat growth.
- Spectral manipulation of new colour ortho-photos that are now available for a portion of the catchment has demonstrated that the bare patches in wheat fields can readily be demarcated, allowing their aerial extent to be quantified.
- Use of a salinity sensor (EM 38) in the field proved to be a successful substitute for detailed soil sampling as a means of quantifying soil salinity and of subjecting its distribution to geostatistical analysis and interpretation in relation to land use and topography.
- Despite the fact that a new, comprehensive database has been assembled by regional water specialists on ground water quality, the records for the drier, more saline sub-catchments of the Berg River remain sparse and are inadequate for establishing a connection between soil or regolith salinity and groundwater

salinity. A comprehensive survey of farmers' boreholes will need to be made in future studies.

- Long-term salinity records of selected tributaries of the Berg River have been built up through regular monitoring by the Department of Water Affairs and Forestry since the mid-1970s when the seminal study on salinization of the Berg River was published by Fourie, who recognized that much of the salt load in the river emanated from non-irrigated areas. Analysis of these records indicates that some trends are discernible, although masked by freshening releases of Theewaterskloof water into the Berg River since the early 1990s. The data seem to confirm the importance of climatic (as opposed to paleo-geologic) factors in determining the development of dryland salinity.
- A research team headed by W Flügel undertook an ambitious hydrological investigation of salinity in a representative sub-catchment of the lower Berg River (the Sandspruit) during the 1980s. The project terminated prematurely because of funding difficulties and the results of one year's monitoring (1986) were only published in 1995. Although this study was primarily hydrological and took neither pedogenic processes nor land use factors into serious consideration in assessing the potential for salt generation, it nevertheless provided an exceptionally valuable basis for calculating likely salt discharge from catchments in the drier parts of the basin and for checking the reliability of model calculations of runoff carried out in the present study.
- Modelling of likely runoff under different vegetation scenarios (winter wheat and renosterveld) using the ACRU model suggested strongly that land use changes potentially have a major impact on salt release from the regolith into surface waters. This confirmed the hypothesis that a switch from perennial deep-rooted renosterveld to annual shallow-rooted wheat would result in less water use and therefore enhanced discharge of salts into the river system, as has been found to have occurred (and is still occurring) in wheat lands of Australia which have replaced *Eucalyptus* scrub over the last century. The ACRU model, with a new salinity subroutine and with further improvements to its accommodation of soil surface characteristics that affect infiltration, will be valuable in making calculations not only of land use effects on salt discharge from catchments but also of the long-term accumulation of atmospheric salts of marine origin in the regolith of semi-arid catchments.

Conclusions and recommendations

There appears to be ample justification for recommending a more detailed survey of salt distribution in the soils, regolith, and ground- and surface waters of the Berg River basin and for undertaking a fundamental study of salt mobilization in response to climatic, topographic and land use factors, making use of a small catchment and taking into account historical changes in vegetation cover in the more saline reaches of the basin. This study should be multidisciplinary and should focus on understanding processes and the quantitative measurement of salt and water fluxes in the regolith of one or more small catchments as a prelude to extrapolation for calculating the extent of the problem through hydrological modelling and geostatistical correlation.

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The steering committee had the following membership:

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1 INTRODUCTION

The nature and growing magnitude of dryland salinity in Australia became dramatically apparent during a visit there by one of the authors in 2000. The cause of the problem in Australia lies in the fact that cultivated crops (especially wheat and pastures) have replaced natural vegetation and altered the water balance. A larger proportion of rainwater infiltrates the soil in winter and a smaller proportion of stored water evaporates during summer so that, gradually over many decades, salt-bearing ground water moves closer to the surface, giving rise to "saline scalds" (patches devoid of vegetation) and ultimately to the discharge of extra salts into rivers.

Dryland salinity is widespread throughout semi-arid regions of the world and its occurrence in many river catchments of the Western Cape should therefore be considered quite normal. Wheat lands in the Swartland and Overberg regions are widely known to contain *brak kolle* - barren, saline patches where wheat fails to germinate. Such natural salinity is already recognized as a source of some of the salts affecting quality of major Cape waterways such as the Berg River, where tributaries draining Malmsbury shale-derived soils are known to contribute disproportionately to the salt load (Fourie and Steer, 1971; Fourie and Görgens, 1977).

A possibility seemingly not yet addressed in numerous studies of South African rivers is that the change from extensive pastoral land use to intensive cropping over the last century or longer may have triggered the same process of salt mobilization as that which is so widespread in Australia. This seems especially likely in the semi-arid parts of the Western Cape which are strikingly similar to Western Australia in respect of climate, soils, natural salt levels in the regolith, topography and land use practices. If this is the case then the consequences for regional management of water quality could be enormous. Water in the Berg River is already seriously salinised. This affects not only irrigated agriculture but also water supply to industry in the Saldanha region and the ecology of the river system itself. Attempts to maintain water of suitable quality could be doomed to failure - with serious environmental and economic consequences - if future discharge of salts from the catchment regolith cannot be predicted. Until now the increase in salinity in major rivers such as the Berg has been attributed to irrigation return flow. This pilot study was conducted to ascertain whether dryland farming, by altering the hydrological cycle, is likely to make a significant and potentially growing contribution to the salt load in the Berg River.

The **objectives** of the study were as follows:

1. To obtain a preliminary estimate of the quantity of salts stored in the regolith of the Berg River catchment.

2. To calculate the current potential for decantation of these salts into the river.
3. To calculate, retrospectively and prognostically, the rate of change of salt discharge in response to changes in land use practices.
4. To make a preliminary assessment of the applicability of the results to other major river systems in the region (e.g. the Breede River) based on existing information on soil properties and the history of catchment land use practices.

The **research approach** adopted was fourfold, involving: (i) field work and sampling for salinity assessment at selected sites, (ii) correlation of remote sensing imagery with salinity, (iii) calculation of likely salt discharge in response to change in land use, and (iv) the synthesis of existing data to produce a picture of likely influences on salt flux the catchment. The report presents a review of relevant literature in Chapter 2 and a description of the methods used and study sites in Chapter 3. A detailed presentation and discussion of the results is provided in Chapter 4 (including field studies at selected sites in sections 4.1-4.5, hydrological modelling in section 4.6, catchment scale assessment of salinity in relation to existing information on geology, climate and water quality in section 4.7 and correlation of salinity with aerial photography in section 4.8). Chapter 5 offers some conclusions and recommendations for further research.

2 LITERATURE REVIEW

The salinization (sometimes referred to as mineralization) of Cape rivers has been known for at least half a century (Fourie, 1976). During the last few decades much South African research has been done on salinity associated with irrigation return flow (Moolman *et al.*, 1983; Flügel, 1995; Kirchner, 1995), a term which refers to drainage water dissolving salts from irrigated lands and then flowing back into the river. The consensus has been that irrigation return flow is the main source of the build-up in river salinity that has been widely encountered.

The Australian experience suggests that we need to look at the effects of land use across the whole catchment (Barrett-Lennard & Nulsen, 1989; Clarke *et al.*, 2002). These effects may be so gradual and insidious that they can escape detection if accurate records are not kept over a long period. Fourie (1976) indicated that certain tributaries of the Berg River are naturally quite saline, especially those on the west bank as well as a number on the east bank below the Voëlvlei Dam. This suggests that the catchments of these tributaries are naturally endowed with a large quantity of salts. Saline soils and groundwater are commonly encountered in these drier parts of the region and it is generally accepted that these salts are associated with Malmsbury rocks (Fourie, 1976) as well as deeply-weathered saprolite linked to remnants of the African (early Tertiary) land surface (F. Ellis, personal communication).

Another explanation for the prevalence of salts in the landscape lies in the combination of a semi-arid climate with proximity to the ocean. Hingston & Gailitis (1976) showed that the annual accretion rate of salt from oceanic aerosols (primarily sodium and chloride ions) in the wheat belt of Western Australia was 100–250 kg/ha in high rainfall coastal areas, falling to 10–20 kg/ha 300 km inland. Day & King (1995) pointed out that river solutes in the south-western Cape are dominated by Na^+ and Cl^-, especially in rivers with catchments close to the ocean. Weaver & Talma (2002) have presented data showing a clear maritime influence in the composition of groundwater on the west coast. Aridity in the region would be expected to effect a long mean residence time of salts in the regolith, implying that maritime salts could be stored in the weathered zone and intermittently displaced during infrequent groundwater recharge, giving rise to a saline groundwater. If this were the case, some correlation between aridity and the salinity of soils and groundwater would be expected. Acworth & Jankowski (2001), in addressing the salt source for dryland salinity in the southern tablelands of New South Wales, concluded that there was no hydrogeochemical evidence to suggest evaporative or transpirative concentration of salt in the groundwater of that region. An alternative model of salt accumulation was proposed with the salt being imported into the catchment along with silt during dust storms in the arid and windy conditions of the last glacial period.

Barrett-Lennard and Nulsen (1989) concluded that while salinised land often developed in lower valley locations and at breaks of slope, topography alone was not sufficient to predict the location of salinised areas. For example dolerite dykes could, according to Engel *et al.* (1987), act as barriers to groundwater flow, causing groundwater to rise and salinity to develop on the upstream side. No systematic survey of salinity, involving demarcation of saline soils, has been carried out for the Berg River catchment as a whole.

A recent publication by Flügel (1995) is extremely pertinent to this study, both in terms of its findings and in its review of dryland salinity in various parts of the world. Flügel reported on a detailed sub-catchment study in the Berg River basin, and it was concluded from a year's detailed hydrological measurements in the Sand river catchment (during 1986) that dryland agriculture was contributing to river salinization on the basis that the annual atmospheric input amounted to only one-third of the total salts emerging in catchment runoff. Although there were certain assumptions necessary for this conclusion to be reached it nevertheless represented the first published attempt to quantify a contribution by dryland salinity to river water quality in the Western Cape.

A valuable collection of papers from a workshop on understanding mineralization processes (Unpublished WRC report, 1980) addresses the various atmospheric, pedological and geological contributions to salinity. Particularly noteworthy is the contribution by Wiplinger (1980), dealing with oceanic water as a source of inland salts. The issue of how much atmospheric input occurs in maritime regions is still unsettled and perhaps a hydrological approach, incorporating long term climate data and catchment modelling such as that provided by ACRU, is necessary in order to quantify the mean residence time of salts in the regolith. Ultimately the origin of the salt is less important than its concentration in the regolith, as is the fact that it is potentially mobilized if there is a change in the hydrological cycle.

The ACRU model (Schulze *et al.*, 2003) is particularly suitable for testing the hypothesis that vegetation and land use changes in the Berg River catchment have led to an increase in the salt load in the river. The development of a recent version dedicated to salinity modelling is nearing completion (S Lorentz, University of Natal, personal communication).

The most comprehensive research effort on dryland salinity has taken place in Australia, and a wealth of information is available in journals (Acworth, 1999; Acworth & Jankowski, 2001; Angus *et al.*, 2001; Clarke *et al.*, 2002), as well as on the Internet, for example:

www.ndsp.gov.au

http://audit.ea.gov.au/anra/atlas_home.cfm and http://www.enn.com/news/enn-stories/1999/06/062599/salt_3990.asp.

In an article at the last of these web sites, Stirzaker *et al.* (2003) present a critical review of the Australian dryland salinity problem and what it will take to rectify it. They conclude that with current best farming practices the growth in salinity cannot be controlled. Much more innovative solutions are needed not only to control salinity and improve the landscape but also to maintain native biodiversity and community well being. Walker *et al.* (1999) have drawn essentially similar conclusions.

3 MATERIALS AND METHODS

3.1 Preliminary steps

To obtain an estimate of the salts stored in the regolith (solum plus weathered saprolite, or, in hydrological terms, the vadose zone), existing information from land type maps as well as aerial photographs were employed as a basis for selecting key areas representative of the significantly saline parts of the Berg River catchment. For the most part these more saline sub-catchments are situated in the Swartland on Malmsbury Group rocks, in contrast to those on Table Mountain Group sandstones that are situated in the elevated terrain to the east and south of the main basin.

Samples of diagnostic horizon and regolith material were collected and analysed for their salinity status in the laboratory. Only essential information was collected and wherever possible shortcuts, such as the field estimation of salinity (EM38 probe), were taken.

Land type maps and other relevant information were used to estimate the aerial extent of different regolith types and to calculate the total quantity of salts stored in the vadose zone. In addition, high-resolution ortho-photos were acquired from DWAF that made mapping of land use unnecessary at this stage. A GIS database was developed for salt distribution in key areas the catchment.

The hydrological model, ACRU (Schulze *et al.*, 2003), was examined for its suitability in calculating water and salt fluxes in response to vegetation changes using selected climate data from different parts of the catchment. Estimates were then made, for different vegetation cover and land use scenarios, of the likely range of intensities of salt discharge into the river system. Appropriate assumptions had to be made on the basis of existing data on infiltration rate, runoff and evapotranspiration for the types of soil and vegetation found in the catchment. This operation was to provide a basis for making a preliminary estimate of salinization potential which can then be compared with water quality records for the Berg River in order to achieve a useful perspective of the likely relative contributions of dryland salinity and irrigation return flow to the total salt load. These calculations were also designed to enable the rate of change in the salt discharge rate to be calculated when natural Renosterveld is supplanted by wheat. Historical records of land use changes could then be coupled with an estimate of the time-lag in salt migration made by hydrological modelling to see whether predicted changes in salinity of the river water accord with those that have been actually recorded. The results of such calculations could well be tenuous but would provide a first approximation of the magnitude of the problem and indicate whether a more intensive, multidisciplinary study, involving meteorology, hydrology and soil science, would be warranted.

3.2 Mapping the geology

For the geology of the region the 1:250000 database was used. All units on the map were converted to stratigraphic units to make for easier comparison with soil and water quality information.

3.3 Incorporating geographic information into the modelling process

Soil and land type maps, climatic data and remote imagery all need to be accommodated in the modelling process. After testing a number of possibilities, including EM38 surveys of specific sub catchments, and after consulting with people active in these fields, the project team felt that these surveys contributed enough to our understanding of the hydrological system to take the next step, entailing the modelling of runoff. The problem then becomes one of where to begin and how to extrapolate the information to other sub catchments.

We envisaged speeding up the extrapolation process through mapping techniques, by which recently acquired land use information coupled with the recently developed soil map and terrain model would be superimposed in a GIS to allow delineation of relatively homogeneous units. The task of characterising these units through field verification would not retard modelling but could be considered as an ongoing process of refining the model output.

A terrain model must be selected. The more terrain morphological units it consists of, the more complex will be the modelling process. In general the toposequence provides a reasonably sound basis for describing the distribution of both salinity and soil types. In selecting a terrain model, use was made of concepts described by Sys *et al*. (1991), and of the versatility of the Arc View program and the way in which it can be accommodated in the program. The study by Flügel (1995) is an example of how terrain type can be employed as a strong indicator of both runoff and soil type. The landform/terrain classes proposed by the FAO and by Sys *et al*. (1991) are given in Table 1.

Table 1. Terrain classes defined in terms of slope angle

Flat and almost flat	2%
Undulating	2-8%
Rolling	8-16%
Hilly	16-30%
Steeply dissected	>30%
Mountainous	Wide range in elevation

The terrain model that was used (Surfer™) calculates the slope angle at any grid node on the surface and incorporates the direction of steepest descent or ascent at that point (terrain aspect). The change in gradient direction across the surface is therefore also reported. Grid files of the terrain slope can be used to generate contour maps that show isolines of constant steepest slope. This feature still has one disadvantage in not distinguishing between crests and valleys. Such distinction is crucial to developing a realistic picture of salinity and soil patterns.

The slope, S, at any point is the magnitude of the gradient at that point, defined as:

$$S = \sqrt{\left(\frac{\partial z}{\partial x}\right)^2 + \left(\frac{\partial z}{\partial y}\right)^2}$$

Using a compass-based, grid notation difference equation,

$$S \approx \sqrt{\left(\frac{Z_E - Z_W}{2\Delta x}\right)^2 + \left(\frac{Z_N - Z_S}{2\Delta y}\right)^2}$$

The terrain slope was reported as a slope angle S_T in degrees, in keeping with terrain modelling literature (e.g. Moore *et al.*, 1993):

$$S_T \approx \frac{360}{2\pi} \cdot \arctan\left[\sqrt{\left(\frac{Z_E - Z_W}{2\Delta x}\right)^2 + \left(\frac{Z_N - Z_S}{2\Delta y}\right)^2}\right]$$

3.4 Relating river water quality to catchment features

Some water quality data were collected during the course of the study. The study of Fourie (1976) was also used as a basis for depicting salt distribution based on data for tributaries. A third data source was acquired from DWAF. This is still by far the largest database available. Most of this information was mapped in a GIS enabling links be made between water quality, geology and climate.

3.5 Site assessments of soil salinity

Various sites in the Berg River catchment were selected (Fig. 1) to assess variation in soil chemical properties related to soluble salts. Such information will facilitate modelling of salinity variation in the Berg River catchment as a whole as well as the interpretation of remotely sensed data.

Eight farms in the Swartland were selected (Fig. 1) to investigate typical salinity-related features. On each farm a typical patch of bare ground (known in the Piketberg district as a *kiewietkol* or "plover patch") and presumed to be a saline scald (Australian terminology) was identified in a wheat field. Most of these bare patches are readily identifiable on aerial photographs, suggesting the possibility of using remote images as a basis for salinity assessment. Soil samples (0-15cm and a subsoil sample from 15cm to the transition to saprolite - usually at about 50-60cm) were taken from the centre of the bare patch to within the standing (relatively healthy) wheat. Readings were taken at each sampling position with an EM38 soil electromagnetic conductance meter.

A second dataset was also compiled by sampling a transect in the vicinity of the saline patch, from the nearest stream channel to above the first terrace away from the stream or to an inclined or mid-slope position. (These streams are all tributaries of the Berg River). Each transect was not longer than 100m and involved at most 5 sampling positions. A third dataset was made up of water samples, each taken from the stream at a point closest to the bare patch (*kiewietkol).*

At the Glenrosa farm (Fig. 1) the soils were mapped in the traditional way and a large number of soil samples were taken on the same grid as that used for mapping the soils. The same area was also surveyed with an EM38 soil electromagnetic conductance meter. All of these data were modelled geostatistically to produce a basis for accommodating spatial variability in making calculations of catchment salinity status from widely spaced sampling points. The coordinates of each soil sampling and measuring position were carefully logged.

Soil samples were air-dried, ground to pass a 2mm screen, and analysed for electrical resistance and conductivity, major cations, anions and pH, using standard methods. The stone fraction (>2mm, otherwise termed the coarse fraction) was weighed and used as a basis for normalising laboratory estimates of salinity for comparison with field measurements. The approach is summarised in Appendix A.

3.6 Runoff modelling

Sites on three farms were chosen for modelling purposes: Rooihoogte, Broodkraal and Glenrosa (Fig. 1). All three farms have good weather records and were included in previous WRC projects, which provided detailed information on soils and indicated that the soils found on these farms are fairly representative of the Berg River Catchment as a whole. When we began modelling, however, Broodkraal and Rooihoogte gave similar results and it was decided to include the farm Heldervue, situated in the Piketberg range and having the highest recorded rainfall in the lower BRC.

BERG RIVER CATCHMENT

Fig. 1. Map of the catchment showing the location of salinity sampling positions on eight farms and the location of three farms (Broodkraal, Rooihoogte and Glenrosa) selected for salinity mapping and modelling.

Modelling was performed with the ACRU program (Schulze *et al.*, 2003). It was decided first to apply ACRU by making use of land type data from the Berg River catchment and long-term climate data from the three weather stations. Soil physical variables were obtained from the database developed for ACRU calculations from land type inventories. These values represent means and medians for each land type.

Crop factors for wheat and renosterveld were acquired from a set of recently revised values (A Pike & R E Schulze, personal communication). The main objective was to compare the calculated transpiration of renosterveld with that of winter wheat.

ACRU needs no introduction and will therefore not be discussed in detail. The manual and an explanation of the model can be downloaded from the web site http://www.beeh.unp.ac.za//. The model and the relationships between its variables are summarized in Fig. 2.

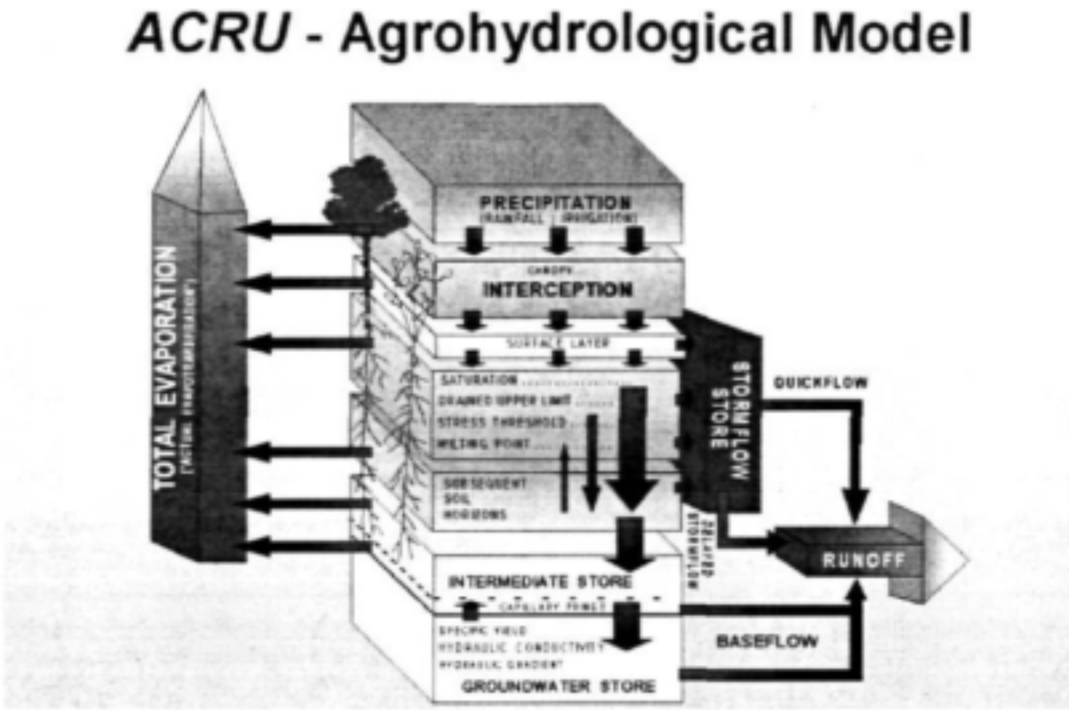

Fig. 2. Conceptual structure of the ACRU model (Schulze *et al.*, 2003)

3.7 A preliminary mapped estimate of salts in the landscape

By combining all the acquired information in a GIS, a map with the likely occurrence of salt over the catchment was generated based on soils information, river water quality, the geology and aerial photography. As the detail in each of the layers in the GIS increases with future research, so too will the delineation of salt in the landscape.

Mapping therefore consists of the geology, the soils and most importantly, a salinity map derived from high-resolution aerial photographs made available by DWAF. It was not feasible to prepare this map for the whole catchment, but rather to focus on areas surrounding the Glenrosa, Rooihoogte and Broodkraal farms.

The technique that was used involved mapping elevation and the variation in the wheat growth pattern. The latter required establishing a relationship between wheat growth pattern from colour aerial photography and soil salinity (EC). Soil EC was also calibrated with EM 38 measurement to enable faster mapping of soil salinity and the coverage of larger areas. These results can ultimately be used to map soil EC over the catchment. However, because these techniques are expensive it was decided that the aims of the project would be served well enough if we could at least demonstrate the viability of the approach since sufficient ground truthing data and other remote sensing techniques such as radar imagery are not currently available.

A large area on the Glenrosa farm was mapped using EM 38 data, which were also correlated with the EC_e of soil samples taken at the same time. The data were kriged and a pixel plot generated. The same plot was sampled from the DWAF image. The DWAF image was then split into red, green and blue (RGB) bands using the ArcView program. We found through an iterative process and from literature that the R-band is not precise and only the upper section of the R-band, approaching near-infrared (NIR), was used in salinity mapping. The R-band data from the Glenrosa image were regressed upon EM 38 data from the kriged image.

This approach highlighted other aspects previously not taken into account in salinity mapping. Elevation is a very important determinant of salinity in the landscape and the mapping technique needs to accommodate to this. It is therefore imperative that high resolution DEM be used in the mapping process. A 20m DEM was tested but failed to do the job and this aspect will need special attention in follow-up studies.

4 RESULTS AND DISCUSSION

4.1 Superficial indications of salinity in the catchment

As the Berg River wends its way northwards and westwards towards the coast the landscape changes from well-watered, high mountains to open, gently rolling wheat fields with an increasingly arid climate. Signs of soil salinity become progressively more evident in the lower, more northerly parts of the catchment. As one travels towards Piketberg from Malmsbury or towards Gouda from Wellington, for example, the first signs appear in the form of saltbush (*Atriplex* spp.) planted as animal fodder in concave foot slope positions along drainage lines. Adjacent wheat fields are invariably patchy in appearance, in some cases partly because of *heuweltjies* or termitaria but also because of what farmers sometimes refer to as *brak kolle* (salty patches) or *kiewietkolle* (plover patches, so named because of the preference which these birds have for bare ground). These barren patches are the equivalent of what the Australian literature terms saline scalds. In many cases, if you walk to the centre of these patches, their cause is easily identified by simply tasting the saltiness of the surface soil. Even wheat, which is one of the most tolerant of commercial crops to salinity, will not germinate when such high levels of salt are present.

We decided that part of our brief for this pilot study should be to obtain a bird's eye view of this patchiness and to quantify its relationship with soil salinity as a possible means of calibrating remote imagery, using air and satellite photos, with the distribution of soil salinity in the catchment. We flew the whole catchment twice in a light aircraft with a professional photographer. Figure 3 provides an illustration of the most severe barrenness associated with concave drainage lines and also the patchy appearance of wheat fields in two successive seasons, the second being exceptionally dry. There is some randomness in the distribution of the patches of poor wheat, with a systematic pattern superimposed on it as a result of cultivation practices (especially the ridge and furrow drainage system, with barrenness being more severe in the furrows). In a large numbers of such photographs, which are archived on CD-ROM, it was clear that the severity of crop damage associated with these poor patches was much greater under the drought conditions of 2003, confirming that the patchiness is probably associated more with salinity than with excessive wetness. Some of the patchiness appeared to be random, with bare areas occurring in mid-slope positions not related to any pattern of cultivation or drainage. Later in this report we present the results of spectral calibration of colour imagery with barren areas with a view to quantifying the distribution of saline soils.

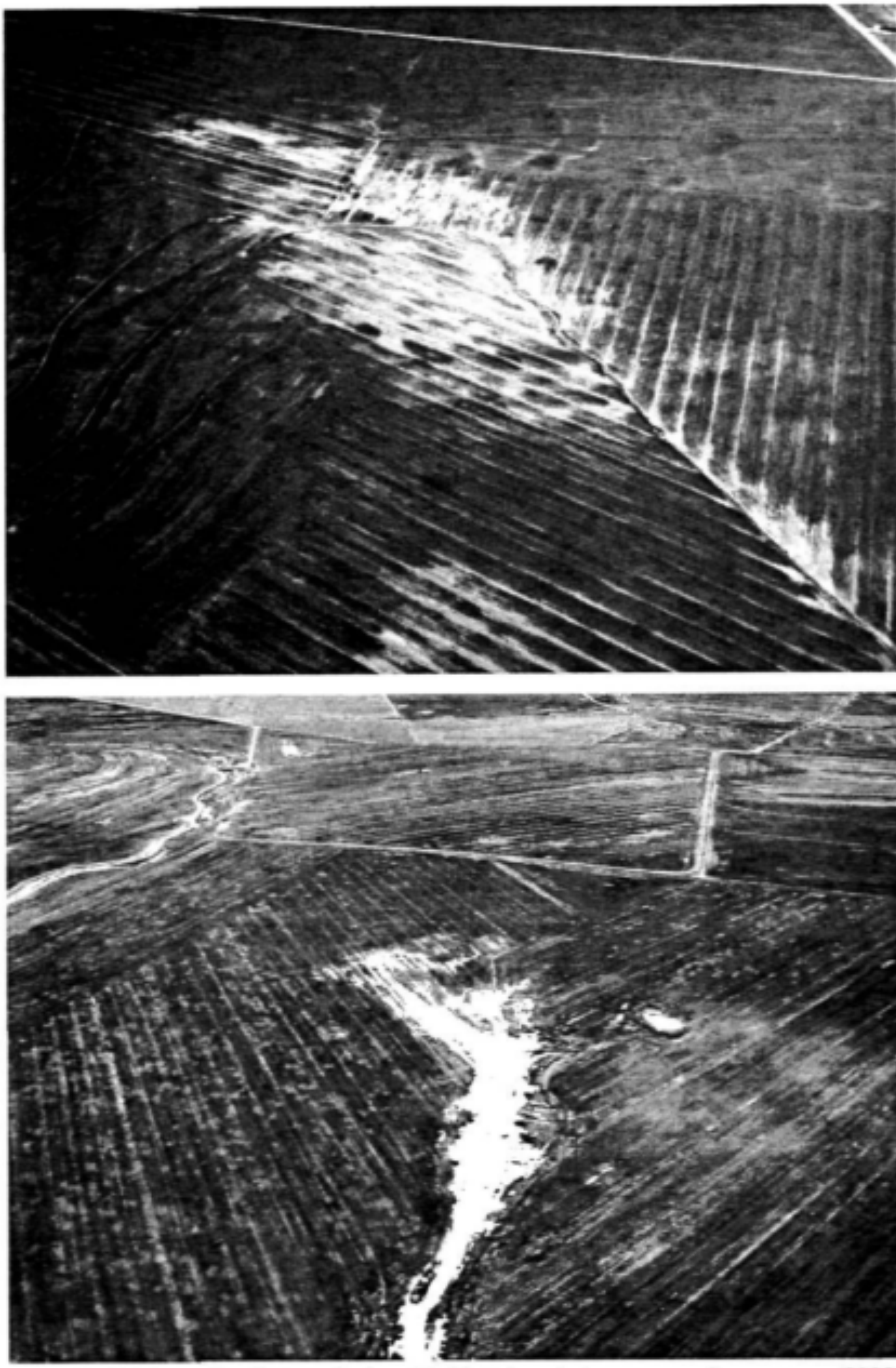

Fig. 3. Oblique air photos of wheat fields taken in two successive seasons (2002 above and 2003 below).

Figure 4 illustrates the appearance of a typical barren patch in a wheat field on one of the eight Swartland farms (the location of which is shown in Figure 1) selected for sampling soil and water salinity.

Fig. 4. Barren patch in a wheat field on the farm BoKuile, across which a transect was sampled for correlating wheat growth with soil salinity.

Soil salinity data for transects spanning these barren patches are summarised in Figure 5 and reveal a consistent gradient from the centre of the barren patch into the peripheral wheat crop, with levels of salinity in some cases being exceptionally high, particularly in the surface soil. (It should be recalled that the salinity determination was done in a 1:5 soil:water extract, which is at least 10 times more dilute than a saturated paste extract. The correlation between EC_e and $EC_{(1:5)}$ is given in Appendix A.) Failure of the wheat to germinate, leaving a completely bare patch of soil, is therefore readily explained. The EC values of Figure 5 were used to calculate the total salt content of the soil profile (Figure 6), which allows the potential magnitude of salt discharge through runoff to be assessed.

Additional information was collected on the same eight farms to assess soil and water salinity in relation to topography. Variation in soil salinity and pH across topographic transects is shown in Table 2. On the farms BoKuile and Vlakkerug, the samples at positions 1 and 2 were taken in recent alluvial sediment near the river. Such alluvium was not present in transects on the other farms. Table 2 indicates that soil pH also tends to increase in a down slope direction (i.e. towards position 1). In Table 3, the EC and pH values of stream water, sampled at the end of the transect on each farm, suggest a fairly substantial salt load and alkalinity in these Berg River tributaries at the end of the wet season.

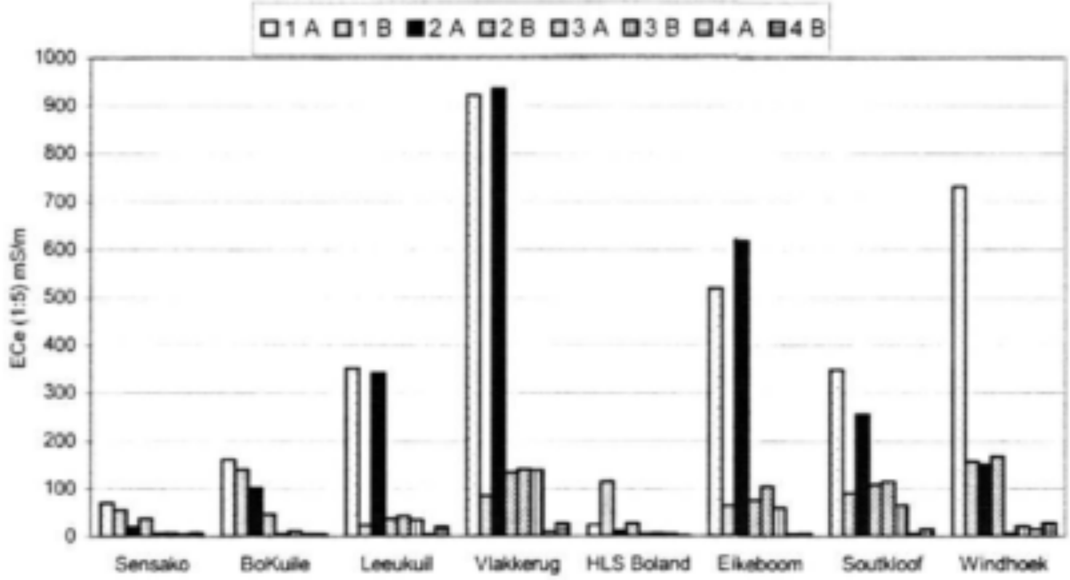

Fig. 5. Soil salinity transects across barren patches in wheat fields on eight Swartland farms. Position 1 is in the centre of a barren patch, position 4 in adjacent healthy wheat, and 1 and 2 are in intermediate positions. A and B signify topsoil (0-15cm) and subsoil samples (15-50cm or saprolite) at each position

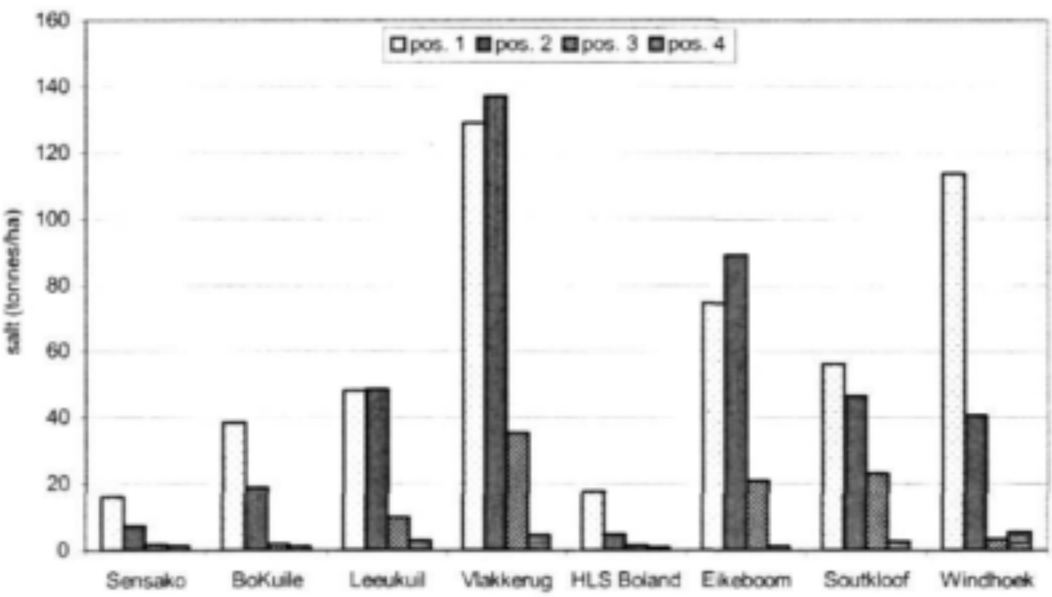

Fig. 6. Total salt content of the soil profile, calculated per unit area, at the sites shown in Figure 5

Table 2. EC_e (mSm^{-1}) and pH measured from the stream bank (Position 1) to the mid slope (Position 4 or 5) of toposequences sampled on eight farms in the Berg river catchment.

Parameter	Toposequence location	Position 1	2	3	4	5
EC_e	Sensako	133	770	46	22	
	BoKuile	769	42	187	112	71
	Leeukuil	47	495	49	18	
	Vlakkerug	2760	3166	53	36	
	HLS Boland	36	131	25	206	
	Eikeboom	27	35	36		
	Soutkloof	56	28	70	23	
	Windhoek	62	40	112	56	
pH	Sensako	6.9	6.4	6.8	6.3	
	BoKuile	7.4	6.8	6.5	7.9	6.1
	Leeukuil	7.7	8	6.7	6.5	
	Vlakkerug	8.0	8.4	5.7	5.3	
	HLS Boland	5.8	8.3	6.2	7.6	
	Eikeboom	5.3	7.2	7.1		
	Soutkloof	6.6	6.3	6.1	5.1	
	Windhoek	7.5	7.1	6.0	6.2	

Table 3. EC and pH of water samples taken from the stream immediately adjacent to each toposequence listed in Table 2.

Stream location	EC (mS/m)	pH
HLS Boland	332	8.53
Sensako (a)	794	8.77
Sensako (b)	931	8.02
Sensako (c)	581	8.48
Eikeboom	559	8.53
Vlakkerug	836	8.11
Leeukuil	325	7.81
Soutkloof	810	8.44
Windhoek	1190	8.37
Bokuile	638	8.47

4.2 Mapping the Glenrosa sub-catchment

Mapped variables derived from soil analysis and remote sensing were correlated in order to test for inter-relationships and to assess spatial variability. First, soil samples were taken on a section of the Glenrosa farm (Fig. 7) and the coordinates of each were logged. The same area on the Glenrosa farm was then scanned with an EM38 (soil electromagnetic conductance meter). These data were calibrated against soil analyses and subsequently related to remote imagery from aerial photography. Each measuring point was carefully logged using GPS of sub-metre accuracy (Fig. 8). The soil samples were analysed and tested for their Ca, Mg, Na, K, Cl, and SO_4 contents. In some of the samples, electrical resistance (ER) was measured. For all samples, however, pH and EC_e were determined. The EM 38 results were correlated with colour imagery as a basis for salinity prediction.

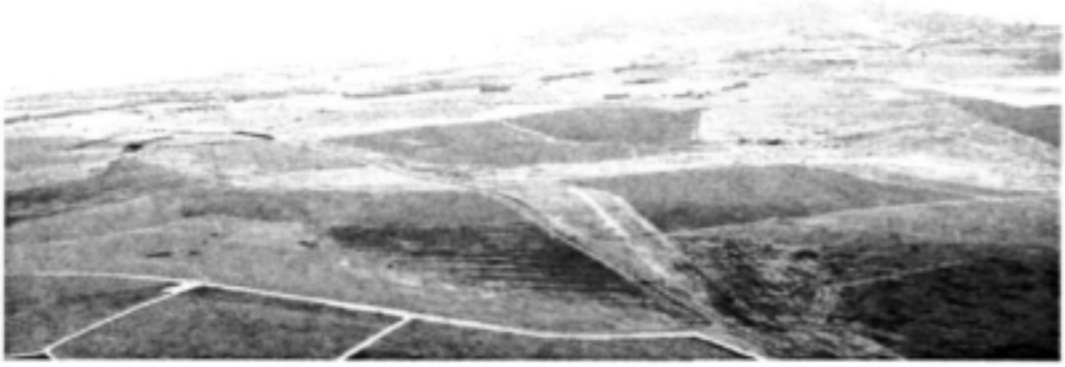

Fig. 7. Aerial view of the Glenrosa farm (Wellington and Paarl Mountain in the background)

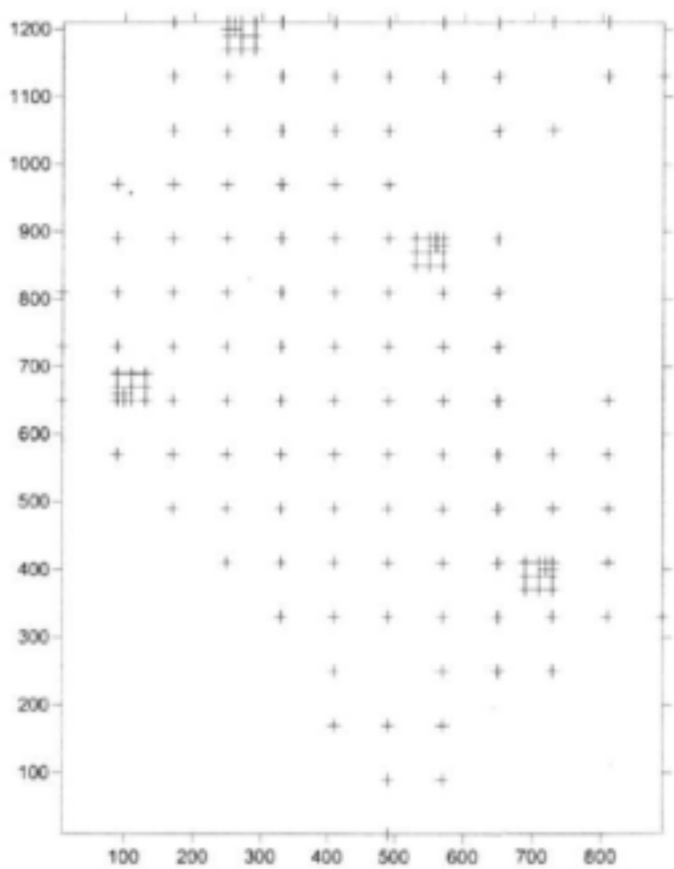

Fig. 8. A post plot showing distribution of soil sampling positions on Glenrosa farm

4.2.1 Demarcating and modelling salinity and sodicity in the landscape

Exploring relationships between ER and EC_e, and between EC_e and EM was important for interpretation of the EM38 dataset. Figure 9 shows the relationship between ER and EC_e.

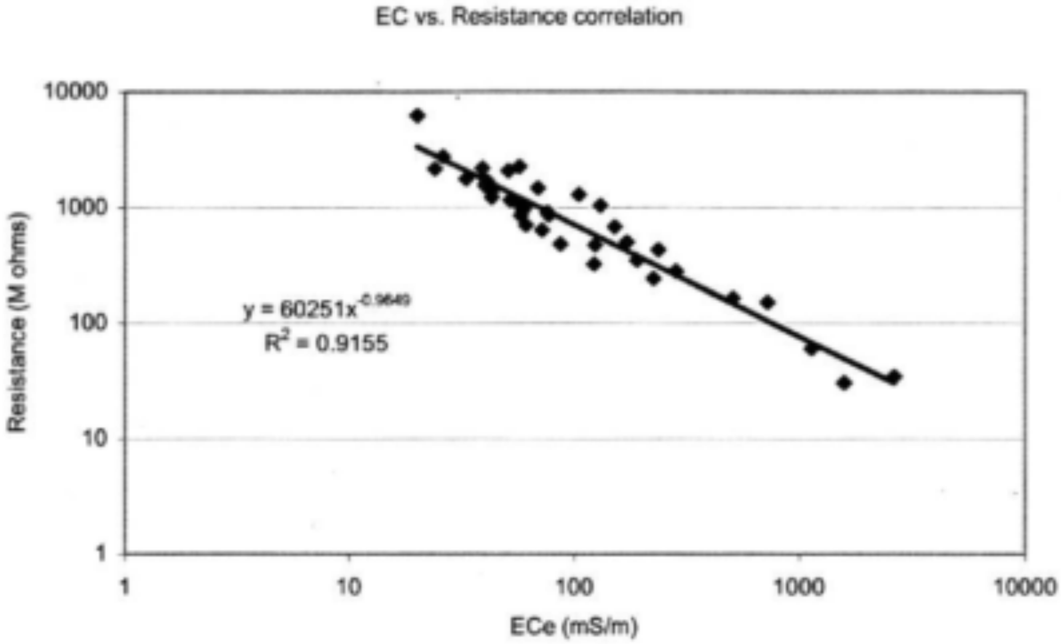

Fig. 9. ER-EC_e relationship for saturated soil pastes: Glenrosa farm

It was necessary to find the relationship in Figure 9 because measurement of ER in the field is very convenient. To effectively map salinity the EM38 was used but to calibrate the EM38, field measurements of ER were employed. This required measuring ER without removing the coarse fraction from the soil. Alternatively, calibration could be performed with field measurements of EC_e, based on a 1:5 soil:water extract.

The relationship between EC_e and total cation content is given in Figure 10. A strong relationship was found which is important for confident interpretation of both EC_e and EM38 measurements. A similar relationship was evident for anions (Fig. 11).

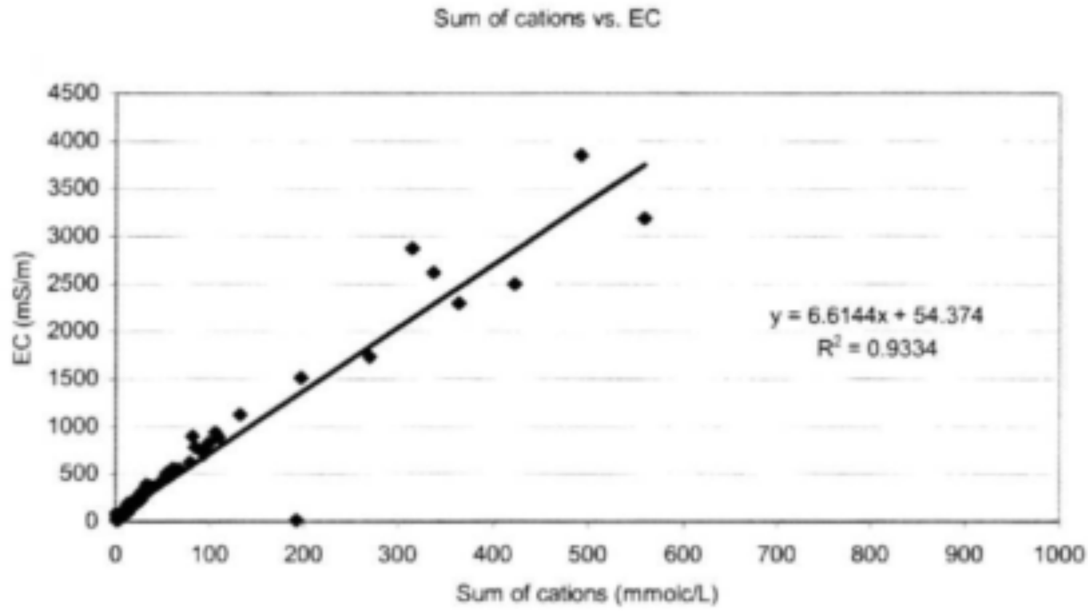

Fig. 10. Relationship between total cation content of saturated soil paste extracts and EC_e - Glenrosa farm

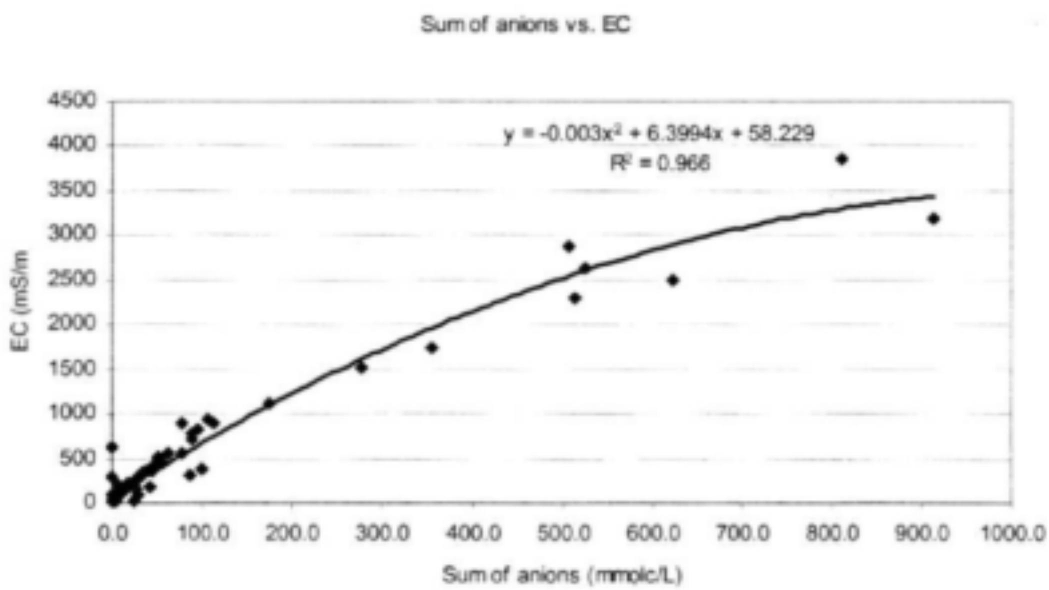

Fig. 11. Relationship between total anion content of saturated soil paste extracts and EC_e - Glenrosa farm

Semi-variogram and variogram models were calculated for EC_e, pH and SAR from data for the Glenrosa farm. The idea was to show the resemblance of the resulting surfaces to the EM38-modelled data. It is clear from the modelled results in the ensuing sections (Figures 12-21) that pH, ECe and SAR and can be modelled from the EM38 results. The relationship between SAR and EC_e in fact depicts the discrepancy between salinity and sodicity in the landscape (Fig. 18). This relationship is fairly strong for SAR < 20.

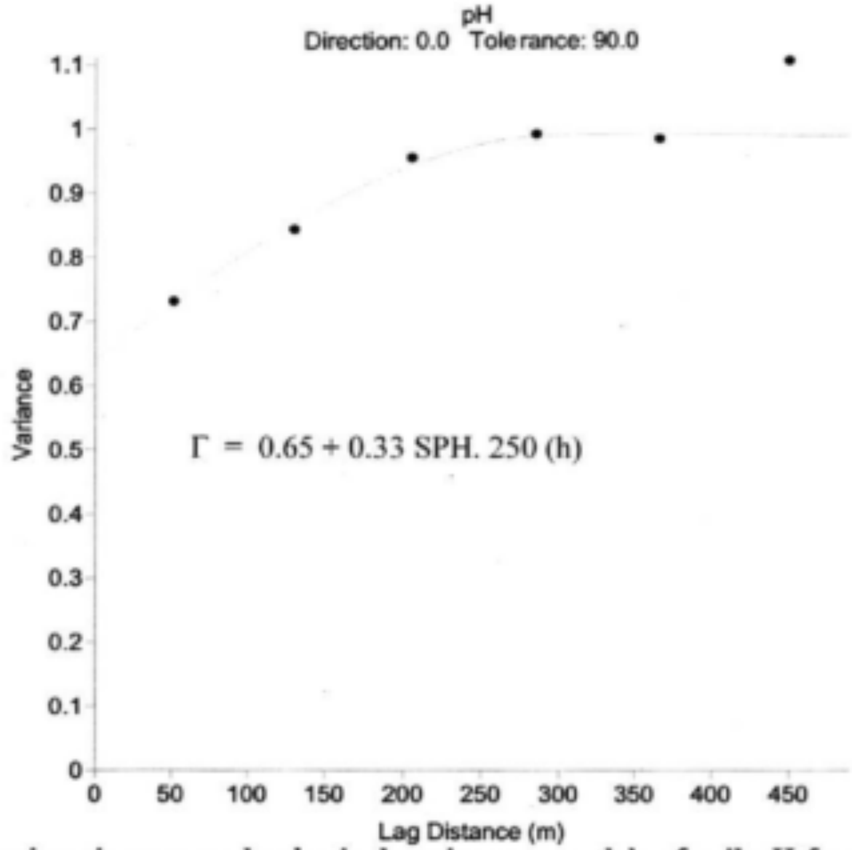

Fig. 12. Semi-variogram and spherical variogram models of soil pH from the Glenrosa farm

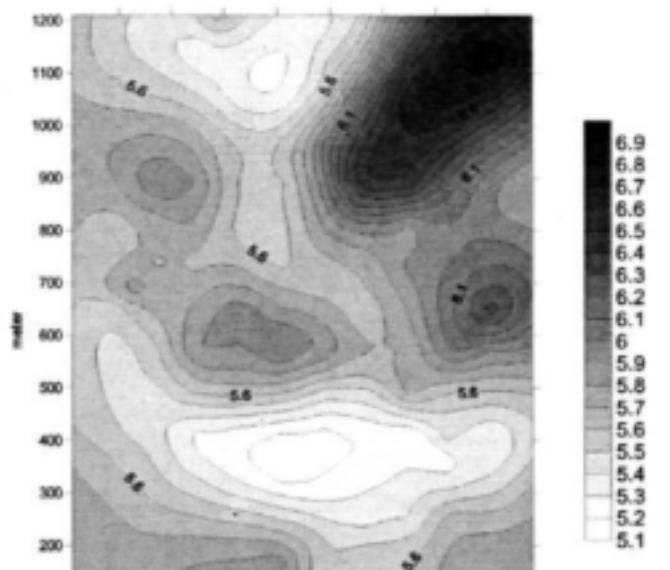

Fig. 13. Contour map of pH based on the variogram model of the Glenrosa farm in Figure 12

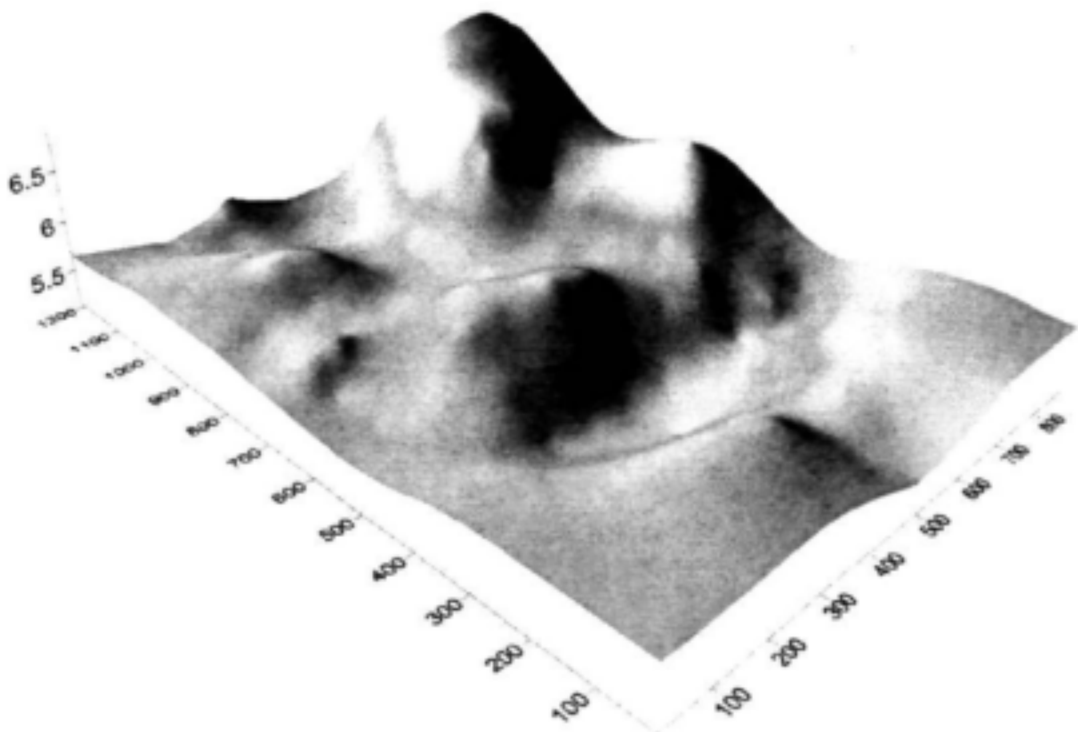

Fig. 14. Digital topographic map of pH based on the variogram model of the Glenrosa farm in Figure 12

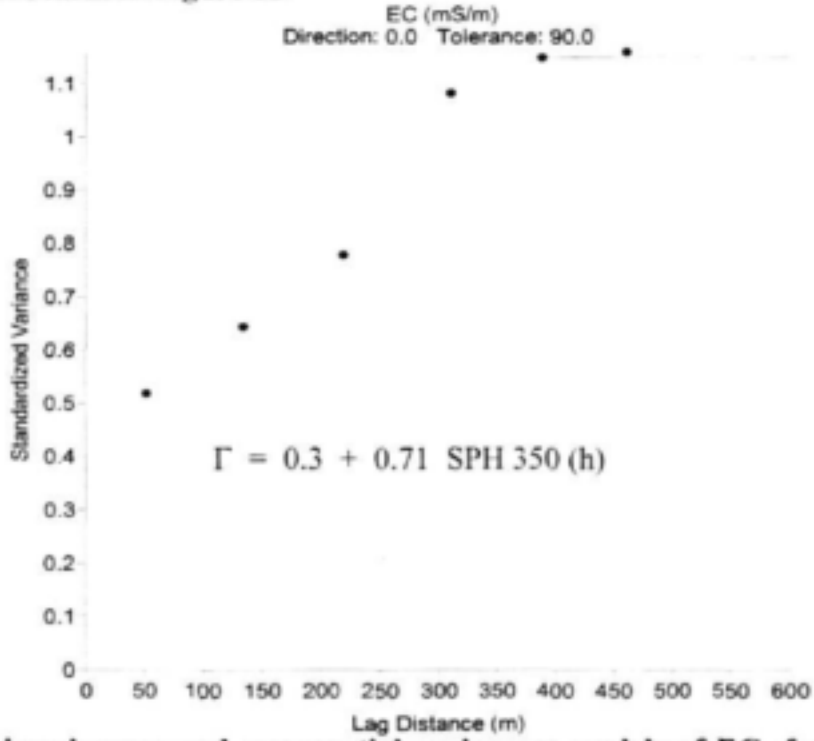

Fig. 15. Semi-variogram and exponential variogram models of EC_e from the Glenrosa farm

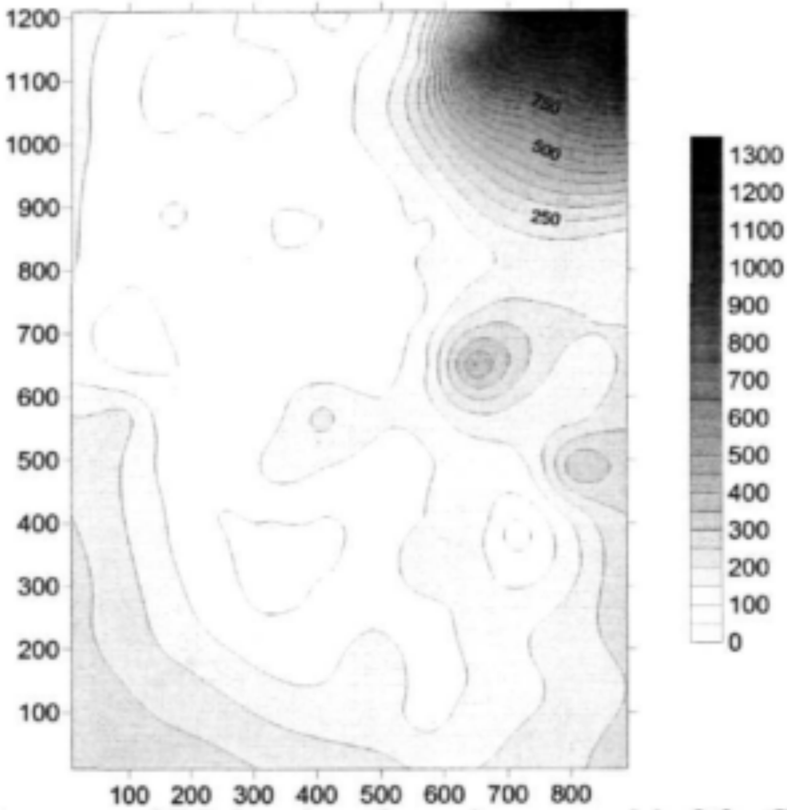

Fig. 16. Contour map of EC_e based on the variogram model of the Glenrosa farm in Figure 15

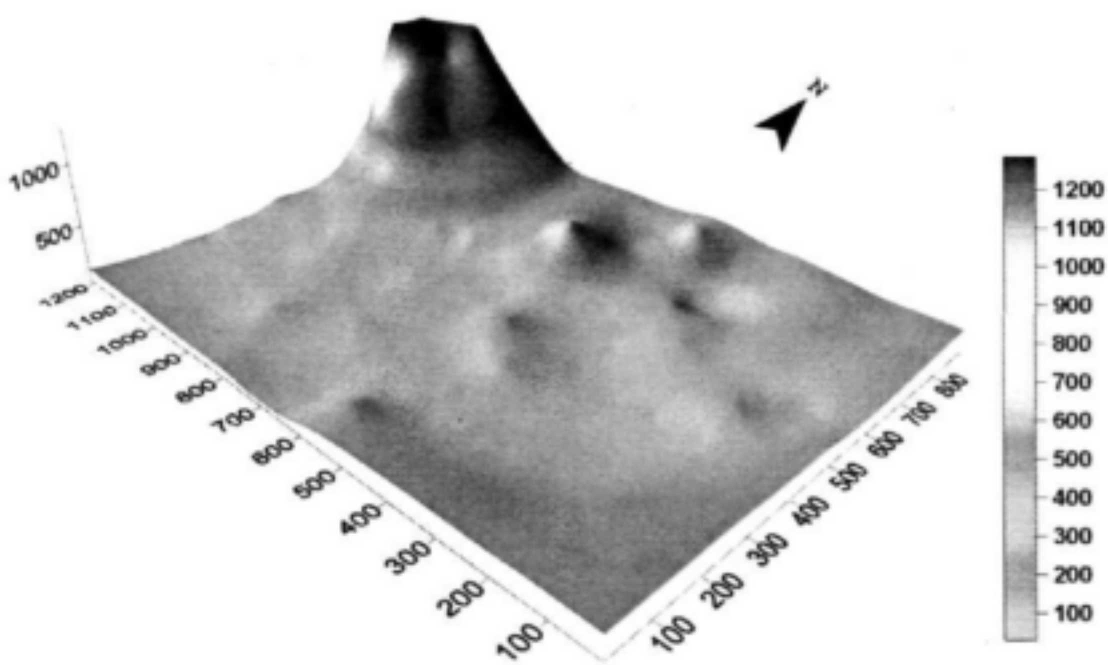

Fig. 17. Digital topographic map of EC_e based on the variogram model of the Glenrosa farm in Figure 15

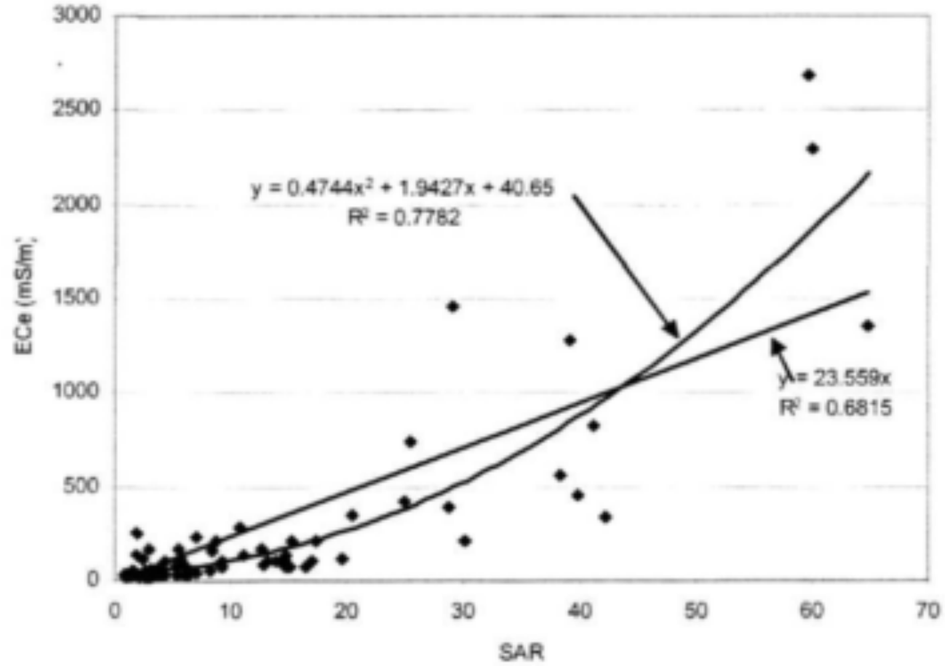

Fig. 18. Relationship between EC_e and SAR from the Glenrosa farm

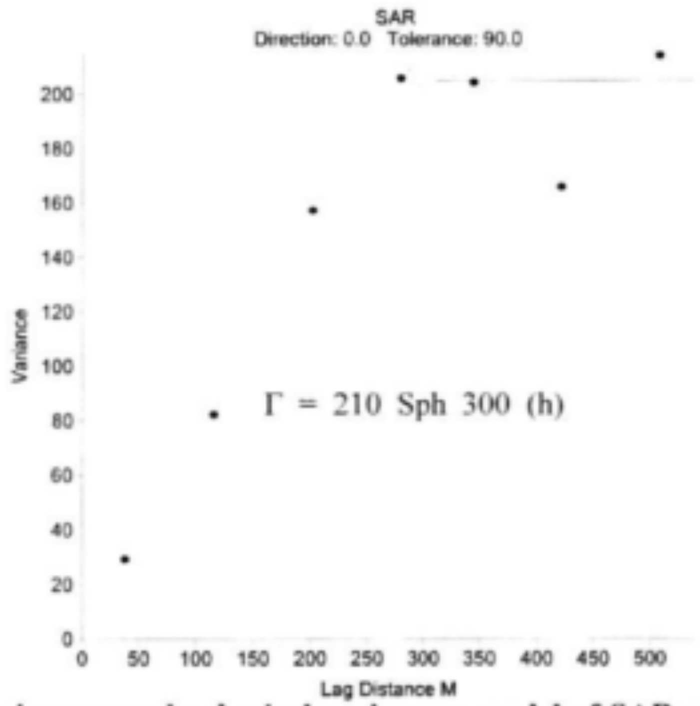

Fig. 19. Semi-variogram and spherical variogram model of SAR on a section of the Glenrosa farm

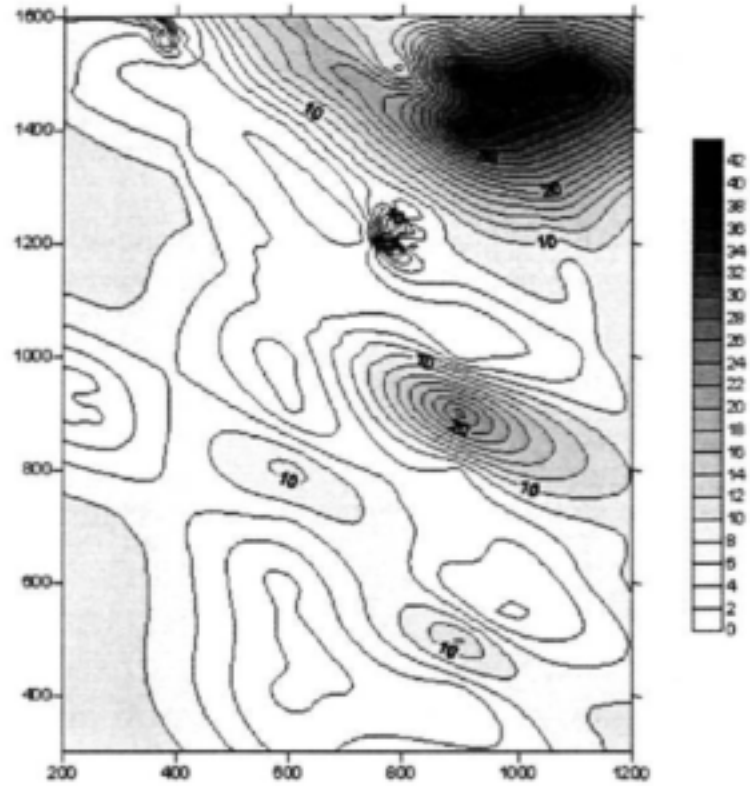

Fig. 20. Contour map of SAR based on the variogram model of the Glenrosa farm in Figure 19

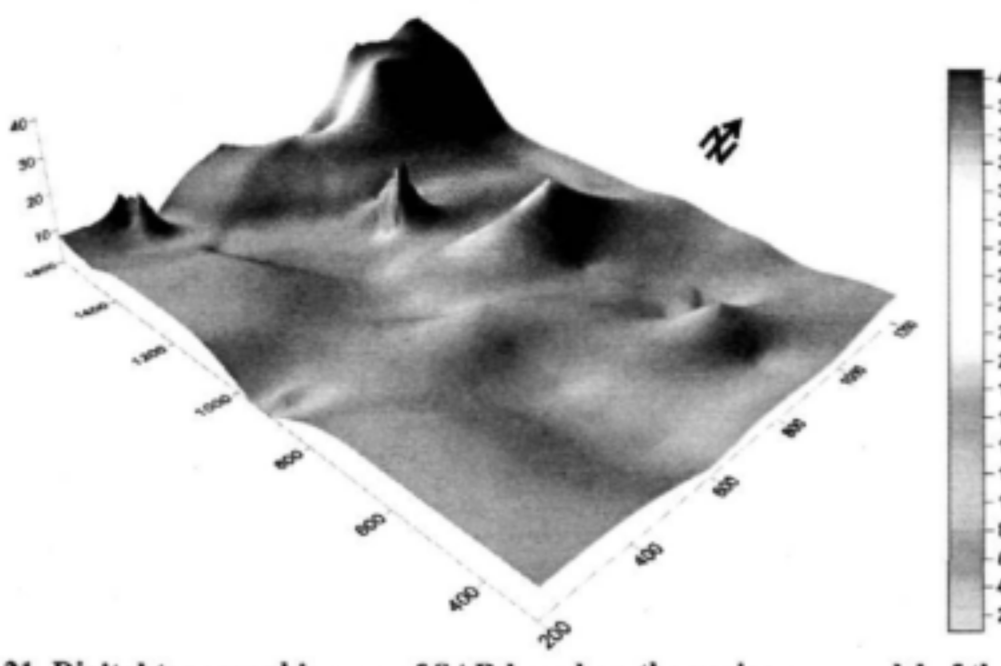

Fig. 21. Digital topographic map of SAR based on the variogram model of the Glenrosa farm in Figure 19

4.2.2 Predicting EC_{em38} over the larger Glenrosa farm

The use of the EM38 and interpretation of the data is a fairly new concept in South Africa whereas in Australia, for example, it is commonly used to quantify salinity in the landscape and for soil mapping. The EM38 is sensitive mainly to four primary variables: the course fraction of the soil, the clay content, the water content and the dissolved salt content. In general, higher water, salt and clay contents produce a higher EM38 reading while a larger coarse fraction produces a lower reading. Since the stone content causes a general lowering of the values, it is important to account for this. The instrument generates an electromagnetic induction field which can penetrate the soil to a depth of 1.5m. The instrument is always field calibrated and the readings are then calibrated using soil samples.

The semi-variance of the Glenrosa EM38 data was modelled using Variowin software. A post plot of the dataset is shown in Figure 22. Correlations of EM38 readings (vertical and horizontal) with ER readings adjusted for stone mass are shown in Figure 23. Good variogram models were found for both the vertical and horizontal EM38 readings (Figs. 24 and 25) with marginal differences between the maps, although these were large when comparing the order of magnitude of the variance produced.

To place these readings in perspective one can consult Figure 23. It was necessary to compare the EM38 readings with ER values acquired from soil samples. It was therefore decided to compare the EM38 readings and the ER of the saturated pastes but to adjust the latter values by taking the stone content into account. We propose this method for calibrating EM38 readings because the ER of an unsieved sample is quick and cost-effective to determine in the field. The method used to translate EC_{EM38} values into EC_e or ER was explained earlier.

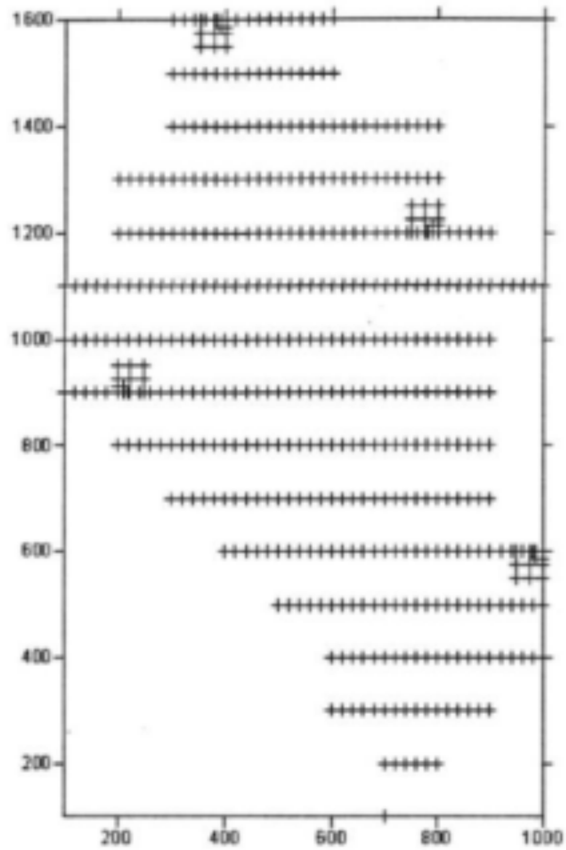

Fig. 22. Postplot of EM38 sampling positions showing four clusters of higher density sampling

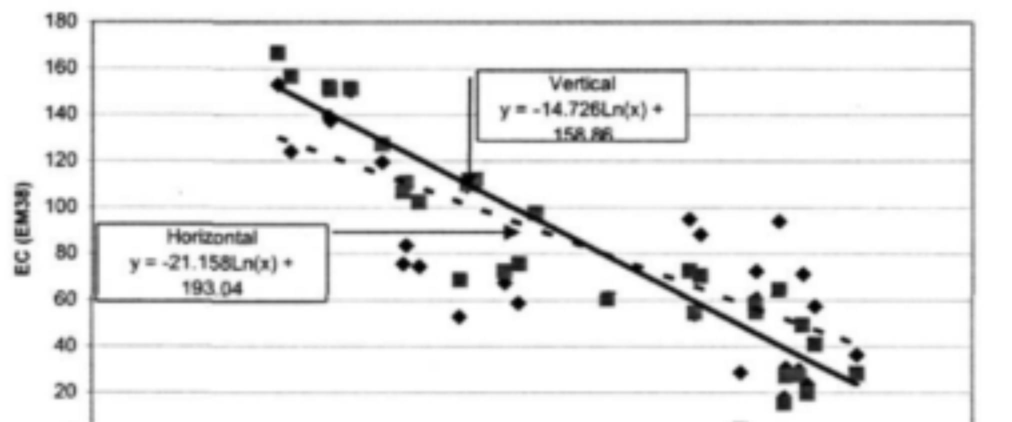

Fig. 23. EM38 readings relative to ER of the saturated paste adjusted to account for stone mass

The semi-variograms in Figs. 24 and 25 were both modelled using spherical models. In both cases the range is about 450m but the variance of vertically and horizontally measured data differs markedly. The main reason is that vertical measurements usually are much larger, by a factor of about two.

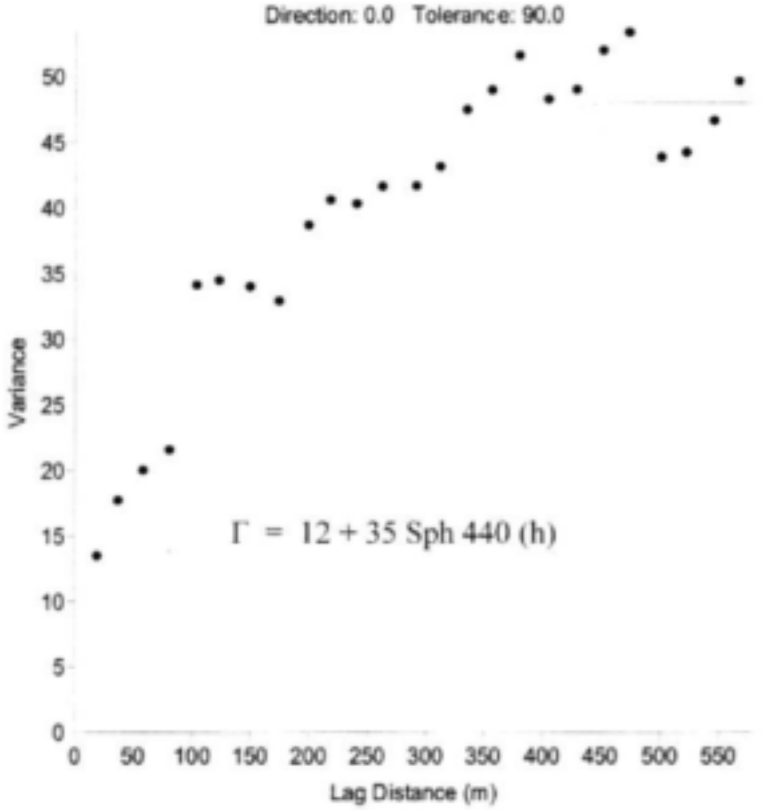

Fig. 24. Glenrosa semi-variogram and exponential variogram model of the EM38 horizontally polarized data

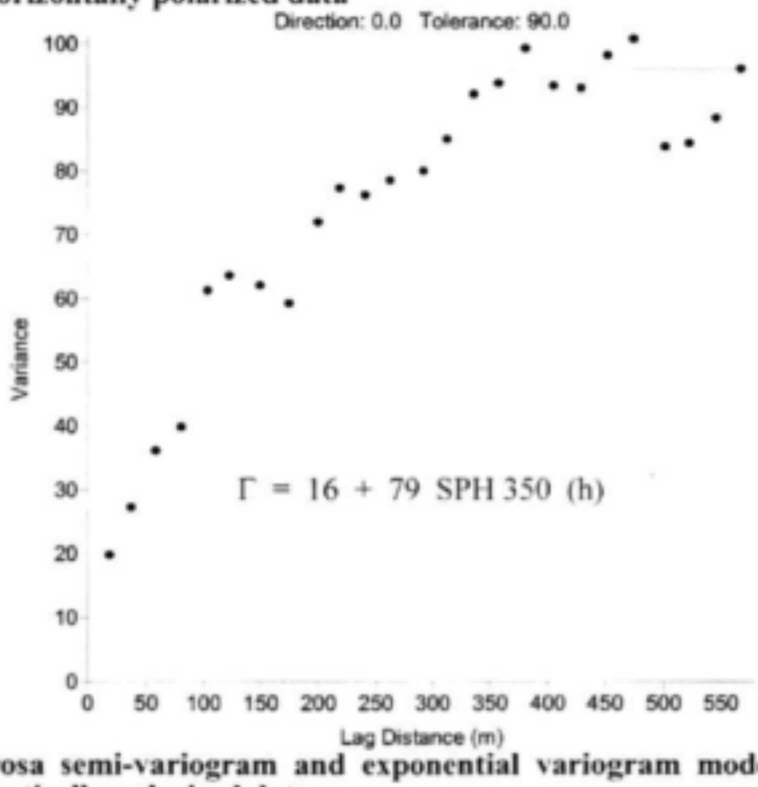

Fig. 25. Glenrosa semi-variogram and exponential variogram model of the EM38 vertically polarized data

The pixel plot of the kriged EM38 data is shown in Fig. 26 and the resultant topographical image of the same data is shown in Fig. 27. The latter makes for a more dramatic representation of the results although both are based on the same data.

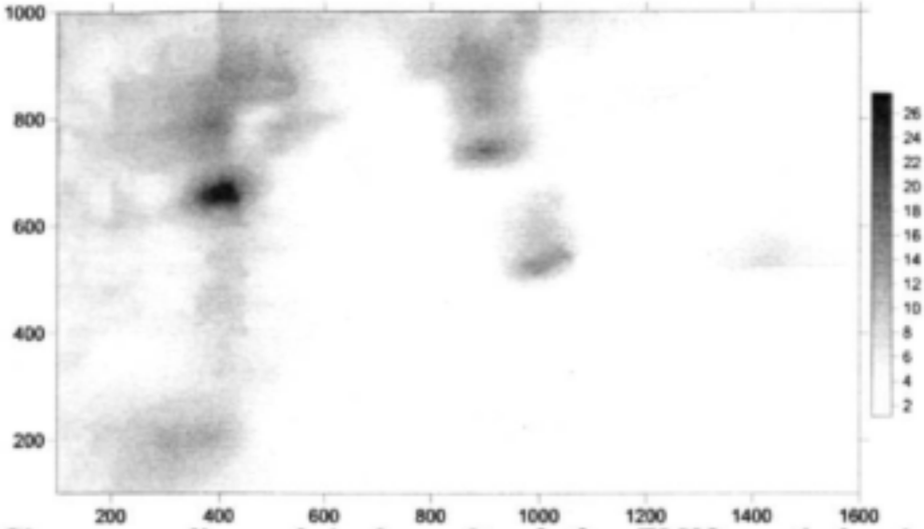

Fig. 26. Glenrosa ordinary kriged result of the EM38 vertical minus horizontal polarization data

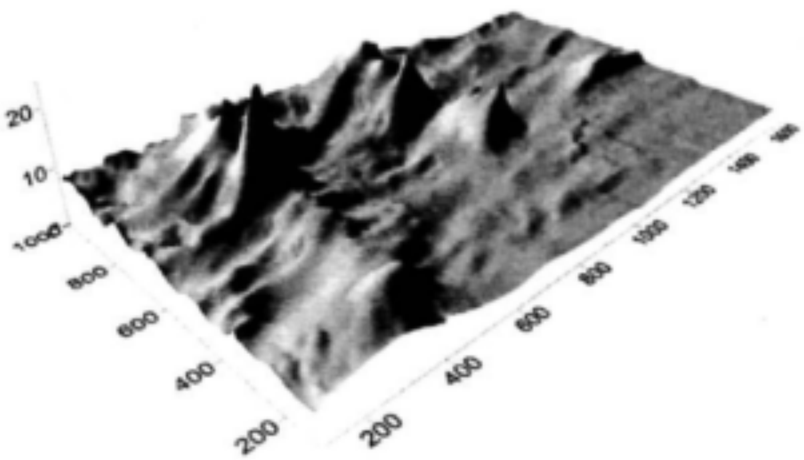

Fig. 27. Topographical map of the soil salinity data (EM38) on Glenrosa farm

4.3 Comparing EM38 readings with RGB bands from aerial photography

A colour aerial photograph of Glenrosa was obtained from DWAF and the red, green and blue (RGB) colour bands were separated using ArcView software. The colour image and the EM38 image were geo-referenced so that the individual pixels on both could be correlated. This process was designed to indicate how the RGB band might be manipulated to mimic the EM38 map. All possible combinations of RGB were tested and we found that they generally produced a very slight variation in the R-band. Since we did not have NIR imagery to work with, it was impossible to calculate a NDVI. Though the RGB-bands can be used to deduce many other properties (for example iron oxides can be highlighted using these bands), salinity, although also sensitive throughout the whole spectrum, was shadowed by the vegetation cover. By comparing EM38 data with the R-band we found, however, that high salinity (or rather, above average salinity) could be mapped. In Figure 28 the group-averaged R-band values are compared with the EM38 readings and it is clear that between R-band values of 110 and 140, much confusion is possible as to what effect is being conveyed by these values. What is, however, promising is the section above 140 that correlates well with the EM38 measurements. Normally through calculating the NDVI, the section below an EM38 value of 13 (Fig. 29) is removed, leading to a clear salinity/plant stress effect. It is also evident from this graph that between EM38 values of 13 and 24 a good first order relation can be defined.

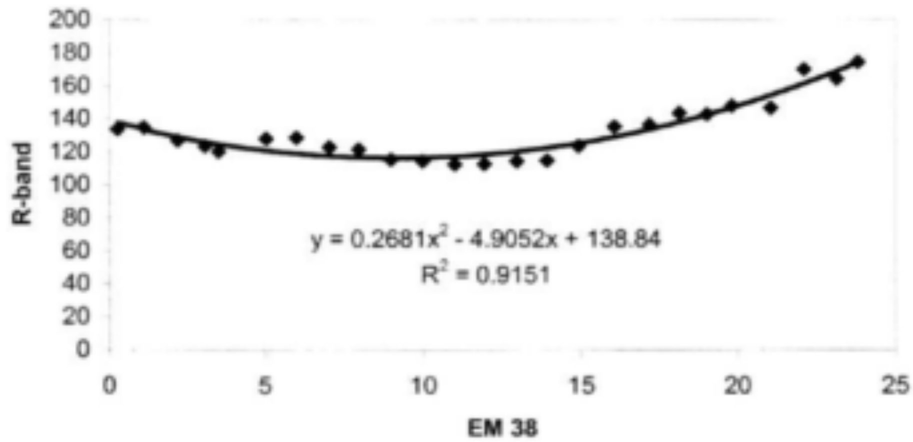

Fig. 28. Comparison of group-averaged R-band values with EM38 readings for a section of the Glenrosa farm

This approach led to the question of how this effect can best be applied in ArcView to highlight only the high salinity range because the lower salinity range might lead to confusion. The second problem was how to deal with the obviously large differences in hue and contrast that exist between photographs. Both these problems were overcome using the mean colour in each of the photographs as the central value and then using the deviation from the mean as an index. The R-band colour data were divided into at least 6 deviation increments away from the mean on either side. This procedure had the advantage that the map was more sensitised to the higher R-band values which would not have been the case had the ordinary R-band been used to map a salinity effect. This effect is clearly visible in the two histograms presented in Fig. 29.

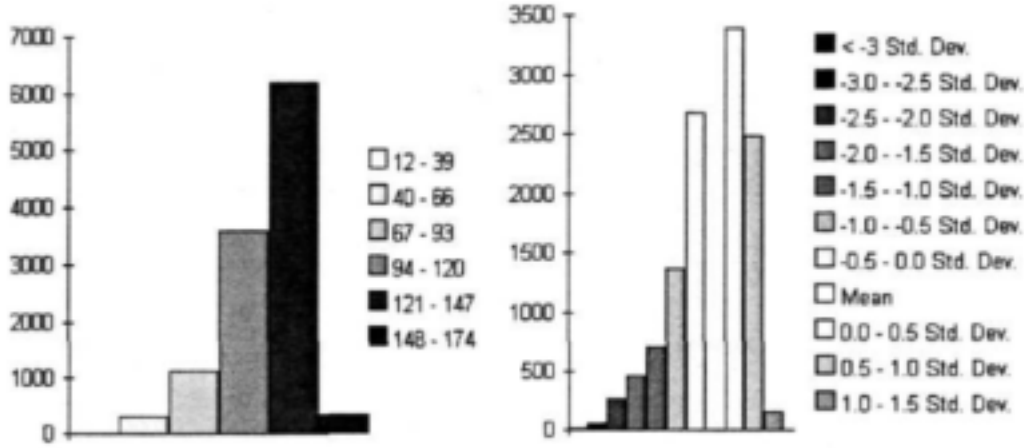

Fig. 29. Comparison of the distribution of R-band values when mapped using a constant interval (left) and the standard deviation (right)

Though more information is needed to fully highlight soil salinity, the indication is that this technique works quite well as a result of the degrading effect salinity has on the wheat stand and natural summer grass. There is a generally good correlation between pixel values sampled from the photograph and corresponding pixels from the mapped EM data.

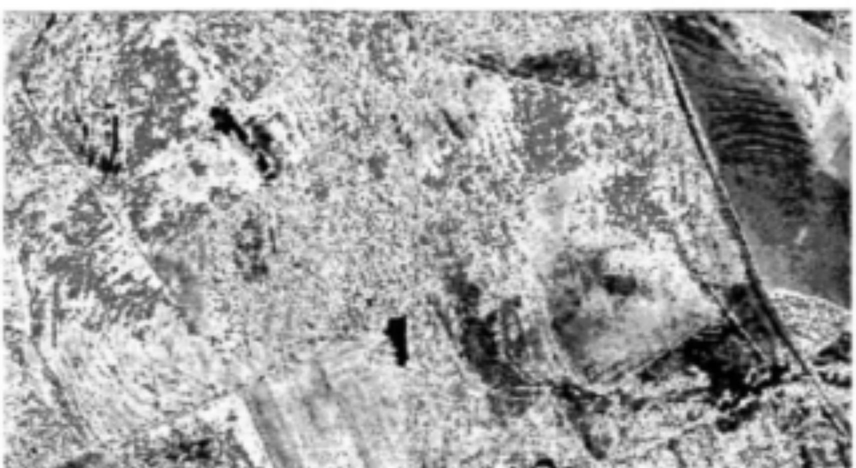

Fig. 30. Aerial photograph of the Glenrosa farm showing adjusted colour bands to accentuate the more saline soils. The blue square is the EM 38 scanned area shown in Figure 31.

Looking at Figures 30 and 31, and taking into account what we now know about the distribution of salinity in the field, red indicates saline soil conditions whereas blue indicates actively growing plants that at this time of year only line the valley floors and gullies where they have access to water, which is usually saline. This vegetation cover is also clearly visibly from the colour photographs. Our field data clearly show that the soil water in these blue areas has a salinity that varies between 400 and 2000 mSm^{-1}. This suggests that the EM38 can clearly map salinity below the vegetation cover while these salt resistant plants show no stress and therefore appear blue in the R-band adjusted image.

Lastly, perhaps the most important finding here is that the adjusted R-band image clearly highlights the general pattern of lowest salinity on the hillcrests, slightly more salinity on the upper convex incline and highest salinity in the lower, concave part of the hill slope. This was found in detailed mapping of the salinity on Glenrosa farm and is nicely confirmed by this method of salinity mapping.

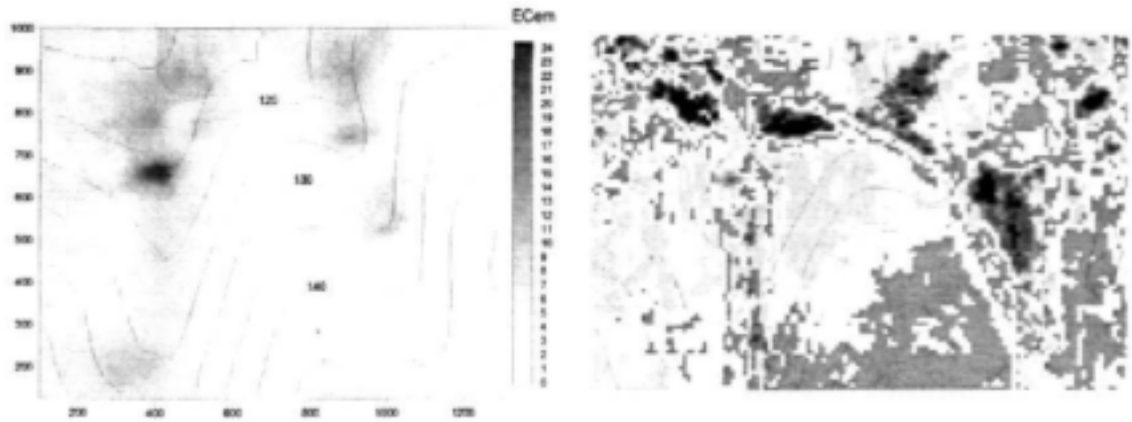

Fig. 31. Comparison between EM38 modelled results (left) and the red band filtered from an aerial photograph (right) (distances are shown in m)

4.4 Mapping the Rooihoogte sub-catchment

An aerial view of Rooihoogte farm is and its environs shown in Fig.32 (*heuweltjies* are in abundant evidence).

Fig. 32. The Rooihoogte sub-catchment with the Rooihoogte farm in the foreground (September 2002)

The primary goal of mapping this small catchment was to map land-use, but also to combine this with remotely sensed salinity information. Görgens *et al.* (2002) reported detailed information on irrigation return flow and the general quality of the water in this tributary. The approach developed in mapping the Glenrosa farm was also applied here, except that the same derivative from the aerial photograph was used with no ground truthing. The salinity image was, however, compared with the sampling positions reported by Görgens *et al.* (2002), and the two compared favourably. Figure 33 depicts land use information and Figure 34 the salinity map.

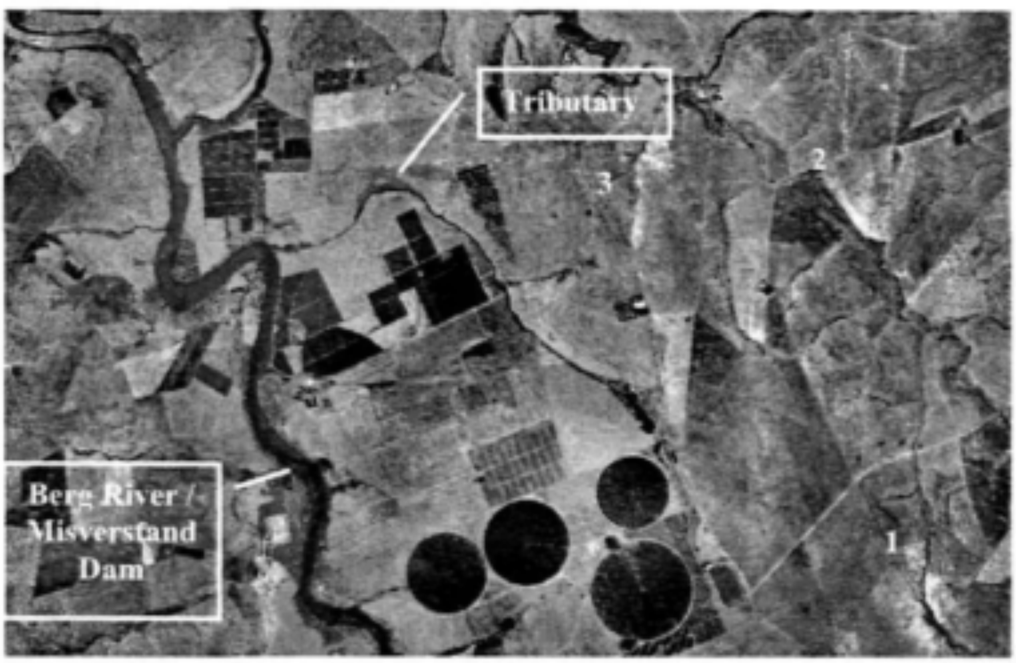

Fig. 33. High-resolution aerial photograph of the Rooihoogte sub-catchment, serving as a land use map

Fig. 34. Normal colour aerial photograph sensitised to salinity in the Rooihoogte sub-catchment. Darker colours are an indication of potentially more saline areas

In Figure 34, the red coloured, numbered patches on the eastern side of the photo are saline spots. These drier, highly saline areas usually have very little vegetation cover and the surface visibility is enhanced by salts that occur as a surface efflorescence (Figure 33). Three of these spots are enlarged and are shown in Figure 35.

4.5 Mapping the Broodkraal sub-catchment

Mapping the Broodkraal sub-catchment followed a similar rationale and approach to that of the Rooihoogte sub-catchment, since Görgens *et al.* (2002) also reported data on irrigation return flow and the quality of water in this tributary. The salinity image compared favourably with the sampling positions reported by Görgens *et al.* (2002). Figure 36 presents land use information in the form of a recent aerial photograph. Here we needed to distinguish only between irrigated and non-irrigated land. Sections of the salinity map of the Broodkraal farm (Figure 37) showed a marked resemblance to the EC map produced by Görgens *et al.* (2002).

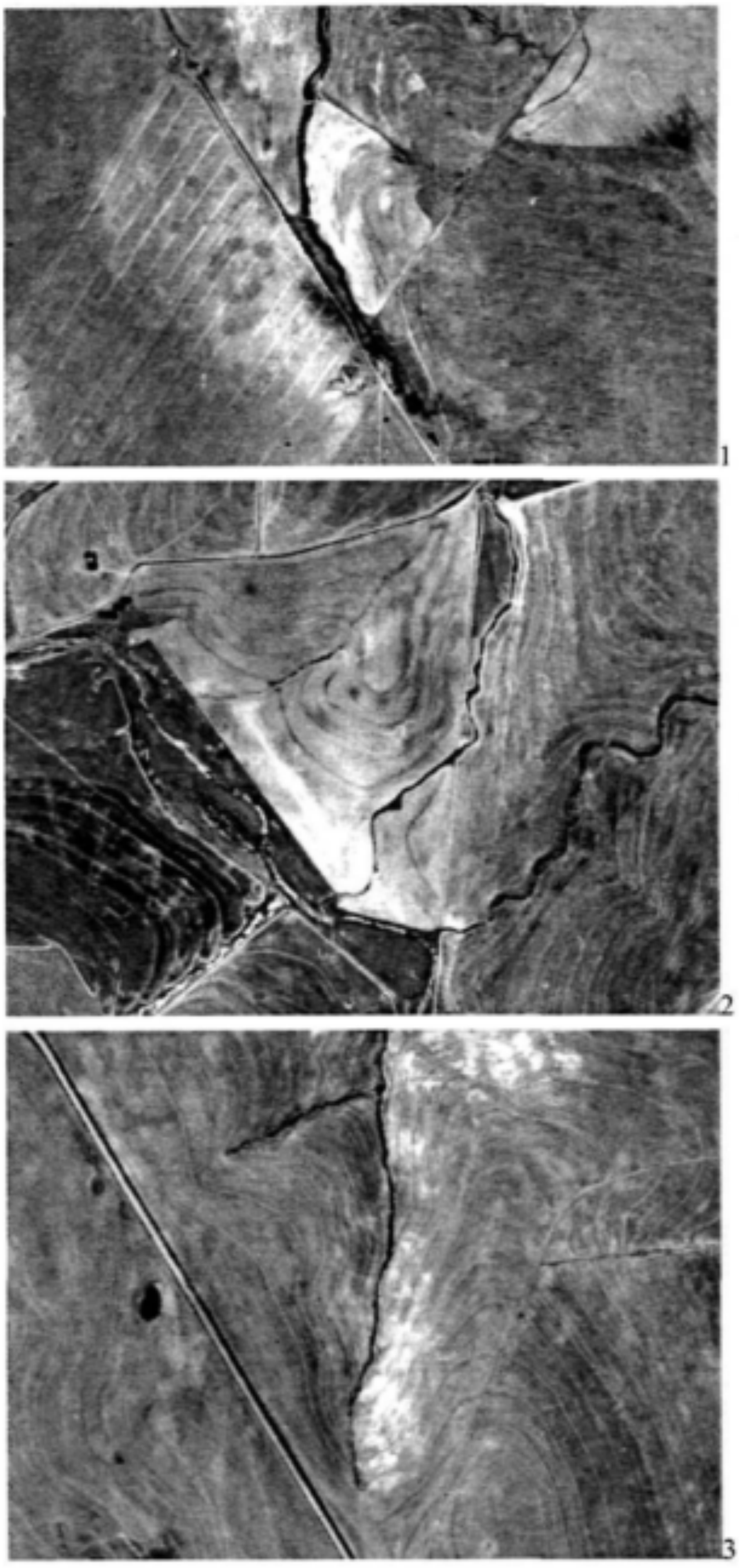

Fig. 35. Enlarged images of salt affected barren patches (numbered 1 to 3 in Figs. 33 and 34) in the Rooihoogte sub-catchment

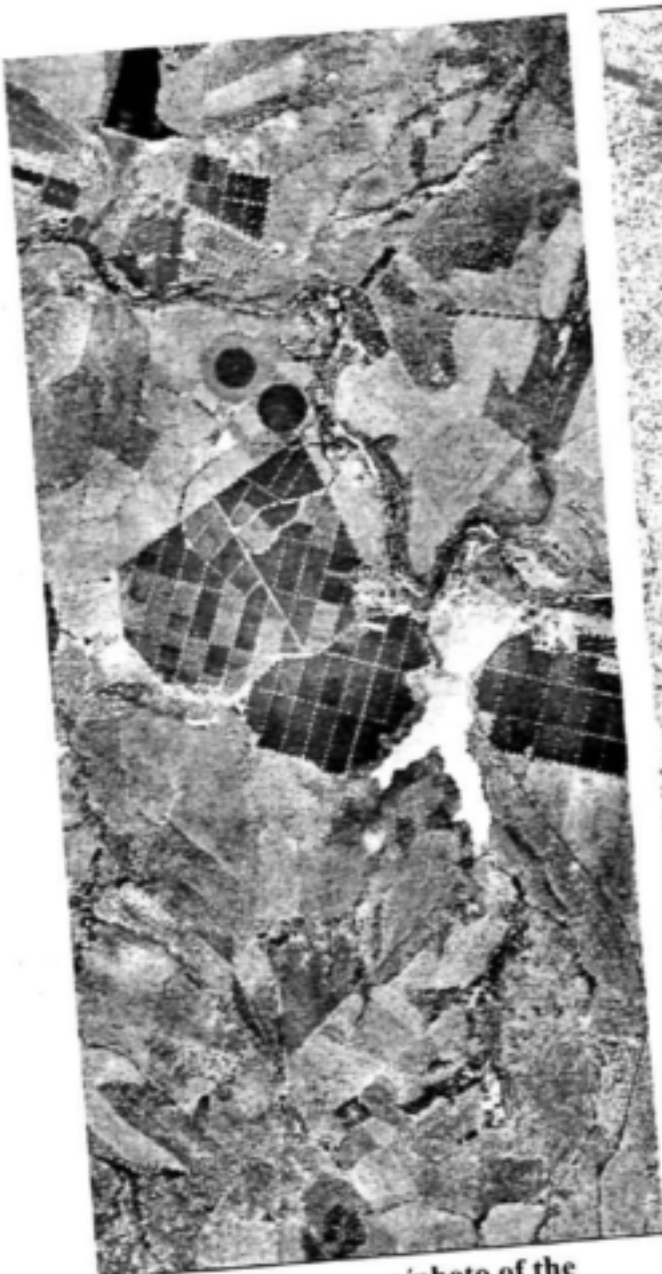

Fig. 36. Land use map/photo of the Broodkraal sub-catchment

Fig. 37. Normal colour, aerial photograph derived salinity image of the Broodkraal sub-catchment

4.6 Defining units for mapping salt in the landscape and modelling runoff

4.6.1 Developing a salinity mapping approach

The map of a small catchment is presented in Fig. 38 to illustrate the results of runoff modelling. The areas with slopes between 0 and 2^o and above 2^o are clearly demarcated. In some places the 2^o line corresponds closely to a change in soil type.

From Figure 39 it is clear that salinity is also related to slope. Figure 40 presents the slope information overlain over the EM38 map presented earlier, confirming this relationship.

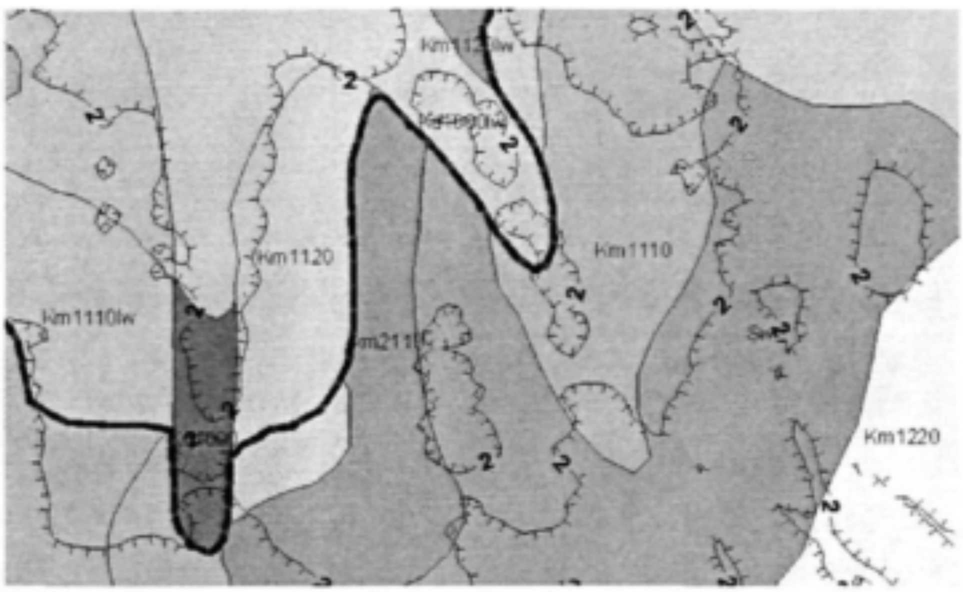

Fig. 38. The Glenrosa sub catchment showing terrain classes (direction of hatches showing zones with less than 2 degree slope) superimposed on the soil map

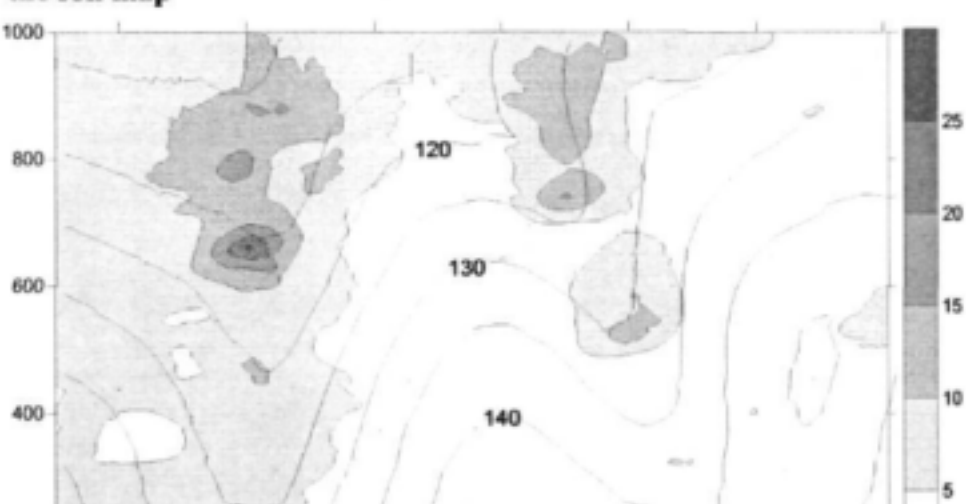

Fig. 39. EM 38 derived salinity map of the Glenrosa sub-catchment overlain by the topography (distances in m; EC_{em38} represents electromagnetic induction values)

The soil map of the same area is shown in Figure 40, with a single isoline derived from an EM38 survey of the region. The broken line, almost following the isoline, was drawn from field data collected during soil mapping. This line was used to demarcate the limit for vine cultivation. Areas to the north of this line were considered unfit for viticulture. The EM38 data effectively mimic this line (EM of 7.5 roughly equates to an EC_e of 150 mS m^{-1}). Figure 41 confirms that this salinity demarcation correlates with topography, strengthening the expectation that existing maps could be used for the extrapolative calculation of salt quantity stored in the catchment.

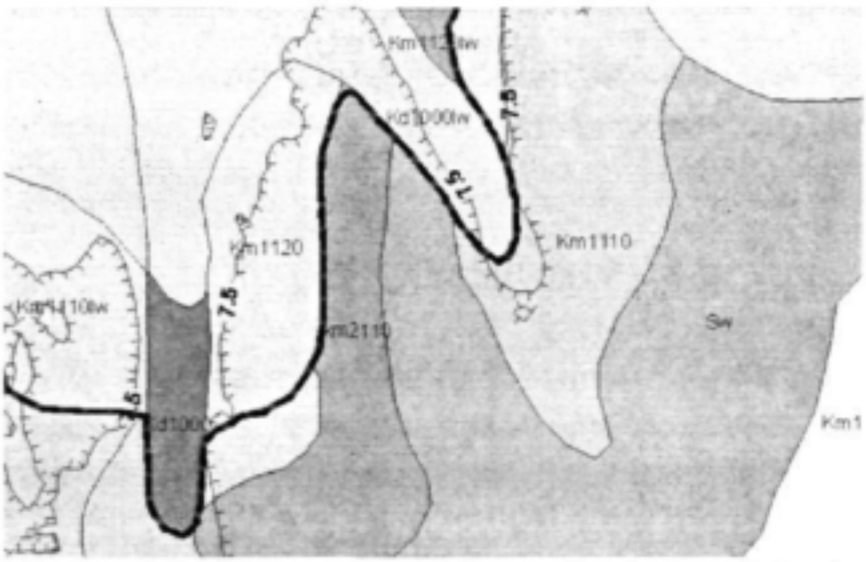

Fig. 40. Soil map of the Glenrosa sub catchment showing a salinity threshold line based on EM38 field measurements

Fig. 41. The 2° slope threshold line (blue) and the EM38-based salinity threshold line (red) for the Glenrosa sub catchment with the direction of hatching showing areas with less salinity (red) and areas with smaller slope (blue)

At this stage it is not feasible to prepare a salinity map for the whole Berg River catchment since not all the DWAF images are available. Furthermore, high resolution DEM data for the whole catchment could not be secured for the project since the current database consists of a 20m height resolution, which is inadequate (too coarse) and was also too expensive for the project.

The preparation of a salinity map will in any event be complicated. As elevation decreases in a down-river direction, for example, free salts become more widely distributed in the landscape. This means that a model has to be developed that evaluates the DEM data, seeks local high points in the landscape and models the tendency for salt to occur down-slope from the local high point. A routine of this kind can also be written to distinguish valleys (concavity) from ridges (convexity), with the former being expected to show a more intense accumulation of salts than the latter. To quantify the distinction, however, would probably require a detailed hydrological investigation of small-scale catchments.

4.6.2 Critical ACRU modelling parameters

ACRU is generally seen as an agro-hydrological model and the hydrological term ***runoff*** is extensively used in the program as well as in all the supplied terminology. It is therefore important to emphasise that the term runoff is an all-inclusive term (*sensu lato*) relating to a catchment, including surface runoff, throughflow and interflow and thus including all water that can be measured by a weir at a suitable low point in the catchment.

The range of inputs needed to run the ACRU model has been summarised earlier in Figure 2. For present purposes such as the estimation of vegetation effects on runoff, the model can be made to focus on simple, one-dimensional water movement through a soil profile. There is ample room to define soil information (especially relating to texture and water holding capacity) although there is still scope for finding ways to include the effect of surface roughness and soil crusting on the proportion of water that infiltrates the soil. The model includes a recently developed soil salinity module which, however, is still provisional and was therefore not available for testing. The inputs that were critical for the present study are described below.

4.6.2.1 Crop factors

Recently revised crop factors for both winter wheat and renosterveld were compared with values normally used in this region (Table 4) and it was found that the standard crop factor for winter wheat peaked at the wrong time of the season. Although referred to locally as winter wheat it is in fact autumn wheat and the crop factor peaks in July rather than in October. Both sets are included, however, to demonstrate the large differences that can result especially when there is a change in the seasonal rainfall pattern. The summer crop factor of 0.2 for wheat is designed to account for grasses that continue to grow during summer, together with evaporation from the bare soil surface.

Table 4. Crop factors for wheat and renosterveld used in the ACRU model

Vegetation type	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Winter wheat	.20	.20	.20	.20	.20	.20	.20	.30	.50	.60	.40	.20
Autumn wheat	.20	.20	.20	.20	.30	.50	.60	.40	.20	.20	.20	.20
Mountain renosterveld	.30	.30	.30	.30	.50	.40	.30	.30	.30	.30	.30	.30
Coastal renosterveld	.40	.40	.40	.45	.50	.50	.50	.50	.50	.45	.40	.40

4.6.2.2 Soil properties

The input of soil information makes use of the national inventory of land types, whereby the database for the ACRU model includes a set of derived, representative soil physical properties for each land type. Specifying the land type is therefore sufficient to ensure the input of meaningful soil data. It will be necessary to revise these soil physical variables, however, when full-scale modelling of the Berg River catchment is attempted.

4.6.2.3 Weather data

The ACRU model has its own climate database drawn from South African Weather Bureau records and will generate a climate record interpolatively from existing stations. An 80-year record of daily rainfall and evaporation was generated for each of the three farms.

4.6.2.4 Soil surface condition

In order to compare runoff *sensu lato* between renosterveld and wheat lands there was assumed to be no difference in surface roughness. Although there will be a difference, one of the deficiencies of the ACRU model lies in the fact that it largely ignores surface mulches (gravel or crop residue) and crust-forming tendencies (soil structural disintegration and surface sealing under raindrop impact) and the effect that these are likely to have on water infiltration. The implications can at least be anticipated qualitatively, however, and an attempt is made to do this in the concluding section of the report.

4.6.3 Modelling results

Comparative runoff for the two vegetation types (each with two sub-types as indicated in Table 4) was calculated on three farms: the Boland Landbou Skool (BLS, near Paarl mountain), Heldervue (near Broodkraal, Piketberg) and Rooihoogte (near

Porterville). It is important to mention that Heldervue was chosen for its location in the Piketberg range. The rainfall here is one of the highest measured in the Berg River catchment.

Because the rooting depth of renosterbos (*Elytropappus* sp., the dominant component of renosterveld) may extend to at least 4m, a number of model runs were performed to illustrate the effect of rooting depth. The results are presented firstly on an annual basis, secondly as monthly trends, and thirdly to illustrate the sensitivity of the calculations to soil depth.

4.6.3.1 Annual runoff

The results in Fig. 42 show consistently greater predicted annual runoff from wheat lands than from natural renosterveld at all three sites. Fig. 43 indicates similar relative differences when the data are presented as ranges and as means rather than median values for the 80-year period. The relative difference is greatly magnified under more arid conditions (Rooihoogte). The choice of crop factors for early, as opposed to standard winter wheat and for coastal, as opposed to mountain renosterveld makes little difference to the comparison between the two vegetation types. The negligible annual runoff under renosterveld at Rooihoogte is consistent with the naturally saline character of most of the regolith at this location (salic, gypsic and calcic horizons and duripans or dorbank are common in the Aridisols in this driest part of the Berg River catchment, providing a clear pedogenic indication of minimal natural leaching).

Wheat cultivation at Rooihoogte would be expected to shift the hydrological balance dramatically in favour of leaching of soluble salts. Although the magnitude of increased runoff under wheat relative to renosterveld is greater at the two higher rainfall localities (Heldervue and BLS), the relative increase is smaller and, at such locations, the soil mantle is likely to be less saline (as suggested by the calculation of significant runoff even under natural vegetation) and so the potential for wheat cultivation to cause salt discharge from the regolith in these higher rainfall parts of the catchment will be smaller. The hypothesis that clearing of indigenous vegetation to cultivate wheat in the Swartland has given rise to enhanced discharge of salts from the catchment is supported by these preliminary calculations using the ACRU model.

4.6.3.2 Monthly runoff

In Figures 44-47 the results are presented on a monthly basis for the three sites. The pattern is essentially the same as that indicated by the annual data. The enhanced runoff under wheat compared with renosterveld is consistent across all months of the year at all three sites.

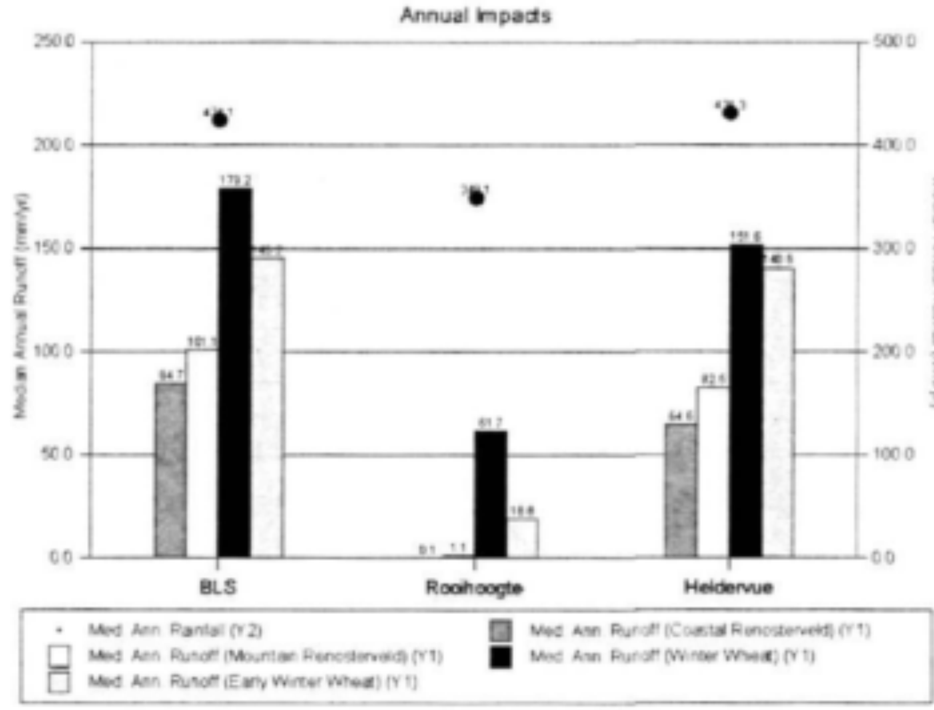

Fig. 42. ACRU-calculated annual runoff from four vegetation types in relation to rainfall at three sites (80-year median)

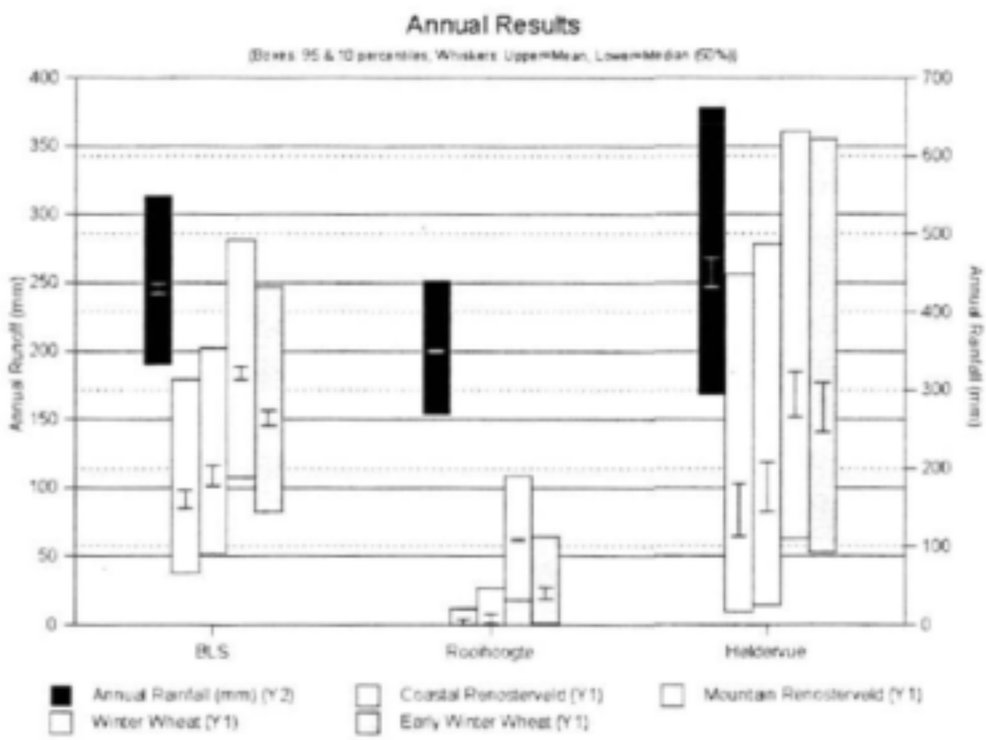

Fig. 43. ACRU-calculated range (10-95 percentiles) in annual runoff over 80 years from four vegetation types in relation to rainfall at three sites (whiskers show range from median to mean)

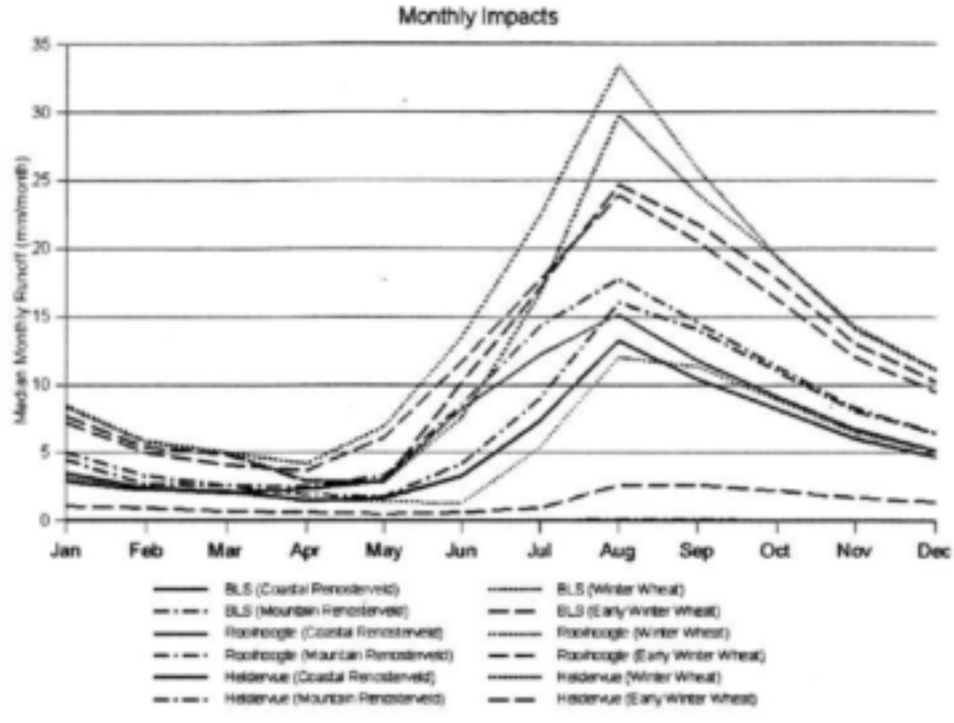

Fig. 44. ACRU-calculated monthly runoff from four vegetation types in relation to rainfall at three sites (80-year median values)

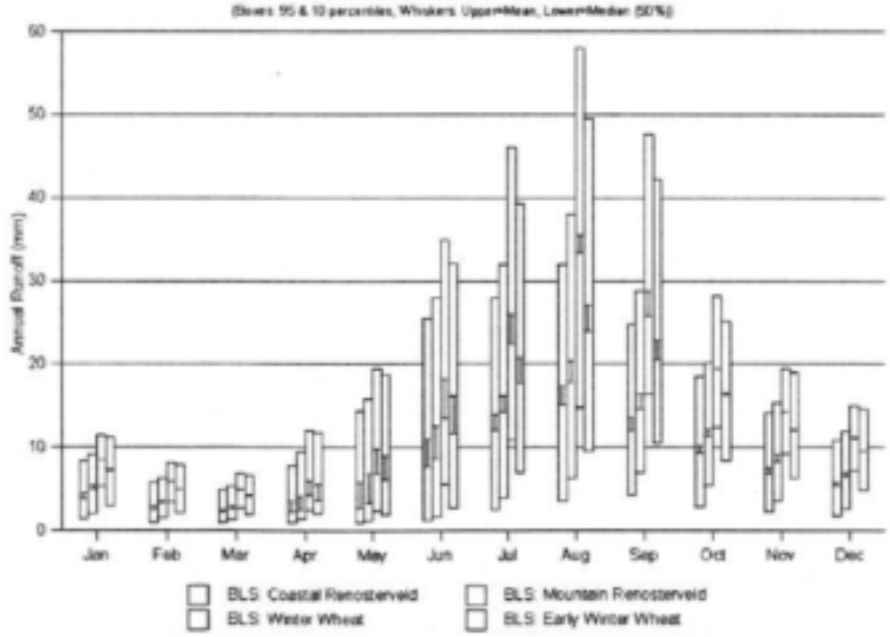

Fig. 45. ACRU-calculated range (10-95 percentiles) in monthly runoff over 80 y from four vegetation types in relation to rainfall at BLS farm (whiskers show range from median to mean)

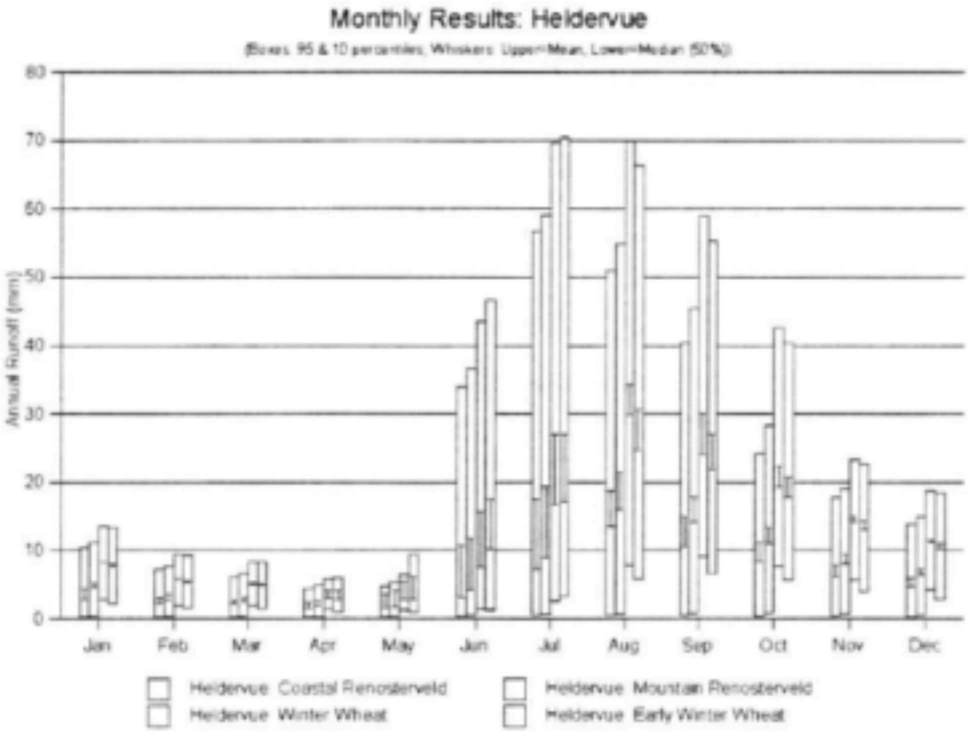

Fig. 46. ACRU-calculated range (10-95 percentiles) in monthly runoff over 80 y from four vegetation types in relation to rainfall at Heldervue farm (whiskers show range from median to mean)

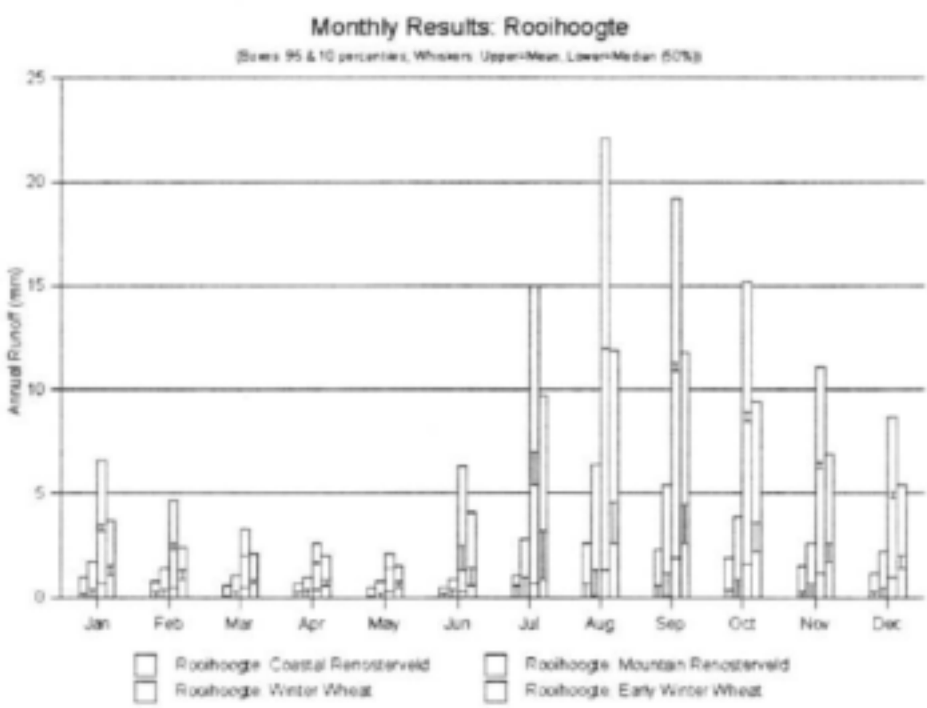

Fig. 47. ACRU-calculated range (10-95 percentiles) in monthly runoff over 80 y from four vegetation types in relation to rainfall on Rooihoogte farm (whiskers show range from median to mean)

4.6.3.3 Runoff in renosterveld in relation to rooting depth

Allowing soil depth available for rooting to vary from 0.3 to 2 m has a large influence on calculated runoff from renosterveld (Fig. 48). Given the perennial and deeply rooting character of renosterveld plants and the annual, shallower rooting nature of the wheat crop, these calculations suggest that if differences in rooting depth and activity are taken into account, the calculated runoff enhancement under wheat cultivation could be even greater than suggested above. The input file used to generate the results in Figure 48 with the ACRU model is given in Appendix C.

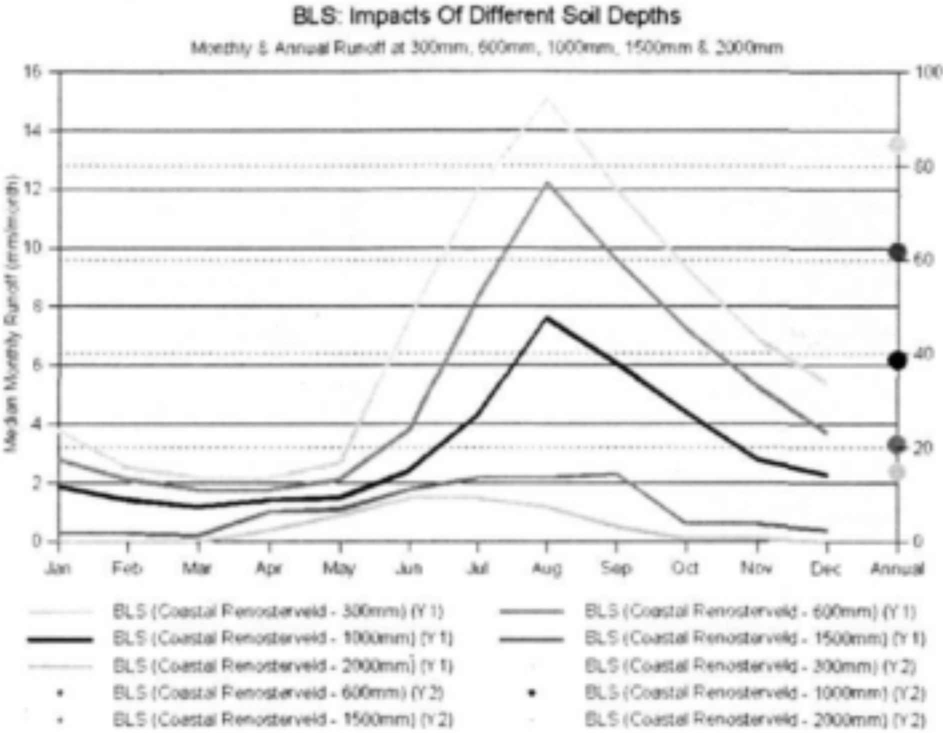

Fig. 48. ACRU-calculated median monthly (lines) and annual (points) runoff over 80 y at the BLS farm, in relation to soil depth under renosterveld

Among other factors likely to affect the comparison of runoff from wheat and renosterveld, soil surface condition (structure, mulch effects of plant litter and gravel, and the tendency for clay dispersion and crusting) is likely to be very important. At this stage we have not distinguished between surface runoff (overland flow) and interflow or through flow in our calculations. The opportunity for runoff to dissolve and transport soluble salts will be greatly affected by infiltration, and unfortunately ACRU is not well designed to accommodate sufficient information (besides surface roughness and bulk density parameters) to be able to accurately predict infiltration rate. Qualitatively, because the canopy of winter wheat is at its most dense during the rainiest months, infiltration under wheat is likely to be greater than under renosterveld. On the one hand this will affect the discharge of salts from the regolith but it will also reduce evaporative losses under renosterveld because the water content of the root zone will be lower than under wheat. This complexity will have to be unravelled before runoff calculations can be employed as a basis for calculating salt discharge from the catchment. Of particular importance in refining the use of ACRU for making such calculations is finding a way to quantify how soil properties (texture, mineralogy, salinity and organic matter) interact with land use practices to affect clay dispersion and the tendency of the soil surface to disintegrate and seal upon raindrop impact (usually termed crusting). This should become an objective of future hydrological studies in small-scale catchments in the region.

4.7 Catchment scale salinity assessment

4.7.1 Factors related to water quality

In this section the water quality data from two sources were mapped and presented against a backdrop of geology, climate and soils of the catchment. The aim was to see whether, by mapping all the information together, the origin of salinity in the landscape can be better understood, especially in the context of long term monitoring records.

The main data sources used in this section were the water quality database of DWAF, information provided by Fourie (1976) and the borehole database currently under construction by DWAF. The soils database and land use map presented by Görgens *et al.* (2002), the published 1:250 000 geological map, and climate data from the Weather Bureau were employed for constructing backdrops to the water data.

Salinity and other water quality characteristics of the Berg River catchment have been monitored by DWAF for the past 30 years. Measurement points used by Fourie (1976) are indicated in Figure 49 and their salinity values are shown in the figures that follow. It is clear from Figure 49 that the major focus has been on the middle section of the BRC. Further upstream, the river drains largely from a higher rainfall region with quartzitic rocks and a non-saline regolith, resulting in low salinity. Downstream of the Misverstand dam the water quality is very poor and the demand is very small.

The monitoring stations are listed in Table 5 together with the period of monitoring. Points with a prefix G1H are located on tributaries and the main channel, while dams are indicated by G1R. In Figures 50-52 the salinity at each station is plotted as a moving average (generally the period for averaging was less than 2 months).

Fig. 49. DWAF water quality measurement points located in the area studied by Fourie (1976)

Table 5. DWAF water quality monitoring stations and periods in the Berg River catchment

DWAF point	Begin year	End year
G1H008	1973	2003
G1H009	1974	2003
G1H010	1974	2002
G1H011	1977	2002
G1H013	1973	2003
G1H021	1976	2003
G1H028	1973	2002
G1H029	1973	2003
G1H031	1974	2003
G1H034	1973	2003
G1H035	1973	2003
G1H036	1978	2003
G1H039	1979	2003
G1H040	1980	2002
G1H041	1979	2003
G1H043	1980	2003
G1H065	1973	2003
G1R001	1973	2003
G1R003	1977	2003

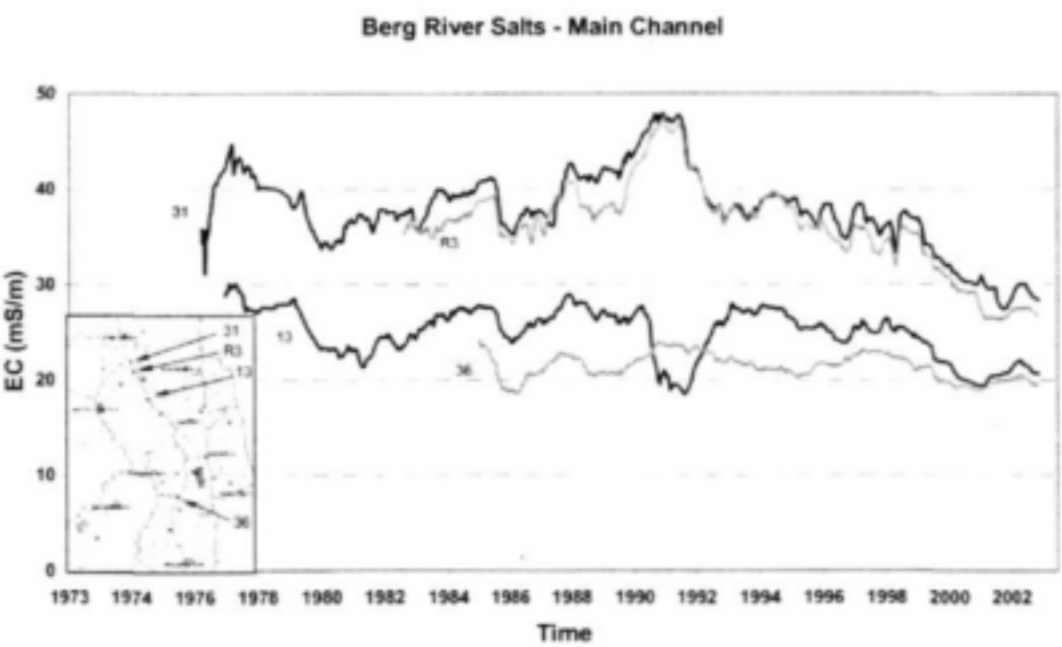

Fig. 50. Salinity trends over 25 y (~ 2 month moving average) in the Berg River main channel

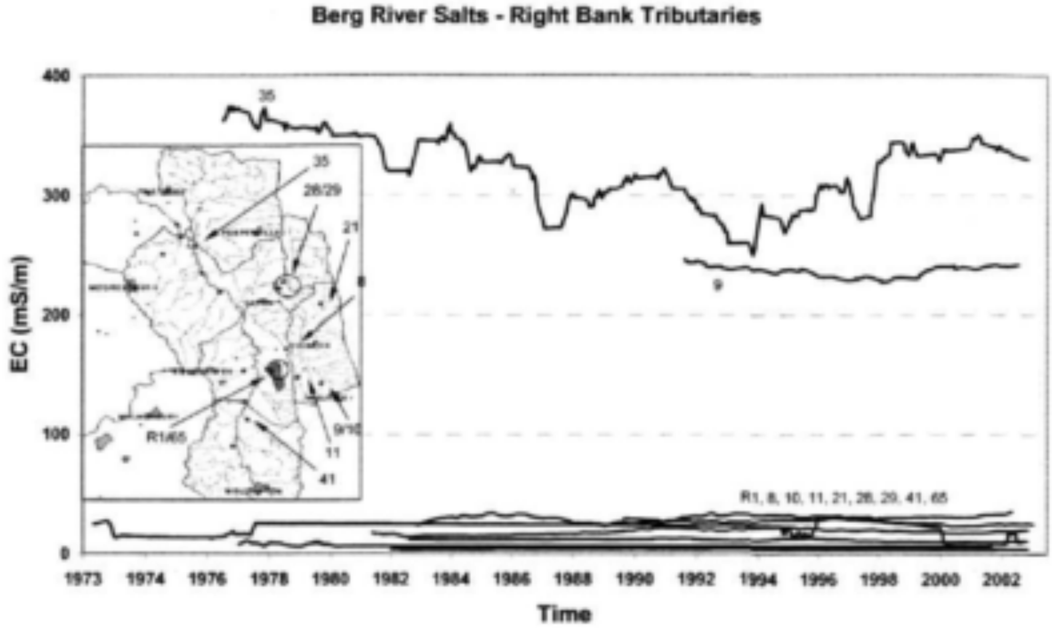

Fig. 51. Salinity trends over 25 y (~ 2 month moving average) in right bank tributaries of the Berg River

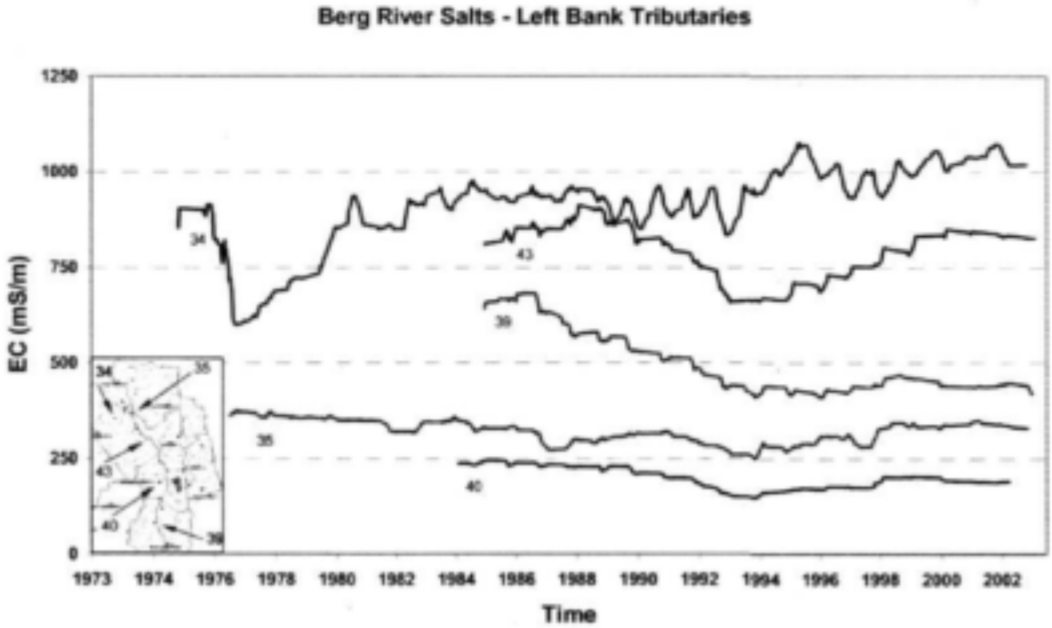

Fig. 52. Salinity trends over 25 y (~ 2 month moving average) in left bank tributaries of the Berg River

Salinity trends in the main channel (Fig. 50) show an upward trend peaking in about 1992 after which there is a reversal in the trend, presumably as a result of dilution from the Theewaterskloof tunnel.

Most of the right-bank tributaries (Fig. 51) have a low salinity reflecting their origin in more leached mountain catchments. The exception is Station 9 for which there is no ready explanation. Station 35 is on the Krom River, which directly enters the Misverstand Dam, draining an extensive area of semi-arid wheat lands in the vicinity of Porterville, Eendekuil and Piketberg. Interestingly, the trend in salinity was distinctly downwards between the mid-1970s and mid-1990s, after which it increased almost to its original level. The data for station 35 are plotted again in Fig. 52 for comparison with the four stations sited on left-bank tributaries. Of these four stations, three show a trend similar to that of station 35 with a salinity minimum in the mid-1990s, suggesting that a regional climatic influence may have prevailed. Station 34, on the other hand, which reflects an extensive sub-catchment in the Moorreesburg region (with mainly dry land wheat cultivation), not only shows a progressive upward trend over the whole monitoring period but is the most saline of all the tributaries. A careful analysis of these trends in relation to climate and land use changes would be very instructive. No attempt has been made to assess the salt load reflected in these trends and the extent to which they impact on water quality in the main Berg River channel. If station 34 can be taken as representative of lower left-bank tributaries, however, it can be concluded that the worsening of the salinization problem since the publication of the study by Fourie (1976) has probably been augmented by salt discharge from dryland farming areas.

This conclusion is supported by Flügel (1995), whose study focused on the Sandspruit River, one of the left-bank tributaries monitored by DWAF (station 43 in Fig. 52). From a single year of hydrological measurements (1986), Flügel estimated that about 8000 tons of salt discharged into the Berg River, mostly during the rainy months of July and August. As much as a quarter of this salt load was accounted for by atmospheric inputs, measured with bulk deposition samplers, with the remainder having come from salts stored in the regolith and groundwater. Flügel (1995) implied that this amounted to an effect of dryland agriculture on river salinization, although it could be argued that if much of the regolith and groundwater salts are a legacy of past inundation by the sea (as discussed by Wiplinger, 1980) and subsequent incomplete weathering and leaching, then the output of salts might simply be described as a natural phenomenon that would have occurred with the same intensity under renosterveld vegetation. This is why land use changes need also to be examined, and their influence on the hydrological cycle estimated through modelling.

4.7.2 Assessing the salinity contribution from sub-catchments

In the study by Fourie (1976), water samples were taken during the winter rainy season of 1973 at about 180 points on tributaries of the Berg River. The river segments corresponding to the sampling positions can be plotted in a GIS using line thickening to give a visual impression of where the most saline waters originate (Fig. 53). In Fig. 54 the same information is presented against a geological backdrop. The impression that salinity in the catchment is associated mostly with Malmsbury Group rocks is largely confirmed. Figure 55 presents a similar geological picture in terms of stratigraphy rather than lithology.

Fig. 53. ArcView image of the Berg River catchment showing salinity classes of tributary segments based on data of Fourie (1976).

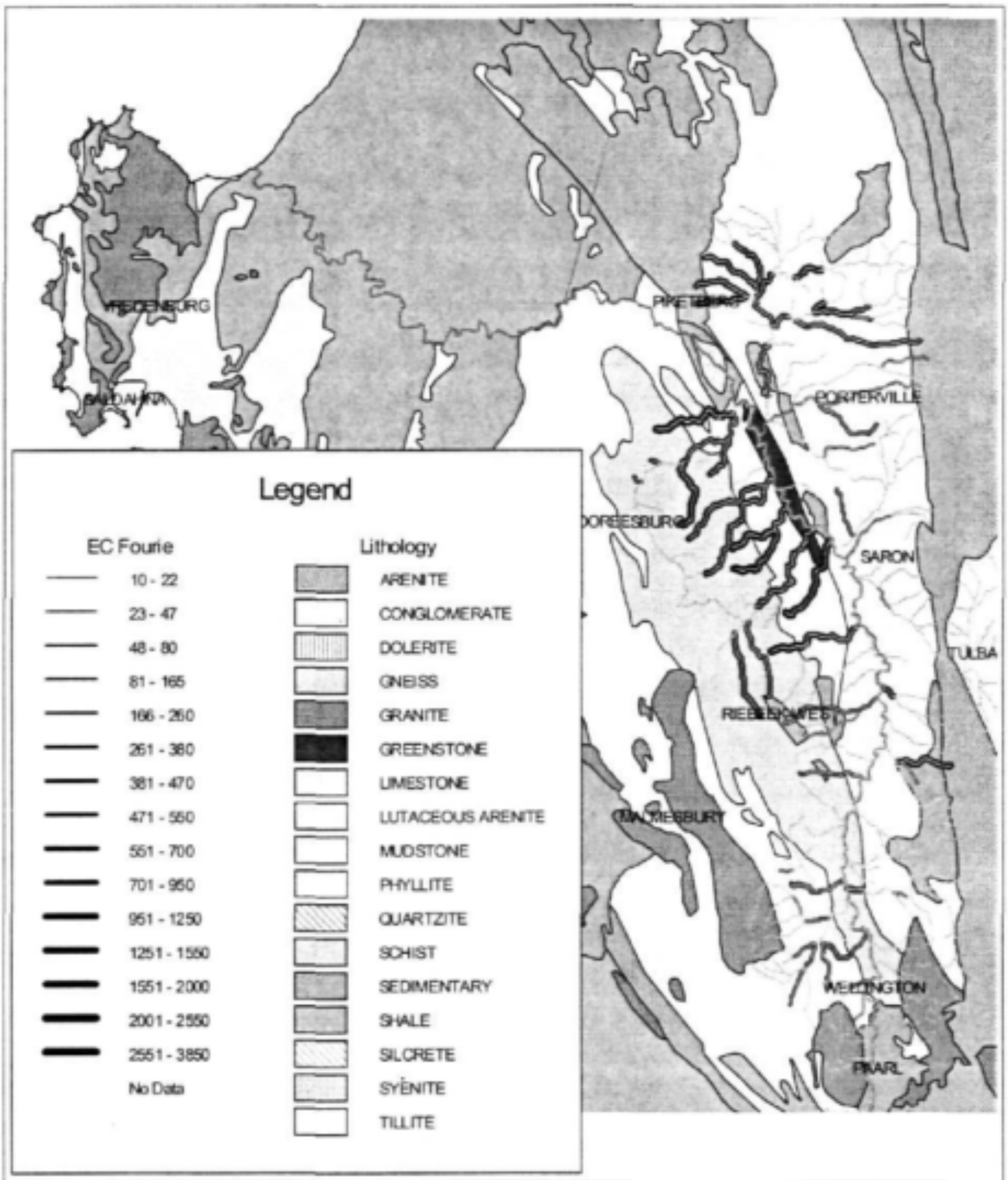

Fig. 54. Salinity classes of tributary segments based on data of Fourie (1976) in relation to geology of the Berg River catchment

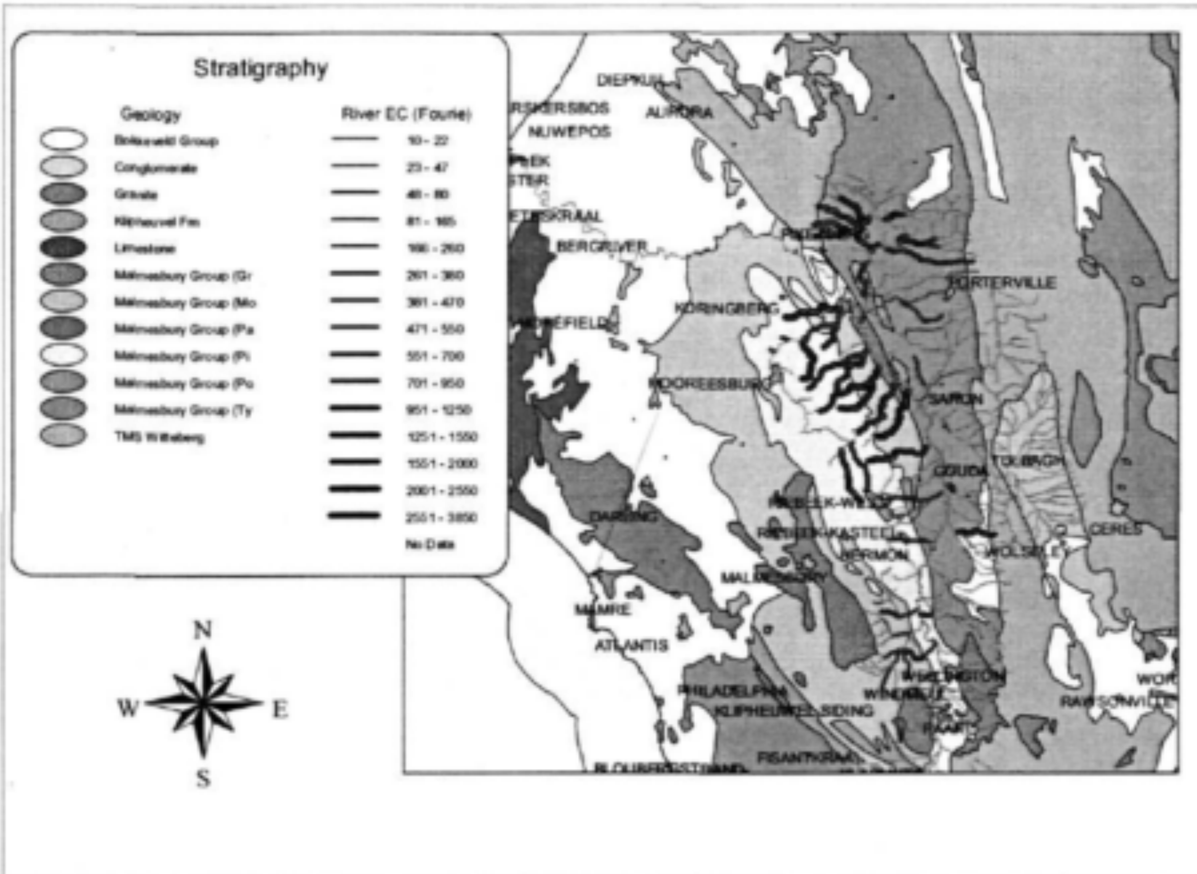

Fig. 55. Salinity classes of tributary segments based on data of Fourie (1976) in relation to geological stratigraphy of the Berg River catchment

While geological factors no doubt contribute to the distribution of salts in the landscape (and here particular cognisance should also be taken of Wiplinger's (1980) comments that the salts possibly represent a residue from oceanic submergence of the coastal plain), a compelling case can nevertheless be made for a climatic effect that is strong enough to override these geological factors. An aridity map of the catchment was prepared from Weather Bureau data (Figure 56). Comparison with Figure 55 indicates that Malmesbury group rocks are for the most part confined to the more arid lower elevations in the catchment, whereas the Table Mountain Group sandstones and quartzites are relief-producing and predominate in elevated terrain with a much higher rainfall. Although groundwater data are sparse for the lower Berg River catchment, at the time of writing this report an atlas of groundwater data for the Berg River catchment was published from which Figure 57 has been prepared, showing that the more saline ground waters (shaded dark green, blue and red) occur in the more arid parts of the catchment. A similar distribution of saline soils and regolith materials to that of saline ground water can be expected.

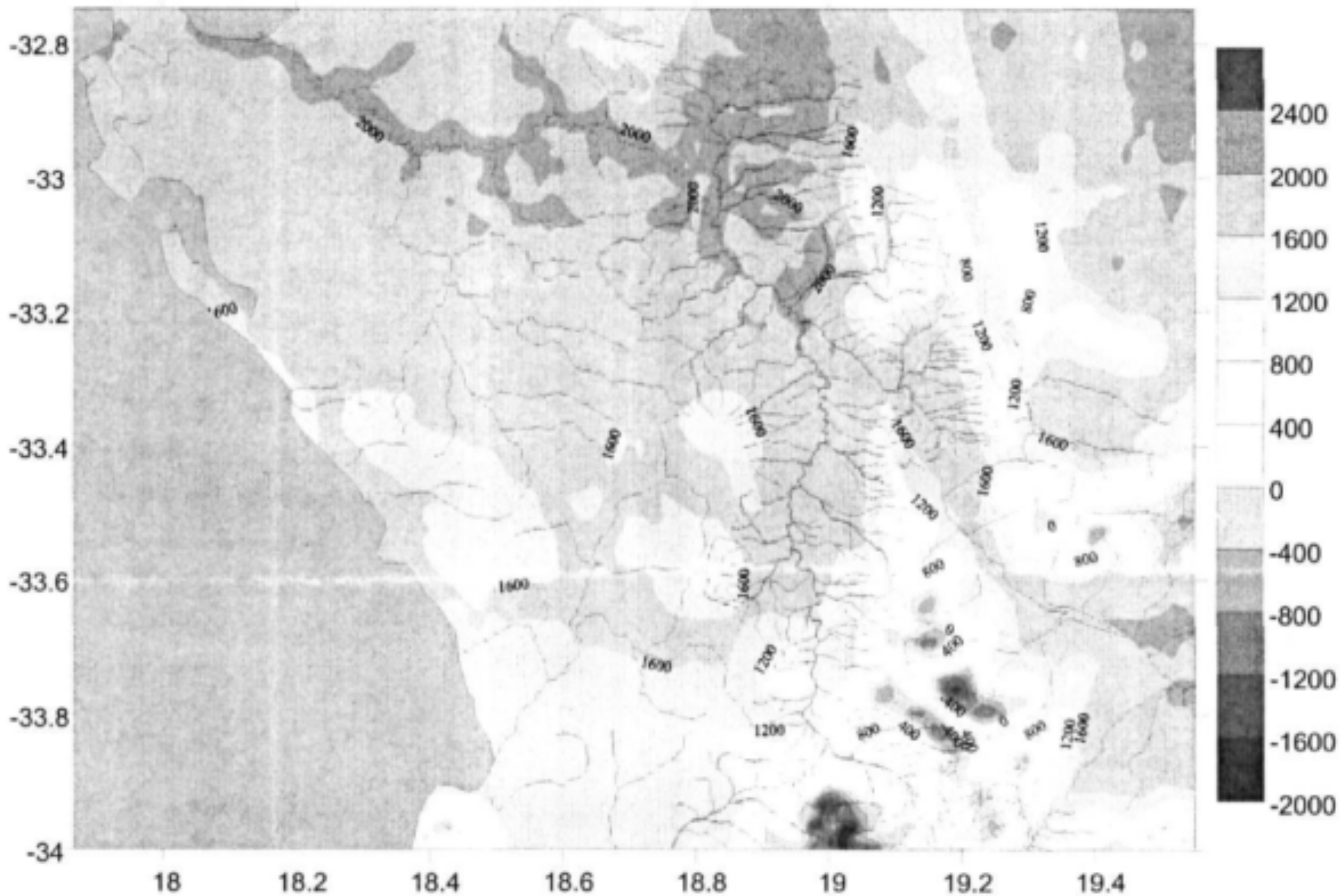

Fig. 56. Aridity map of the Berg River catchment (index generated from Weather Bureau data calculated as mean annual evaporation less mean annual precipitation)

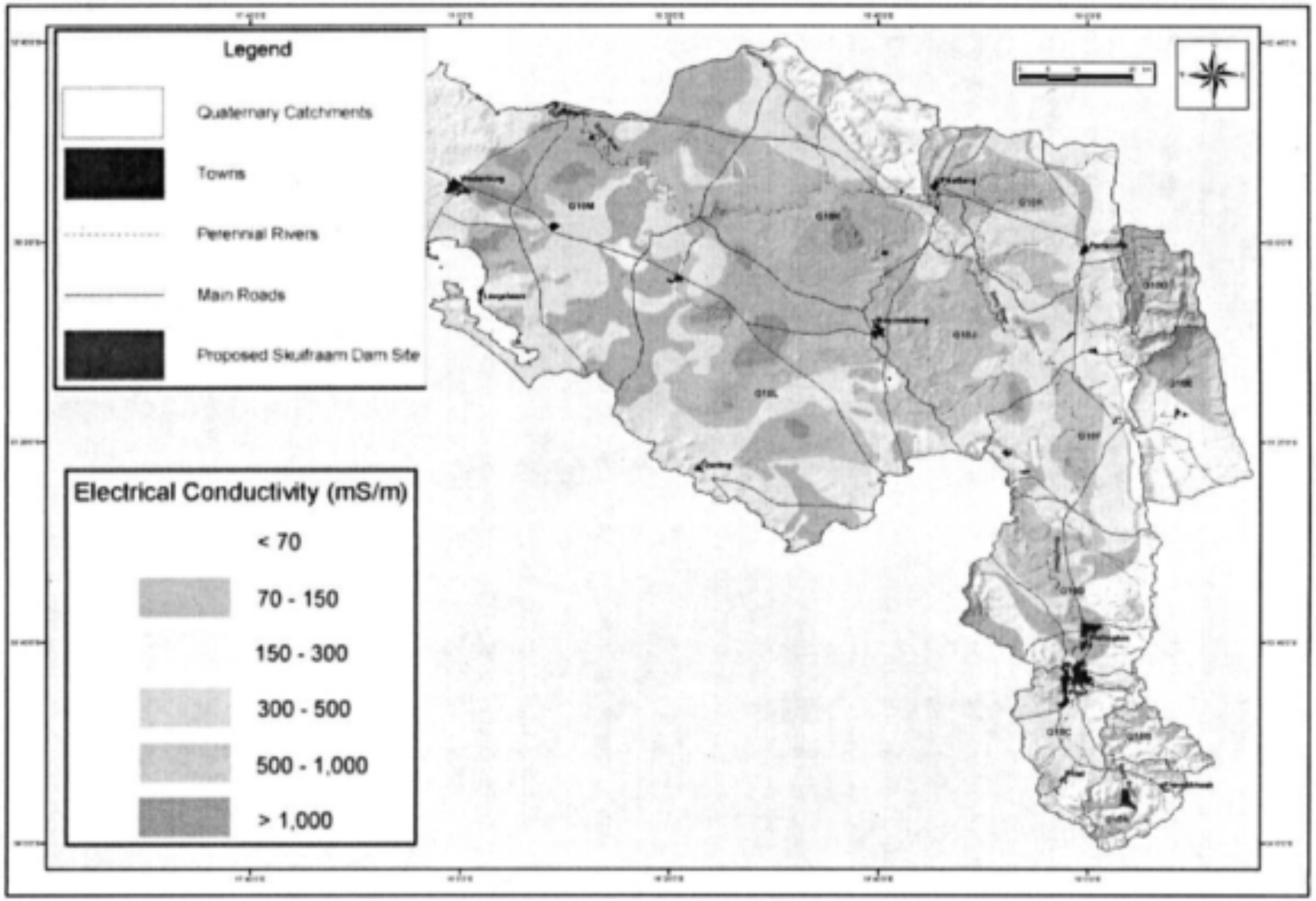

Fig. 57. Groundwater salinity map of the Berg River catchment (courtesy of Roger Parsons and Associates, 2004)

Certainly if circumstantial evidence on the distribution of saline soils and ground waters is considered, the correlation with rainfall is very strong. The fact that so few of the east bank tributaries are saline despite draining semi-arid areas with widespread soil salinity is probably due to their flow coming predominantly from relatively well watered mountain catchments on the eastern east flank of the valley where the regolith is regularly leached of free salts. By contrast the west bank tributaries towards the lower end of the catchment mostly emanate from areas of low rainfall, where saline soil (or at least regolith) and groundwater are the rule rather than the exception. Here again Flügel's (1995) measurements and calculations are a valuable guide to the likely salt balance, especially when considered in conjunction with the results of ACRU modelling for different vegetation types. In 1986, the Sandspruit catchment had rainfall (325 mm) close to average, of which only 3.5% (11 mm) was discharged as runoff into the Berg River, along with 8000 tons of salt from a catchment area of about 150 km^2 (i.e. about 50 kg/ha). Only about 1800 tons of salt (<15 kg/ha) could be accounted for by atmospheric deposition. This means that for the year there was a leaching loss of salt of about 35 kg/ha.

At Rooihoogte, which is adjacent to the Sandspruit across the Berg River and has a similar rainfall, ACRU calculations (Fig. 42) predicted that under renosterveld, water use by vegetation reduces annual runoff to a meagre 1 mm. This increases to 18 mm or more (up to 60 mm) under winter wheat. The figures are not greatly at variance with the measured runoff in the Sandspruit. The proportional increase in runoff from renosterveld to wheat is much less in higher rainfall parts of the catchment, and the increase in contribution to catchment salt load would be smaller still because less salt is stored in high rainfall catchments. (Of course ultimately it is the mass of salt entering the main channel from each tributary that really matters.) This suggests that with increasing aridity, there is an increase both in the salt trapping effect from atmospheric deposition under natural vegetation and in the sensitivity of the catchment to releasing a substantial salt load into the river system when wheat replaces renosterveld. When considered together, Flügel's figures and our ACRU modelling strongly suggest that the main source of salts stored in the basin is atmospheric deposition and that up to three times as much salt can be discharged from the drier catchments under wheat cultivation than under renosterveld. These figures give a useful first approximation of the magnitude of dryland salinity contributions by west bank tributaries to river water quality.

4.8 Using remote imagery to delineate land use and salt distribution

The DWAF colour ortho-photos provide an opportunity for mapping land use in the catchment. Although it was not the intention to accomplish this for the whole BRC, the possibility of doing it was nevertheless explored. As indicated in the ensuing figures, not only can land use be mapped but it is also possible to delineate saline spots. At the time the report was compiled DWAF had released only about a third of the colour images covering the BRC.

The quality of the images is good enough to form a basis for mapping the whole of the BRC in due course.

Certain features can be distinguished from adjusted R-band images. Figure 58 shows differences in vegetation along the banks of the Krom River, the tributary which enters the Misverstand Dam. In Figures 58 and 59 a transect is indicated where soil sampling and EM38 measurements were carried out. The salinity values are shown in Figure 59 indicating that the technique shows some promise.

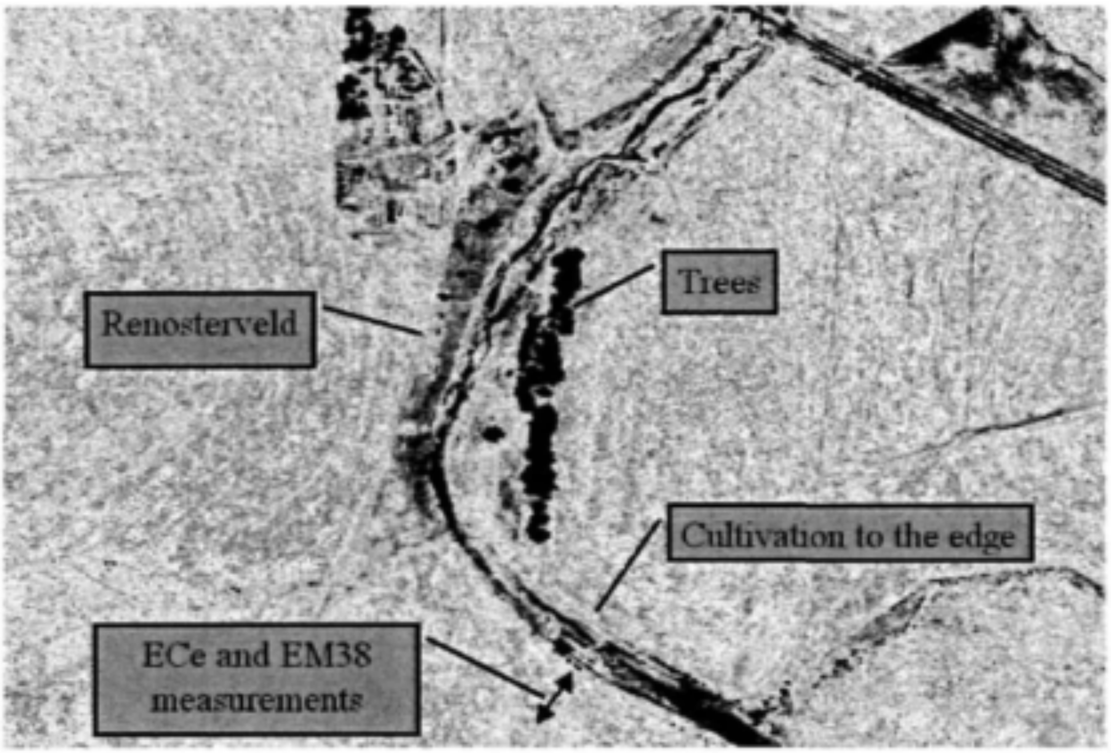

Fig. 58. R-band adjusted image of the Krom River on the farm Bo-Kuile near Piketberg reflecting differences in vegetation on the banks of the river.

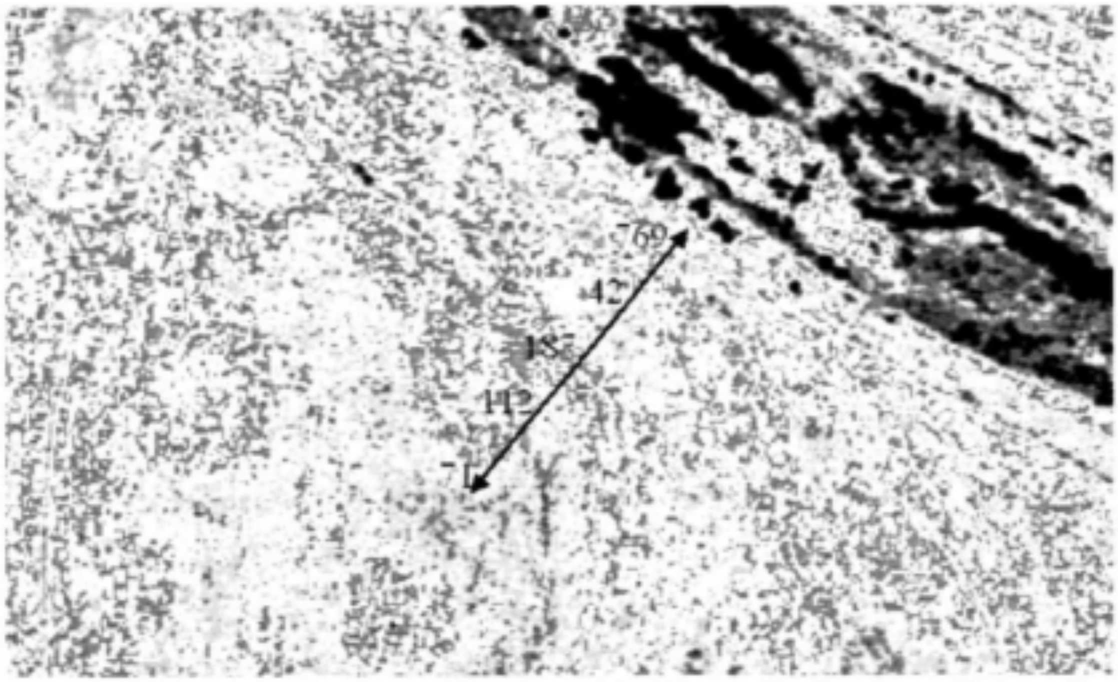

Fig. 59. Enlargement of the transect indicated in Figure 57 showing salinity values based on EC_e and EM38 measurements made in the field.

During the project two sets of oblique aerial photographs were taken from a light aircraft at a height of about 300m. The images were recorded in the later part of the wheat season and were remarkably useful for distinguishing saline areas with poor wheat growth. An example of such an image and its spectral manipulation is shown in Figure 60. A full, annotated compilation of such images is available as an electronic appendix to the report.

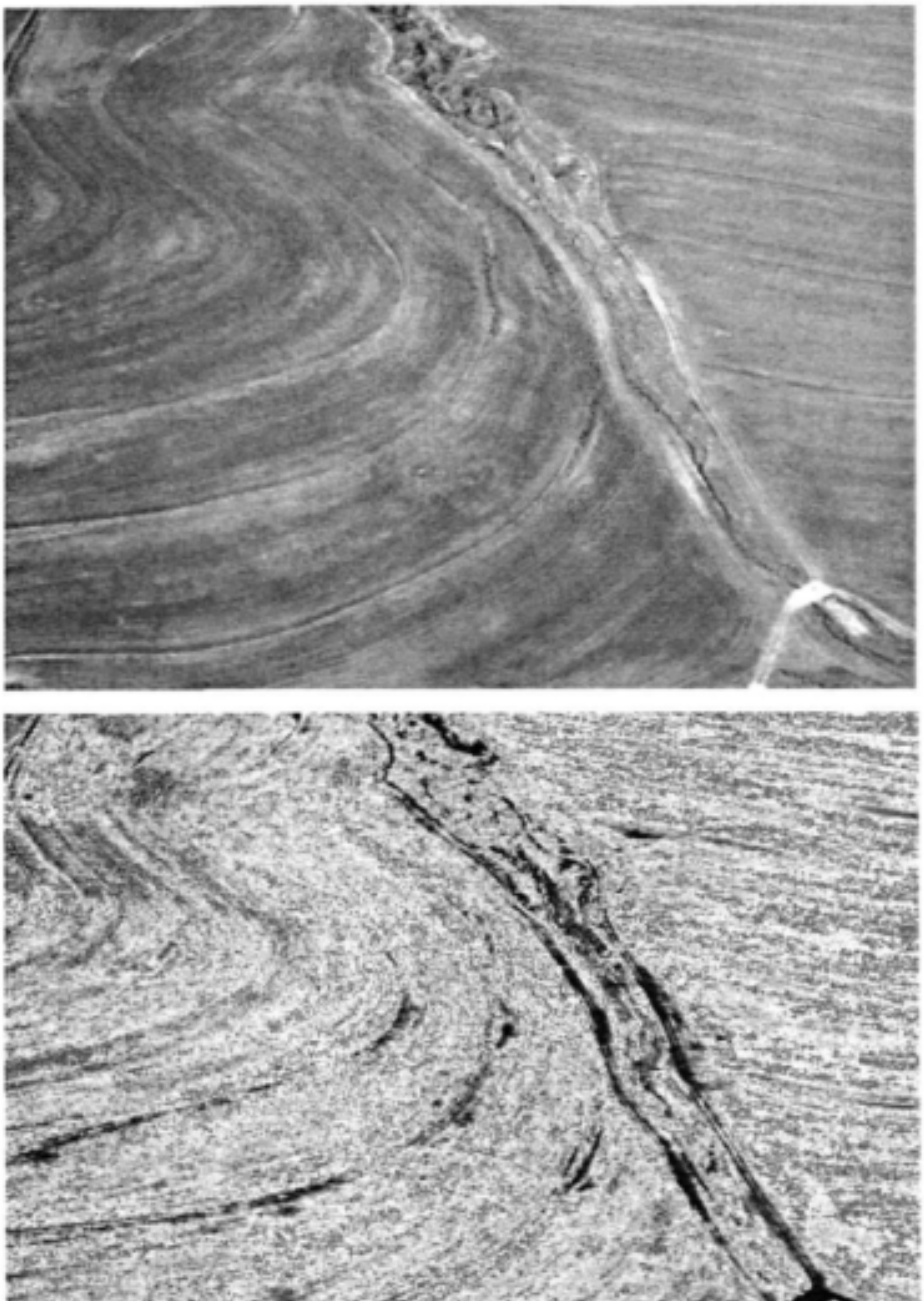

Fig. 60. Oblique aerial photograph of wheat lands taken in October 2003 (above) and its spectral transformation (below). Barren patches (kiewietkolle) are clearly evident in the spectral transformation, in which green pixels represent the median condition of the image.

5 CONCLUSIONS AND RECOMMENDATIONS

This pilot study has confirmed that dryland salinity is extensive in the Berg River catchment and that it probably has a significant impact on water quality in the river. A more detailed study seems justified, aimed at fully understanding and quantifying the problem.

The main conclusions are as follows:

- Remote sensing through aerial photography indicates that there is widespread patchiness in croplands, especially in wheat fields that dominate land use in the catchment.
- Ground truthing by soil sampling and analysis of transects through the barren patches (*kiewietkolle*) at several locations has consistently confirmed that they are associated with soil salinity which is of sufficient magnitude to explain the poor wheat growth.
- Spectral manipulation of new colour ortho-photos that are now available for a portion of the catchment has demonstrated that the bare patches in wheat fields can readily be demarcated, allowing their aerial extent to be quantified.
- Use of a salinity sensor (EM 38) in the field proved to be a successful substitute for detailed soil sampling as a means of quantifying soil salinity and of subjecting its distribution to geostatistical analysis and interpretation in relation to land use and topography.
- Despite the fact that a new, comprehensive database has been assembled by regional water specialists on ground water quality, the records for the drier, more saline sub-catchments of the Berg River remain sparse and are inadequate for establishing a connection between soil or regolith salinity and groundwater salinity. A comprehensive survey of farmers' boreholes will need to be made in future studies.
- Long-term salinity records of selected tributaries of the Berg River have been built up through regular monitoring by the Department of Water Affairs and Forestry since the mid-1970s when the seminal study on salinization of the Berg River was published by Fourie, who recognized that much of the salt load in the river emanated from non-irrigated areas. Analysis of these records indicates that some trends are discernible, although masked by freshening releases of Theewaterskloof water into the Berg River since the early 1990s. The data seem to confirm the importance of climatic (as opposed to paleo-geologic) factors in determining the development of dryland salinity.

- A research team headed by W Flügel undertook an ambitious hydrological investigation of salinity in a representative sub-catchment of the lower Berg River (the Sandspruit) during the 1980s. The project terminated prematurely because of funding difficulties and the results of one year's monitoring (1986) were only published in 1995. Although this study was primarily hydrological and took neither pedogenic processes nor land use factors into serious consideration in assessing the potential for salt generation, it nevertheless provided an exceptionally valuable basis for calculating likely salt discharge from catchments in the drier parts of the basin and for checking the reliability of model calculations of runoff carried out in the present study.
- Modelling of likely runoff under different vegetation scenarios (winter wheat and renosterveld) using the ACRU model suggested strongly that land use changes potentially have a major impact on salt release from the regolith into surface waters. This confirmed the hypothesis that a switch from perennial deep-rooted renosterveld to annual shallow-rooted wheat would result in less water use and therefore enhanced discharge of salts into the river system, as has been found to have occurred (and is still occurring) in wheat lands of Australia which have replaced *Eucalyptus* scrub over the last century. The ACRU model, with a new salinity subroutine and with further improvements to its accommodation of soil surface characteristics that affect infiltration, will be valuable in making calculations not only of land use effects on salt discharge from catchments but also of the long-term accumulation of atmospheric salts of marine origin in the regolith of semi-arid catchments.

There appears, consequently, to be abundant justification for embarking on a more detailed survey of salt distribution in the soils, regolith, and ground- and surface waters of the Berg River basin and for undertaking a fundamental study of salt mobilization in response to climatic, topographic and land use factors, making use of a small scale catchment and taking into account historical changes in vegetation cover in the more saline reaches of the basin. This study should be multidisciplinary and should focus on understanding processes and the quantitative measurement of salt and water fluxes in the regolith of one or more small catchments as a prelude to extrapolation and calculation of the extent of the problem through hydrological modelling and geostatistical correlation.

6 REFERENCES

Acworth, R. I., 1999. Investigation of dryland salinity using the electrical image method. *Aust. J. Soil Res.* 37, 623-636. .

Acworth, R. I. & Jankowski, J., 2001. Salt source for dryland salinity—evidence from an upland catchment on the Southern Tablelands of New South Wales. *Aust. J. Soil Res.* 39, 39–59. .

Angus, J.F., Gault, R.R., Peoples, M.B., Stapper, M. and Van Herwaarden, A. F., 2001. Soil water extraction by dryland crops, annual pastures, and lucerne in south-eastern Australia. *Aust. J. Agric. Res.* 52, 183–192.

Barrett-Lennard, E.G. and Nulsen, R.A., 1989. Dryland soil salinity—cure, containment or catastrophe. In Proceedings 5th Australian Agronomic Conference, Perth. pp. 304–311 (Australian Society of Agronomy: Melbourne).

Clarke, C. J., George, R. J., Bell, R. W. and Hatton, T. J., 2002. Dryland salinity in south-western Australia: its origins, remedies, and future research directions *Aust. J. Soil Res.* 40, 93–113.

Day, J.A. & King, J.M., 1995. Geographical patterns, and their origins, in the dominance of major ions in South African rivers. *S A J Sci.* 91, 299-306

Donkin, M.J. and Fey, M.V., 1993. Relationships between soil properties and climatic indices in southern Natal. *Geoderma* 59, 197-212. .

Engel R., McFarlane D.J. and Street, G., 1987. The influence of dolerite dykes on saline seeps in southwestern Australia. *Aust. J. Soil Res.* 25, 125–136.

Flügel, W.A. 1995. River salinity due to dryland agriculture in the Western Cape Province, Republic of South Africa. *Env. Int.* 21, 679-686.

Fourie, J.M. 1976. Mineralization of Western Cape Rivers. PhD dissertation, University of Stellenbosch.

Fourie, J.M. and Görgens, A.H.M., 1976. Mineralization Studies of the Berg River (1974 to 1976). CSIR Research Report 334, Pretoria.

Hingston, F.J. & Gailitis, V., 1976. The geographic variation of salt precipitated over Western Australia. *Aust. J. Soil Res.* 14, 319-335.

http://audit.ea.gov.au/anra/atlas_home.cfm: AUSTRALIAN NATURAL RESOURCES ATLAS provides useful information on the dryland salinity problem in Australia.

http://www.enn.com/news/enn-stories/1999/06/062599/salt_3990.asp: Dryland salinity threatens Australia.

http://www.ndsp.gov.au: The National Dryland Salinity Program (NDSP) is Australia's lead knowledge broker of research, development and extension efforts to combat the risk of dryland salinity to our land and water resources.

Johnston, M. A., 1993. An evaluation of the four-electrode and electromagnetic induction techniques of soil salinity measurement. WRC Report, 269/1/94, Pretoria.

Moore, I. D., Lewis, A. and Gallant, J. C., 1993. Terrain Properties: Estimation Methods and Scale Effects. In A.J. Jakeman *et al.* (eds.) Modelling Change in Environmental Systems. John Wiley and Sons, New York.

Schulze, R.E., 2001. Hydrology and agrohydrology: A text to accompany the agrohydrological modelling system. University of Natal, Pietermaritzburg

Schulze, R.E., Maharaj M., Lynch S.D., Howe B.J. and Melvil-Thomson B., 1997. South African Atlas of Agrohydrology and Climatology. WRC Report TT82/96, Pretoria.

Surfer Manual, 2002. Surfer users guide. Colorado, USA. http://www.goldensoftware.com.

Sys, C., Van Ranst, E. and Debaveye, J., 1991. Land Evaluation. Part 1: principles in land evaluation and crop production calculations. Agricultural publication No.7, General Adm. for Development and Cooperation, Brussels, Belgium.

Talbot, W.J., 1949. Swartland and Sandveld: a survey of land utilization and soil erosion in the Western Cape lowlands of the Cape Province. Cape Town, Oxford University Press.

Walker, G., Gilfedder, M. and Williams, J., 1999. Effectiveness of current farming systems in the control of dryland salinity. CSIRO Publishing, Adelaide.

Weaver, J.M.C. and Talma A.S., 2002. Cumulative Rainfall Collectors - A Tool for Assessing Groundwater Recharge.Groundwater Division, Western Cape Conference: Tales of a hidden treasure; Somerset West, Sept. 2002. 8pp.

Wiplinger, O., 1980. Oceanic water as a source of salt in inland surface and underground water. Proceedings of a workshop on understanding mineralization processes, Water Research Commission, Pretoria.

7 APPENDIX A: MEASURES OF SALINITY AND SOIL TEXTURAL CONSIDERATIONS

In all soil samples the stone fraction (>2mm, otherwise termed the coarse fraction or cf) was separated and weighed as a basis for normalising laboratory estimates of salinity for comparison with field measurements, using the following equation:

$$EC_{e(adjusted)} = EC_{e(soil)} * (m_{cf}/m_s)$$

In which m_{cf} is the mass of the coarse fraction and m_s is the total mass of the soil sample. This approach was adopted based on the strength of the regression between adjusted EC_e and true EC_e, and will probably be refined in future work to include a correction factor specific to each soil type.

The electrical resistance (ER) of some soil samples (without removal of the coarse fraction) was also determined because of convenience of measurement and correlated with EM38 readings. In the present study the following parameters and their empirical inter-conversions were determined and are used in various parts of the report:

Parameter	Units	Method	Relationship to EC_e
EC_e	mSm^{-1}	Saturated paste extract	-
$EC_{(1:5)}$	mSm^{-1}	1:5 soil:water extract	$EC_{(1:5)} = EC_e/11$
ER	ohm	Resistance saturated paste	$ER = 66000/EC_e$
EC_{EM38}	mSm^{-1}	Measured with the EM38	$EC_{EM38} \sim EC_e / 5$

8 APPENDIX B: ARCHIVING OF DATA

Archiving the data has required special measures. A single TIFF image file takes up 185MB of disk space. There are about 50 such files and generating R-band images potentially doubles this number. Each run of the ACRU model also generates sizeable output files.

All data generated by the study are stored on a dedicated computer hard drive with a capacity of 80GB in the Soil Science department at the University of Stellenbosch.

9 APPENDIX C: EXAMPLE OF THE MENU PARAMETER FILE USED IN ACRU

```
      Mode of simulation (point/lumped vs distributed)
     -------------------------------------------------
ICELL
....I
   1

      Distributed model specifications
     ---------------------------------
 ISUBNO MINSUB MAXSUB LOOPBK
....III,...III,...III,.....,I
     3      1      3      0

      Hydrograph routing options
     ---------------------------
 IROUTE DELT
......I,FFFF.F
     0 1440.0

      Subcatchment configuration information
     ---------------------------------------
ICELLN IDSTRM PRTOUT
...III,...III,.....,F
     1      2      0                                                            1
     2      3      0                                                            2
     3      3      0                                                            3

      Rainfall file organisation
     ---------------------------
IRAINF
AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA AAAAAAAAAAAA
bls.21639_A.sdl                                                                 1
rooihoogte.41575_A.sdl                                                          2
heldervue.62379AW.sdl                                                           3

      Rainfall information
     ---------------------
 FORMAT PPTCOR    MAP
......F,.....F,.IIIII
     2      1    491                                                            1
     2      1    429                                                            2
     2      1    851                                                            3

      Monthly rainfall adjustment factors, CORPPT(i)
     -----------------------------------------------
  JAN  FEB  MAR  APR  MAY  JUN  JUL  AUG  SEP  OCT  NOV  DEC
,F.FF,F.FF,F.FF,F.FF,F.FF,F.FF,F.FF,F.FF,F.FF,F.FF,F.FF,F.FF
 0.91 0.92 0.95 0.98 1.00 0.99 1.00 0.99 0.99 0.99 1.00 0.94                    1
 0.97 1.09 1.09 1.08 1.07 1.09 1.08 1.07 1.07 1.08 1.06 1.00                    2
 0.96 0.97 0.96 1.00 1.00 0.99 1.00 0.99 1.00 1.00 1.00 0.99                    3

      Availability of observed streamflow data
     -----------------------------------------
IOBSTQ IOBSPK IOBOVR
.....I,.....I,.....I
     0      0      0                                                            1
     0      0      0                                                            2
     0      0      0                                                            3

      Streamflow file organisation
     -----------------------------
ISTRMF
AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
                                                                                1
                                                                                2
```

```
                                                                                                3
      Dynamic file option
      ---------------------
DNAMIC
F
0                                                                                               1
0                                                                                               2
0                                                                                               3

      Dynamic file organisation
      -------------------------
IDYNFL
AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
                                                                                                1
                                                                                                2
                                                                                                3

      General heading of simulation
      -------------------------------
HEAD
AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
HLS Boland-Coastal Rhenosterbosvel                                                              1
Rooihoogte-Coastal Rhenosterbosvel                                                              2
Heldervue -Coastal Rhenosterbosvel                                                              3

      Locational information
      ------------------------
  CLAREA   ELEV  ALAT ALONG IHEMI IQUAD
FFFFF.FF,FFFF.F,FF.FF,FF.FF,....I ....I
    1.00  123.0 33.65 18.87     2     1                                                         1
    1.00   49.0 33.08 18.83     2     1                                                         2
    1.00  759.0 32.82 18.72     2     1                                                         3

      Period of record for simulation
      ---------------------------------
IYSTRT IYREND
..IIII,..IIII
     0      0                                                                                   1
     0      0                                                                                   2
     0      0                                                                                   3

      Simulation printout options
      -----------------------------
WRIDY WRIMO
....F,....F
    0     1                                                                                     1
    0     1                                                                                     2
    0     1                                                                                     3

      Statistical output options (I)
      --------------------------------
SUMMRY ICOMPR
....FF,.....I
     1      0                                                                                   1
     1      0                                                                                   2
     1      0                                                                                   3

      Statistical output options (II)
      ---------------------------------
 ICOMPV LOGVAL
......I,.....I
      0      0                                                                                  1
      0      0                                                                                  2
      0      0                                                                                  3

      Monthly means of daily max temperature, TMAX(i)
      -------------------------------------------------
   JAN   FEB   MAR   APR   MAY   JUN   JUL   AUG   SEP   OCT   NOV   DEC
,FFF.F,FFF.F,FFF.F,FFF.F,FFF.F,FFF.F,FFF.F,FFF.F,FFF.F,FFF.F,FFF.F,FFF.F
  28.0  29.0  27.0  24.0  20.0  18.0  17.0  17.0  19.0  22.0  25.0  27.0                        1
  30.0  31.0  29.0  26.0  22.0  19.0  18.0  19.0  21.0  24.0  27.0  29.0                        2
  26.0  27.0  25.0  21.0  17.0  15.0  14.0  15.0  17.0  20.0  23.0  25.0                        3
```

```
      Monthly means of daily min temperature, TMIN(i)
      -----------------------------------------------
  JAN   FEB   MAR   APR   MAY   JUN   JUL   AUG   SEP   OCT   NOV   DEC
,FFF.F,FFF.F,FFF.F,FFF.F,FFF.F,FFF.F,FFF.F,FFF.F,FFF.F,FFF.F,FFF.F,FFF.F
 15.0  15.0  14.0  12.0   9.0   7.0   6.0   7.0   8.0  10.0  12.0  14.0      1
 15.0  15.0  14.0  12.0  10.0   8.0   7.0   7.0   8.0  10.0  13.0  14.0      2
 12.0  13.0  12.0   9.0   8.0   5.0   5.0   5.0   6.0   8.0  10.0  11.0      3

#     Reference potential evaporation control variables
      -------------------------------------------------
EQPET
,,FFF
  102                                                                         1
  102                                                                         2
  102                                                                         3

      Evaporation input availability control flags
      --------------------------------------------
 IEIF  ILRF  IWDF  IRHF  ISNF  IRDF  IPNF
.....I.....I.....I.....I.....I.....I.....I
     1     0     0     0     0     0     0                                    1
     1     0     0     0     0     0     0                                    2
     1     0     0     0     0     0     0                                    3

      Means of monthly totals of pan evaporation, E(i)
      ------------------------------------------------
  JAN   FEB   MAR   APR   MAY   JUN   JUL   AUG   SEP   OCT   NOV   DEC
,FFF.F,FFF.F,FFF.F,FFF.F,FFF.F,FFF.F,FFF.F,FFF.F,FFF.F,FFF.F,FFF.F,FFF.F
313.0 265.0 233.0 141.0  86.0  61.0  62.0  82.0 117.0 190.0 252.0 303.0      1
346.0 296.0 258.0 169.0 107.0  75.0  73.0  93.0 139.0 216.0 296.0 353.0      2
287.0 236.0 210.0 122.0  71.0  48.0  59.0  82.0 103.0 167.0 226.0 289.0      3

      Temperature adjustment for altitude
      -----------------------------------
 TELEV LRREG
FFFF.F,,,,II
1040.0    0                                                                   1
1040.0    0                                                                   2
1040.0    0                                                                   3

      Mean lapse rates for min and max temperatures
      ---------------------------------------------
 TMAXLR  TMINLR
FFFF.FF,FFFF.FF
   7.00    5.50                                                               1
   7.00    5.50                                                               2
   7.00    5.50                                                               3

      Mean daily windspeed (m/s)
      --------------------------
WNDSPD
,,FF.F
   1.6                                                                        1
   1.6                                                                        2
   1.6                                                                        3

      Windspeed region number
      -----------------------
LINWIN
,,,III
     0                                                                        1
     0                                                                        2
     0                                                                        3

      Monthly means of daily windrun (km/day), WIND(i)
      ------------------------------------------------
  JAN   FEB   MAR   APR   MAY   JUN   JUL   AUG   SEP   OCT   NOV   DEC
,FFF.F,FFF.F,FFF.F,FFF.F,FFF.F,FFF.F,FFF.F,FFF.F,FFF.F,FFF.F,FFF.F,FFF.F
 11.0  11.0  11.0  11.0  11.0  11.0  11.0  11.0  11.0  11.0  11.0  11.0      1
 11.0  11.0  11.0  11.0  11.0  11.0  11.0  11.0  11.0  11.0  11.0  11.0      2
 11.0  11.0  11.0  11.0  11.0  11.0  11.0  11.0  11.0  11.0  11.0  11.0      3

      Monthly means of daily average relative humidity, RH(i)
      -------------------------------------------------------
```

```
  JAN  FEB  MAR  APR  MAY  JUN  JUL  AUG  SEP  OCT  NOV  DEC
,FF.F,FF.F,FF.F,FF.F,FF.F,FF.F,FF.F,FF.F,FF.F,FF.F,FF.F,FF.F
 55.0 55.0 55.0 55.0 55.0 55.0 55.0 55.0 55.0 55.0 55.0 55.0                 1
 55.0 55.0 55.0 55.0 55.0 55.0 55.0 55.0 55.0 55.0 55.0 55.0                 2
 55.0 55.0 55.0 55.0 55.0 55.0 55.0 55.0 55.0 55.0 55.0 55.0                 3

      Penman equation control variables
      ---------------------------------
ALBEDO ICONS ISWAVE
..F.FF.....I.....I
   .25     0     0                                                           1
   .25     0     0                                                           2
   .25     0     0                                                           3

      Monthly means of daily hours of sunshine, ASSH(i)
      -------------------------------------------------
  JAN  FEB  MAR  APR  MAY  JUN  JUL  AUG  SEP  OCT  NOV  DEC
,FF.F,FF.F,FF.F,FF.F,FF.F,FF.F,FF.F,FF.F,FF.F,FF.F,FF.F,FF.F
  2.0  2.0  2.0  2.0  2.0  2.0  2.0  2.0  2.0  2.0  2.0  2.0                 1
  2.0  2.0  2.0  2.0  2.0  2.0  2.0  2.0  2.0  2.0  2.0  2.0                 2
  2.0  2.0  2.0  2.0  2.0  2.0  2.0  2.0  2.0  2.0  2.0  2.0                 3

      "A" coefficient in Penman equation, ACONS(i)
      --------------------------------------------
  JAN  FEB  MAR  APR  MAY  JUN  JUL  AUG  SEP  OCT  NOV  DEC
,F.FF,F.FF,F.FF,F.FF,F.FF,F.FF,F.FF,F.FF,F.FF,F.FF,F.FF,F.FF
  .27  .27  .28  .24  .24  .25  .24  .21  .23  .23  .22  .24                 1
  .27  .27  .28  .24  .24  .25  .24  .21  .23  .23  .22  .24                 2
  .27  .27  .28  .24  .24  .25  .24  .21  .23  .23  .22  .24                 3

      "B" coefficient in Penman equation, BCONS(i)
      --------------------------------------------
  JAN  FEB  MAR  APR  MAY  JUN  JUL  AUG  SEP  OCT  NOV  DEC
,F.FF,F.FF,F.FF,F.FF,F.FF,F.FF,F.FF,F.FF,F.FF,F.FF,F.FF,F.FF
  .52  .49  .52  .52  .51  .50  .51  .55  .57  .56  .58  .54                 1
  .52  .49  .52  .52  .51  .50  .51  .55  .57  .56  .58  .54                 2
  .52  .49  .52  .52  .51  .50  .51  .55  .57  .56  .58  .54                 3

      Monthly means of daily incoming radiation, RADMET(i)
      ----------------------------------------------------
  JAN  FEB  MAR  APR  MAY  JUN  JUL  AUG  SEP  OCT  NOV  DEC
,FF.F,FF.F,FF.F,FF.F,FF.F,FF.F,FF.F,FF.F,FF.F,FF.F,FF.F,FF.F
 12.0 12.0 12.0 12.0 12.0 12.0 12.0 12.0 12.0 12.0 12.0 12.0                 1
 12.0 12.0 12.0 12.0 12.0 12.0 12.0 12.0 12.0 12.0 12.0 12.0                 2
 12.0 12.0 12.0 12.0 12.0 12.0 12.0 12.0 12.0 12.0 12.0 12.0                 3

      Penman equation option for either S-tank or A-pan equivalent evaporation
      ------------------------------------------------------------------------
SAPANC
.....I
     0                                                                       1
     0                                                                       2
     0                                                                       3

      Smoothed mean monthly A-pan/S-pan ratios, SARAT(i)
      --------------------------------------------------
  JAN  FEB  MAR  APR  MAY  JUN  JUL  AUG  SEP  OCT  NOV  DEC
,F.FF,F.FF,F.FF,F.FF,F.FF,F.FF,F.FF,F.FF,F.FF,F.FF,F.FF,F.FF
 1.26 1.25 1.26 1.27 1.30 1.34 1.36 1.37 1.35 1.32 1.28 1.27                 1
 1.26 1.25 1.26 1.27 1.30 1.34 1.36 1.37 1.35 1.32 1.28 1.27                 2
 1.26 1.25 1.26 1.27 1.30 1.34 1.36 1.37 1.35 1.32 1.28 1.27                 3

      Pan adjustment option
      ---------------------
PANCOR
.....F
     0                                                                       1
     0                                                                       2
     0                                                                       3

      Monthly pan adjustment factors, CORPAN(i)
      -----------------------------------------
  JAN  FEB  MAR  APR  MAY  JUN  JUL  AUG  SEP  OCT  NOV  DEC
,F.FF,F.FF,F.FF,F.FF,F.FF,F.FF,F.FF,F.FF,F.FF,F.FF,F.FF,F. FF
```

```
 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00        1
 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00        2
 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00        3

#      Level of soils information
      ---------------------------
PEDINF
.....F
     1                                                              1
     1                                                              2
     1                                                              3

       Soils texture information
      --------------------------
 ITEXT
....II
     7                                                              1
     7                                                              2
     7                                                              3

       Soil physics based infiltration/soil water redistribution option
      ------------------------------------------------------------ ---
REDIST
.....F
     0                                                              1
     0                                                              2
     0                                                              3

       Rainfall intensity distribution type
      -------------------------------------
IRDIST
.....I
     1                                                              1
     1                                                              2
     1                                                              3

       Soil thickness information
      ---------------------------
 PEDDEP
......F
      2                                                             1
      2                                                             2
      2                                                             3

       Soils information (adequate)
      -----------------------------
DEPAHO DEPBHO  WP1  WP2  FC1  FC2  PO1  PO2 ABRESP BFRESP
,FF.FF,,FF.FF,.FFF,.FFF,.FFF,.FFF,.FFF,.FFF,,FF.FF,,FF.FF
   .20    .11 .160 .240 .230 .300 .420 .420    .27    .27           1
   .27    .50 .110 .150 .200 .240 .450 .430    .50    .50           2
   .27    .47 .090 .090 .180 .200 .460 .450    .52    .52           3

       Shrink-swell soils option
      --------------------------
ICRACK
.....I
     0                                                              1
     0                                                              2
     0                                                              3

       Initial values of soil water retention constants
      -------------------------------------------------
 SMAINI SMBINI
,FFF.FF,FFF.FF
  20.00  20.00                                                      1
  20.00  20.00                                                      2
  20.00  20.00                                                      3

       Option for statistical analysis of soil water regime
      -----------------------------------------------------
SWLOPT
.....F
     0                                                              1
     0                                                              2
```

```
    0                                                                    3

       Soil water content thresholds for A horizon, SWLAM(i)
      -----------------------------------------------------
   1       2       3       4       5       6
..F.FFF,.F.FFF,.F.FFF,.F.FFF,.F.FFF,.F.FFF
   .018    .050    .100    .150    .200    .300                          1
   .018    .050    .100    .150    .200    .300                          2
   .018    .050    .100    .150    .200    .300                          3

       Soil water content thresholds for B horizon, SWLBM(i)
      -----------------------------------------------------
   1       2       3       4       5       6
..F.FFF,.F.FFF,.F.FFF,.F.FFF,.F.FFF,.F.FFF
   .018    .050    .100    .150    .200    .300                          1
   .018    .050    .100    .150    .200    .300                          2
   .018    .050    .100    .150    .200    .300                          3

#      Level of land cover information
      ------------------------------
LCOVER
.....I
     1                                                                   1
     1                                                                   2
     1                                                                   3

       Land cover number information
      -----------------------------
    CROPNO
...FFFFFFF
   2020104                                                               1
   2020104                                                               2
   2020104                                                               3

       Determination of canopy interception loss
      ----------------------------------------
INTLOS
.....I
     1                                                                   1
     1                                                                   2
     1                                                                   3

       Leaf area index information
      ---------------------------
 LAIND
.....I
     0                                                                   1
     0                                                                   2
     0                                                                   3

       Monthly means of crop coefficients, CAY(i)
      ----------------------------------------
  JAN  FEB  MAR  APR  MAY  JUN  JUL  AUG  SEP  OCT  NOV  DEC
.F.FF,F.FF,F.FF,F.FF,F.FF,F.FF,F.FF,F.FF,F.FF,F.FF,F.FF,F.FF
  .40  .40  .40  .45  .50  .50  .50  .50  .50  .45  .40  .40            1
  .40  .40  .40  .45  .50  .50  .50  .50  .50  .45  .40  .40            2
  .40  .40  .40  .45  .50  .50  .50  .50  .50  .45  .40  .40            3

       Monthly means of leaf area index, ELAIM(i)
      ----------------------------------------
  JAN  FEB  MAR  APR  MAY  JUN  JUL  AUG  SEP  OCT  NOV  DEC
.F.FF,F.FF,F.FF,F.FF,F.FF,F.FF,F.FF,F.FF,F.FF,F.FF,F.FF,F.FF
  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00            1
  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00            2
  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00  .00            3

       Canopy interception loss (mm) per rainday, VEGINT(i)
      ---------------------------------------------------
  JAN  FEB  MAR  APR  MAY  JUN  JUL  AUG  SEP  OCT  NOV  DEC
.F.FF,F.FF,F.FF,F.FF,F.FF,F.FF,F.FF,F.FF,F.FF,F.FF,F.FF,F.FF
  .80  .80  .80 1.00 1.20 1.20 1.20 1.20 1.00  .80  .80  .80            1
  .80  .80  .80 1.00 1.20 1.20 1.20 1.20 1.00  .80  .80  .80            2
  .80  .80  .80 1.00 1.20 1.20 1.20 1.20 1.00  .80  .80  .80            3
```

```
      Fraction of active root system in topsoil horizon, ROOTA(i)
      -------------------------------------------------------------
  JAN  FEB  MAR  APR  MAY  JUN  JUL  AUG  SEP  OCT  NOV  DEC
,F.FF,F.FF,F.FF,F.FF,F.FF,F.FF,F.FF,F.FF,F.FF,F.FF,F.FF,F.FF
  .95  .95  .95  .90  .90  .90  .90  .90  .95  .95  .95  .95                    1
  .95  .95  .95  .90  .90  .90  .90  .90  .95  .95  .95  .95                    2
  .95  .95  .95  .90  .90  .90  .90  .90  .95  .95  .95  .95                    3

      Effective total rooting depth
      -----------------------------
EFRDEP
FFF.FF
   .00                                                                           1
   .00                                                                           2
   .00                                                                           3

      Total evaporation control variables
      -----------------------------------
 EVTR FPAW
....F,...F
    2    0                                                                       1
    2    0                                                                       2
    2    0                                                                       3

      Fraction of PAW at which plant stress sets in
      ---------------------------------------------
CONST
FF.FF
  .40                                                                            1
  .40                                                                            2
  .40                                                                            3

      Critical leaf water potential
      -----------------------------
 CRLEPO
FFFFF.F
     .0                                                                          1
     .0                                                                          2
     .0                                                                          3

      Option for enhanced wet canopy evaporation
      ------------------------------------------
FOREST
.....F
     0                                                                           1
     0                                                                           2
     0                                                                           3

      Option for simulation under enhanced atmospheric CO2 levels
      -----------------------------------------------------------
CO2TRA
,FFF.F
    .0                                                                           1
    .0                                                                           2
    .0                                                                           3

      Mean temperature threshold (øC) for active growth to take place
      ---------------------------------------------------------------
TMPCUT
,,FF.F
   1.0                                                                           1
   1.0                                                                           2
   1.0                                                                           3

      Unsaturated soil moisture redistribution
      ----------------------------------------
IUNSAT
.....I
     1                                                                           1
     1                                                                           2
     1                                                                           3

      Option for lysimeter routine
      ----------------------------
```

```
LYSIM
....I
    0                                                                      1
    0                                                                      2
    0                                                                      3

     Streamflow simulation control variables
    -----------------------------------------
QFRESP   COFRU SMDDEP IRUN ADJIMP DISIMP STOIMP
,FF.FF,,,F.FFF,FFF.FF,,,,I,,F.FFF,,F.FFF,,,F.FF
   .30    .009    .00    1   .000   .000   1.00                            1
   .30    .009    .00    1   .000   .000   1.00                            2
   .30    .009    .00    1   .000   .000   1.00                            3

     Coefficient of initial abstraction, COIAM(i)
    ---------------------------------------------
  JAN  FEB  MAR  APR  MAY  JUN  JUL  AUG  SEP  OCT  NOV  DEC
,F.FF,F.FF,F.FF,F.FF,F.FF,F.FF,F.FF,F.FF,F.FF,F.FF,F.FF,F.FF
  .30  .30  .30  .30  .30  .30  .30  .30  .30  .30  .30  .30               1
  .30  .30  .30  .30  .30  .30  .30  .30  .30  .30  .30  .30               2
  .30  .30  .30  .30  .30  .30  .30  .30  .30  .30  .30  .30               3

#    Peak discharge : option
    ------------------------
PEAK
...F
   0                                                                       1
   0                                                                       2
   0                                                                       3

     Peak discharge : control variables (I)
    ----------------------------------------
 LAG SLOPE
...I,FFF.F
   1  12.3                                                                 1
   1  12.3                                                                 2
   1  12.3                                                                 3

     Peak discharge : control variables (II)
    -----------------------------------------
  HYLEN CNII
FFFFF.F,,FF.
  145.7  51.                                                               1
  145.7  51.                                                               2
  145.7  51.                                                               3

     Peak discharge : control variables (III)
    ------------------------------------------
  XI30
FFF.FF
   .00                                                                     1
   .00                                                                     2
   .00                                                                     3

     Peak discharge : control variables (IV)
    -----------------------------------------
  TCON
FFF.FF
   .00                                                                     1
   .00                                                                     2
   .00                                                                     3

#    Sediment yield : option
    ------------------------
MUSLE
....I
    0                                                                      1
    0                                                                      2
    0                                                                      3

     Sediment yield : variables (I)
    -------------------------------
 SOIFC1 SOIFC2 ELFACT PFACT ICOVRD SEDIST
,FFF.FF,FFF.FF,FFF.FF,FF.FF,,,,,,I,FFF.FF
```

```
     .52    .51    .00    .00      0    .45                                          1
     .52    .51    .00    .00      0    .45                                          2
     .52    .51    .00    .00      0    .45                                          3

       Sediment yield : variables (II)
      ---------------------------------
    ALPHA     BETA
,FFFF.FFF,FFFF.FFF
    8.934     .560                                                                   1
    8.934     .560                                                                   2
    8.934     .560                                                                   3

       Means of monthly cover factors, COVER(i)
      ----------------------------------------
  JAN  FEB  MAR  APR  MAY  JUN  JUL  AUG  SEP  OCT  NOV  DEC
,F.FF,F.FF,F.FF,F.FF,F.FF,F.FF,F.FF,F.FF,F.FF,F.FF,F.FF,F.FF
  .50  .50  .50  .50  .50  .50  .50  .50  .50  .50  .50  .50                        1
  .50  .50  .50  .50  .50  .50  .50  .50  .50  .50  .50  .50                        2
  .50  .50  .50  .50  .50  .50  .50  .50  .50  .50  .50  .50                        3

#      Hydrograph routing input
      ------------------------
 XMUSK     XAK   FTINC
,,FF.F,,FFFF.F,,FFFF.F
    .2   360.0    30.0                                                               1
    .2   360.0    30.0                                                               2
    .2   360.0    30.0                                                               3

       Hydrograph routing input : channel dimensions (I)
      -------------------------------------------------
ISHAPE FDEPTH   ROUGHN   CSLOPE    CHLEN
.....I,,FFF.F,,,,F.FFF,,,,FF.FF,,FFFFF.F
     4    2.0     .100      .65   2300.0                                             1
     4    2.0     .100      .65   2300.0                                             2
     4    2.0     .100      .65   2300.0                                             3

       Hydrograph routing input : channel dimensions (II)
      --------------------------------------------------
BWIDTH
,FFF.F
   1.0                                                                               1
   1.0                                                                               2
   1.0                                                                               3

       Hydrograph routing input : channel dimensions (III)
      ---------------------------------------------------
ZSIDE
,,F.F
  1.0                                                                                1
  1.0                                                                                2
  1.0                                                                                3

       Hydrograph routing input : channel dimensions (IV)
      --------------------------------------------------
TWIDTH
,FFF.F
   1.0                                                                               1
   1.0                                                                               2
   1.0                                                                               3

       Wetland input options
      ---------------------
IVLEI    CAPM3S
....I,.....FF.F
    0       1.2                                                                      1
    0       1.2                                                                      2
    0       1.2                                                                      3

#      Shallow groundwater : analysis option
      -------------------------------------
IGWATR
.....I
     0                                                                               1
     0                                                                               2
```

```
    0                                                                                          3

       Shallow groundwater : variables for vertical flow
      ---------------------------------------------------
IZTEXT  POIZ   FCIZ   WPIZ  DEPIMP  DEPROT
...II,,F.FFF,,F.FFF,,F.FFF,,FFFFFF,,FFFFFF
     3  .400   .200   .130   90000     800                                                     1
     3  .400   .200   .130   90000     800                                                     2
     3  .400   .200   .130   90000     800                                                     3

       Shallow groundwater : variables for lateral flux
      ---------------------------------------------------
    VALUEK    ALTIS   ALTIR     ALTH     DISTR     DISTA  SIZEHA  OBSWTD
...FFF.FFFF,,FFFF.F,,FFFF.F,,FFFF.F,,FFFFF.F,,FFFFF.F,,FFFF.F,,FF.FFF
   250.0000     1.1      .1    110.2    6000.3    2000.4  9200.5   4.659                         1
   250.0000     1.1      .1    110.2    6000.3    2000.4  9200.5   4.659                         2
   250.0000     1.1      .1    110.2    6000.3    2000.4  9200.5   4.659                         3

#      Irrigation : option
      --------------------
IRRIGN WRIRR
.....I,....,F
     0     0                                                                                   1
     0     0                                                                                   2
     0     0                                                                                   3

       Irrigation : month for application, IRRMON(i)
      -----------------------------------------------
  JAN  FEB  MAR  APR  MAY  JUN  JUL  AUG  SEP  OCT  NOV  DEC
....I....I....I....I....I....I....I....I....I....I....I....I
    0    0    0    0    0    0    0    0    0    1    0    0                                    1
    0    0    0    0    0    0    0    0    0    1    0    0                                    2
    0    0    0    0    0    0    0    0    0    1    0    0                                    3

       Irrigation : areas, HAIRR(i)
      ------------------------------
  JAN    FEB    MAR    APR    MAY    JUN    JUL    AUG    SEP    OCT    NOV    DEC
,FFFF.,FFFF.,FFFF.,FFFF.,FFFF.,FFFF.,FFFF.,FFFF.,FFFF.,FFFF.,FFFF.,FFFF.
    0.     0.     0.     0.     0.     0.     0.     0.     0.     1.     0.     0.            1
    0.     0.     0.     0.     0.     0.     0.     0.     0.     1.     0.     0.            2
    0.     0.     0.     0.     0.     0.     0.     0.     0.     1.     0.     0.            3

       Irrigation : catchment rainfall adjustment, PPTIRR(i)
      -------------------------------------------------------
  JAN  FEB  MAR  APR  MAY  JUN  JUL  AUG  SEP  OCT  NOV  DEC
,F.FF,F.FF,F.FF,F.FF,F.FF,F.FF,F.FF,F.FF,F.FF,F.FF,F.FF,F.FF
 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00                                   1
 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00                                   2
 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00                                   3

       Irrigation : coefficient of initial abstractions, COIAIR(i)
      -------------------------------------------------------------
  JAN  FEB  MAR  APR  MAY  JUN  JUL  AUG  SEP  OCT  NOV  DEC
,F.FF,F.FF,F.FF,F.FF,F.FF,F.FF,F.FF,F.FF,F.FF,F.FF,F.FF,F.FF
  .20  .20  .20  .20  .20  .20  .20  .20  .20  .20  .20  .20                                   1
  .20  .20  .20  .20  .20  .20  .20  .20  .20  .20  .20  .20                                   2
  .20  .20  .20  .20  .20  .20  .20  .20  .20  .20  .20  .20                                   3

       Irrigation : soils information (I)
      ------------------------------------
ITEXTI
....II
     2                                                                                         1
     2                                                                                         2
     2                                                                                         3

       Irrigation : soil information (II)
      ------------------------------------
IRRPED
.....I
     1                                                                                         1
     1                                                                                         2
     1                                                                                         3
```

```
     Irrigation : soil information (III)
    -----------------------------------
 WPIR FCIR POIR
,.FFF,.FFF,.FFF
 .200 .300 .450                                                      1
 .200 .300 .450                                                      2
 .200 .300 .450                                                      3

     Irrigation : crop coefficients, CAYIRR(i)
    -----------------------------------------
  JAN  FEB  MAR  APR  MAY  JUN  JUL  AUG  SEP  OCT  NOV  DEC
,F.FF,F.FF,F.FF,F.FF,F.FF,F.FF,F.FF,F.FF,F.FF,F.FF,F.FF,F.FF
  .80  .80  .80  .80  .80  .80  .80  .80  .80  .80  .80  .80        1
  .80  .80  .80  .80  .80  .80  .80  .80  .80  .80  .80  .80        2
  .80  .80  .80  .80  .80  .80  .80  .80  .80  .80  .80  .80        3

     Irrigation : interception loss, DINTIR(i)
    -----------------------------------------
  JAN  FEB  MAR  APR  MAY  JUN  JUL  AUG  SEP  OCT  NOV  DEC
,F.FF,F.FF,F.FF,F.FF,F.FF,F.FF,F.FF,F.FF,F.FF,F.FF,F.FF,F.FF
  .10  .10  .10  .10  .10  .10  .10  .10  .10  .10  .10  .10        1
  .10  .10  .10  .10  .10  .10  .10  .10  .10  .10  .10  .10        2
  .10  .10  .10  .10  .10  .10  .10  .10  .10  .10  .10  .10        3

     Irrigation : rooting characteristics
    ------------------------------------
RDMAX   RDUP
,F.FF,,,F.FF
 1.50   1.00                                                         1
 1.50   1.00                                                         2
 1.50   1.00                                                         3

     Irrigation : total evaporation control variables
    ------------------------------------------------
 CCOV  CCMAX  PGRDM   CRLW
,F.FF,,,F.FF,,FFF.F,,,FFFFF.F
  .80    .79   95.5  -1200.0                                         1
  .80    .79   95.5  -1200.0                                         2
  .80    .79   95.5  -1200.0                                         3

     Irrigation : mode of scheduling, ISCHED(i)
    ------------------------------------------
  JAN  FEB  MAR  APR  MAY  JUN  JUL  AUG  SEP  OCT  NOV  DEC
....I....I....I....I....I....I....I....I....I....I....I....I
    1    1    1    1    1    1    1    1    1    1    1    1        1
    1    1    1    1    1    1    1    1    1    1    1    1        2
    1    1    1    1    1    1    1    1    1    1    1    1        3

     Irrigation : scheduling control variables (I), STPRO(i)
    -------------------------------------------------------
    JAN  FEB  MAR  APR  MAY  JUN  JUL  AUG  SEP  OCT  NOV  DEC
...F.FF,F.FF,F.FF,F.FF,F.FF,F.FF,F.FF,F.FF,F.FF,F.FF,F.FF,F.FF
    .20  .20  .20  .20  .20  .20  .20  .20  .20  .20  .20  .20       1
    .20  .20  .20  .20  .20  .20  .20  .20  .20  .20  .20  .20       2
    .20  .20  .20  .20  .20  .20  .20  .20  .20  .20  .20  .20       3

     Irrigation : scheduling control variables (II)
    ----------------------------------------------
  IRAMT  IRCYC
....III.....II
    123     17                                                       1
    123     17                                                       2
    123     17                                                       3

     Irrigation : scheduling control variables (III)
    -----------------------------------------------
  RLIM
..FF.F
  15.1                                                               1
  15.1                                                               2
  15.1                                                               3

     Irrigation : application control variables
    ------------------------------------------
```

```
 ILOS IRUNIT
....I......I
   1      1                                                                  1
   1      1                                                                  2
   1      1                                                                  3

      Irrigation : scheduling control variables (IV), RASTO(i)
     ---------------------------------------------------------
    JAN  FEB  MAR  APR  MAY  JUN  JUL  AUG  SEP  OCT  NOV  DEC
...FF.F,FF.F,FF.F,FF.F,FF.F,FF.F,FF.F,FF.F,FF.F,FF.F,FF.F,FF.F
    1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0              1
    1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0              2
    1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0              3

      Irrigation : supply losses
     ---------------------------
CONLOS FAMLOS  EVWIN
,F.FF,,,,F.FF,,,F.FF
   .00     .00    .10                                                        1
   .00     .00    .10                                                        2
   .00     .00    .10                                                        3

      Irrigation : catchment supplying water
     ---------------------------------------
IRSPLY
...III
     1                                                                       1
     1                                                                       2
     1                                                                       3

      Irrigation : water supply information
     --------------------------------------
IRRAPL INCELL UPSTIR
.....I......I......F
     0      0      0                                                         1
     0      0      0                                                         2
     0      0      0                                                         3

      Option for domestic abstractions
     ---------------------------------
 IDOMR
.....I
     0                                                                       1
     0                                                                       2
     0                                                                       3

      Domestic abstractions per day * 1000, DOMABS(i)
     ------------------------------------------------
   JAN   FEB   MAR   APR   MAY   JUN   JUL   AUG   SEP   OCT   NOV   DEC
,FFF.F,FFF.F,FFF.F,FFF.F,FFF.F,FFF.F,FFF.F,FFF.F,FFF.F,FFF.F,FFF.F,FFF.F
   1.0   2.0   3.0   3.0   3.0   3.0   3.0   3.0   3.0   3.0   3.0  12.7      1
   1.0   2.0   3.0   3.0   3.0   3.0   3.0   3.0   3.0   3.0   3.0  12.7      2
   1.0   2.0   3.0   3.0   3.0   3.0   3.0   3.0   3.0   3.0   3.0  12.7      3

#     Reservoir yield analysis : option
     ----------------------------------
RESYLD
.....F
     0                                                                       1
     0                                                                       2
     0                                                                       3

      Reservoir yield analysis : control variables (I)
     -------------------------------------------------
    DAMCAP  SURFAR  ARCAP    QNORM     SEEP PCCDAM PERDAM DEDSTO
,FFFFFFFFF..FFF.FF,,,,,,F,FFFFFF.F,FFFFFF.F,,FFF.F,,FFF.F,FFF.F
   5550700. 148.00      1   3329.1       .0    1.0     .2     .1             1
   5550700. 148.00      1   3329.1       .0    1.0     .2     .1             2
   5550700. 148.00      1   3329.1       .0    1.0     .2     .1             3

      Reservoir yield analysis : control variables (II)
     --------------------------------------------------
  WIDTH
FFFF.FF
```

```
   1.00                                                                          1
   1.00                                                                          2
   1.00                                                                          3

       Reservoir yield analysis : control variables (III)
       ---------------------------------------------------
RESCON RESEXP
FFF.FF,,FF.FF
   .80    .00                                                                    1
   .80    .00                                                                    2
   .80    .00                                                                    3

       Hydrograph routing : options
       ----------------------------
SWIDTH  CDISCH     RTINC IRESUP
,FF.FF,,,,F.FF,,,,FFFF.F,,,,III
  1.00     .50      30.0     10                                                  1
  1.00     .50      30.0     10                                                  2
  1.00     .50      30.0     10                                                  3

       Reservoir yield analysis : additions and abstractions (I), PANDAM(i)
       ---------------------------------------------------------------------
  JAN  FEB  MAR  APR  MAY  JUN  JUL  AUG  SEP  OCT  NOV  DEC
,F.FF,F.FF,F.FF,F.FF,F.FF,F.FF,F.FF,F.FF,F.FF,F.FF,F.FF,F.FF
  .61  .61  .61  .61  .61  .61  .61  .61  .61  .61  .61  .61                    1
  .61  .61  .61  .61  .61  .61  .61  .61  .61  .61  .61  .61                    2
  .61  .61  .61  .61  .61  .61  .61  .61  .61  .61  .61  .61                    3

       Reservoir yield analysis : additions and abstractions (II), PUMPIN(i)
       ----------------------------------------------------------------------
   JAN    FEB    MAR    APR    MAY    JUN    JUL    AUG    SEP    OCT    NOV    DEC
,FF.FF,FF.FF,FF.FF,FF.FF,FF.FF,FF.FF,FF.FF,FF.FF,FF.FF,FF.FF,FF.FF,FF.FF
   .00    .00    .00    .00    .00    .00    .00    .00    .00    .00    .00    .00      1
   .00    .00    .00    .00    .00    .00    .00    .00    .00    .00    .00    .00      2
   .00    .00    .00    .00    .00    .00    .00    .00    .00    .00    .00    .00      3

       Reservoir yield analysis : additions and abstractions (III), XDRAFT(i)
       -----------------------------------------------------------------------
   JAN    FEB    MAR    APR    MAY    JUN    JUL    AUG    SEP    OCT    NOV    DEC
,FF.FF,FF.FF,FF.FF,FF.FF,FF.FF,FF.FF,FF.FF,FF.FF,FF.FF,FF.FF,FF.FF,FF.FF
   .00    .00    .00    .00    .00    .00    .00    .00    .00    .00    .00    .00      1
   .00    .00    .00    .00    .00    .00    .00    .00    .00    .00    .00    .00      2
   .00    .00    .00    .00    .00    .00    .00    .00    .00    .00    .00    .00      3

       Off-channel storage : option
       ----------------------------
IOFCHW
.....I
    0                                                                            1
    0                                                                            2
    0                                                                            3

       Off-channel storage : pump & pumping control variables
       ------------------------------------------------------
IPCAP IPNUM IPHRS IPCPMN IFLDLM
..III,,,,II,,,,II,,,,,II,IIIIII
   50     4    24     25   2000                                                  1
   50     4    24     25   2000                                                  2
   50     4    24     25   2000                                                  3

#      Crop yield : option
       -------------------
  CROP WRTYLD
.....F,.....F
    0     0                                                                      1
    0     0                                                                      2
    0     0                                                                      3

       Crop yield : method of determining planting dates
       -------------------------------------------------
 PLDATE
......F
     0                                                                           1
     0                                                                           2
```

```
      0                                                                   3

      Crop yield : planting dates
      ----------------------------
ISTDAY ISTMO
....II....II
     1    10                                                              1
     1    10                                                              2
     1    10                                                              3

      Crop yield : length (days) of growing season
      --------------------------------------------
LENGTH
...III
    95                                                                    1
    95                                                                    2
    95                                                                    3

      Crop yield : ACRU maize yield model option (I)
      ----------------------------------------------
HKSINF
.....F
     0                                                                    1
     0                                                                    2
     0                                                                    3

      Crop yield : ACRU maize yield model option (II)
      -----------------------------------------------
 YLDPOT ELAMD1 ELAMD2 ELAMD3 IPRD1 IPRD2 IPRD3 IPRD4
...FF.F...FF.F...FF.F...FF.F..IIII..IIII..IIII..IIII
    3.0     .5     .5     .5   100   700  1100  1700                      1
    3.0     .5     .5     .5   100   700  1100  1700                      2
    3.0     .5     .5     .5   100   700  1100  1700                      3

      Crop yield : ACRU sugar cane yield options
      ------------------------------------------
IRRDRY IREG NRAT
.....I...I...II
     1   1    6                                                           1
     1   1    6                                                           2
     1   1    6                                                           3

      Crop yield : ACRU wheat yield option (I)
      ----------------------------------------
RASINF
.....F
     0                                                                    1
     0                                                                    2
     0                                                                    3

      Crop yield : ACRU wheat yield option (II)
      -----------------------------------------
 WTPOT WLAMD1 WLAMD2 WLAMD3 IWPRD1 IWPRD2 IWPRD3
..FF.F...FF.F...FF.F...FF.F...IIII...IIII...IIII
   3.5     .5     .5     .5     10     20     31                          1
   3.5     .5     .5     .5     10     20     31                          2
   3.5     .5     .5     .5     10     20     31                          3

      Crop yield : economic analysis option
      -------------------------------------
IEANAL
.....I
     0                                                                    1
     0                                                                    2
     0                                                                    3

      Crop yield : economic analysis input variables
      ----------------------------------------------
 SPRICE BRKEVN
FFFF.FF.FFF.FF
  12.70  11.23                                                            1
  12.70  11.23                                                            2
  12.70  11.23                                                            3
```

```
#       Extreme value analysis : extreme values
        ----------------------------------------
  IEVD
.....I
     0                                                                  1
     0                                                                  2
     0                                                                  3

        Extreme value analysis : extreme events variable selection
        ----------------------------------------------------------
IRANK IPRTRK
....I......I
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        Extreme value analysis : months to be included in stats, MOSTAT(i)
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    0    0    0    0    0    0    0    0    0    1    0    0             1
    0    0    0    0    0    0    0    0    0    1    0    0             2
    0    0    0    0    0    0    0    0    0    1    0    0             3

        Extreme value analysis : probability distribution selection
        ------------------------------------------------------------
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.....F...F
     1   1                                                              1
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MENUBUILDER VERSION 2.22 Output created on 10/ 4/2003
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10 APPENDIX D: CAPACITY BUILIDING AND TECHNOLOGY TRANSFER

A number of individuals made important contributions to aspects of the study: M Gordon, J Smith, T Kotze, F Seghers, K Davidse, P Shange and K Crombie provided assistance in the field and/or laboratory while A Pike undertook the modelling calculations with ACRU. Roger Parsons and Associates provided spatial data on groundwater salinity. Some of the aerial photography was done by Anton Jordaan of Stellenbosch University.

Human Resource Development: The following persons from the designated group worked full time on the project as Laboratory Assistants:

Ms Kamilla Crombie
Mr Kenneth Davidse

During the course of this project, the two above mentioned persons were also trained in aspects of data manipulation that mainly involved repetitive actions.

Due to the limited aims and duration of this project, and the fact that it was only a pilot study, student involvement was minimal. One student from the Ghent University in Belgium graduated in Belgium but his thesis project was based on information from this project. We also had a post graduate student from the Soil Science section of the Leuven University, Eva Sinjan, that worked on this project and mainly helped with the GIS interpretation of results.

Student projects.

F. Seghers: Mapping of salinity on the Glenrosa farm. MSc (agricultural engineering), Dept. Soil management, Ghent University, Belgium.

WP de Clercq: Mapping soil salinity in South Africa. PhD (agricultural engineering), Ghent University. In Progress.

Technology Transfer:

A: In August 2003, three seminars were held on the farm Môrester:

1. Fey MV. *Dryland salinity and its threat to sustained water quality.*
2. De Clercq WP. *Irrigation water quality guidelines and minimising returnflow.*
3. De Clercq WP. *Die omvang van brak, bestuur daarvan en die toekoms.*

B: April 2004, a public invited lecture at the Saldanha water management body monthly meeating.

The dryland salinity influence on the Berg River water.

An article highlighting the possible effect winter wheat production has on the quality of the water in the Berg river appeared in amongs others, the "Landbouweekblad" and the " Farmers Weekly".

An article highlighting the EM38 (electromagnetic induction soil salinity meter) as an aid in soil mapping appeared in the "Wynboer":

De Clercq W.P. 2003. The application of soil electromagnetic induction techniques in aid of soil mapping. Wynboer South Africa Julie 2003.

Three articles were presented at conferences as follows:

HN Engelbrecht, and WP de Clercq, (2003): A soil irrigation suitability study for the lower Berg River catchment. SSSA Congess, Stellenbosch.

De Clercq, W.P., Van Meirvenne, M. 2003. Effect of long term irrigation application on the variation of soil electrical conductivity in vineyards. Pedometrics Conference 2003.

WP de Clercq. Seasonal soil salinity dynamics in a vineyard subjected to saline irrigation water. SSSSA Congress, Stellenbosch 2003 .

One article was accepted by an international journal:

De Clercq, W.P., Van Meirvenne, M. 2003. Effect of long term irrigation application on the variation of soil electrical conductivity in vineyards. *Geoderma*, accepted for publication, April 2004.

Other related WRC reports available:

A Guide to nonpoint source assessment to support water quality management of surface water resources in South Africa.

GC Pegram and AHM Görgens

The primary focus of this Guide is to support water quality management of surface water resources, and particularly non-point sources management, by providing appropriate and cost effective information for decision making. The Guide aims to assist users in understanding their non-point sources assessment needs in a particular situation, and thereby enable them to identify and apply appropriate non-point source assessment techniques.

The Guide is primarily targeted at non-point source decision makers and those practitioners who are involved in non-point source studies aimed at providing management oriented information. Both decision makers and practitioners are assumed to have an understanding of water resource issues, but not necessarily non-point sources. Therefore, the document has been written to be accessible to people with varying expertise and knowledge, including relatively uninformed readers. This implies some redundancy for experienced users, but an attempt has been made to enable quick referencing of pertinent information, thereby avoiding the need to read the entire document.

This document has been presented in four parts, each serving different but interrelated purposes:

- **Part 1** provides a brief overview of the management context of non-point source assessment, which provides the user with an understanding of the policy and legal environment of non-point source management.
- **Part 2** provides an overview of the issues and information needs associated with non-point source assessment, as related to the non-point source area character, water quality concerns and management goals.
- **Part 3** presents the guide itself, which assists the user in defining their non-point source task, translating this into criteria for non-point source assessment and indicating appropriate assessment techniques.
- **Part 4** describes the non-point source assessment techniques referred to in the guide, and in some cases presents relevant information necessary to apply them, illustrated by South African case studies.

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