DATA ACQUISITION AND EVALUATION OF SOIL CONDITIONS IN IRRIGATED FIELDS IN THE BREEDE RIVER VALLEY

by

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VOLUME II

of a report to the Water Research Commission on the project

"AN EVALUATION OF THE ABILITIES OF SEVERAL ROOT ZONE SOLUTE AND WATER TRANSPORT MODELS TO ADEQUATELY PREDICT THE QUANTITY AND QUALITY OF WATER LEAVING THE ROOT ZONE"

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EXECUTIVE SUMMARY

1 INTRODUCTION

Much research in the fields of soil physics and soil chemistry has, since the early 1960's, been directed toward developing scientific aids to deal with subjects such as the impact of irrigation on the environment, water reuse projects, and estimations of the travel time of water and chemicals trough the root zone of soils. One such aid has been the development of unsaturated zone leaching models for predicting movement and, in some cases, the degradation of agricultural chemicals. Scientific reports describing various aspects of this research, i.e. theory and development, validation, application, etc., are abundant in the literature. The result is that, at least within the research community, modelling has become an accepted way of predicting and estimating the outcome of agricultural activities. However, there are serious difficulties which are hampering the selection of suitable models and which are preventing the use of these potentially powerful tools in everyday practical applications. Some of these problems include problems of scale, spatial variability, cost-benefit ratios and multidimensional flow directions.

Solute transport models have been used in a number of case studies in South Africa e.g. Van Rooyen (1977), Van Rooyen & Moolman (1980), Moolman and Beukes (1980) and Hall and Du Plessis (1984). These applications unveiled a number of questions and uncertainties regarding the use of solute transport models. An example of these uncertainties is how the results of different rootzone hydrosalinity models compare with respect to their potential applications under conditions such as:

i) varying the scale of application, e.g. catchment vs. farm scale;
ii) different conditions of spatial variability;
iii) different levels of input data availability;
iv) different irrigation management strategies, e.g. complete wetting vs. partial wetting of the soil surface (flood vs. drip irrigation).

2 OBJECTIVES

In order to try and resolve some of these issues a research project with the following aims was formulated and conducted by the Department of Soil and Agricultural Water Science, University of Stellenbosch:

i) To determine, with the aid of the most appropriate water and solute transport model, the minimum amount of input data necessary to adequately predict the quantity and quality of water leaving the root zone for various scales of application and modes of surface wetting.

ii) To investigate the sensitivity of various hydrosalinity models to a change in input variables, with special emphasis on the effect of spatial variability of soil properties on the accuracy of model predictions of the quantity and quality of the deep percolate.

iii) To illustrate how solute transport models can be used to change surface water management strategies in order to decrease the salt load of the deep percolate.

iv) To compile a comprehensive literature review of solute transport models. (This objective is not listed in the original research contract, but, on request of the steering committee, was included as a separate aim of the project.)

Several solute and water transport models for the root zone of agricultural lands are available. These models differ in their level of sophistication and input demands. Ideally all of these models should be included in a study of this kind. However, because of time and financial constraints, this is not a feasible approach. Therefore, the models included in this study were selected using the following guidelines:

i) A model should be able to simulate both the flow of water and solutes, with associated inorganic chemical processes, through the root zone. Models simulating the chemistry of pesticides and nitrogen were excluded.

ii) At least one example of a mechanistic model and one functional model should be evaluated.

iii) One of the models should describe the chemistry of all the major cations and anions.

iv) Duplication should be avoided, i.e. if two models differ only with respect to minor detail, one only will be studied.

Several models were found that met two or more of these criteria. Recognizing the criteria stated above, as well as constraints imposed by time and manpower, this study was limited to the following three models: BURNS (Burns, 1974), LEACHM (Wagenet and Hutson, 1989), and TETRans (Corwin and Waggoner, 1990).

In order to address adequately these research goals, observed field information from irrigated areas are required as reference data against which model predictions can be evaluated. Such reference data sets must include, on both a spatial and temporal scale:

i) salt composition and distribution within and below the root zone;

ii) soil water content and distribution within and below the root zone;

iii) drainage water (deep percolate) quantity, and chemical composition;

iv) irrigation, precipitation and evapotranspiration information;
v) all the necessary physical and chemical soil properties (including spatial statistics), required as input by solute transport models.

A survey of literature revealed that no local (South African) or international data set can meet all these requirements for periods exceeding two years. Consequently, during 1986 and 1987 two irrigated vineyards in the Breede River Valley were instrumented as "*field laboratories*" in which the parameters listed above were monitored at varying time scales up to June 1990.

The results of this research project are presented in two volumes. Volume I focuses on the main thrust of this research, i.e. to evaluate different solute transport models. Volume II deals with the data acquisition and surveys that were conducted as part of the field study.

In Volume I the three models used in this study are described in detail. Each of the research objectives were addressed separately and the results are presented as different chapters of Volume I. It includes a literature survey of models, the results of a sensitivity study of two different models, and the results of the application of some of the models mentioned above on both a micro- and mesoscale. The microscale study was conducted using the information of a drip irrigated vineyard located in the Breede River Valley of South Africa, while the mesoscale study was based on the results of an irrigation project conducted in the San Joaquin Valley of California.

Volume II of this report deals with the data acquisition programme and the various surveys and field studies that were conducted between 1986 and 1990 in the Breede River Valley of South Africa. Examples of the data and the format in which it can be made available to other interested people, are included in this volume. It also contains the interpretation of some the results which are presented in different chapters as independent scientific papers.

3 SUMMARY OF RESULTS AND CONCLUSIONS.

3.1 Evaluation of transport models of the unsaturated zone.

3.1.1 Literature Survey Of Transport Models.

The highlights of the review on transport models of the unsaturated zone can be summarized as follows:

a) No model can be identified as representing the ultimate state of the art. Neither has any one model, or even modelling approach, received wide scale acceptance. Furthermore, the reported success rate of model application studies, especially when used by non-modellers (i.e. researchers, managers, farmers, etc. etc.) can at best be described as being moderate to fair. According to Wagenet (1988), at present, only approximate prediction of water movement and chemical distributions can be made.

b) Based on the results and suggestions found in literature, it seems logical and scientifically sound to conclude that the more mechanistic models are superior to the more simple non-mechanistic, capacity type models. However, this alleged superiority might be negated when models are used to predict responses in large irrigated areas bordering on the order of basin scale. When models are applied to large areas, other factors might be of greater importance than, for example, the hydrologic variability of field soils.

c) None of the models reviewed can effectively describe the movement of chemicals under conditions of macropore flow.

d) Time and effort to meet the data demands of a specific model will play a role in model selection, especially for macroscale applications. On a macroscale, variables such as rainfall, irrigation and evapotranspiration amounts might be of far greater importance than detailed and accurate information of soil properties such as cation exchange capacity and cation selectivity coefficients.

e) The choice of the appropriate model to use will depend on three factors:
   i) the specific application;
   ii) the required accuracy of prediction;
   iii) how much information is available and how much time and effort can be spent in obtaining the required information, and
   iv) the knowledge of the user of the model.

3.1.2 Sensitivity analysis of two different transport models.

The objective of this study was to evaluate the effect of a number of model parameters on the predicted quantity and quality of soil water leaving the root zone of irrigated agricultural lands. The study was conducted using deterministic mechanistic, and deterministic capacity type of water and salt transport simulation models. A sensitivity analysis was performed which involved six input parameters required by the mechanistic LEACHM model. The parameters that were studied are: airentry potential, slope of the soil water characteristic (i.e. Campbell's *a* and *b* coefficients), saturated hydraulic conductivity, cation exchange capacity, Ca/Na selectivity coefficient, and the difference between the evapotranspiration and irrigation quantities. The latter parameter and field capacity were evaluated with the simpler Burns model. With both models a hypothetical soil profile and irrigation frequency were used. The results indicate that:

a) The net flux of water moving through the soil, simplified by the ratio of evapotranspiration and irrigation, i.e. the ET/I ratio, is by far the most important factor in determining the quantity of water and salt that will be leached out of the root zone. Both of the two models that were used, showed that even a relatively small change in the ET/I ratio, e.g. from 1,00 to 0,90, will significantly effect the flux of water and solutes through the soil. In practice this indicate that accurate estimates of the irrigation and evapotranspiration should receive more attention than other physical and chemical properties such as water retention, hydraulic conductivity and CEC when scaling up from the micro- to the macroscale.

b) Unbalanced combinations of hydrological parameters have a profound effect on model predictions of mechanistic models. In this regard the air entry potential was of particular importance. A high potential (i.e. small negative) in combination with medium to low saturated hydraulic conductivities had a critical effect on the estimate of the unsaturated conductivity. In extreme cases, such low values for the unsaturated hydraulic conductivities can be obtained that no movement of water and salt will be possible. It is quite possible that the unsuspecting model user could come to the spurious conclusion that soils in which macro pores predominate, i.e. soils with large airentry potentials, will have a low salt output irrespective of the ET/I ratio. This obviously is an inconsistent result.

c) The ranking of the rest of the parameters that were evaluated, was complicated by the large impact that one unbalanced combination of hydrological parameters had on the results. The ranking is also strongly influenced by the magnitude of the flux of water moving through the soil profile. By using the predicted results obtained with a certain combination of input parameters as the norm, the effect on the predicted salt load and water flux of the six variables that were evaluated could be evaluated. A moderate decrease in the ET/I ratio from 1,0 to 0,9 which, in this study corresponded to an in crease in the water flux from 49 to 182 mm m^{-1}, yielded the following rank (in order of decreasing effect):

ET/I > > Ksat > *a* ≥ *b* > CEC = k-Ca/Na

By using a similar procedure as above, but changing the ET/I ratio from 1,0 to 0,5 (which increased the water flux from 49 to 910 mm a^{-1}), a different rank order is obtained:

ET/I > > > CEC > *b* > k-Ca/Na = *a* > Ksat

This big increase in the water flux reduced the effect of Ksat to such an extent that it moved from the second to the last position in the rank order. In contrast, the salt supplying capacity of the soil, which in this study was quantified by using different CEC values, became more important and moved up several positions in the rank order.

In view of this result, it seems as if the relative importance of the cation exchange capacity and the hydraulic conductivity as properties that will influence the salt load in the deep percolate of irrigated lands, will depend on the magnitude of the water flux. At small fluxes, i.e. where AET ≈ irrigation, the rate of water movement through the soil is more important than the salt supply capacity of the soil. At greater fluxes, i.e. irrigation > > AET, the rate of water movement becomes less important while the capacity of the soils to supply salt, increases in importance.

d) With the capacity type model of Burns, the field capacity of the fictitious soil did influence the leachable quantity of water and salt, but it's effect was secondary to that of the ET/I ratio.

e) Several model parameters were not investigated, with the result that the effect of the chemical, but more specifically the hydrological parameters, remain somewhat inconclusive. The effect of the boundary conditions at the bottom of the soil profile might influence the relative importance of the *a*, *b* and Ksat parameters.

3.1.3 Microscale application of the mechanistic transport model LEACHM.

The objective of this part of the research project was to evaluate how accurately a mechanistic research model can simulate transport processes under microscale field conditions (< 1 ha). Only one model, namely LEACHM (Wagenet & Hutson, 1989), was used for this study. The data that were used to evaluate the predicted soil water and soluble salt contents over time, are based on field measurements made during a period of two and half years in a 0,5 ha drip irrigated vineyard in the Breede River Valley of South Africa. In addition to the primary objective, this application of LEACHM was also meant to serve as a test of the application of a one-dimensional model to a case where the irrigation is applied at a point source and the water and salts subsequently redistributed in three dimensions. LEACHM was used to simulate the chemistry and transport of soil water and salt that occurred during the period 1 May 1987 to 30 June 1989. Soil properties of four different locations in the vineyard were used as input for the model, and at each location the 2,5 m^2 area served by one emitter was divided into four sectors with each sector being simulated separately.

The results of this study gave a rather pessimistic picture on the ability of LEACHM to simulate accurately the chemical processes in drip irrigated row cropped fields. Some of the results are also conflicting and can be summarized as follows:

a) In terms of the predicted soil water contents and fluxes, the numerical statistics and visual comparisons give different impressions of the adequacy of LEACHM as a method to calculate accurately the fate of applied water in this drip irrigated vineyard. Based on statistical norms, neither the coefficients of determination (R^2), nor the d-index of Wilmot (1981) justify any confidence in the model at all. The maximum R^2 value and d-index that were obtained are 0,306 and 0,774 respectively. However, judging the adequacy of prediction in terms of visual comparisons only, give a slightly better view of the predictive ability of LEACHM. Except for marked underpredictions in the soil water content of the shallower soil layers during the summer of 1987/88, the predicted water contents as well as the temporal trends did not deviate too much from the measured values and trends.

b) The visual comparison between the predicted and observed drainage rates is promising, especially in view of the fact that the predicted daily drainage volumes and rates of a known area (0,5 ha) were compared with the observed values from an unknown area.

c) The poor prediction of soil water contents and fluxes should be judged against the complexity of the three dimensional flow patterns in the drip irrigated field to which a one-dimensional model was applied. Based on the results of the sensitivity study, it was concluded that in cases where a certain surface area of the soil only is wetted, even a small error in the conversion of volume of applied water to depth units is likely to result in substantial differences in the measured and predicted water contents and fluxes. Because the real wetted area is unknown and difficult to determine, using different areas when converting from volume to depth units of irrigation water can have a profound effect on the outcome of the modelling study. Consequently, in this particular application of LEACHM, the statistically poor match between predictions and observations might be related to either model inadequacies, or input errors and it is rather difficult to distinguish between these two.

d) Serious numerical problems were encountered with the chemistry version of LEACHM, i.e. LEACHC, and did little to install confidence in the model. It was found that the code of LEACHM is such that under circumstances, the square root of a negative number, or division of a value by zero, is attempted. However, it was virtually impossible to predict when and under which conditions this situation will occur. In this study all of these cases were associated with the chemistry of the calcium ion. It is speculated that the numerical instability is related to the large amount of non-saline, low salt water that was applied to a saline soil with a rather low cation exchange capacity in the presence of small quantities of gypsum and free lime. This set of conditions can possibly lead to a situation where, according to the algorithms used in, and rationale behind LEACHM, calcium concentrations become very small.

e) The information and experience gained with this microscale study indicate that the application of one-dimensional transport models to drip irrigated, widely spaced, row-cropped fields, by nature of the model construction will lead to poor results.

3.1.4 Evaluation of three transport models on a mesoscale.

The objective of this part of the research project was to apply one mechanistic research model, and two functional management models to field data and to assess their accuracy of prediction at a mesoscale (1 - 10 ha). The models used were LEACHM (Wagenet and Hutson, 1989), BURNS (Burns, 1974), and TETrans (Corwin and Waggoner, 1990). Because no local (South African) data on a meso scale could be found, use was made of the results of two treatments of a 61 ha irrigation experiment conducted in the San Joaquin Valley of California. The two treatments that were used are a 5,7 ha furrow irrigated, and a 2,4 ha drip irrigated plot. The main results and conclusions of this study are as follows:

a) Based on the quantitative statistics, it seems as if the predictive capability of the leaching model LEACHM when applied on a mesoscale, is rather poor. For example, predicted soil water contents, when evaluated on a temporal scale, could not adequately match the observed data. Furthermore very low R^2 values and d-indexes were obtained when the predicted and observed results were compared on a temporal scale. However, inspection of the observed soil water contents gave strong indications that the inadequate prediction by LEACHM might be related to measurement errors and inadequacies. This is supported when considering the few samples that were taken and the large spatial variability among them. One example of this is the case of the 5,7 ha furrow irrigated plot where the maximum number of samples taken at any one of the four sampling dates between 1983 and 1986, was never more than three. Previous studies on sampling strategies in saline soils, have proved that a large number of spatially distributed samples is required in order to detect trends and calculate means. Notwithstanding the inadequacies of the measured data that were available, the predicted results indicate that the chemistry of calcium and magnesium are not satisfactorily dealt with by LEACHM.

b) In contrast to the rather poor numerical statistics obtained with LEACHM, graphical comparison between the observed and predicted results at the end of the simulation period, i.e. the final ion concentrations, lead to a different conclusion, namely a good predictive capability. In this study, LEACHM predicted that the soluble salt content of soils that are irrigated with saline drainage water, will increase appreciably. Not only was this confirmed with measured data, but the predicted salt concentrations and distributions with depth closely matched the observed results. A similar result was obtained even when good quality water was used with furrow irrigation as an application method.

c) The two functional type models, i.e. Burns and TETrans, predicted chloride concentrations that bear no resemblance with the measured data, both in terms of numerical statistics and graphical comparisons. The accordance between the LEACHM predictions and observed data were substantially better than the Burns and TETrans predictions. The superior predictive ability of the LEACHM model over the Burns and TETrans models is supported by the root mean square error and d-index values.

d) The application of LEACHM, which is a one-dimensional flow model, to the 2,4 ha drip irrigated field, resulted in a fair to good prediction of the actual chemical composition of the soil as observed at the end of the irrigation experiment. This is contrary to what was found with the microscale study conducted in the drip irrigated vineyard in the Breede River Valley of South Africa. In the latter case the LEACHM-predicted salt concentrations did not accord with the observed data at all. It is concluded that this apparent anomaly can be explained by the differences in emitter spacing. In the mesoscale study the emitter spacing was 1 m x 1 m, as opposed to the 1 m x 2,5 m in the case of the microscale study. It is reasonable to assume that in the former case, the more densely spaced emitters will result in a flow pattern that is essentially one-dimensional, in contrast to the three dimensional flow pattern that is expected to predominate when the emitter spacing is less dense.

e) It was also found that the results of the drip simulation are more accurate than the furrow plot simulation. It was inferred that this is probably due to the fact that controlling and measuring the amount of water applied with drip irrigation is easier and more accurate than with furrow irrigation. Therefore, in the case of the drip irrigated plot, the amount of applied irrigation water supplied as input, was a more accurate account of the actual field infiltrated water than was the case with the furrow applied water.

3.1.5 Simulating the effect of different leaching strategies on the salt load of the deep percolate of irrigated lands

The aim of this study was to illustrate how solute transport models can be used to change surface water management strategies in order to decrease the salt load of the deep percolate. The effect of six different salinity control measures as affected by using various leaching strategies, simulated for three consecutive years, on the salt and water flux of a hypothetical irrigated soil were investigated. For each year and leaching strategy (with the exception of one scenario), the same rainfall and actual evapotranspiration (AET) data were used throughout. The soil properties, irrigation water composition and irrigation management strategies that were used as the basis for the different leaching strategies, are all common to the Breede River (South Western Cape, South Africa).

As was the case in Chapter 4 where LEACHM was used to simulate the water and salt distribution in a drip irrigated vineyard, numerical instabilities were also encountered in this study. A weekly irrigation frequency was the only salinity control measure that could be simulated for a full three year period. However, based on the results of the first summer and winter cycle, the following conclusions can be made regarding the effect of different leaching strategies that can be used to minimise the salt load of the deep percolate of irrigated lands:

a) For a particular leaching fraction, the total flux of water at the bottom of the root zone at the end of a summer and winter cycle will be nearly the same, irrespective of whether: i) a daily or weekly irrigation frequency is used during summer, and ii) the leaching water is applied with every irrigation during summer, or as a single application during winter.

b) Although only to a degree, the total salt load of the deep percolate will increase in the order: no leaching during summer, with a single leaching in winter < leaching during summer on a daily frequency < leaching during summer on a weekly frequency.

c) The temporal distribution of the salt load and water flux suggests that controlled leaching of salts during winter is more beneficial for the control of the salt concentration of receiving rivers.

d) For the irrigation water that was used (EC ≈ 100 mS m^{-1}), an irrigation practice where no leaching is employed during the summer period, will result in a considerable accumulation of salts in the bottom half of the root zone during the irrigation season. If a winter leaching is applied, a significant portion of these salts will be leached and the predictions suggest that the salt content within the root zone at the onset of the second irrigation season, will be less than the initial values.

e) The fact that LEACHM predicted similar water and salt fluxes for a daily and a weekly irrigation frequency should be treated with caution. This result, in all likelihood stems from the fact that LEACHM can handle D'Arcian type flow only and not macropore flow. In practice, low irrigation frequencies involving large amounts of irrigation water at greater applications rates than smaller quantities at higher frequencies but lower application rates, will yield larger water fluxes and salt loads.

f) In spite of the general shortcoming of the presently used water and salt transport models not being able to simulate non-D'Arcian type of water flow (e.g. macropore flow), they still are useful tools that can be used to evaluate and design different salinity control strategies. Computer investigations such as the one reported on in this study, are far cheaper to conduct than expensive field trials. The results of simulation studies can then be used to select, test and verify certain salinity control strategies under field conditions. Unfortunately, the particular model that was used in this study, LEACHM, under certain unknown and unpredictable circumstances, turned out to be numerically unstable.

3.2 Data acquisition and evaluation of changes in the temporal and spatial soil conditions in irrigated fields in the Breede River Valley

In Volume II of the report, a number of aspects associated with spatial and temporal variability of soil properties that impact on the validation of water and salt transport models, were investigated. This was done by investigating some aspects of the data that were acquired during the course of a three year field study which led to the establishment of a considerable data base on soil chemical and hydrological properties. The most important research findings will be highlighted here.

3.2.1 The effect of spatial variability on the estimation of the soluble salt content in a drip irrigated saline loam soil.

The distribution and total mass of soluble salt in a drip irrigated vineyard was investigated. Eighty four positions in a 0,475 ha area were sampled at five depths each, resulting in a total sample number of 420.

a) The salt content increased exponentially with distance from the emitter. At equal distances from the emitter, significantly higher values were observed outside, compared to within the vineyard row. Outside the row the salt content decreased significantly with depth, but within the row the salt content was constant down to 1 m. Depth, distance from emitter and position relative to the emitter could account for 52% of the observed variation in salt content.

b) The total salt mass within the study area to a depth of 1 m, was estimated to be ca. 22,5 ton ha^{-1}. Calculation of the required sample size, combining the central limit theorem with the statistics of the present study, showed that at certain spatial positions relative to an emitter, the type II error of erroneously accepting the null hypothesis and the first estimate of the salt content could be as high as 41%. The initial sampling scheme could be improved by taking account of the observed spatial variation.

3.2.2 Using the probability density function of soil water content to locate representative soil water monitoring sites in a drip irrigated vineyard.

This study investigated whether the probability density function of spatially measured soil water content at the first stage of a field study can be used to identify statistically important field locations. The soil water content at 14 sites was monitored at 15 different times over a period of 18 months in a drip irrigated vineyard.

a) It was found that certain sampling locations conserve the property to represent the mean and extreme values of the field water content over time. The presence of transpiring vines and irrigation applications increased the variability of the measured values without any big influence on the ranking position of the various monitoring sites as they initially appear on the probability density curve. The locations that were identified as being representative of the field mean water content during summer, also represented the mean during winter when irrigation and transpiration were absent.

b) The positions representing the field mean and extreme water contents of the topsoil differ significantly in space from the corresponding subsoil positions.

c) It was concluded that, because of the temporal stability of the ranking position of the measuring sites, the probability density curve of one sampling only can be used to identify representative sites (e.g. the median), that can be used for soil water monitoring and irrigation scheduling. However, cognizance should be taken of the confounding effects that are likely to occur with depth.

3.2.3 The design and use of a tipping flow gauge for the measurement of subsurface- and surface drainage water.

During the course of the study it became clear that there are few instruments available that can accurately measure flow rates in subsurface drains. A tipping bucket flow gauge was therefore designed for direct measurement of flow rates in subsurface drains of agricultural lands. The free-board problem in a manhole was overcome by using two reservoirs and pump system. The flow gauge was connected to a standard data logger with low power consumption. The flow gauge can also be easily adapted for measuring surface runoff. Results obtained with the flow gauge in irrigated vineyards in the Breede River Valley show a positive correlation between irrigation applications and flow rates in subsurface drains.

3.2.4 Water balance studies in a drip irrigated vineyard in the Breede River Valley: A comparison of different methods.

The evapotranspiration, irrigation, soil water content and drainage flow rates of three irrigation seasons were used to estimate the water balance of a 0,475 ha drip irrigated vineyard. The five different methods employed to calculate the leaching fraction, gave widely varying results.

a) From the field capacity of the soil, class A-pan estimated evapotranspiration data and measured irrigation quantities, it was inferred that with the exception of 1987/88, the amount of water that will percolate through the root zone of the drip irrigated vines, will be insignificant.

b) However, quantitative measurement of the soil water content and the applied irrigation amounts during two individual events, suggest significant losses of water out of the root zone, probably due to macropore- and preferential flow. The drainage hydrograph and chloride distribution in the soil volume in the immediate vicinity of the emitters, provide further evidence of significant losses due to macropore- and preferential flow.

c) It is inferred that a water balance based on irrigation and evapotranspiration amounts alone, might lead to spurious conclusions regarding the harmful, e.g. salinization, effects of irrigated agriculture on the water resources of an environment.

d) Most water and salt transport models cannot simulate macropore- and preferential flow. In view of the results of this study, it is possible that water and salt balances calculated using these models which rely heavily on evapotranspiration and irrigation inputs, might be far removed from actual field conditions.

3.3 Extent to which the contract objectives have been reached.

Although all of the objectives have been addressed in this study, not all of them have been met with equal success. Some of the original questions regarding the use of transport models in irrigated environments have been left unanswered. This study improved our knowledge about the strengths and weaknesses of soil and water transport models, as well as the role that they can play in the applied and predictive hydrology. This statement is based on the following aspects:

a) There are strong indications that the minimum input requirements in transport modelling involve those variables controlling the water and salt fluxes through the soil, i.e. irrigation, precipitation and evapotranspiration amounts, as well as the salt content of the soil and irrigation water.

b) Models designed to simulate one dimensional flow processes, should be expected to yield poor results when applied to irrigated field where the soil surface is only partially wetted, e.g. drip- and micro irrigated fields.

c) Validating models with field studies and on a scale larger than small experimental plots (i.e. >25 m^2), requires large data sets gathered using a sampling protocol that are designed to minimize the effect of statistical uncertainties, both in time and space.

d) This was one of the few studies of its kind that compared and evaluated different models at varying scales and under different environmental conditions.

4 RECOMMENDATIONS

a) In order to increase and improve data that can be used to validate water and salt transport models of the unsaturated zone, the monitoring of soil conditions in selected irrigated fields should continue.

b) A study involving the comparison of two sophisticated mechanistic models should be conducted. This should include LEACHM and another model also capable of simulating the chemistry of all the major cations and anions found in agricultural soils. However, the study will only have merit if another such a sophisticated model can be found.

c) Develop a two- and three dimensional model that can simulate the transport of water and chemical processes in drip irrigated fields.

5 REFERENCES

Burns, I.G. 1974. A model for predicting the redistribution of salts applied to fallow soils after excess rainfall or evaporation. *J. Soil Sci. 25:165-178.*

Corwin, D. & B. Waggoner. 1990. TETrans, Solute transport modeling software, IBM-Compatible version 1.5, U.S. Salinity Laboratory, USDA-ARS, Riverside, California.

Hall, G.C. & H.M. Du Plessis, 1984. Studies of mineralization in the Great Fish and Sundays Rivers. Volume 2: Modelling river flow and salinity. C.S.I.R. Special report WAT 63. National Institute for Water Research, C.S.I.R. Pretoria.

Moolman, J.H., & D.J. Beukes. 1980. A field test of a conceptual computer simulation model for predicting water and salt distribution. *Irrig. Sci. 2: 33-47.*

Van Rooyen, P.C. 1977. Moderne tegnieke vir die evaluering van besproeiingswaterkwaliteit. *Elsenburg Joernaal 1: 23-27.*

Van Rooyen, P.C., & J.H. Moolman. 1980. Effect of irrigation management and water table depth on water and salt distribution as predicted by a computer simulation model. *Water S.A. 6:66-78.*

Wagenet, R.J. 1988. Modelling soil hydrology: Perspectives, perils and directions. pp. 1-9. In: Proceedings of the International Symposium on modelling agricultural, forest and rangeland hydrology. December 12-13, 1988, Chicago, Illinois.

Wagenet, R.J., & J.L. Hutson. 1989. LEACHM (Version 2). Leaching estimation and chemistry model. A process based model of water and solute movement, transformations, plant uptake and chemical reactions in the unsaturated zone. Continuum Vol. 2, Water Resources Institute, Cornell University, Ithaca, NY.

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CHAPTER 2
DESCRIPTION OF THE TEMPORAL AND SPATIAL SAMPLING NETWORK AND DATA ACQUISITION IN A DRIP IRRIGATED VINEYARD AT ROBERTSON

2.1 DESCRIPTION OF THE STUDY AREA

An area of approximately 0,5 ha of a drip irrigated vineyard on a commercial farm near Robertson (i.e. in the Breede River Valley) was selected as one of the so-called field laboratories. The soil of the vineyard belongs for the most part, to the Katspruit Killarney and Westleigh Rietvlei series (MacVicar et al, 1977). From 0,45 m downwards the B-horizon is mottled, indicating hydromorphic conditions in the subsoil. Morphological descriptions of two soil profiles were obtained from L. Barkhuizen (personal communication) and are given in Table 2.1. The vine cultivar is Vitis vinifera cv. Colombard.

Table 2.1 Morphological description of two soil profiles in the drip irrigated vineyard at Robertson

Profile nr	1		2		
Soil form Soil Series	Katspruit Killarney		Westleigh Rietvlei		
Diagnostic Horizon	A1 Orthic	G Horizon	A1 Orthic	B Soft plinthite	C Uncon- solidated
Depth (m)	0-0,35	0,35-1,50+	0-0,2	0,2-0,9	0,9-1,5
Transition	Gradual		gradual	gradual	
Restriction		wetness		wetness	
Grade		severe		severe	
Texture	loam	loam	loam	fine sa. lm.	fine sa. lm.
Coarse material	none	none	none	none	none
Structure	apedal	massive	weak blocky	weak blocky	weak blocky
Consistency	firm	firm	massive	massive	massive
Free lime	none	none	none	none	none
Visual salt	abundant	abundant	abundant	abundant	abundant
Root distribution %	100	0	60	40	0

The vineyard is underlain by a drainage system at 2 m depth which was installed in 1984. During the study period the vines were irrigated with low-salinity water using a drip irrigation system with a row and emitter spacing of 1 m and 2,5 m respectively. Prior to the onset of irrigation in 1984, the soil was very saline. No record was kept of the actual salt content at that stage, but the soil was so saline that two fertilizer companies independently advised the owner of the land that the soil is too saline for the production of vines. Despite this advice, the owner decided to install the drains and to establish a vineyard. A map of the study area is given in Figure 2.1.

Between December 1986 and July 1989, the soil of the vineyard were sampled at different time intervals to establish a record of changes in the water and salt content with time and in space. During the course of the study, the vineyard was instrumented to monitor certain hydrological and meteorological parameters on a more continuous basis. Most of these instruments were installed in 1987. A tipping bucket rain gauge, tipping bucket flow gauge, pump sampler, automatic recording tensiometers and an electronic thermometer all of which were connected to an onsite datalogger, were used. At the time of writing of this report (August 1992) some of these parameters were still being monitored while others have since been discontinued. In the following sections the *ad hoc* surveys, instrumentation and continuous monitoring actions are introduced. In paragraph 2.4 examples of the different data bases are given. Apart from being used in the study where LEACHM was evaluated on a micro-spatial scale, the data have not been fully exploited and investigated as yet. Those aspects that have already been interpreted and published elsewhere, appear as separate chapters in this report.

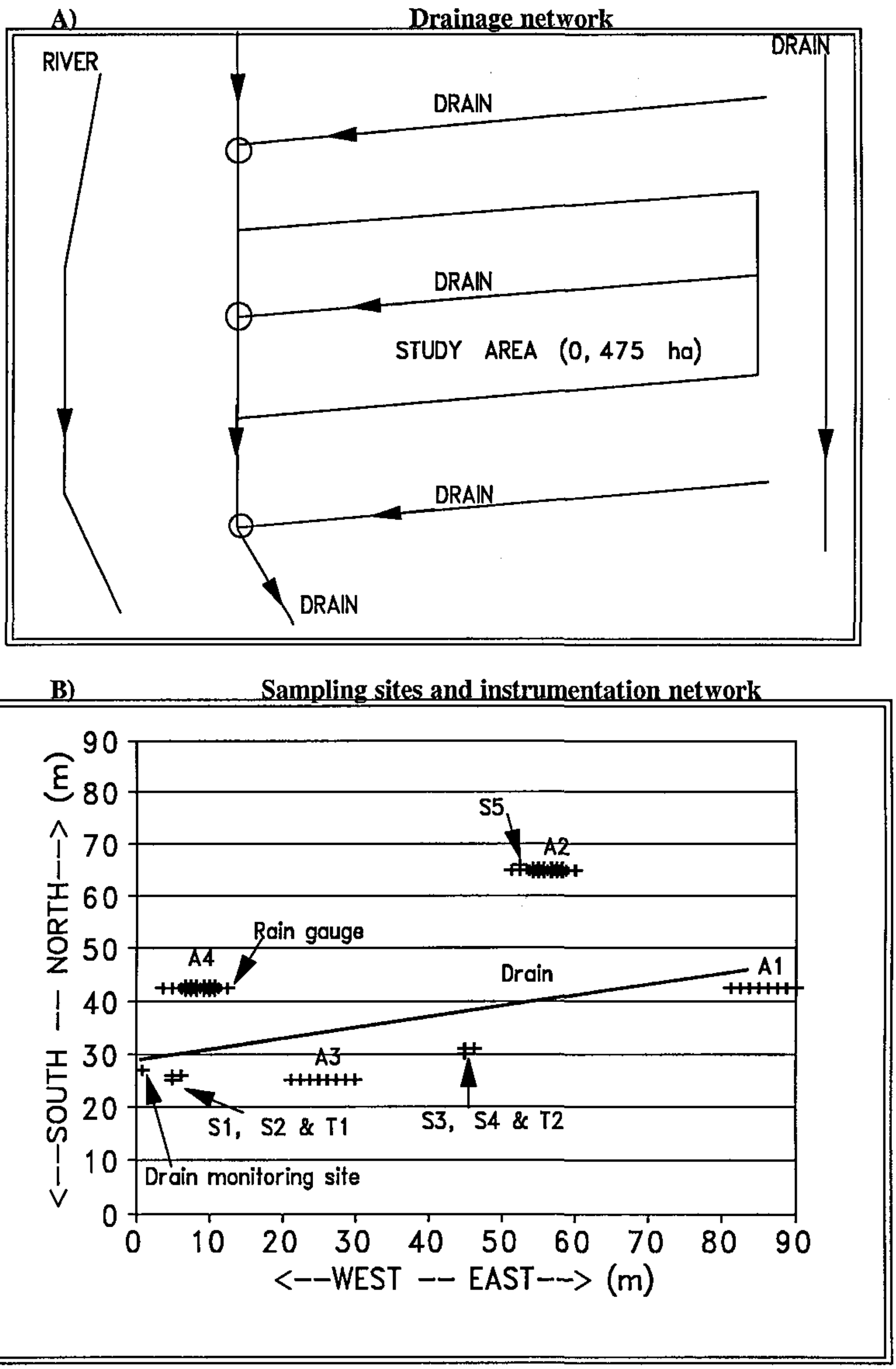

Figure 2.1 Map of the study area showing the sampling sites and instrumentation network

2.2 AD HOC SURVEYS OF THE SOIL CONDITIONS, SAMPLING PROCEDURE AND ANALYTICAL METHODS

2.2.1 General

During the period December 1986 to July 1989, soil samples were collected at the following five dates: December 1986, May 1987, 8 and 23 August 1988, and July 1989. The purpose of these surveys was to establish a data base of the temporal and spatial changes of the chemical and physical soil properties of the study area that ultimately could be used to evaluate and validate different water and salt transport simulation models. The samples of May 1987 were also used to determine some physical properties of the soil. In addition to the laboratory studies, *in situ* determinations of the bulk density, infiltration rate, internal drainage rate and field capacity (or upper drained limit) were conducted. The physical and chemical properties determined in May 1987 were used as input for the hydrosalinity model, LEACHM (see Volume I).

In the following paragraphs, the different sampling designs and analytical techniques will be described. These two aspects will be dealt with separately. The analytical techniques will furthermore be split into chemical and physical properties. Excerpts of the data that were collected during the course of this study are presented in section 2.4. In some cases tabulated summaries of a particular result are included in the text. All data are electronically stored in spreadsheet format (LOTUS 1-2-3 or QUATTRO PRO) on diskettes, copies of which can be obtained from the authors.

2.2.2 Description of the different sampling designs

a) December 1986

A survey to determine the spatial distribution of soluble salt in the 0,5 ha study area was conducted in December 1986. Four areas, coded A1, A2, A3 and A4 were randomly chosen. These four areas are indicated in Figure 2.1. In each area, referred to as a macroposition, the area surrounding one drip emitter was selected for sampling purposes. The soil was sampled using a Veihmeyer auger at predetermined distances from the emitter. The emitter formed the centre point of the bigger area that was sampled according to the diagram given in Figure 2.2.

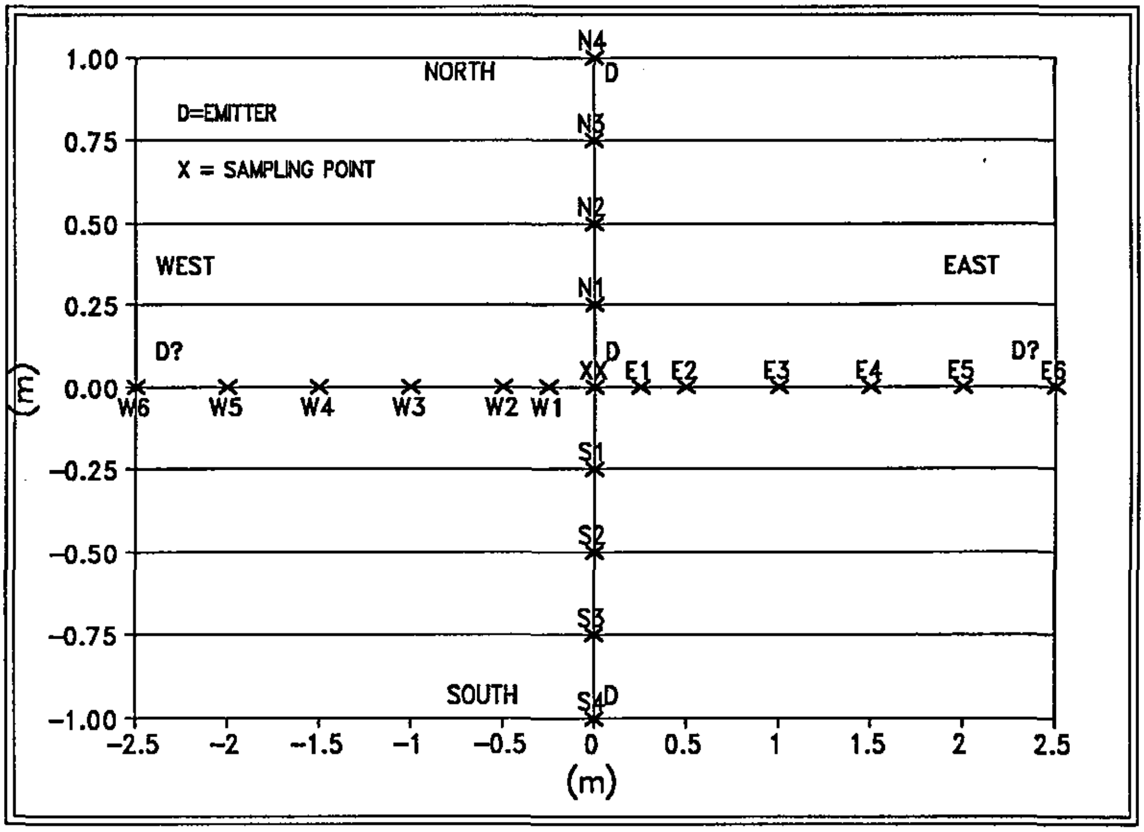

Figure 2.2 Schematic diagram of the sampling scheme used in December 1986; the 21 positions surrounding one emitter is shown (the same scheme was used at sites A1, A2, A3 and A4)

Within the row, i.e. in a north-south direction, the sampling interval was 0,25 m, starting directly below the centre emitter and ending at the next emitter on either side of the centre point. Across the row, i.e. both in an east and west direction, samples were collected at 0,25, 0,50, 1,00, 1,50, 2,00 and 2,50 m distances from the centre point emitter. This sampling scheme was replicated at macropositions A1, A2, A3 and A4. As can be seen from Figure 2.2, the 2,50 m sampling points were situated within the next vineyard row and the distance from these sampling points to the closest drip emitter within that row, differed between the four areas that were sampled. With this particular sampling scheme, the maximum attainable distance between a sampling point and the closest drip emitter is 0,50 m within the row (north-south) and 1,00 m across the row (east-west). At each sampling point the following five depth layers were sampled; 0-0,05, 0,05-0,15, 0,15-0,30, 0,30-0,60 and 0,60-1,00 m. A total of 420 samples (i.e. 4 x 21 x 5) were collected. The data of this survey were used to evaluate the effect of spatial variability on estimates of the soluble salt content of drip irrigated fields. This aspect is presented as Chapter 3 of this volume.

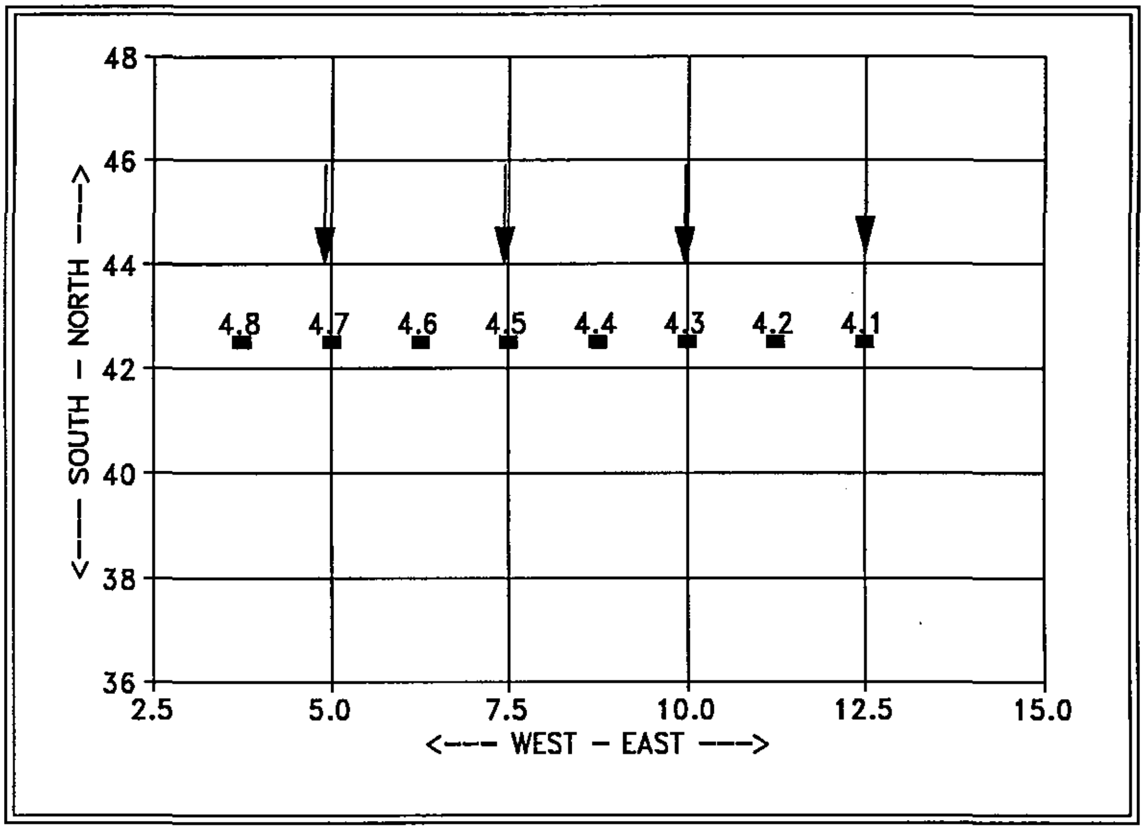

Figure 2.3 Sampling network and identification of the eight positions sampled at macroposition A4 (similar schemes and identifications were used at A1, A2 and A3). The arrows indicate the vineyard rows.

b) May 1987

In May 1987 thirty two neutron access tubes were installed in the vineyard but eventually only 30 of these sites were used (see section 2.3). The soil that was excavated while installing the 32 tubes, were used for analytical purposes. Eight sampling positions at each of macropositions A1 to A4 (Fig. 2.1) were selected. These eight positions were divided into four pairs. A pair consisted of one sampling position located 0,3 m from an emitter within the vineyard row, while the other sampling position was situated midway between two adjacent vineyard rows 1,25 m from an emitter. A total of 16 pairs of sampling positions were therefore used. These positions were numbered with a 2-digit identification code, where the first digit indicates the macroposition, i.e. A1, A2, A3 and A4, and the second digit the position with a group. With the second digit, odd numbers were used for the positions within the vineyard row, while even numbers refer to the positions between the vineyard row. An example of this sampling- and identification scheme for macrosite A4 are given in Figure 2.3. The soil was sampled in 0,3 m depth increments to a total depth of 1,5 m. For the 0-0,3 m depth layer two 0,15 m increments were used. Therefore, a total of 192 soil samples were collected (i.e. 32 x 6).

c) 8 August 1988

On 8 August 1988 the original four emitters at macropositions A1 to A4 (Fig. 2.1) used in the December 1986 survey, were sampled again, but this time a coarser sampling network was used. Four positions to the east, west, south and north at a distance 0,5 m from each emitter were sampled (see Figures 2.1 and 2.2). Four depths, namely the 0-0,15 m, 0,15-0,30 m, 0,30-0,60 m and 0,60-1,0 m layers, were sampled.

d) 23 August 1988

On 23 August 1988 an additional 32 neutron probe access tubes were installed at sites 2.3, 2.5, 4.3 and 4.5. The access tubes were placed 0,25 m and 0,50 m from the emitters. The sampling scheme of site 4.3 and 4.5, which is similar to that of sites 2.3 and 2.5, is given in Figure 2.4. The same depth increments as that of the May 1987 survey were used. A total of 32 x 6 = 192 sampled were collected.

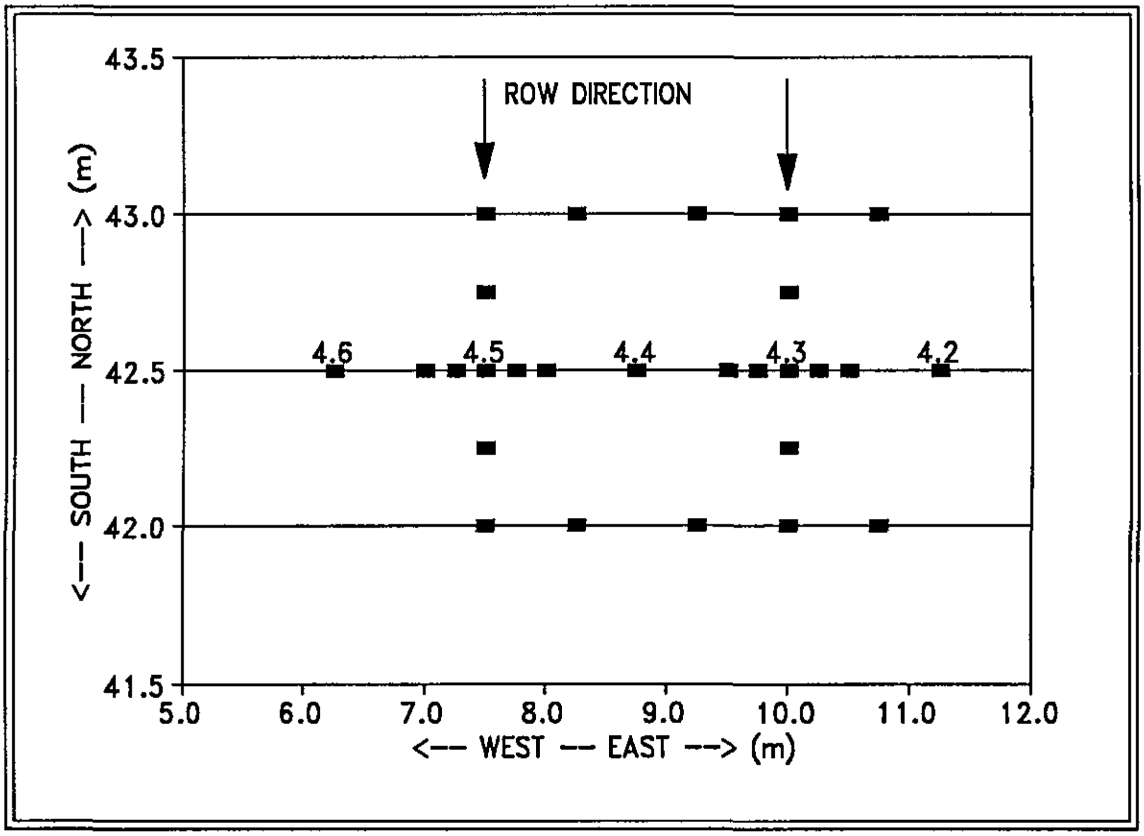

Figure 2.4 Sampling network and design used on 23 August 1988 at sites 4.3 and 4.5 of macroposition A4 of the drip irrigated vineyard at Robertson

e) July 1989

The last survey of the chemical composition of the soil of the study area was conducted in July 1989. The following ten sites at macropositions A1 to A4 were sampled: A1.3, A1.4, A1.5, A2.4, A2.5, A3.4, A3.5, A4.5, A4.6 and A4.7. Again the last digit refer to the position within the respective macropositions with odd numbers being used for the sampling sites within the vineyard row and the even numbers for those sites between two adjacent rows (Fig. 2.3). The depth increments at each sampling position were the same as those of May 1987 and a total number of 10 x 6 = 60 samples were taken.

2.2.3 Chemical properties

a) Soluble salt content

The samples that were collected with the surveys mentioned above, were dried, sieved and a 40% water saturated paste made. With all of the sampling events, the extract of this paste was used to measure the electrical conductivity (EC), the soluble Ca, Mg, Na, K, Cl, HCO_3 and SO_4. The only exception was the samples collected on 8 August 1988 which were analysed for the EC of the extract only. The cation concentrations were determined with an atomic absorption spectrophotometer, while the anions were analysed using the methods described by Richards (1952). Excerpts from the chemical data base resulting from the different surveys are given in Tables 2.4 to 2.8 in section 2.4.

b) Exchangeable cation composition

The extractable cation composition and cation exchange capacity of the soils were determined on two occasions, namely in May 1987 and July 1989. The former was done using the standard ammonium acetate (pH=7) method (Richards, 1952) while the latter was determined by displacing the ammonium acetate with potassium sulphate and by determining the amount of displaced ammonium in the eluate. The exchangeable cation content was calculated from the extractable and soluble salt concentrations. Examples of the exchangeable cation composition taken from the chemical data base, are listed in Tables 2.5 and 2.8 in section 2.4.

2.2.2 Physical and hydrological properties

a) Textural composition and clay mineralogy

The particle size analysis of all 192 samples collected in May 1987 were determined using the pipet method (Gee and Bauder, 1986). The arithmetic mean and standard deviation for the different size classes for macropositions A1, A2, A3 and A4 are listed in Table 2.9 of section 2.4.

b) *In situ* drainage rate and field capacity.

Following the installation of the neutron access tubes in May 1987, the in situ drainage curve and field capacity were measured at 30 sites within the vineyard. A method similar to that of Jones and Wagenet (1984) were used. At each of the 30 neutron access tubes, two 0,45 m high metal rings with an internal diameter of 0,40 m, were pushed 0,15 m into the soil. One ring was placed concentric over the neutron access tube while the other was placed right next to it. In the latter ring, mercury manometer tensiometers were installed at the 0,15 m, 0,30 m, 0,60 m, 0,9 m and 1,2 m depths. Water was continuously ponded in both rings and the wetting of the soil was monitored with the neutron moderation technique and tensiometers until the soil was either saturated or satiated to a depth of 1,2 m. At that stage the additional water was removed, the sites covered with plastic and the decrease of the soil water content and matric potential, due to internal drainage, followed with time. The water content and matric potential was measured for a period of ten to fourteen days. The rate of drainage levelled off after about two to three days. This water content was used as the so-called field capacity of the soil. The field capacity of each measuring position as well as the mean per macroposition are summarised in Table 2.10. The complete data set is available on request.

c) Infiltration rate

Thirty two infiltration tests were carried out on the 0,475 ha study area at Robertson. The positions where the tests were conducted were located 5 meters to the north of each neutron access tube (which is the same position where the internal drainage rates were determined).

A double ring infiltrometer technique was used to determine the infiltrability of the study area. The inner ring had a diameter of 0,13 m and was pushed 0,10 m into the soil. The 0,40 m diameter outer ring was pushed 0,15 m into the soil. The outer ring acted as a buffer and ensured that vertical flow only was measured in the inner ring. Special care was taken to avoid soil disturbance in the smaller inner ring.

Soil samples were taken within the big cylinder, prior to the start of the infiltration run, with a Veihmeyer auger (outside diameter 20 mm) at 0-0,1 0,1-0,2 and 0,2-0,3 m depths, and placed in closed tins. Later, they were used in the laboratory to determine the antecedent soil moisture contents. A perspex tube, graduated every 5 ml, was used as a one-liter-reservoir of water for the inner ring. It was filled with water up to the calibrated zero mark and closed tightly with a rubber stopper. Then it was placed in a retort stand in such a way that its outlet was located 40 mm above the soil surface inside the inner ring. This infiltrometer is very similar to the one designed by Malik, Sharma and Dhankar (1985) and is illustrated in Fig. 2.5.

Forty mm of water were manually ponded into the big outer ring and immediately thereafter, the same depth of water into the inner ring. At all times of the experiment, the depth of water over the soil was kept the same in both rings. At $t=0$, the tap of the perspex tube, which was in hydraulic contact with the 40 mm depth of water in the inner ring, was opened. A ponding depth of 40 mm was maintained in the inner ring by means of Mariotte's principle. Thus, each time the water level in the inner ring was sufficiently low, it was automatically readjusted by water flowing out of the perspex tube. In the outer cylinder, the water level was manually maintained at the same depth as that of the inner ring. The choice for the 40 mm depth of water above the soil avoided potential problems that could be caused by microrelief variations, i.e. to ensure an equal wetting of the soil within the rings. On the other hand the depth of ponding was not large enough to cause an over-estimation of infiltrability. In previous studies it has been reported that the initial infiltration rate increases with the increase in depth of water over the soil (Philip, 1958).

The measurements were made in cumulative ml of water and transformed to mm of infiltrated water per hour. The readings were taken every 30 seconds from 0 to 3 minutes, followed by readings at 4, 5, 7, 10, 15, 20 and 30 minutes, and then every 15 minutes up to 2 hours. This procedure is very similar to the one used by Sharma *et al* (1980) who noticed that a steady state was reached, in all cases, within one hour.

A summary of the results in terms of the infiltration rates after 120 minutes of infiltration is presented in Table 2.11.

d) Bulk density

During the winter of 1987, eight soil profiles were dug in the vineyard, with two profiles per macroposition (Fig. 2.1). Undisturbed soil cores were taken and the bulk density determined using the cylinder method. A summary of the mean bulk densities per depth and position is given in Table 2.12.

e) Soil water characteristic curves

The soil water characteristic curve of the soil was determined using the soil cores mentioned above. In addition to these measurements, the characteristic curves of sieved samples (i.e. < 2 mm diameter), were also determined. A synopsis of the results are listed in Table 2.13.

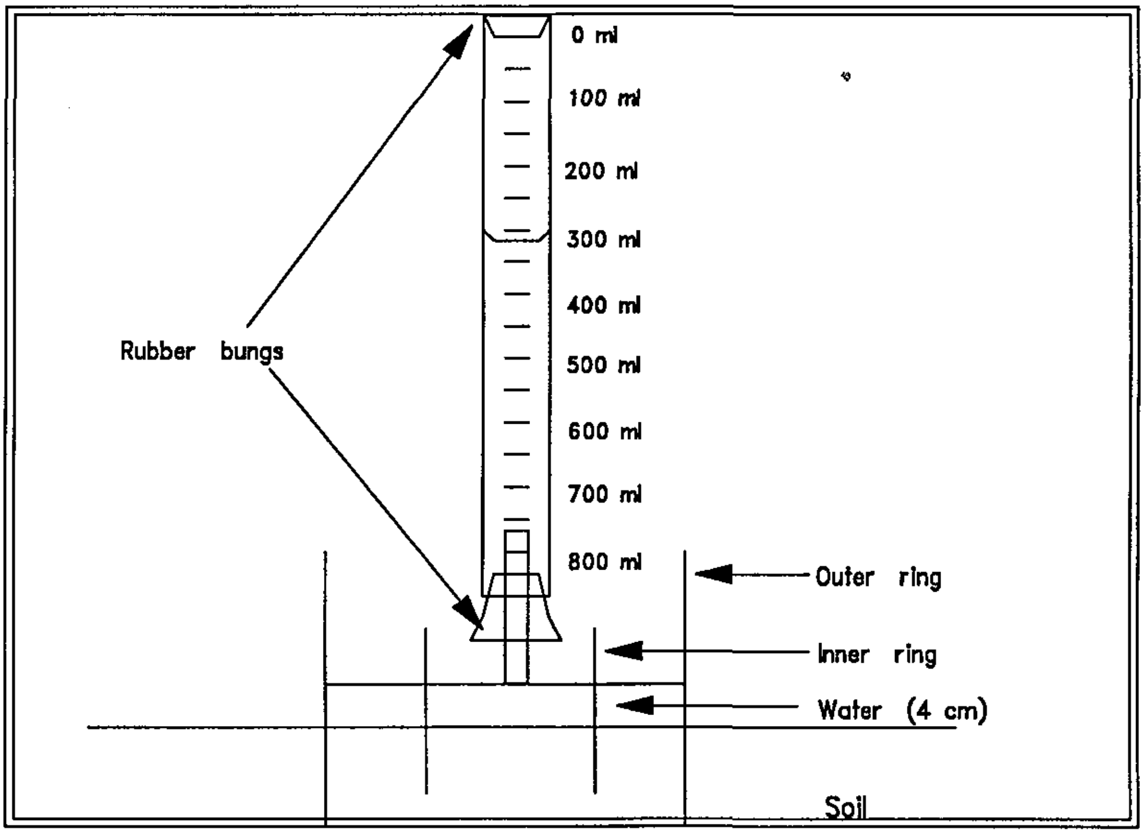

Figure 2.7 Schematic diagram of the infiltrometer that was used to determine the infiltrability of the soil at Robertson

2.3 CONTINUOUS MONITORING OF HYDROLOGICAL PROPERTIES

2.3.1 Meteorological data

Potential evapotranspiration was monitored with a class A-pan, that was placed approximately 200 m from the vineyard. Cumulative rainfall was measured with a standard raingauge next to the evaporation pan. Both the pan and rain gauge was read every morning at 08h00. Daily evapotranspiration depths were estimated using the appropriate crop factors for vines i.e. Sept 0,20; Oct 0,27; Nov 0,37; Dec 0,42; Jan 0,42; Feb 0,46; March 0,44. The class A-pan monitoring was started in June 1987 and at the time of writing (August 1992) was still being continued.

Two-hourly values of the air temperature were obtained using an electronic thermometer and pyranometer respectively, each connected to the same datalogger. Monitoring of temperature started in November 1988 and was discontinued in August 1991.

2.3.2 Irrigation water: quantity and chemical composition

During the different irrigation events the amount of water applied to the vineyard was measured every two hours using a tipping bucket rain gauge and a data logger, the former being placed below the dripper line directly underneath one emitter (Fig. 2.1). This measurement was started in May 1987 and is still (August 1992) being continued. Because of the high coefficient of uniformity (0,93) of the irrigation system in this vineyard, (Moolman & De Clercq, 1991), the volume of water recorded at this one emitter could be used to calculate the total amount of water applied on the 0,475 ha area by multiplying with the number (1850) of emitters. Unfortunately, instrument failures occurred from time to time resulting in an incomplete record in places.

Samples of the Robertson canal water used to irrigate the vineyard were taken from time to time. This was done while an irrigation event was in progress and the samples were collected in the vineyard itself at the emitters. A total of 32 samples were collected and analysed for electrical conductivity, pH, Ca, Mg, K, Na, Cl, HCO_3 and SO_4 content. An excerpt of the chemical composition of the irrigation water used during the 1988/89 season is listed in Table 2.7.

2.3.3 Drainage water: volume, flow rate and chemical composition

Measurement of the drainage rates and volumes started in June 1987. This was accomplished by determining the flow rate at the outlet end of the study area in the drain pipe indicated in Figure 2.1. A custom designed tipping bucket flow gauge and a datalogger were used (see also Chapter 5 of this report). The drainage volumes were recorded every two hours which means that changes in the flow rate could be detected with a two hour time resolution. The flow gauge was placed in the inspection manhole on the extreme west side of the study area (Fig. 2.1). This particular drain is bordered on all sides by other drains. Consequently, the assumption could be made that all water intercepted by it, constitutes the deep percolate of the irrigated area (0,475 ha) overlying this particular pipe only. During the first season, i.e. 1987/88, instrument failures led to a considerable loss of data. The problem was subsequently rectified and for the 1988/89 season a complete flow record with a two hourly time resolution could be obtained. This particular measurement is presently still being done.

Temporal changes in the chemical composition of the drainage water were followed by taking one sample per day (at 16h00) directly from the drain using an automatic pump sampler. The electrical conductivity of all samples were determined while the pH, Ca, Mg, Na, K, Cl, HCO_3 and SO_4 contents of selected samples only were determined. Chemical analysis of the drain water was discontinued towards the end of 1990. The complete record of all these chemical analyses for the period July 1987 to December 1990 is available on request. An example of the chemical data base is given in section 2.4.

2.3.4 Soil water content

In May 1987 thirty aluminium neutron access tubes were installed to a depth of 1,5 m. The access tubes were installed as fifteen pairs that were divided into four groups coded for identification purposes as A1, A2, A3 and A4 (Fig. 2.1). At each of these four groups, and with the exception of A3, four pairs of tubes were installed. A pair of access tubes consisted of one tube located 0,3 m from an emitter within the vineyard row, while the other tube was installed midway between two vineyard rows 1,25 m from an emitter. Early on during the course of the investigation, one of the access tubes was irreparably damaged by a tractor wheel, leaving only 29 locations of which the data could be used. The remaining 29 sites were numbered with a 2-digit identification code, where the first digit indicates the group position and the second the position within a group (Fig. 2.1 and 2.3). With the second digit, odd numbers were used for the identification of the positions within the vineyard row, while even numbers were used for positions between the rows.

During the installation of the access tubes the soil was sampled in 0,3 m increments to a depth of 1,2 m and the gravimetric water content and soil texture of each sample determined. Bulk densities were determined with a gamma probe and the gravimetric water contents converted to volumetric units. These initial gravimetric water contents were used to calibrate a CPN-neutron probe that was subsequently used to monitor the soil water content.

Since May 1987 the soil water content at each of the 29 sites within the vineyard row were determined at 37 different dates using at variable time intervals (Table 2.2). The water content measured in 0,3 m depth increments to a depth of 1,2 m. For the 0-0,3 m soil layer two 0,15 m depth increments were used.

Table 2.2 Dates, given as DDMM, at which the soil water content was monitored at the 29 different sites at positions A1, A2, A3 and A4 in the drip irrigated vineyard during 1987, 1988, 1989 and 1990

1987	1988	1989	1990
07/07	14/01	12/01	24/01
02/10	28/01	09/02	16/02
29/10	26/02	22/03	08/03
26/11	24/03	04/04	29/03
	21/04	29/06	19/04
	21/05	10/08	07/06
	16/06	31/08	05/07
	28/07	21/09	16/08
	23/09	12/10	17/10
	19/10	02/11	16/08
	25/10		
	22/11		
	14/12		

In August 1988 an additional 8 tubes per emitter were installed at four emitters located within sites A2 and A4. A year later, in August 1989, a further 8 tubes were installed at these positions resulting in 15 monitoring positions per 2,5 m^2 at each of these four emitters. The spatial arrangement of the 29 access tubes at site A2 and A4 was identical and is indicated in Figure 2.4. (N.B. There are 15 monitoring positions per emitter, but because one access tube is common to two adjacent emitters, a total of 29 positions are indicated in Figure 2.4). The purpose of this very dense network of neutron probe access tubes was an attempt to get a better understanding of the spatial distribution of the soil water around the emitters. During two specific irrigation events, the monitoring positions were also used to establish a water balance. The soil water content at these 58 positions were determined on a few occasions only, the respective dates being listed in Table 2.3. The monitoring of the soil water content was terminated in August 1990.

Table 2.3 Dates at which the soil water content was measured at 58 locations at macropositions A2 and A4

29/06/89	30/11/89
10/08/89	01/12/89
31/08/89	11/12/89
2/109/89	

2.3.5 Tensiometer readings

In January 1987 eight mercury manometer tensiometers were installed at site T2 (Fig. 2.1). Two tensiometers were installed at the 0,15 m, 0,3 m and 0,6 m depths with one tensiometer placed within a 0,2 m radius from an emitter The other tensiometer was placed at the maximum distance, 0,5 m, from the same emitter, also within the vineyard row. The 0,9 m and 1,2 m deep tensiometers were placed approximately 0,3 m from the emitter. Micro-scale spatial variations in the matric potential at this one site could thus be evaluated. Daily values of the matric potential (08h00) are available for the period January 1987 to August 1992.

In May 1987 five tensiometers, equipped with pressure transducer cells and connected to a data logger, were installed at a site T1 (Fig 2.1), situated close to the drain inspection hole. These instruments were installed at depths of 0,15 m, 0,30 m, 0,60 m, 0,9 m and 1,2 m. Although this system in theory allowed the matric potential to be monitored on a more continuous (two hourly) basis than the mercury manometer tensiometers, instrument failures (mainly leakages) left many gaps in the temporal record. The tensiometers were removed in 1990.

2.3.6 Soluble salt content

At five positions within the vineyard, porous cup suction samplers were installed. These positions are indicated as S1 to S5 in Figure 2.1. At each position, a cup sampler was placed at the 0,15 m, 0,3 m, 0,6 m, 0,9 m and 1,2 m depths. Samples of the soil solution was obtained by manually applying a vacuum to these instruments. In theory this was meant to be done every fortnight, but it was seldom possible to obtain a complete set of water samples every fortnight, i.e. for each depth and site. Samples of the soil solution were collected on 33 different dates between 21 May 1987 and 1 September 1989. The samples were analysed in the same manner as the irrigation and drainage waters. An example of the data base is given in section 2.4.

2.4 EXAMPLES OF DATA BASE

Tables 2.4 to 2.19 are examples of the hydrological and chemical data that can be obtained from the authors.

Table 2.4 Example of the chemical data base resulting from the survey of December 1986

Site*	Depth (m)	Dist (m)	Dir.	pH	EC (mS/m)	Ca <----	Na	Mg	K (mg/dm³)	HCO_3	Cl	SO_4 --->
1XX	0,05	0,00	N	6,78	268	660	161	141	22	122	27	2369
1XX	0,15	0,00	N	7,72	273	460	113	17	12	61	153	1163
1XX	0,30	0,00	N	7,79	314	442	186	25	7	91	179	1241
1XX	0,60	0,00	N	8,16	181	41	320	6	1	213	161	404
1XX	1,00	0,00	N	7,43	193	24	353	4	0	30	289	392
1N1	0,05	0,25	N	7,30	345	610	104	17	38	18	102	1644
1N1	0,15	0,25	N	7,73	353	615	501	20	21	30	61	2519
1N1	0,30	0,25	N	8,05	210	132	214	16	5	103	187	497
1N1	0,60	0,25	N	8,15	160	25	288	4	1	183	170	303
1N1	1,00	0,25	N	7,27	201	17	374	4	0	24	289	425
1N2	0,05	0,50	N	7,06	349	711	93	13	32	61	119	1781
1N2	0,15	0,50	N	7,65	216	325	151	10	8	24	119	961
1N2	0,30	0,50	N	7,97	219	257	130	16	5	48	110	770
1N2	0,60	0,50	N	7,91	219	81	314	11	2	115	255	455
1N2	1,00	0,50	N	7,34	215	28	372	5	0	18	358	360
1N3	0,05	0,25	N	6,96	374	720	126	14	24	53	150	1830
1N3	0,15	0,25	N	7,35	363	556	154	137	6	103	187	1864
1N3	0,30	0,25	N	7,62	433	611	248	161	17	18	272	2249
1N3	0,60	0,25	N	7,55	407	187	581	131	3	109	306	1674
1N3	1,00	0,25	N	7,39	558	587	551	190	26	67	468	2647
1N4	0,05	0,00	N	6,85	341	657	110	18	19	0	127	1726
1N4	0,15	0,00	N	7,39	351	606	127	127	8	134	136	1936
1N4	0,30	0,00	N	7,69	398	551	222	196	6	97	170	2256
1N4	0,60	0,00	N	7,79	185	33	311	6	1	48	204	435
1N4	1,00	0,00	N	7,34	408	117	687	20	6	45	306	1348

*See Figure 2.2 for site identification; Dist = distance from emitter; Dir = direction of sampling position relative to emitter.

Table 2.5 Example of the chemical data bases resulting from the of survey of May 1987: 8 sites of macroposition A4

a) **Soluble salts**

Posn.	Depth (m)	EC (mS/m)	pH	Ca <---	Mg	Na	K (mg/dm^3)	HCO_3	Cl	SO_4 --->
A4.1	0,45	452	7,72	383	133	255	10	213	511	1130
A4.1	0,75	650	8,00	260	232	839	16	183	1022	1785
A4.1	1,05	756	7,92	164	171	1242	8	164	1448	1582
A4.1	1,35	741	7,15	159	168	1170	3	183	1661	1098
A4.1	1,50	700	6,25	174	174	1023	6	91	1278	1445
A4.2	0,15	1108	7,85	643	340	1598	12	115	1789	3722
A4.2	0,45	1147	7,80	510	310	1650	21	201	2641	2185
A4.2	0,75	952	7,90	350	230	1365	21	176	2002	1774
A4.2	1,05	966	7,82	331	238	1460	8	158	2172	1729
A4.2	1,35	850	7,32	192	178	1278	3	67	1917	1189
A4.2	1,50									
A4.3	0,15	546	7,45	1377	101	100	26	311	170	3467
A4.3	0,45	367	7,83	336	150	178	10	152	136	1479
A4.3	0,75	382	8,08	161	127	391	9	140	255	1261
A4.3	1,05	408	8,05	80	57	621	5	195	460	943
A4.3	1,35	526	7,65	89	83	795	3	79	894	934
A4.3	1,50	780	6,37	191	203	1155	5	73	1491	1604
A4.4	0,15	1770	7,75	871	503	2668	25	122	4856	3005
A4.4	0,45	903	7,80	230	221	1284	20	140	2130	1136
A4.4	0,75	760	8,00	189	163	1124	19	195	1704	1008
A4.4	1,05	756	7,93	169	161	1143	9	146	1874	786
A4.4	1,35	586	7,55	106	111	936	4	73	1320	806
A4.4	1,50									
A4.5	0,15	601	7,40	1317	208	128	30	244	127	3917
A4.5	0,45	440	7,80	406	240	230	14	158	247	1959
A4.5	0,75	474	7,95	256	205	471	10	140	264	1953
A4.5	1,05	388	7,85	97	83	615	4	158	281	1346
A4.5	1,35	478	7,75	167	116	738	5	158	468	1646
A4.5	1,50									
A4.6	0,15	1475	7,92	1072	261	2230	30	134	2044	5418
A4.6	0,45	885	7,85	326	149	1173	14	152	1661	1468
A4.6	0,75	574	7,90	148	80	798	8	146	979	906
A4.6	1,05	803	7,70	307	133	1123	5	109	1405	1627
A4.6	1,35	752	7,65	310	118	1029	4	122	1150	1710
A4.6	1,50									
A4.7	0,15	603	7,70	158	130	447	26	353	511	887
A4.7	0,45	400	7,88	269	97	350	7	140	298	1258
A4.7	0,75	448	7,65	177	80	591	3	146	315	1436
A4.7	1,05	664	7,25	411	147	756	6	91	852	1930
A4.7	1,35	443	6,75	110	70	591	3	36	494	1081
A4.7	1,50	504	5,90	159	92	581	3	36	596	1128
A4.8	0,15	883	7,90	543	141	1130	8	170	1022	2710
A4.8	0,45	763	7,90	340	138	960	4	189	1363	1379
A4.8	0,75	468	8,00	135	59	647	5	158	545	1054
A4.8	1,05	554	7,43	269	81	698	4	158	553	1556
A4.8	1,35	491	6,75	104	24	672	3	36	596	917
A4.8	1,50	573	7,10	168	73	713	4	158	766	1026

Table 2.5 (contd)

b) Exchangeable cations

Posn	Depth (m)	CEC <---	Ca1	Ca2 (cmol(+)/kg)	Mg	Na	K --->	ESP (%)
A4.1	0,45	8,90	19,63	4,14	4,02	0,45	0,29	5,02
A4.1	0,75	8,34	17,73	0,19	6,51	1,24	0,40	14,86
A4.1	1,05	9,23	17,05	0,24	6,60	2,13	0,26	23,08
A4.1	1,35	10,30	5,76	3,58	5,05	1,54	0,14	14,90
A4.1	1,50	10,52	3,50	6,52	3,35	0,52	0,13	4,95
A4.2	0,15	7,48	10,44	1,87	3,88	1,54	0,19	20,58
A4.2	0,45	8,29	15,53	1,52	4,87	1,58	0,32	19,06
A4.2	0,75	8,22	17,60	0,49	5,62	1,74	0,37	21,12
A4.2	1,05	9,46	15,52	1,72	5,62	1,89	0,23	19,97
A4.2	1,35	12,33	6,37	3,71	5,81	2,69	0,13	21,79
A4.2	1,50							
A4.3	0,15	7,64	23,13	5,63	1,57	0,13	0,31	1,65
A4.3	0,45	8,56	18,58	3,15	4,74	0,38	0,29	4,44
A4.3	0,75	7,42	19,61	0,59	5,73	0,80	0,30	10,76
A4.3	1,05	9,56	13,72	2,36	5,30	1,68	0,21	17,57
A4.3	1,35	8,63	4,90	2,01	4,65	1,85	0,13	21,40
A4.3	1,50	9,33	4,12	4,39	3,89	0,90	0,14	9,66
A4.4	0,15	6,99	14,49	0,55	4,39	1,79	0,26	25,61
A4.4	0,45	9,02	17,82	0,92	5,94	1,76	0,40	19,48
A4.4	0,75	8,22	19,10	0,38	5,83	1,59	0,42	19,39
A4.4	1,05	8,71	16,99	0,17	6,24	2,01	0,29	23,10
A4.4	1,35	9,14	5,02	2,38	4,75	1,88	0,14	20,59
A4.4	1,50							
A4.5	0,15	8,05	19,12	4,29	3,13	0,24	0,39	2,95
A4.5	0,45	8,68	19,94	2,29	5,64	0,40	0,35	4,61
A4.5	0,75	8,99	18,42	1,42	6,30	0,96	0,31	10,69
A4.5	1,05	11,13	9,54	3,87	5,43	1,65	0,19	14,83
A4.5	1,35	11,90	8,95	4,10	5,70	1,95	0,15	16,36
A4.5	1,50							
A4.6	0,15	8,42	7,45	0,86	5,05	2,17	0,34	25,79
A4.6	0,45	9,75	17,20	1,10	6,61	1,71	0,33	17,54
A4.6	0,75	8,93	15,53	0,70	6,35	1,63	0,25	18,28
A4.6	1,05	9,58	10,38	1,18	6,17	2,06	0,17	21,47
A4.6	1,35	6,96	9,71	0,73	4,64	1,46	0,13	20,98
A4.6	1,50							
A4.7	0,15	9,64	29,18	4,29	4,34	0,62	0,38	6,46
A4.7	0,45	7,94	18,41	0,91	6,11	0,69	0,23	8,69
A4.7	0,75	9,10	9,20	3,10	4,88	0,99	0,13	10,90
A4.7	1,05	8,81	6,88	2,82	4,67	1,15	0,17	13,00
A4.7	1,35	8,35	3,96	1,27	5,45	1,50	0,13	17,99
A4.7	1,50	6,54	2,76	2,26	3,70	0,51	0,08	7,77
A4.8	0,15	8,76	19,31	1,31	5,52	1,37	0,56	15,68
A4.8	0,45	8,43	19,42	0,41	6,46	1,15	0,41	13,65
A4.8	0,75	8,38	20,66	0,49	6,26	1,44	0,19	17,22
A4.8	1,05	6,73	8,11	1,56	4,04	1,00	0,13	14,92
A4.8	1,35	9,68	3,92	2,38	5,48	1,67	0,15	17,26
A4.8	1,50	8,75	4,34	2,65	4,98	1,01	0,12	11,52

Posn = position (see Fig. 2.1 & 2.3); CEC=cation exchange capacity; Ca1=analytically determined Ca; Ca2 = CEC-Sum(Na+Mg+K)

Table 2.6 Example of the chemical data base resulting from the survey of 8 August 1988: samples of macroposition A4

Posn	Dir.	Depth (m)	pH	EC (mS/m)	Posn	Dir.	Depth (m)	pH	EC (mS/m)
A4	S	0,05	8,37	1824	A4	E	0,05	8,03	865
A4	S	0,15	8,13	406	A4	E	0,15	7,90	600
A4	S	0,30	7,99	231	A4	E	0,30	8,08	505
A4	S	0,60	7,94	217	A4	E	0,60	8,12	547
A4	S	1,00	8,04	291	A4	E	1,00	7,79	618
A4	N	0,05	6,88	328	A4	W	0,05	7,66	251
A4	N	0,15	7,38	322	A4	W	0,15	8,02	258
A4	N	0,30	7,59	335	A4	W	0,30	8,23	367
A4	N	0,60	7,51	420	A4	W	0,60	8,21	494
A4	N	1,00	7,48	390	A4	W	1,00	7,07	821
A4	Dr	0,05	6,34	117					
A4	Dr	0,15	7,31	176					
A4	Dr	0,30	7,83	212					
A4	Dr	0,60	7,59	689					
A4	Dr	1,00	7,77	470					

Posn = position (see Fig 2.1 & 2.3); Dr=emitter, S=south, N=north, W=west, E=east
All samples, except Dr taken 0,50 m from emitter

Table 2.7 Example of the chemical data base resulting from the survey of 23 August 1988: samples of macroposition A4

Posn	Depth (m)	Dist. (m)	Dir.	pH	EC (mS/m)	Ca <--	Mg	Na	K (mg/dm^3)	HCO_3	Cl	SO_4 -->
A4	0,15	0,50	N	6,85	222	298	82	140	7	988	149	312
A4	0,30	0,50	N	7,56	152	102	52	170	5	420	124	205
A4	0,60	0,50	N	7,81	181	112	52	220	5	378	215	370
A4	0,90	0,50	N	7,77	450	206	138	600	5	329	580	1646
A4	1,20	0,50	N	7,26	248	52	48	390	2	280	323	633
A4	1,50	0,50	N	7,50	201	40	34	320	1	140	232	526
A4	0,15	0,25	N	7,52	172	104	46	150	6	402	116	304
A4	0,30	0,25	N	7,78	124	124	36	120	4	463	116	156
A4	0,60	0,25	N	7,87	195	132	82	290	8	347	265	419
A4	0,90	0,25	N	7,89	315	104	98	400	5	408	398	905
A4	1,20	0,25	N	7,56	322	98	74	530	1	268	373	1127
A4	1,50	0,25	N	6,66	408	112	94	630	2	0	439	1679
A4	0,15	0,25	S	6,85	378	750	48	110	5	329	82	2156
A4	0,30	0,25	S	7,49	425	570	175	170	6	323	141	2427
A4	0,60	0,25	S	7,59	429	450	215	290	5	213	132	2419
A4	0,90	0,25	S	7,71	353	152	104	460	3	311	182	1423
A4	1,20	0,25	S	7,45	233	40	32	360	0	97	199	707
A4	1,50	0,25	S	6,73	589	268	180	800	2	0	348	2847
A4	0,15	0,50	S	7,39	860	980	310	730	21	768	978	3160
A4	0,30	0,50	S	7,51	352	450	106	150	5	469	174	1580
A4	0,60	0,50	S	7,71	302	385	130	110	6	0	99	1316
A4	0,90	0,50	S	7,70	397	440	240	220	5	219	132	2288
A4	1,20	0,50	S	7,45	582	720	320	590	3	158	257	3440
A4	1,50	0,50	S	7,30	735	550	280	900	3	79	398	4008

Posn = position (see Fig 2.1 & 2.3); Dist = distance from emitter, Dir = direction from emitter (N=north, S=south)

Table 2.8 Example of chemical data base resulting from the survey of July 1989

a) Soluble salt

Posn	Depth (m)	pH	EC (mS/m)	Ca <--	Mg	Na (mg/dm^3)	K	HCO_3	Cl	SO_4 -->
A4.5	0,05	7,8	322	670	61	60	12	312	118	1694
A4.5	0,15	7,4	305	580	80	100	4	327	115	1666
A4.5	0,30	7,7	331	480	130	160	3	218	150	1666
A4.5	0,60	7,9	328	330	180	220	5	218	249	1521
A4.5	0,90	8,0	379	200	150	400	4	218	505	1105
A4.5	1,20	7,9	503	170	160	650	3	284	695	1461
A4.5	1,50	8,0	346	800	50	384	2	148	490	
A4.6	0,05	7,6	5140	1980	3200	9000	150	265	16917	4654
A4.6	0,15	7,8	3600	1440	1700	6000	78	226	9960	3941
A4.6	0,30	7,8	1561	430	470	2050	28	554	3636	
A4.6	0,60	8,0	973	310	300	1360	23	499	2094	1381
A4.6	0,90	8,1	687	190	170	1000	10	296	1304	1013
A4.6	1,20	7,5	639	170	140	1000	5	460	1185	1085
A4.6	1,50	7,9	435	100	80	710	6	437	447	
A4.7	0,05	6,9	353	630	100	84	21	476	189	1566
A4.7	0,15	7,4	400	620	90	190	4	546	300	1642
A4.7	0,30	7,7	483	590	160	380	5	281	490	2010
A4.7	0,60	7,7	458	410	240	410	9	242	458	1790
A4.7	0,90	7,9	536	260	230	640	5	796	743	1910
A4.7	1,20	8,0	437	130	110	700	3	187	505	1473
A4.7	1,50	8,0	228	30	30	330	1	148	300	552

b) Exchangeable Cations

Position	Depth (m)	Ca <---	Mg (cmol(+)/kg)	Na	K --->
A4.5	0,05	16,13	1,03	1,37	0,35
A4.5	0,15	11,32	1,38	0,00	0,17
A4.5	0,30	9,52	2,36	0,03	0,17
A4.5	0,60	8,82	3,67	0,14	0,23
A4.5	0,90	2,59	4,10	0,17	0,23
A4.5	1,20	7,15	5,21	0,13	0,20
A4.5	1,50	2,89	3,44	1,94	0,57
A4.6	0,05	13,01	4,67	3,91	0,41
A4.6	0,15	8,10	4,67	3,48	0,40
A4.6	0,30	7,13	4,77	2,09	0,44
A4.6	0,60	7,37	4,67	1,55	0,12
A4.6	0,90	7,11	4,44	1,61	0,34
A4.6	1,20	7,15	4,13	1,57	0,23
A4.6	1,50	5,79	4,08	1,85	0,26
A4.7	0,05	10,22	1,48	0,16	0,40
A4.7	0,15	11,74	1,51	0,28	0,19
A4.7	0,30	10,80	2,51	0,47	0,23
A4.7	0,60	9,16	4,46	0,55	0,35
A4.7	0,90	6,47	4,41	0,67	0,20
A4.7	1,20	6,23	4,07	1,43	0,17
A4.7	1,50	6,43	5,48	2,73	0,13

Posn = position (see Fig 2.1 & 2.3)

Table 2.9 Mean (first figure) and standard deviation (second figure) of the particle size composition of positions A1, A2, A3 and A4 in the drip irrigated vineyard at Robertson

Posn.	Depth (m)	Clay	Fine silt	Coarse silt	Very fine sand	Fine sand	Medium sand	Coarse sand
A1	0,15	20,0	25,0	17,5	15,8	11,9	6,6	3,3
A1		0,9	2,1	2,3	3,5	2,1	0,6	1,2
A1	0,45	21,8	25,8	18,4	17,3	8,6	5,8	2,3
A1		1,5	2,5	2,5	2,6	1,9	1,4	0,6
A1	0,75	23,8	26,1	18,4	17,1	8,5	5,7	2,2
A1		1,4	2,3	3,1	2,1	0,8	0,8	0,5
A1	1,05	23,5	27,0	17,1	17,2	8,5	5,6	2,1
A1		1,7	1,9	2,6	2,8	1,5	1,1	0,4
A1	1,35	21,0	27,2	17,4	16,6	8,3	5,6	2,1
A1		1,6	3,0	2,7	1,5	2,0	1,0	0,4
A1	1,50	20,3	27,0	17,4	16,6	8,5	5,8	2,2
A1		1,8	1,7	2,4	2,6	2,9	1,3	0,4
A2	0,15	20,9	17,7	17,6	16,5	14,9	9,1	3,3
A2		0,9	1,6	1,0	1,2	0,6	0,3	0,2
A2	0,45	20,0	18,0	17,6	17,2	15,0	9,0	3,1
A2		1,5	2,0	1,1	0,7	1,3	0,6	0,4
A2	0,75	21,1	13,2	16,4	17,1	19,1	9,8	3,3
A2		1,9	2,7	2,8	1,0	2,8	2,8	0,3
A2	1,05	19,9	10,2	12,6	17,0	24,1	13,3	2,9
A2		2,0	1,9	2,2	1,0	1,2	0,5	0,5
A2	1,35	15,6	11,7	13,2	17,1	26,2	13,6	2,6
A2		1,5	1,3	1,7	0,8	1,3	1,5	1,0
A2	1,50	13,7	13,1	14,8	16,4	25,4	13,7	2,9
A2		2,4	1,4	2,0	1,6	2,7	2,5	1,2
A3	0,15	19,2	21,6	18,0	15,7	14,6	7,9	3,0
A3		1,6	0,7	2,0	2,1	2,2	1,3	0,7
A3	0,45	21,6	20,8	18,2	12,3	14,7	9,1	3,3
A3		2,0	5,6	2,4	2,4	3,5	1,3	1,2
A3	0,75	21,9	18,2	16,8	14,3	15,4	10,1	3,3
A3		1,2	5,1	1,4	2,5	1,2	0,9	0,4
A3	1,05	19,5	16,3	15,9	15,1	17,4	12,1	3,6
A3		1,9	5,6	1,0	1,9	3,3	2,6	1,0
A3	1,35	18,6	16,2	12,7	12,5	18,1	16,9	5,0
A3		4,1	8,3	1,6	2,8	5,1	6,5	1,5
A3	1,50	18,3	16,5	13,5	11,8	16,6	18,1	5,3
A3		4,4	7,2	2,0	2,3	3,6	8,0	1,7
A4	0,15	16,4	19,2	19,5	17,2	16,9	8,6	2,1
A4		3,1	2,6	1,6	0,9	2,3	1,2	0,5
A4	0,45	17,8	22,2	19,8	15,8	14,0	8,0	2,4
A4		0,7	0,7	1,4	2,0	2,3	1,0	0,3
A4	0,75	18,2	22,0	20,4	15,8	12,8	7,8	2,8
A4		0,9	2,3	2,9	1,8	1,9	1,3	0,4
A4	1,05	20,4	22,4	19,2	13,8	12,9	8,5	3,0
A4		1,7	5,5	6,5	5,5	3,0	2,2	0,7
A4	1,35	23,1	25,4	17,1	12,3	11,9	7,7	2,5
A4		3,1	8,9	4,4	2,7	3,5	2,3	0,6
A4	1,50	24,1	29,3	13,5	10,9	12,2	7,7	2,2
A4		6,8	10,9	1,8	3,8	6,8	3,9	1,1

Posn = position; Cl= <0,002mm, F.Sl= <0,02mm, C.Sl= <0,05mm, V. fine Sa= <0,106mm, F. Sa= <0,250mm, Med. Sa= <0,500mm, C. Sa= <2,00mm

Table 2.10 Field capacity values (drained upper limits) of 32 sites in the drip irrigated vineyard at Robertson

Secondary Position	Water contents at macrosite: A1	A2 (mm/1,05m)	A3	A4
1	312,7	290,6		266,1
2	309,5	291,1	296,8	281,6
3	313,6	296,7	294,4	256,6
4	296,8	283,0	290,1	289,5
5	295,1	285,4	284,3	291,6
6	295,1	260,8	324,6	294,5
7	296,6	238,5	343,7	314,0
8	291,6	262,6	350,9	304,1
Mean	301,4	276,1	312,1	287,3
Std Dev	8,4	18,8	25,3	17,7

Table 2.11 Infiltration rates in mm/h after 120 minutes at the different macro- and micropositions in the vineyard at Robertson

Secondary Position	Macrosite A1	A2	A3	A4
1	18,1	39,2	28,6	7,5
3	3,0	3,0	90,5	3,0
5	117,6	1,5	3,0	9,0
7	3,0	1,5	87,4	0,1
2	76,9	280,4	283,4	4,5
4	42,2	60,3	140,2	3,0
6	37,7	3,0	111,6	88,9
8	72,4	129,6	102,5	60,3
Mean within row	35,4	11,3	52,4	4,9
Std Dev	47,8	16,1	37,7	3,6
Mean between rows	57,3	118,3	159,4	39,2
Std Dev	17,5	103,8	72,9	36,9
Overall mean	46,4	64,8	105,9	22,1
Std Dev	37,6	91,5	79,0	31,3

Table 2.12 Bulk densities at the different depths of the four macropositions in the vineyard at Robertson

Position	Bulk Density (kg/m³)				
Depth (m)-->	0,15	0,30	0,60	0,90	1,20
A1					
1,1	1545	1554	1637	1627	1595
1,2	1499	1597	1720	1697	1606
1,3	1545	1554	1637	1627	1595
1,4	1499	1597	1720	1697	1606
1,5	1509	1375	1609	1480	1656
1,6	1495	1426	1536	1605	1664
1,7	1509	1375	1609	1480	1656
1,8	1495	1426	1536	1605	1664
A2					
2,1	1523	1704	1822	1810	1707
2,2	1563	1874	1818	1811	1796
2,3	1523	1704	1822	1810	1707
2,4	1563	1874	1818	1811	1796
2,5	1626	1869	1805	1928	1702
2,6	1578	1759	1671	1675	1644
2,7	1626	1869	1805	1928	1702
2,8	1578	1759	1671	1675	1644
A3					
3,1	1587	1505	1629	1742	
3,2	1356	1757	1805	1674	
3,3	1587	1505	1629	1742	
3,4	1356	1757	1805	1674	
3,5	1470	1423	1430	1740	1798
3,6	1540	1531	1567	1680	1675
3,7	1470	1423	1430	1740	1798
3,8	1540	1531	1567	1680	1675
A4					
4,1	1421	1731	1559	1435	1404
4,2	1579	1492	1607	1578	1457
4,3	1421	1731	1559	1435	1404
4,4	1579	1492	1607	1578	1457
4,5	1460	1523	1431	1629	1653
4,6	1389	1576	1347	1556	1649
4,7	1460	1523	1431	1629	1653
4,8	1389	1576	1347	1556	1649

Table 2.13 Mean values of the soil water retention data at different pneumatic pressures for the different depths of the soil in the Robertson vineyard

a) undisturbed soil cores

Position*	kPa--> / Depth (m)	0,1	1	5	10	30	50	100	300
		Volumetric water content (m^3/m^3)							
A1	0,15	0,459	0,429	0,367	0,331	0,290	0,281	0,261	0,231
	0,30	0,467	0,443	0,400	0,360	0,326	0,314	0,292	0,253
	0,60	0,449	0,436	0,405	0,375	0,327	0,319	0,296	0,267
	0,90	0,448	0,424	0,390	0,368	0,345	0,338	0,323	0,302
	1,20	0,479	0,458	0,416	0,394	0,362	0,355	0,330	0,303
A2	0,15	0,422	0,402	0,351	0,312	0,258	0,243	0,213	0,181
	0,30	0,369	0,350	0,326	0,310	0,280	0,264	0,236	0,209
	0,60	0,377	0,366	0,337	0,323	0,308	0,294	0,272	0,246
	0,90	0,376	0,369	0,338	0,317	0,293	0,271	0,231	0,190
	1,20	0,401	0,381	0,340	0,314	0,283	0,265	0,238	0,198
A3	0,15	0,420	0,387	0,344	0,315	0,283	0,273	0,246	0,209
	0,30	0,387	0,378	0,350	0,337	0,314	0,303	0,286	0,264
	0,60	0,381	0,375	0,358	0,340	0,319	0,306	0,280	0,245
	0,90	0,450	0,403	0,355	0,325	0,289	0,261	0,244	0,197
	1,20	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
A4	0,15	0,400	0,390	0,339	0,297	0,241	0,227	0,198	0,152
	0,30	0,451	0,411	0,376	0,347	0,311	0,280	0,247	0,212
	0,60	0,443	0,407	0,375	0,341	0,300	0,273	0,244	0,211
	0,90	0,489	0,447	0,407	0,376	0,335	0,319	0,289	0,246
	1,20	0,430	0,406	0,371	0,338	0,305	0,281	0,262	0,227

* see Fig 2.1 for sampling positions

b) sieved soil

Position*	Depth (m)	Volumetric water content (m³/m³) kPa--> 1	5	10	50	100	500	1500
A1	0,15	0,565	0,449	0,413	0,267	0,300	0,199	0,161
	0,30	0,545	0,439	0,391	0,266	0,282	0,202	0,163
	0,60	0,552	0,441	0,412	0,269	0,321	0,194	0,155
	0,90	0,592	0,470	0,451	0,326	0,356	0,255	0,211
	1,20	0,625	0,498	0,484	0,339	0,390	0,244	0,185
A2	0,15	0,525	0,439	0,357	0,237	0,295	0,178	0,148
	0,30	0,553	0,493	0,425	0,281	0,298	0,212	0,178
	0,60	0,524	0,405	0,368	0,254	0,283	0,194	0,157
	0,90	0,574	0,440	0,421	0,260	0,279	0,195	0,163
	1,20	0,471	0,355	0,320	0,177	0,245	0,145	0,118
A3	0,15	0,597	0,471	0,413	0,272	0,235	0,163	0,143
	0,30	0,551	0,456	0,398	0,280	0,224	0,168	0,152
	0,60	0,577	0,452	0,403	0,267	0,237	0,167	0,156
	0,90	0,544	0,420	0,365	0,239	0,206	0,142	0,130
A4	0,15	0,509	0,415	0,377	0,211	0,205	0,111	0,101
	0,30	0,607	0,482	0,440	0,283	0,252	0,152	0,136
	0,60	0,597	0,485	0,434	0,303	0,266	0,162	0,149
	0,90	0,587	0,463	0,422	0,268	0,245	0,154	0,148
	1,20	0,605	0,476	0,443	0,309	0,290	0,239	0,158

* see Fig 2.1 for sampling positions

Table 2.14 Chemical composition of the irrigation water during the 1988/89 season and the start of the 1989/90 season

YYMMDD	EC mS/m	pH	Ca <-------	Mg	K	Na mg/dm³	HCO_3	Cl	SO_4	TDS ------->
880924	21,8	6,73	5,0	6,6	0,7	26,0	30,5	58,9	nd	127
881001	22,3	6,65	5,0	6,5	0,8	24,0	30,5	52,7	nd	119
881101	122,6	3,51	18,0	14,9	1,4	43,0	0,0	88,3	nd	165
881104	36,3	6,19	11,0	11,2	0,9	41,0	42,7	89,9	nd	196
881125	35,4	6,24	10,0	10,4	0,7	40,0	47,6	87,4	nd	196
881209	28,8	6,37	6,0	7,9	4,7	33,0	42,7	72,2	nd	166
881217	28,2	6,34	7,0	8,1	0,8	33,0	35,4	76,6	nd	160
881223	28,1	6,28	7,0	8,0	0,9	35,0	30,5	73,8	nd	155
890102	25,8	6,28	5,0	7,2	0,7	29,0	34,2	72,8	nd	148
890120	22,8	6,36	5,0	5,9	0,5	25,0	36,6	61,4	nd	134
890126	21,1	6,33	4,0	5,7	0,8	24,0	36,6	55,8	nd	126
890203	22,4	6,10	5,0	5,5	1,8	24,0		34,6	nd	70
890206	46,6	3,10	5,0	6,9	36,0	25,0		43,2	nd	116
890211	19,9	6,36	6,0	5,5	0,6	23,0	12,2	51,9	nd	99
890219	20,6	6,41	5,0	5,6	0,5	25,0	12,2	50,2	nd	98
890304	37,5	5,90	5,0	4,9	11,1	23,0	6,1	46,7	nd	96
890307	20,9	5,84	5,0	5,4	0,6	25,0	18,3	50,2	nd	104
890312	20,4	6,78	6,0	5,5	0,7	22,0	12,2	51,9	nd	98
890322	20,7	6,62	6,0	5,6	0,7	25,0	12,2	43,2	nd	92
890328	88,3	4,48	11,0	10,4	1,7	25,0	2,4	51,9	nd	102
890918	24,6	7,19	9,0	7,0	2,0	30,0	24,4	51,9	24,7	148
891019	31,5	6,16	8,0	7,0	4,5	36,0	18,3	51,9	37,0	162
891109	44,9	6,66	13,0	12,0	2,0	52,0	36,6	86,5	53,5	255
891118	46,8	6,54	13,0	12,0	2,5	52,0	48,8	86,5	49,4	264
891120	46,0	6,52	13,0	12,0	2,5	54,0	48,8	103,8	57,6	291

YYMMDD= date given as year, month, day; nd = not determined

Table 2.15 Example of the data base for daily meteorological and hydrological data measured at the drip irrigated vineyard at Robertson: Data of December 1988

Day	Julian day	Irrig. (m^3/d)	Drain. (m^3/d)	Mean daily temp (°C)	Max. temp (°C)	Min. temp (°C)	Daily A-Pan (mm)
1	336	42,64	23,29	20,33	30,45	10,56	8,5
2	337	0,00	25,05	22,24	30,45	14,36	9,0
3	338	41,00	22,97	21,73	29,52	17,70	9,0
4	339	0,00	24,45	18,69	20,16	16,38	6,0
5	340	42,40	23,21	18,94	25,87	13,77	6,5
6	341	0,00	25,02	19,76	28,24	9,19	7,0
7	342	38,70	23,45	20,52	31,51	12,05	7,5
8	343	0,00	24,81	25,01	35,25	15,34	8,0
9	344	38,85	22,87	25,86	39,42	16,20	12,0
10	345	0,00	22,48	20,41	26,44	14,04	14,0
11	346	39,47	20,93	18,37	27,91	5,42	14,5
12	347	0,00	23,29	20,15	30,67	11,08	6,5
13	348	40,55	21,68	22,20	32,98	9,83	8,8
14	349	0,00	20,94	24,25	32,98	17,97	11,0
15	350	42,20	18,23	17,28	20,31	15,41	10,0
16	351	0,00	20,44	20,91	26,24	14,58	4,5
17	352	39,94	17,93	21,95	32,58	13,74	9,5
18	353	0,00	18,48	24,72	33,48	13,74	11,0
19	354	42,16	20,42	21,21	28,11	17,34	7,0
20	355	0,00	22,70	24,53	31,27	19,23	10,0
21	356	19,50	19,05	23,31	31,27	15,26	12,5
22	357	0,00	18,25	23,91	31,89	15,66	10,5
23	358	39,82	18,74	25,85	33,85	16,75	8,0
24	359	0,00	17,15	22,73	28,71	15,83	11,3
25	360	38,71	15,84	23,32	30,42	18,45	14,5
26	361	0,00	16,17	21,77	28,04	16,92	10,0
27	362	38,13	15,75	24,72	36,11	15,34	7,0
28	363	0,00	17,71	28,38	39,57	18,81	8,5
29	364	39,15	15,35	25,01	32,18	19,75	10,0
30	365	0,00	16,55	25,29	32,26	19,73	7,0
31	366	38,26	16,11	27,24	40,44	16,57	8,0

Table 2.16 Chemical composition of drainage water, 1988/89 season

YY MMDD	EC mS/m	pH	Ca	Mg	K	Na	HCO_3	Cl	SO_4
			<			mg/dm^3			>
880901	553	8,35	111	155	4,23	925	366	1377	440
880913	562	8,16	104	150	4,02	912	494	1369	448
880923	553	8,06	106	153	4,2	932	518	1344	349
880924	547	8,50	107	158	4,08	914	274	6981	604
880930	545	8,62	105	156	3,96	904	286	6856	613
881006	546	8,49	105	154	4,14	890	329	7115	506
881017	559	8,58	100	154	3,99	904	500	6931	580
881031	564	8,08	104	158	4,23	920	341	1553	506
881103	560		135	158	4,35	946	292	1553	510
881121	581		103	161	4,2	914	292	1319	526
881123	566	7,93	123	161	4,2	926	329	1603	559
881201	584	8,07	103	159	4,2	918	341	1653	526
881214	589	7,63	101	161	4,08	926	335	1603	563
881215	566	7,82					341	1603	448
881222	571	8,42	29	156	4,17	930			
881228	564	8,51	28	150	4,2	910			
890104	566	8,33	43	150	3,96	912			
890112	561	8,49	40	135	3,3	920	323	1539	493
890119	565	8,33	50	135	3,3	920	335	1548	460
890126	579	8,06	74	135	3,4	890	274	1530	469
890127	552	8,25	32	135	3,5	900	280	1495	481
890207	560	8,16	52	135	3,4	900	366	1513	481
890209	573	7,54	46	135	3,3	900	341	1513	473
890216	560	8,09	116	140	3,2	900	341	1530	473
890223	574	7,78	100	120	3,2	880	292	1513	477
890224	556	8,19	55	135	3,6	900	366	1530	444
980302	558	8,13	89	130	3,4	900	347	1530	419
890316	556	7,98	69	130	3,4	900	311	1478	448
890322	565	7,37	100	105	3,4	900	317	1478	469
890323	538	8,55	11	105	3,4	900	317	1495	473
890329	557	8,00	108	105	3,3	880	390	1495	473

Table 2.17 Example of the data base of total soil water content per 1,05 m that was measured with a neutron probe at 29 different sites in the drip irrigated vineyard at Robertson

	DATES							
Pos.	880421	880521	880616	880728	880923	881019	881214	890322
1,1	300,2	284,9	277,3	264,5	297,4	288,2	300,7	342,1
1,3	280,8	260,4	263,7	256,8	276,6	276,8	269,5	312,9
1,5	285,8	249,7	252,7	246,7	263,9	284,1	262,9	304,3
1,7	268,1	230,1	240,3	233,3	262,3	282,1	285,1	307,8
2,1	289,9	273,2	276,9	267,7	296,2	289,9	286,3	312,8
2,3	275,2	260,5	262,0	273,6	283,7	286,4	295,8	306,5
2,5	247,0	226,4	234,1	234,2	262,2	261,3	272,6	294,9
2,7	230,0	241,6	224,0	228,3	240,7	198,2	226,9	269,1
3,5	261,5	243,8	244,6	231,1	271,0	265,1	209,5	270,1
3,7	301,7	295,4	293,7	282,3	319,7	327,4	280,8	355,2
4,1	291,7	242,2	232,8	250,5	275,4	267,4	175,4	308,0
4,3	238,3	215,5	220,1	189,8	237,0	229,3	253,1	213,6
4,5	279,3	265,6	257,2	248,9	286,9	271,5	289,0	253,3
4,7	300,7	293,9	292,6	267,8	293,5	306,7	284,1	306,5

Pos. = Position indicated on Figure 2.1 and 2.3, Date as year, month and day
Data available per depth layer as well.

Table 2.18 Example of the data base containing two-hourly values of the irrigation, drainage and tensiometric data for the period 03 to 04 December 1988.

Date	Time(h)	Irrig (dm³/0,5ha)	Drain (dm^3)	Tensiometer reading at different depths 0,15 m kPa	0,30 m kPa	0,60 m kPa	0,90 m kPa	1,20 m kPa
3	2		1936	36,58	63,52	73,83	67,61	28,47
3	4		1939	38,49	64,99	74,28	67,45	26,85
3	6		1939	41,11	66,80	74,89	68,06	26,15
3	8		1930	41,70	67,06	74,33	67,11	23,14
3	10		1911	39,19	66,72	72,31	65,29	20,32
3	12		1903	49,78	71,04	73,48	66,45	23,62
3	14		1920	56,02	73,66	74,05	66,66	25,94
3	16	7072	1883	56,24	63,78	73,89	66,46	25,74
3	18	7831	1859	51,52	62,30	76,31	71,09	32,91
3	20	7283	1848	39,21	54,03	77,47	70,89	33,91
3	22	7831	1895	22,58	16,02	78,31	71,48	33,20
3	24	7455	2005	10,48	3,12	78,51	71,69	32,30
4	2	3199	2098	6,81	3,08	78,75	71,73	30,18
4	4	325	2133	7,15	6,05	78,99	71,97	28,68
4	6	312	2123	7,71	8,80	79,03	71,61	27,38
4	8	275	2083	7,71	11,01	78,83	71,81	25,78
4	10	250	2049	8,71	12,95	78,46	71,26	24,88
4	12	137	2026	8,65	14,56	70,05	70,66	23,08
4	14	237	2048	11,46	19,16	31,59	70,45	22,28
4	16	62	2039	14,26	24,77		70,25	21,88
4	18		2027	16,86	30,78		70,70	23,08
4	20		1981	18,79	35,29		71,50	23,80
4	22	87	1924	18,99	37,39		71,34	23,31
4	24	25	1918	19,92	39,39		71,34	23,11

Table 2.19 Daily tensiometric data (kPa) of the mercury manometer tensiometers at site T2 (Fig. 2.1): December 1988

DATE Depth--->	Pos 1 0,15 m	Pos 2 0,15 m	Pos 1 0,30 m	Pos 2 0,30 m	Pos 1 0,60 m	Pos 2 0,60 m	Pos 1 0,90 m	Pos 1 1,20 m
1	18,1	13,8	26,2	74,9	13,4	11,8	7,0	1,9
2	2,8	1,0	21,7	60,2	13,0	12,0	6,9	1,7
3	28,0	20,0	18,0	27,4	12,0	11,0	6,4	2,1
4	45,0	3,0	23,6	11,0	12,0	11,0	6,2	1,6
5	49,6	7,4	20,6	9,4	12,0	11,0	6,4	1,8
6	5,0	3,0	17,5	2,2	12,1	10,1	6,6	1,7
7	28,0	17,0	16,0	7,5	11,8	10,0	6,4	1,9
8	68,0	2,6	23,6	10,8	11,6	9,5	6,1	1,7
9	77,8	26,8	30,9	14,7	11,5	9,1	6,0	1,9
10	77,0	5,1	47,2	24,8	12,3	9,0	6,2	2,0
11	85,0	22,8	50,5	23,2	13,8	10,6	6,9	2,1
12	84,8	2,6	59,5	25,8	14,3	10,9	7,0	1,9
13	82,0	22,6	58,3	20,1	13,9	10,0	7,0	2,0
14	0,0	2,2	69,1	3,5	14,9	11,0	7,2	2,0
15	1,1	17,8	60,5	9,3	13,5	10,3	7,0	2,1
16	2,8	2,0	45,9	1,2	13,2	10,2	7,0	1,9
17	2,8	14,0	34,9	5,5	12,0	9,1	6,5	2,0
18	2,6	2,0	35,1	1,2	11,5	8,5	6,3	2,0
19	0,0	1,5	7,5	4,5	10,5	7,9	6,0	2,2
20	0,0	2,1	0,5	0,8	4,5	1,5	3,2	1,8
21	4,5	8,5	4,0	3,2	4,8	2,9	3,2	1,7
22	4,5	6,4	5,2	3,3	5,0	3,1	3,5	1,7
23	4,0	2,1	8,9	5,8	5,7	4,9	3,7	2,0
24	4,7	5,4	7,2	3,0	6,1	5,1	4,0	1,7
25	5,1	34,8	11,0	6,6	7,2	5,5	4,7	2,0
26	6,6	2,1	13,1	1,5	8,0	6,0	5,1	2,0
27	6,9	15,0	12,5	5,0	7,5	5,6	4,8	2,0
28	5,3	2,2	5,3	1,1	7,0	5,0	4,4	1,7
29	5,8	25,2	11,9	5,8	7,3	5,3	4,5	2,0
30	7,0	2,0	10,5	1,1	8,0	5,8	5,0	2,0
31	7,0	17,3	10,5	5,0	7,2	5,1	4,5	1,9

Position 1 is at a distance 0,2 m from emitter; Position 2 is 0,5 m from emitter

2.5 REFERENCES

Gee, G.W. & J.W. Bauder 1982. Particle size analysis. In: A.Klute (ed.) Methods of soil analysis. Part 1. American Society of Agronomy, Madison, Wisc.

Jones, A.J. & R.J. Wagenet. 1984. In situ estimation of hydraulic conductivity using simplified methods. *Water Res. Research* 20: 1620-1626

MacVicar, C.N., J.M. De Villiers, R.F. Loxton, E. Verster, J.J.N. Lambrechts, F.R. Merryweather, J. Le Roux, T.H. Van Rooyen & H.J. Von M. Harmse, 1977. Soil Classification. A binomial system for South Africa. Science Bulletin 390. Dept. Agric. Techn. Services, Pretoria.

Malik, R.S., S.K. Sharma & J.S. Dhankar 1985. Design of a sensitive and practical closed-top infiltrometer. *Soil Sci.* 139: 452-457

Moolman, J.H. & W.P. de Clercq. 1991. Using the probability density function of soil water content to locate representative soil water monitoring sites in a drip irrigated vineyard. Paper delivered at the Southern African Irrigation Symposium, July 1991, Durban.

Philip, J.R. 1958. The theory of infiltration: 6. The effect of water depth over soil. *Soil Sci.* 85: 278-286

Richards, L.A. 1952. Diagnosis and improvement of saline and alkali soils. USDA Handbook No. 60. U.S. Govt. Print. Office, Washington, DC.

Sharma, M.L., G.A. Gander & C.G. Hunt. 1980. Spatial variability of infiltration in a watershed. *J. Hydrology* 45: 101-122

CHAPTER 3
THE EFFECT OF SPATIAL VARIABILITY ON THE ESTIMATION OF THE SOLUBLE SALT CONTENT IN A DRIP IRRIGATED SALINE LOAM SOIL

THE EFFECT OF SPATIAL VARIABILITY ON THE ESTIMATION OF THE SOLUBLE SALT CONTENT IN A DRIP IRRIGATED SALINE LOAM SOIL**

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ABSTRACT

The distribution and total mass of soluble salt in a drip irrigated vineyard was investigated. Eighty four positions in a 0,52 ha area were sampled at five depths each, resulting in a total sample number of 420. The salt content increased exponentially with distance from the emitter. At equal distances from the emitter, significantly higher values were observed outside, compared to within the vineyard row. Outside the row the salt content decreased significantly with depth, but within the row the salt content was constant down to 1 m. Depth, distance from emitter and position relative to the emitter could account for 52% of the observed variation in salt content. The total salt mass within the study area to a depth of 1 m, was estimated to be ca. 22,5 ton ha^{-1}.* Calculation of the required sample size, combining the central limit theorem with the statistics of the present study, showed that at certain spatial positions relative to an emitter, the type II error of erroneously accepting the null hypothesis and the first estimate of the salt content could be as high as 41% . The initial sampling scheme could be improved by taking account of the observed spatial variation.

3.1 INTRODUCTION

Quantitative predictions of the effects of irrigation agriculture on the quality of water resources such as rivers and storage dams, are problematic, but can to a certain extent be achieved through computer simulation model studies. Solute transport models for example, can be used to predict changes in the salt balance of irrigated lands (Jury, 1982). They can also be used to simulate and evaluate the effect of various irrigation water management strategies on the salt content of a receiving river (Keys, 1976). However, these computer predictions always require some form of validation and for this purpose an accurate knowledge of soil conditions is necessary.

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*ton = 1000 kg

An agricultural expansion programme which will significantly increase the area under irrigation is presently under investigation in the Breë River Valley situated in the South Western part of South Africa. One result of this scheduled expansion is that, due to a possible increase in saline irrigation return flow that will accrue in the Breë River, the mineral (salt) content of the river will increase beyond present levels (Fourie, 1976; Moolman, 1983). Thus, in order to evaluate the effect of the expected mass emission of soluble salts from the irrigated lands on the receiving river, and to validate results predicted by simulation model studies, it is necessary to quantify by means of surveys the amount of salt present in the soil prior, and subsequent to the onset of irrigation.

The sample size that is required to estimate the total salt content of a particular area, can be calculated using the central limit theorem (Snedecor & Cochran, 1967). In soils having large spatial variability, such as alluvial soils, the design of an adequate sampling scheme is a practical problem. Large variations tend to increase the sample size, while the presence of a spatial structure in the particular soil property, influences the positioning of sampling points. The salt content of both non-irrigated (Wagenet & Jurinak, 1978) and irrigated soils (Hajrasuliha et al, 1980), was found to vary considerably in space. However, most of the studies dealing with the salt content of soils were conducted over large areas, e.g. 150 ha to 400 ha (Hajrasuliha et al, 1980), and even as large as 800 km2 (Wagenet & Jurinak, 1978), and only a few concentrated on smaller irrigated areas (<10 ha), e.g. Miyamoto & Cruz, (1986).

Unpublished local data indicate that in future, the majority of irrigated lands in the Breë River Valley, will be drip irrigated. The marked changes over short distances that occur in the salt content of drip irrigated soils, are well documented. In earlier studies it was reported that the highest salt concentrations occurred in the surface soil midway between drip emitters and at the perimeter of the wetted zone (Bernstein & Francois, 1973; Tscheschke et al, 1974). The expected large variation in the solute concentration over such short distances, will have a profound effect on the sample size predicted by classical statistical theory. The level of confidence that can be placed in the calculated amount of salt present in a volume of soil, will amongst other things, be a function of the sampling strategy that was used. The aim of this study therefore, was:

a) to investigate the spatial distribution of soluble salts in a drip irrigated soil and,

b) to use the results to design a more adequate sampling scheme to accurately quantify the salt content of a drip irrigated field.

3.2 METHODS

3.2.1 Study area and sampling scheme

The spatial distribution of soluble salt in a three year old drip irrigated vineyard, situated on a commercial farm, was investigated. The soil of the study area belongs for the most part to the Westleigh Rietvlei series (MacVicar et al, 1977). From 0,45 m downwards, the B-horizon is mottled indicating hydromorphic conditions in the subsoil. Only 0,52 ha of this particular soil, which is underlain by tile drains at 2 m depth, were included in the study. The tile drains were installed in 1984 and the vineyard has since been drip irrigated with low salinity water. The total dissolved solid content of the water generally varies between 110 and 150 mg l^{-1} and the SAR between 2 and 2,5 (meq $l^{-1})^{1/2}$. A summary of the textural composition of four soil profiles (Table 3.1) indicates a high silt plus clay content at all depths, with a slight increase in the latter size class with depth. The interrow spacing of the vineyard is 2,5 m with the drip emitters spaced at 1 m intervals within the row.

Table 3.1 Particle size analysis(%) of four soil profiles

Depth(m)	Profile number											
	Sand(2-0,05 mm)				Silt(0,05-0,002 mm)				Clay(<0,002mm)			
	1	2	3	4	1	2	3	4	1	2	3	4
0,05	38	48	49	41	45	36	36	48	18	17	15	11
0,15	44	43	47	46	37	36	35	42	19	18	18	11
0,30	38	44	47	44	43	39	36	46	19	20	17	12
0,60	27	47	48	43	51	31	31	43	23	17	17	15
1,00	31	55	59	43	47	28	24	42	23	17	17	15

Prior to the onset of drip irrigation in 1984 the soil was found to be very saline. Unfortunately, while developing this particular vineyard, the number of soil samples collected was later found to be insufficient to quantify the salt content accurately. However, in an adjacent non-irrigated soil belonging to the same series as the soil under study, the salt content to a depth of 1 m was calculated to be 21,1 ton ha^{-1} (unpublished data). Although highly variable, no particular structure in the spatial distribution of the soluble salt in this latter non- irrigated soil could be detected.

Three years after the onset of irrigation, the soil of the study area were sampled (using a Veihmeyer auger) at predetermined distances from a drip emitter which was randomly chosen. The drip emitter formed the centre point of a bigger area that was sampled according to the diagram given in Figure 3.1. Within the row, i.e. in a north-south direction, the sampling interval was 0,25 m, starting directly below the centre emitter and ending at the next emitter on either side of the centre point. Across the row, i.e. both in an east and west direction, samples were collected at 0,25, 0,50, 1,00, 1,50, 2,00 and 2,50 m distances from the centre point emitter. This sampling scheme was replicated at four locations within the 0,52 ha study area. As can be seen from Figure 3.1, the 2,50 m sampling points were situated within the next vineyard row and the distance from these sampling points to the closest drip emitter within that row differed between the four areas that were sampled. With this particular sampling scheme, the maximum attainable distance between a sampling point and the closest drip emitter is 0,50 m within the row (north-south) and 1,00 m across the row (east-west). At each sampling point the following five depth layers were sampled; 0-0,05, 0,05-0,15, 0,15-0,30, 0,30-0,60 and 0,60-1,00 m. A total of 420 samples (i.e. 4 x 21 x 5) were collected.

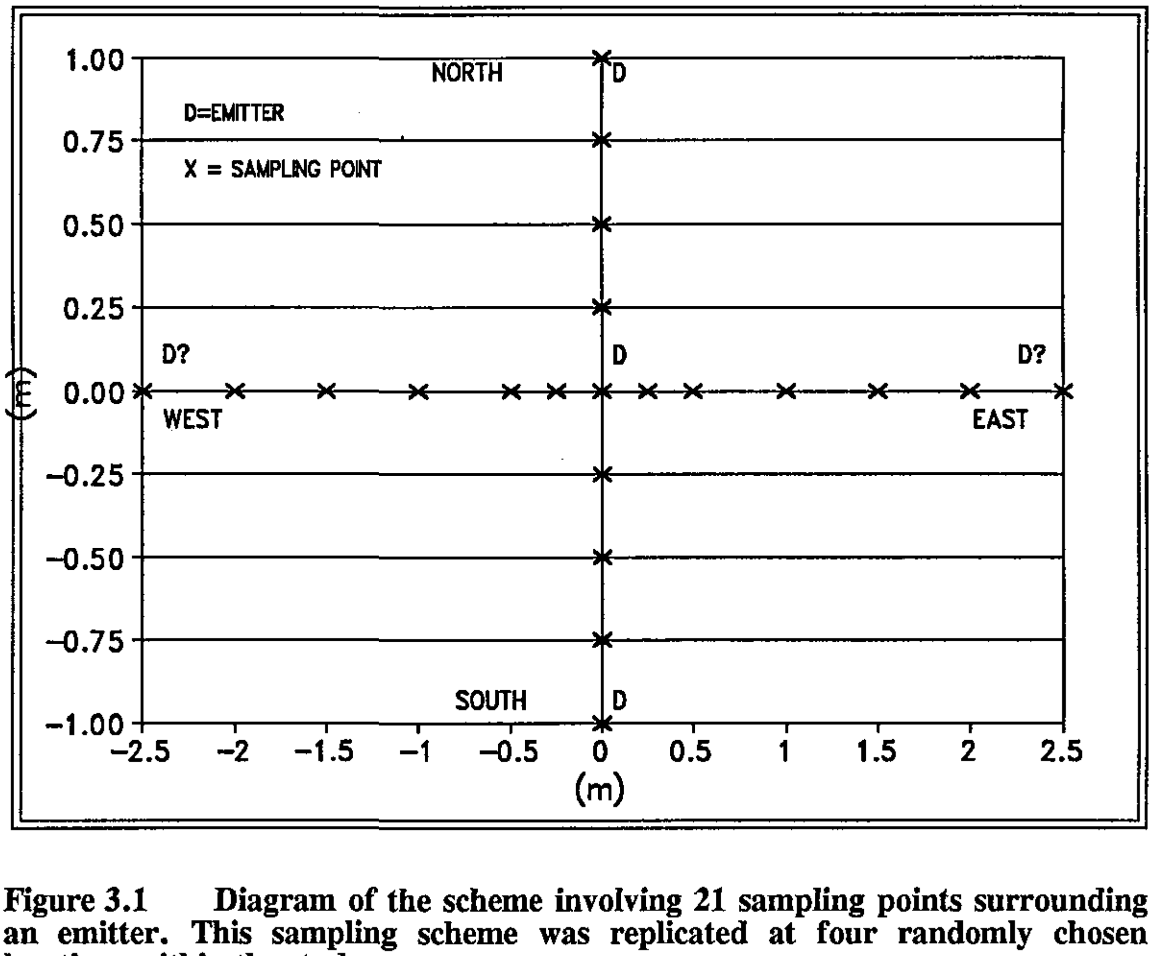


Figure 3.1 Diagram of the scheme involving 21 sampling points surrounding an emitter. This sampling scheme was replicated at four randomly chosen locations within the study area.

3.2.2 Analytical techniques

The specific electrical conductivity (EC) of a 40% water saturated soil extract was used as the index of the total dissolved solids content (TDS) of each sample. The chemical composition of the saturated extracts was determined according to the normal analytical techniques of Richards (1952). In this paper, only the EC and the index of total salt content calculated with the equation (Richards, 1952):

$$TDS(mg\ l^{-1}) = EC(mS\ m^{-1})\ x\ 6,4 \qquad \ldots.(1)$$

will be used.

3.2.3 Statistical techniques

The data were analysed according to standard statistical techniques (Snedecor and Cochran, 1967), such as analysis of variance and multiple regression analysis for which purpose the "Statgraphics" (Statistical Graphics Corporation) statistical software package was used. During the initial data analysis, the spatial structure and coefficient of variation of the salt content at each similar sampling position (i.e. positions at equal distances from the drip emitter) were determined. Using these initial results the sample size that is required to estimate the total salt content within the 0,52 ha at a predetermined level of probability, was calculated. A useful feature of the latter procedure in "Statgraphics" is that the level of tolerance for both the type I and type II error can be specified. The type I error refers to the probability of rejecting the null hypothesis if it is true, while the type II error refers to the probability that the null hypothesis is erroneously accepted.

3.3 RESULTS

3.3.1 Spatial distribution of salts

The chemical composition of the soluble salt content of two representative sampling sites is presented in Table 3.2 as background information only and will not be discussed in this paper. The frequency histogram of the pooled EC data, irrespective of sampling depth or distance from the emitter, is lognormal (Fig. 3.2a+b) and indicates that the values are not symmetrically distributed around the arithmetic mean. This result is not uncommon and is in accordance with data published elsewhere e.g. Wagenet & Jurinak (1978), and Moolman (1985). When grouped according to specific sampling positions, e.g. all data collected at the 300 mm depth layer along the north-south transect, the EC distribution of the raw data is less skew (Fig. 3.3a). Although the natural logarithm transformation of the grouped data, in some cases, also failed to produce the typical Gaussian normal distribution (Fig. 3.3b), all data were, because of greater consistency, transformed to their natural logarithm values. The transformed values were used in all of the subsequent statistical analyses. It is important to note that in this paper, the term "*geometric*" mean is used for the mean of the transformed data, backtransformed to its original units (mS m^{-1}), i.e.

$$geometric\ mean = alog[1/n \sum_{i=1}^{n} log(X_i)]$$

Table 3.2 Chemical composition (mg L^{-1}) of the saturated soil extract of two representative soil profiles

Depth(m)	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	HCO_3^-	Cl^-	SO_4^{2-}
Within the row (North-south) directly below an emitter							
0,05	660	141	161	23	122	27	2370
0,15	460	17	113	13	61	153	1164
0,30	442	25	186	8	92	179	1241
0,60	42	6	320	2	214	162	404
1,00	24	5	353	1	31	290	393
Outside the row (East-west) 1,00 m from emitter							
0,05	638	1548	9500	102	159	6395	18678
0,15	557	525	3630	21	92	2131	8009
0,30	456	274	1350	10	61	1236	3258
0,60	109	91	1068	4	110	937	1479
1,00	243	150	1170	2	85	1023	2149

The geometric means of each sampling position and the number of samples used in calculating the particular mean are presented in Table 3.3. The statistical significance of the differences between the various means is listed in Table 3.4. The overall geometric mean EC for this 0,52 ha area is 359 mS m^{-1}, which according to the norm of 400 mS m^{-1} used to distinguish between a saline and non-saline soil (Richards, 1952), indicates "*non-saline*" conditions. However, the mean of the north-south transect (within the row) is approximately two and a half times less than the mean along the east-west transect and this difference is significant at $P=0,01$ (Table 3.4). The depth weighted means of each sampling point, increase significantly with distance from the nearest emitter along both of the transects. The increase along the east-west transect is much more pronounced than along the north-south transect. This is also reflected in the difference between the respective F-ratios obtained during the analysis of variance of the data of the two transects, i.e. $F=4,60$ (north-south), and $F=77,28$ (east-west) (Table 3.4). Within the row (north-south), no significant trend with depth was apparent but along the east-west transect, the salt content decreases significantly with depth (P=0,05, Table 3.4).

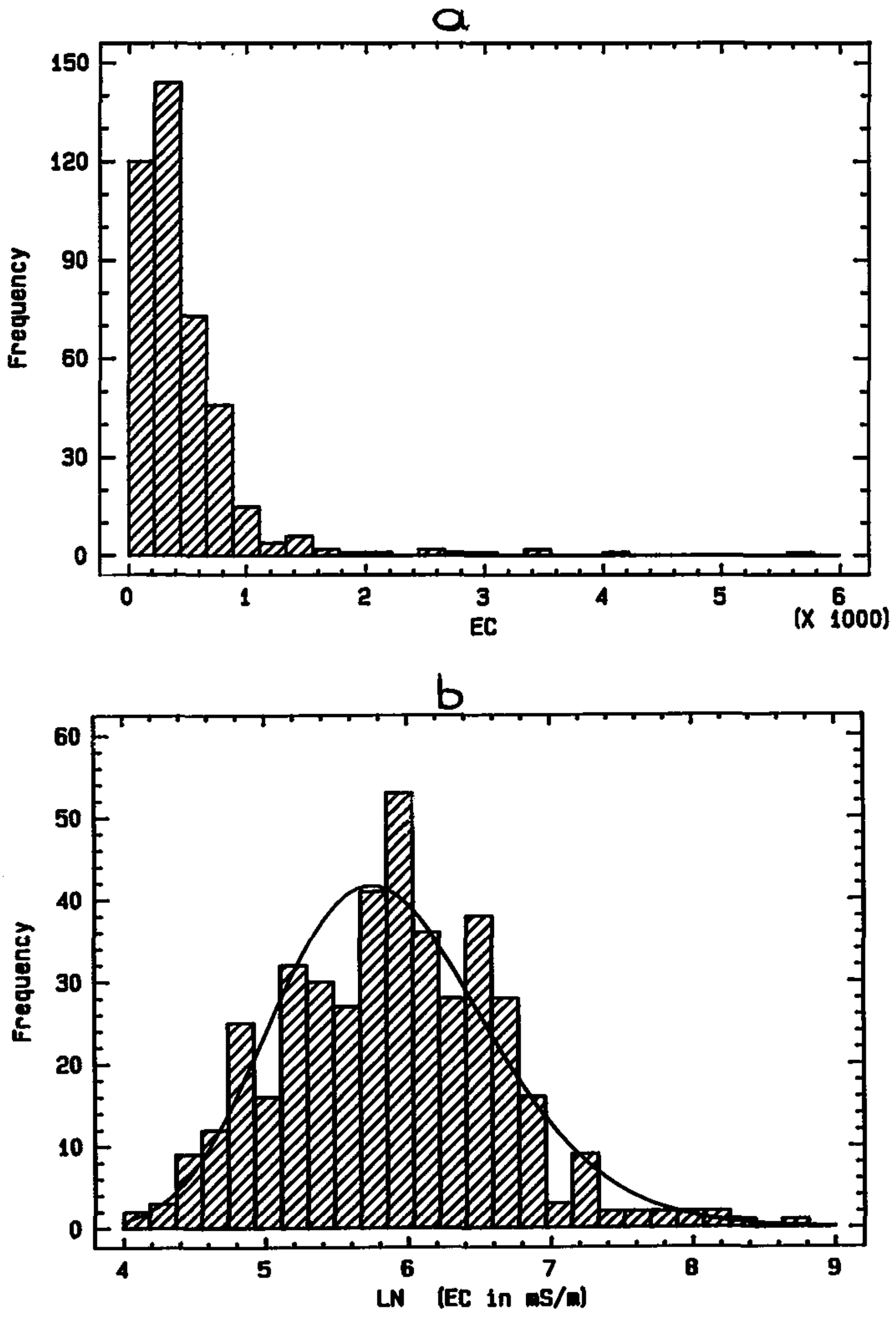


Figure 3.2 Frequency histogram of the pooled EC data, irrespective of depth and position: a)untransformed, and b)ln transformed.

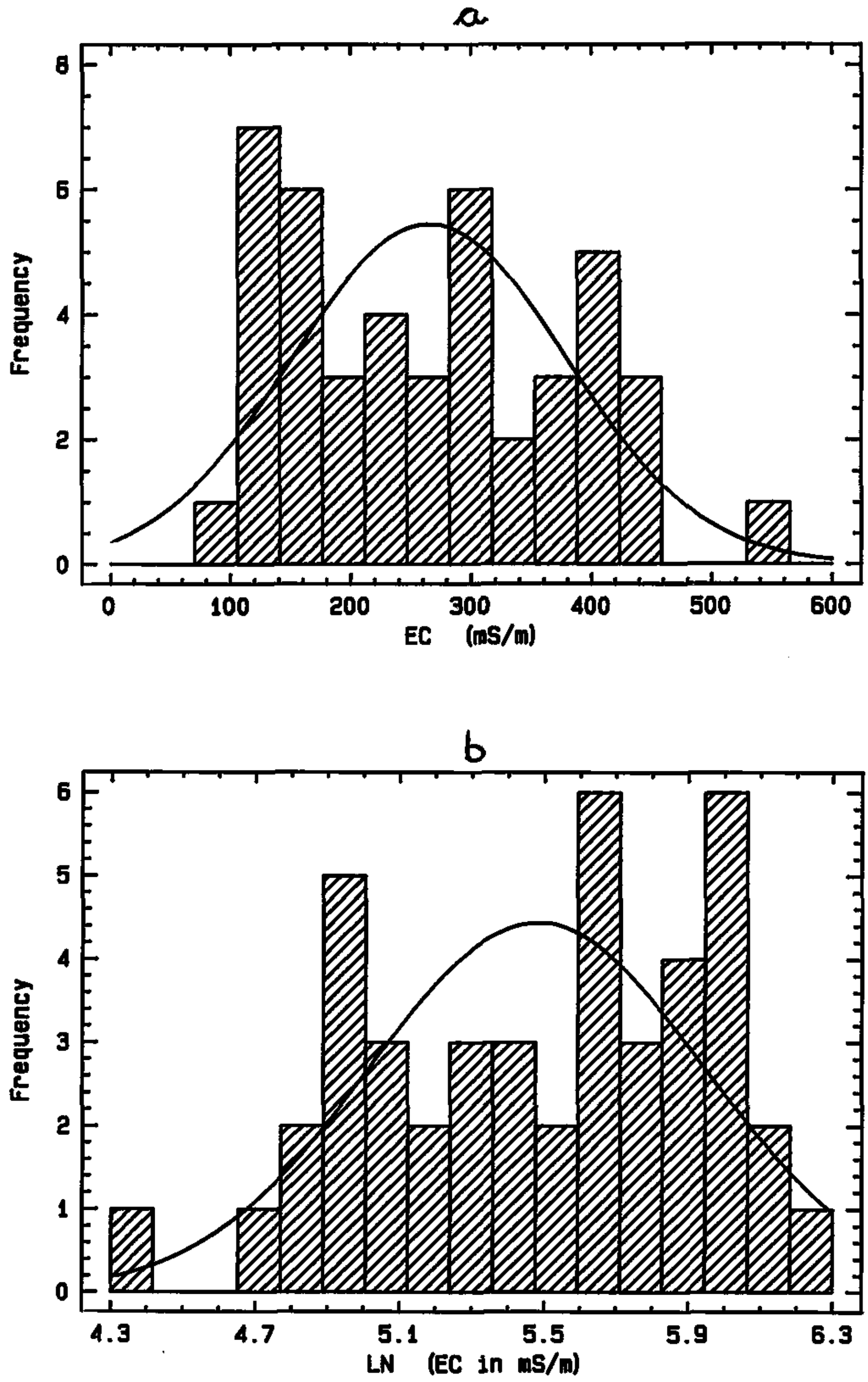


Figure 3.3 Frequency histogram of EC at the 0,30 m depth along the north-south transect: a)untransformed, b)ln transformed.

Table 3.3 Geometric mean EC (mS m^{-1}) per sampling position and depth

Global means: 359

Overall Transect: North-south=236; East-west=569 (East=636,West=510)

Depth means and depth weighted means per distance.

Depth(m)	Distance(m) & number of observations (in brackets).					
	North-South			*East-West*		
	0(14)	0,25(19)	0,5(11)	0,25(8)	0,5(16)	1,0(16)
0,05	209	256	309	497	673	1536
0,15	227	258	283	373	495	1016
0,30	224	227	287	336	432	915
0,60	190	203	249	253	394	768
1,00	232	224	229	241	351	651
Weighted	223	233	258	291	427	835

Table 3.4 Statistical significance (*F*-ratios) of differences between various means

Transect comparison		
North-South vs East-West:	97,6 **	
Trend comparison	*Depth*	*Distance*
North-South transect	0,2 NS	4,6 *
West-East transect	7,3*	77,3 **

* P = 0,05; ** P = 0,01; NS = not significant.

By fitting a second degree polynomial function to the various geometric means, a three dimensional surface plot of the salt distribution around the drip emitter could be constructed (Fig. 3.4). To the east of the emitter the slope of the increase in salt content with distance from the emitter, is steeper than to the west. Inspection of the data subsequently revealed that at each of the four locations that were sampled, the majority of the samples (16 out of 20) taken directly to the east of a drip emitter had a higher total salt content than the equivalent sample to the west. The reason for this unequal distribution is under investigation at present, but is most likely a result of differences in the soil water regime that prevails to the east and west of an emitter. The difference between the two respective geometric means (east = 636 mS m^{-1}, west = 510 mS m^{-1}, see Table 3.3), is significant at P=0,05 (Table 3.4). This result was unexpected and as will be shown in a following section, complicated the calculation of the required sample size.

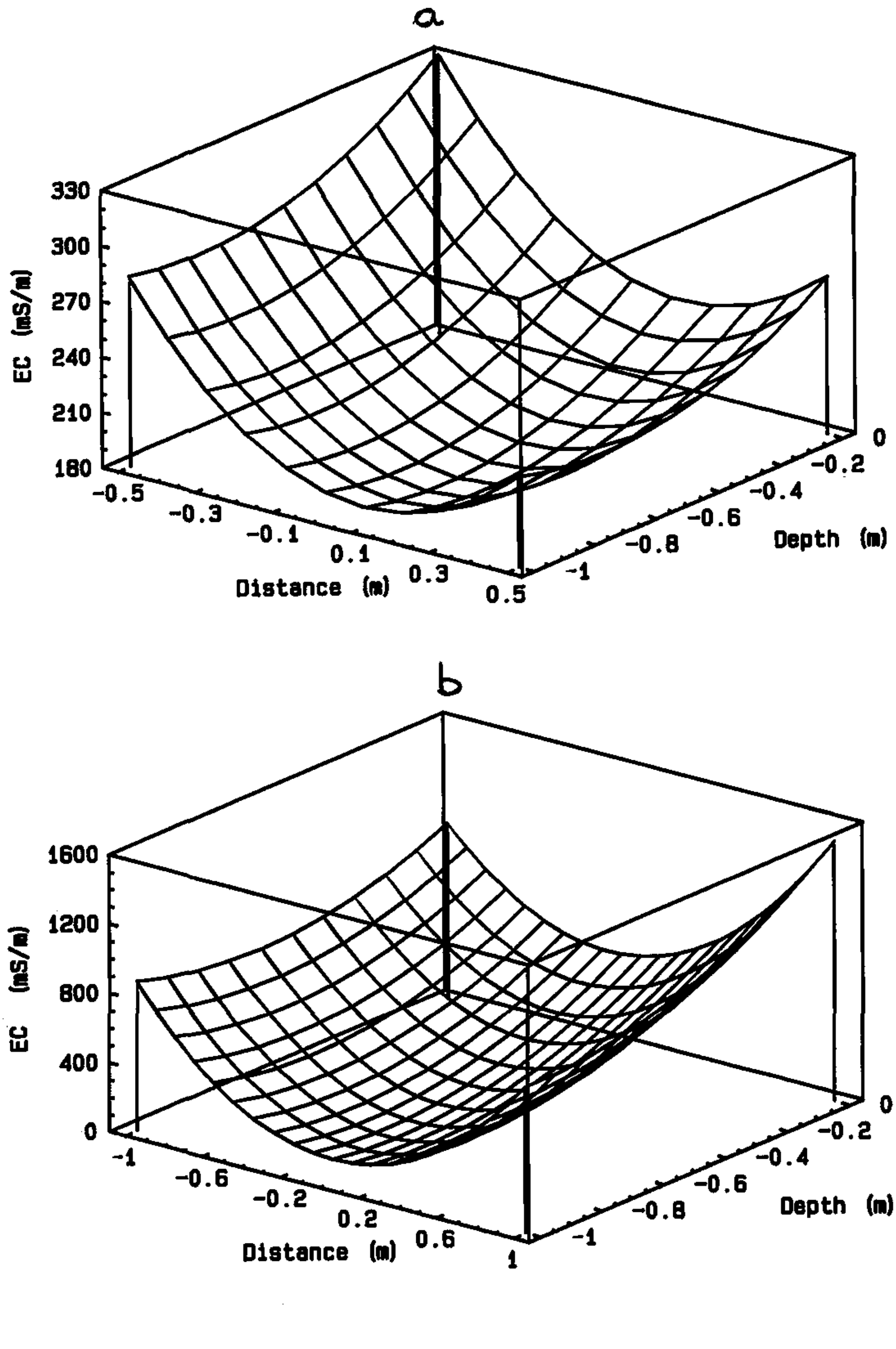


Figure 3.4 Three dimensional surface plot of salt distribution around an emitter as viewed from two different directions: a)north-south direction, b)east-west direction. Negative distances indicate points south and west of the centre emitter.

The asymmetrical distribution of salt within and outside the row at equivalent distances from the drip emitter is illustrated in Figure 3.5 for the 0,05 m and 1,00 m depth layers. Similar distribution patterns were observed at all the other depths. In most cases the increase in salt content with distance from the emitter could best be described with exponential functions. For example, for the 0,05 m depth layer, the increase in the salt content of the soil (indicated by the EC of the extract), from the emitter to a point 1,00 m to the east of it, is given by

$$EC(mS\ m^{-1}) = 240{,}2exp(0{,}002x)\ ,(r^2 = 0{,}983)$$

where x is the distance (mm) from the emitter.

A multiple regression analysis of the salt content as a function of depth (X_1), distance (X_2), and position relative to the drip emitter (i.e. north-south, east or west) (X_3) yielded the following regression equation:

$$ln(EC) = 5{,}108 - 0{,}004X_1 + 0{,}011X_2 + 0{,}262X_3\ (R^2 = 0{,}518).$$

The three categories according to which each sample could be classified thus explain only 52% of the observed variation in salt content.

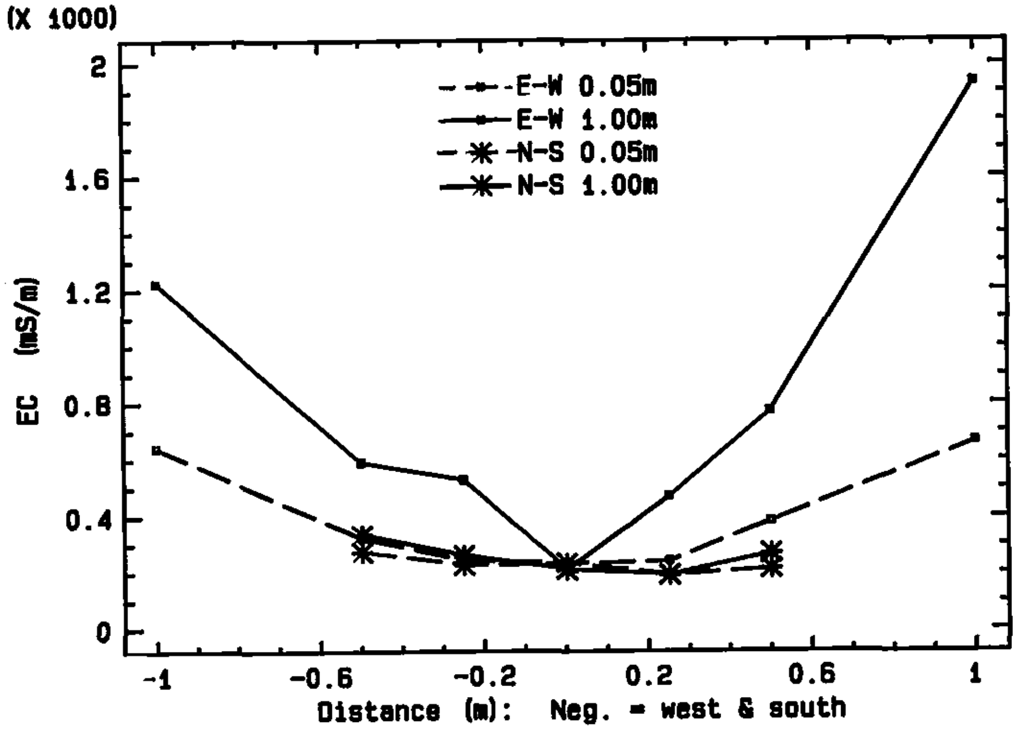


Figure 3.5 Distribution of salt at the 0,05 m and 1,0 m depth layers as a function of distance from the emitter

3.3.2 Total salt content

The results obtained with the initial sampling scheme were used to estimate the salt mass of the soil in the study area according to three different approaches. With the first approach, the total salt content to a depth of 1,00 m at each of the four locations was calculated by using the EC values of each depth layer of all the sampling points situated within 0,50 m of the central drip emitter in a north-south direction, and within 1,00 m in the east-west direction (Fig. 3.1). In essence this meant that the salt content in the volume of soil surrounding each drip emitter was calculated. By using eq. 1 and appropriate soil bulk densities for this particular soil, determined in situ at two representative soil profiles, the electrical conductivities were converted to a salt mass per volume of soil. The salt masses obtained at each of the four locations were reduced to a mean value and from the latter the salt content of the study area (0,52 ha) was calculated in units of tons per ha over 1 m. From the above explanation, it follows that only 11 of the 21 sampling points per location (Fig 1.) were used in calculating the total salt content for this soil. This calculation yielded a salt mass of 22,6 ton ha^{-1} over 1 m depth, and for the current study, was regarded to be the most accurate estimate of the total salt content in this field.

With the second approach all 420 samples (84 positions, 5 depths) were used to calculate depth weighted mean EC values per position for every sampling distance per transect. For example, the depth weighted mean of all points 0,25 m to the east of a drip emitter were reduced to the geometric mean of all similar positions. According to this calculation the total salt mass to a depth of 1 m, is 21,4 ton ha^{-1}.

The third way of arriving at the total salt mass was similar to the second, with the exception that selected depth weighted means only were used. All sampling points within 0,25 m of an emitter, irrespective of transect, were excluded from the calculation. This calculation yielded a salt mass of 21,8 ton ha^{-1} per meter. The last two estimates are both within 6% of the first one and indicates that the error that is introduced by using depth weighted mean EC values and by ignoring the 0,25 m sampling points, is insignificant. Therefore, if the objective is to quantify the total salt mass within the irrigated land, samples need not be taken at distances less than 0,25 m from the emitter. Further analysis of the total salt content indicates that, if the vineyard row is defined as having a width of 0,75 m, 15% of the salt are located within the row and 85% between the rows.

3.3.3 Sample size

The density of sampling is equal to 161 positions per hectare (i.e. 84/0,52), which seemingly should be sufficient to estimate the total salt mass with a relatively high degree of precision. However, due to the large variation in salt content over short distances, as well as the large coefficients of variation observed with the untransformed EC values per sampling position (Table 3.5), the present sample size and sampling locations might still be inadequate to arrive at a sufficiently accurate estimate for the total salt mass. This possibility was evaluated by calculating the required sample size per position (i.e. distance from emitter per transect) and by specifying the level at which the type I and type II errors can be tolerated, the latter being 5% and 10% respectively. Because of the results mentioned in the previous section, all the 0,25 m sampling points were excluded from this calculation.

Table 3.5 Coefficients of variation associated with the arithmetic and untransformed mean EC per sampling position

Global Means.						
Overall 1,08 Transect: North-south=0,52; East-west=0,92						
Depth weighted means per distance.						
	North-South			East-West		
Distance(m)	0	0,25	0,50	0,25	0,50	1,00
	0,48	0,58	0,46	0,48	0,67	0,78

The algorithm used to calculate sample size requires information about the assumed mean EC and standard deviation per sampling position. At the east-west transect, because of the significant difference in the salt content of samples taken to the east and west of an emitter, the initial set of samples per distance (Table 3.3) had to be split into two subsets, namely east and west. This resulted in a limited number of samples per position and consequently, unreliable estimates for the mean and standard deviation. This shortcoming of the initial data set was overcome by estimating the mean and standard deviation of each sampling position using the bootstrap method (Efron, 1982). With the bootstrap method a data set is duplicated numerous times, and sets of subsamples are subsequently drawn from this expanded data set. The method only requires that each individual subset can be drawn randomly. In the present study, a particular data set, e.g. the weighted mean of the 8 observations made 0,50 m to the east of an emitter, was expanded to 100 subsets, with each subset consisting of 8 values drawn randomly from the original observations. The mean EC of each subset was calculated, resulting in 100 estimates of the mean EC for a particular sampling position. After testing for normality, the mean and standard deviation of these 100 bootstrapped means were used in the calculation of the required sample size. The results are listed in Table 3.6.

The calculated sample sizes per individual position sum to 78 and with the exception of samples taken directly below an emitter, all positions were undersampled, some to the extent of 10 samples per position, e.g. the positions 0,50 m to the east of the emitter (Table 3.6). This suggests that the first estimates of the salt mass contained in the study area might be wrong. This deduction is amplified by calculating the likelihood of making a type II error with the existing data set. As indicated in Table 3.6, the chance of erroneously accepting the null hypotheses at a specific sampling position varies between 6% and 41%.

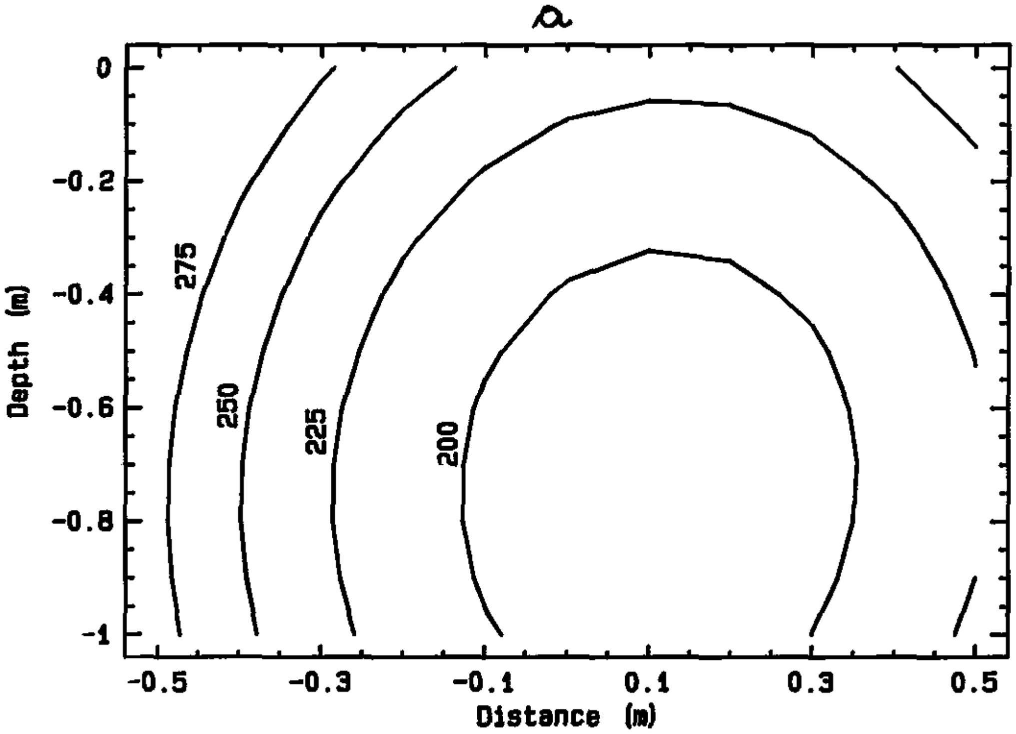
Table 3.6 Sample size(n) necessary to estimate the total salt content at a 95% level of confidence

Distance from emitter (m)	Present n	Required n (α=0,05;ß=0,10)	Present ß
0,0	14	12	0,06
0,5	11	16	0,22
0,5(west)	8	12	0,23
0,5(east)	8	18	0,41
1,0(west)	8	11	0,19
1,0(east)	8	9	0,12

α & ß = Levels of tolerance for the type I and II errors respectively.

3.4 DISCUSSION AND CONCLUSIONS

The distribution of soluble salt around the drip emitters is highly variable as well as asymmetrical. At equal distances from the emitter the salinity outside the vineyard row, is significantly higher than within the row (i.e. along the laterals). This distribution pattern can best be described by iso-conductivity diagrams which indicate iso-lines spaced more closely in the east-west direction than in the north-south direction (Fig. 3.6). Electrical conductivities as high as 1200 mS m^{-1} occur at the 0,05 m soil depth at a distance 1,00 m from the emitter (Fig.3.6b). Because of the absence of wetting and therefore, leaching of soluble salt during the irrigation season, the observed high salinities at these latter positions are to be expected.



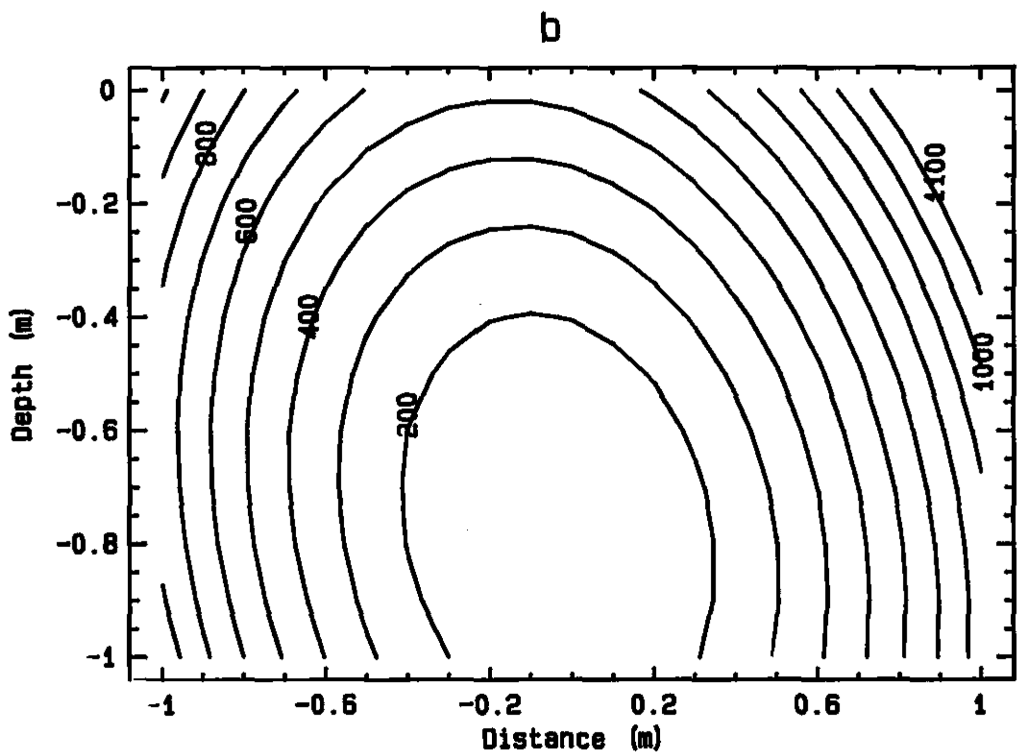


Figure 3.6 Iso-conductivity lines (mS m^{-1}) around an emitter: a)north-south transect, b)east-west transect. Negative distances indicate points to the south and west of the centre emitter.

At distances closer to the emitter where equal quantities of water assumedly infiltrates the soil, the spatial distribution of salt was anticipated to be more symmetrical. However, at the 0,25 m distance the salt concentrations were found to be unequal. This is most likely the result of an emitter discharge rate (2 L h^{-1}) that exceeds the steady state infiltration rate of the soil. In a separate study the steady state mean infiltration rate within the row was determined as 8 mm h^{-1}. Inspection of the micro-relief of the soil directly below the emitters (within the row) revealed the presence of a slight depression that runs from north to south (Fig 3.1). When the application rate exceeds the infiltration rate, the water spread along the surface in this slightly depressed area and within the row, the wetting fronts of two adjacent emitters have been observed to meet at the soil surface and not at a point below the surface. The presence of this shallow depression limits the horizontal distribution of surface water in an east-west direction. Consequently, at the 0,25 m distance from an emitter, more water percolates through the soil within the vineyard row, with limited wetting only materializing outside the row. The fact that the salt content within the row does not differ significantly with depth also points to continuous leaching and possibly even to over-irrigation.

The autocorrelogram of the depth weighted mean EC of the soil (i.e. salt content) along the east-west transect, suggests a significant cyclic pattern with a wavelength of 2,5 m (Fig. 3.7) which is equal to the vineyard row spacing. No such cyclic pattern was observed along the north-south transect. Therefore, in a spatial context the salt content in this drip irrigated field is not randomly distributed nor will the variance be constant. A total random sampling strategy that disregards these two aspects, will lead to an inaccurate estimate of the total salt mass. Alternatively, if a total random sampling strategy is nevertheless followed, the sample size required to estimate the mean with a high level of accuracy will, according to the central limit theorem, lead to such a large number of samples to be taken that the exercise becomes impractical. Specifying a 95% level of confidence and using the pooled mean and standard deviation of the set of 84 depth weighted means for each of the sampled sites (i.e. ignoring the observed spatial structure), for example yields 169 sampling points per 0,52 ha. However, when the spatial structure and variability of the salt distribution around the emitters are considered and the required sample size at each position relative to the emitter is calculated separately using the same level of confidence, the total number of sampling positions sums to 78 (Table 3.6). This represents a considerable reduction in the required sample size compared to a sampling strategy that disregards the spatial structure. Therefore, to quantify accurately the salt mass of this drip irrigated field, samples should be taken directly below and 0,5 m from the emitter within vineyard row, and at the 0,5 and 1,0 m distances across the row. If the salt content within the root zone volume of soil only is to be determined, i.e. the volume of soil within 0,5 m of the emitter, the required number of sampling points can be reduced by 20 (Table 3.6).

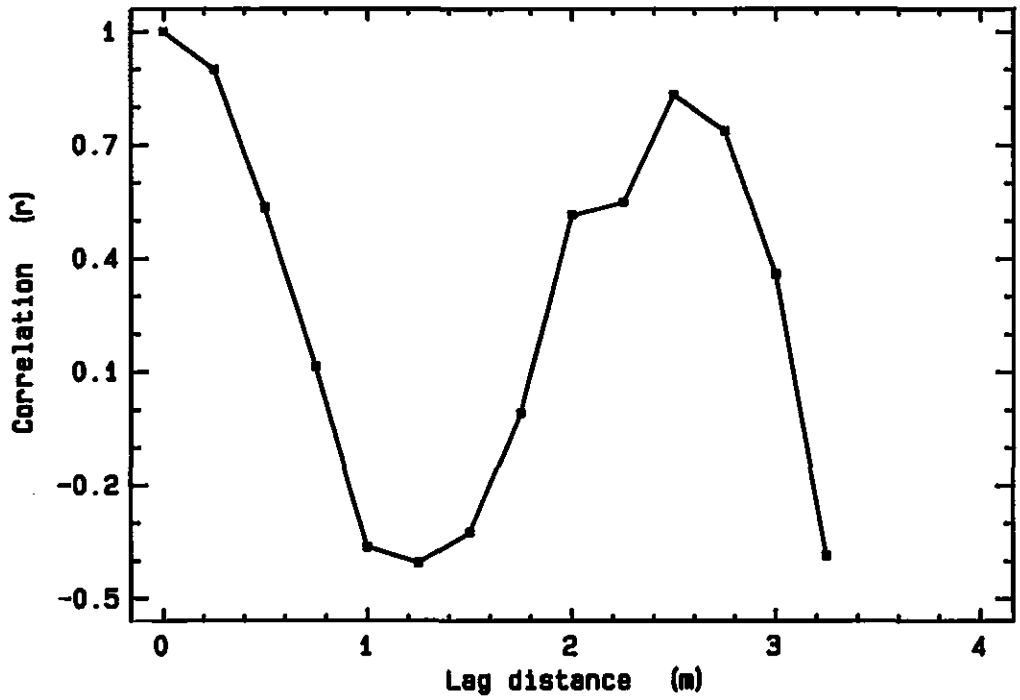


Figure 3.7 Autocorrelogram of salt (EC) distribution along the east-west transect

The calculated sample size (78) required for an accurate estimate of the salt content is equivalent to 150 sampling points per hectare. This high sampling density is a direct consequence of the large spatial variability of soluble salt in drip irrigated saline soils. It furthermore illustrates the high input requirements necessary to monitor accurately fluctuations in the salt balance of spatially variable fields following a change from dryland to irrigation agriculture.

Finally, it should be recognised that the spatial distribution of salt around a point source, such as an emitter, depends on the hydraulic properties of the soil and the prevailing leaching fraction. A change in anyone of these two will alter the distribution pattern which in turn will influence the optimum sampling strategy to be used in order to quantify the salt content in the soil.

Acknowledgement

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3.5 REFERENCES

Bernstein,L. & Francois, L.E.,1972. Comparisons of drip, furrow, and sprinkler irrigation. *Soil Sci.* 115,73-86.

Efron,B.,1982. The jackknife, the bootstrap and other resampling plans. Soc. for Industrial and Applied Mathematics. Monograph No. 38. J.W.Arrowsmith Ltd.,Bristol,U.K. 92pp.

Fourie,J.M.,1976. Mineralization of Western Cape rivers: An investigation into deteriorating water quality related to drainage from cultivated lands along selected catchments, with special reference to the Great Berg River. Unpublished Ph.D thesis, University of Stellenbosch, Stellenbosch, South Africa.

Hajrasuliha,S., Baniabbassi,N, Metthey,J. & Nielsen,D.R., 1980. Spatial variability of soil sampling for salinity studies in southwest Iran. *Irrig. Sci.* 1, 197-208.

Jury,W.A., 1982. Use of solute transport models to estimate salt balance below irrigated cropland. *Adv. Irrig.* 1, 87-104.

Keys,J.W., 1976. Water and flow study of the Oahe Unit, South Dakota. Proceedings of the international conference on managing saline water for irrigation: Planning for the future. Lubbock, Texas, pp 109-126.

MacVicar,C.N., De Villiers,J.M., Loxton,R.F., Verster,E., Lambrechts,J.J.N., Merryweather,F.R., Le Roux,J., Van Rooyen,T.H. & Harmse,H.J.Von M., 1977. Soil Classification. A binomial system for South Africa. Science Bulletin 390. Dept. Agric. Techn. Services, Pretoria.

Miyamoto,S. & Cruz,I., 1986. Spatial variability and soil sampling for salinity and sodicity appraisal in surface-irrigated orchards. *Soil Sci. Soc. Am. J.* 50, 1020-1026.

Moolman,J.H., 1983. The effect of irrigation practices in the Breë River Valley on the salt content of a small river. *Irrig. Sci.* 4, 103-116.

Moolman,J.H., 1985. Spatial variability of two selected soil properties in a semi-arid subcatchment of the Lower Great Fish River. *S.Afr.J.Plant Soil* 2, 72-78.

Richards,L.A.(ed.) 1954. The diagnosis and improvement of saline and alkali soils. USDA Handbook No. 60,U.S. Govt. Printer.

Snedecor,G.W., & Cochran., 1967. Statistical methods. Iowa State University Press, Ames, Iowa, U.S.A.

Tscheschke,P., Alfaro,J.F., Keller,K., & Hanks,R.J., 1974. Trickle irrigation soil water potential as influenced by management of highly saline water. *Soil Sci.* 117, 226-231.

Wagenet,R.J. & Jurinak,J.J., 1978. Spatial variability of soluble salt content in a Mancos shale watershed. *Soil Sci.* 126, 342-349.

CHAPTER 4
USING THE PROBABILITY DENSITY FUNCTION OF SOIL WATER CONTENT TO LOCATE REPRESENTATIVE SOIL WATER MONITORING SITES IN A DRIP IRRIGATED VINEYARD

USING THE PROBABILITY DENSITY FUNCTION OF SOIL WATER CONTENT TO LOCATE REPRESENTATIVE SOIL WATER MONITORING SITES IN A DRIP IRRIGATED VINEYARD*

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ABSTRACT

This study investigated whether the probability density function of spatially measured soil water content at the first stage of a field study can be used to identify statistically important field locations. The soil water content at 14 sites was monitored at 15 different times over a period of 18 months in a drip irrigated vineyard. It was found that certain sampling locations conserve the property to represent the mean and extreme values of the field water content over time. The presence of transpiring vines and irrigation applications increased the variability of the measured values without any big influence on the ranking position of the various monitoring sites as they initially appear on the probability density curve. The locations that were identified as being representative of the field mean water content during summer, also represented the mean during winter when irrigation and transpiration were absent. However, the positions representing the field mean and extreme water contents of the topsoil differ significantly in space from the corresponding subsoil positions. It is concluded that, because of the temporal stability of the ranking position of the measuring sites, the probability density curve of one sampling only can be used to identify representative sites (e.g. the median), that can be used for soil water monitoring and irrigation scheduling. However, cognizance should be taken of the confounding effects that are likely to occur with depth.

4.1 INTRODUCTION

Proper scheduling of irrigation involves two aspects, namely how much and when, should water be applied. Several techniques are available to accomplish this, e.g. monitoring of the soil water content and matric potential, or monitoring of crop and/or atmospheric factors (Campbell and Campbell, 1982). These two authors argue that since the soil is the primary recipient of the irrigation water, monitoring of the soil water content should be the logical method of scheduling.

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* Copy of a paper delivered at the Souther African Irrigation Symposium, 4-6 June 1991, Durban.

Although irrigation scheduling does not require knowledge of the field average soil water content (Campbell and Campbell, 1982), the site or sites used for monitoring the status of soil water, should be representative of the field. Because of soil spatial variability the selection of a representative site is difficult. Previous studies indicate that a large number of samples have to be collected and analyzed before such a representative site or sites can be decided upon, e.g. Nielsen et al., (1973), and Moolman, (1989). However, a study by Vachaud et al. (1985), showed that some sampling locations conserve the property to represent the mean and extreme values of the field water content at any time during the year. In view of this, Wagenet (1985), suggested that a gravimetric sampling and analysis at the first stage of a field study could identify statistically important field locations at which could then be located more detailed and intensively monitored sampling devices. If the results of Vachaud et al. (1985), are generally applicable, their technique can be extended to select a limited number of monitoring sites which can then be used for both irrigation scheduling as well as to estimate the mean and variance of water storage of an irrigated field. However, the degree to which the time stability of the spatial distribution and variability of soil water content is influenced by the method of irrigation, the presence of evapotranspiring crops, and other soil factors such as salinity, has not been investigated.

The aim of this study is, therefore, to report on the application of the concept of time stability as reported by Vachaud *et al.* (1985), in a drip irrigated vineyard in which the water uptake varies with soil properties, depth, season, and spatial differences in root and crop activity.

4.2 METHODS AND MATERIALS

4.2.1 Theory of time stability of the probability density function

The concept of the time stability of the probability density function of spatially measured soil water content, is described by Vachaud *et al* (1985). According to this concept, at a given time t, sufficient field observations are available to determine their classical statistical parameters. If the location of each observation within the field is known, the spatial distribution of the variable allows the nature of the spatial structure to be identified. By ranking the observations from the smallest to the largest values, and identifying the cumulative probability density function as normal, the particular location associated with a probability of 50% can be found. The observation at that location taken at the time of sampling will then characterize the mean of the soil water content for the entire field. Similarly the locations associated with cumulative probabilities of, for example, 17% or 83%, can be selected to identify values one standard deviation from the mean.

In order to evaluate the time stability of a particular location's rank position in the cumulative probability density function, Vachaud *et al* (1985), calculated the temporal mean relative difference in soil water content. This was achieved by obtaining the difference Δ_{ij} between an individual determination of soil water content S_{ij} at location $i(i=1...n)$ at time $j(j=1...nn)$, where n and nn are the number of sampling locations and times of sampling respectively, and the mean water storage S'_j at the same time:

$$\Delta_{ij} = S_{ij} - S'_j$$

with

$$S'_j = (1/n)\sum_{i=1}^{n} S_{ij}$$

This corresponds to the relative difference:

$$\delta_{ij} = \Delta_{ij}/S'_j$$

Therefore, for any location i the time average δ'_i and the temporal standard deviation $\sigma(\delta_{ij})$ can be calculated for the whole series of nn soil water content observations. It follows from the above that for the field mean soil water content, Δ_{ij} will be 0.

4.2.2 Soil and crop information

The study was conducted on 5 000 m^2 of a 3-year old drip irrigated vineyard in the Robertson area, situated in the south-western part of South Africa. The soil of the study area is moderately to very saline (Moolman, 1989) and belongs, for the most part, to the Westleigh rietvlei series (MacVicar *et al.*, 1977). From 0,45 m downwards, the B-horizon is mottled, indicating hydromorphic conditions in the subsoil. The interrow spacing of the vineyard is 2,5 m, with the drip emitters spaced at 1 m intervals within the row.

In May 1987, as part of a long term study of the spatial variability of soil water content in this vineyard, thirty neutron access tubes were installed to a depth of 1,5 m. The access tubes were installed as fifteen pairs that were divided into four groups (Fig. 4.1). A pair consisted of one tube located 0,3 m from an emitter within the vineyard row, while the other tube was installed midway between two vineyard rows 1,25 m from an emitter. Only the information of the 15 sites located 0,3 m from the emitter, were used to test the concept of time stability of the probability density function. The rationale for this decision was that the purpose of this investigation was to identify representative sites for irrigation scheduling. In practice it is unlikely that a position between two vineyard rows, i.e. near to the maximum distance from a drip emitter and outside the wetted zone, will be used for irrigation scheduling. Early on during the course of the investigation, one of the access tubes was damaged by a tractor wheel, leaving only 14 locations of which the data could be used. The remaining fourteen sites were numbered with a 2-digit identification code, where the first digit indicates the group position and the second the position within a group (Fig. 4.1b).

During the installation of the tubes the soil was sampled in 0,3 m increments to a depth of 1,2 m and the gravimetric water content and soil texture of each sample determined. Bulk densities were determined with a gamma probe and the gravimetric water contents converted to volumetric units. Following the installation of the access tubes and during the winter of 1987, the so-called field capacity of each of the 15 sites was determined. This was done by saturating the soil to a depth of 1,2 m and determining the soil water content after 4 days of drainage in the absence of evapotranspiration. Because of the hydromorphic and saline subsoil conditions (Moolman, 1989), root growth and water uptake are restricted to approximately 1 m depth.

Subsequent to the initial measurements, the soil water content at each of the 14 sites within the vineyard row were determined at variable time intervals, but never more than 7 weeks apart, at 15 different times from July 1987 to December 1988. This was done by measuring the soil water content in 0,3 m depth increments to a depth of 0,9 m using the neutron moderation technique. For the 0-0,3 m depth two 0,15 m increments were used. Assuming that the neutron probe measures soil water in a sphere with a radius of 0,15 m, the total soil water storage to a depth of 1,05 m can be calculated. At any one time the soil water storage could furthermore be split into the topsoil (0-0,45 m) and subsoil (0,45-1,05 m) components. The 15 temporal observations could also be divided into 10 measurements made during the active growing season of the vines (October to March, referred to as the summer measurements), and 5 measurements made during the winter (April to September) when the vines were dormant.

The statistical uniformity of emitter flow in the area where the soil water content was monitored, was determined as 93%. This was done by measuring the flow at 25 randomly selected emitters, all in close proximity of the access tubes, and using the following equation (Bralts and Edwards, 1987):

$U_s = 100(1\text{-}S_q/q')$

with U_s = statistical uniformity, S_q = standard deviation of emitter flow, and q' = mean emitter flow rate or volume.

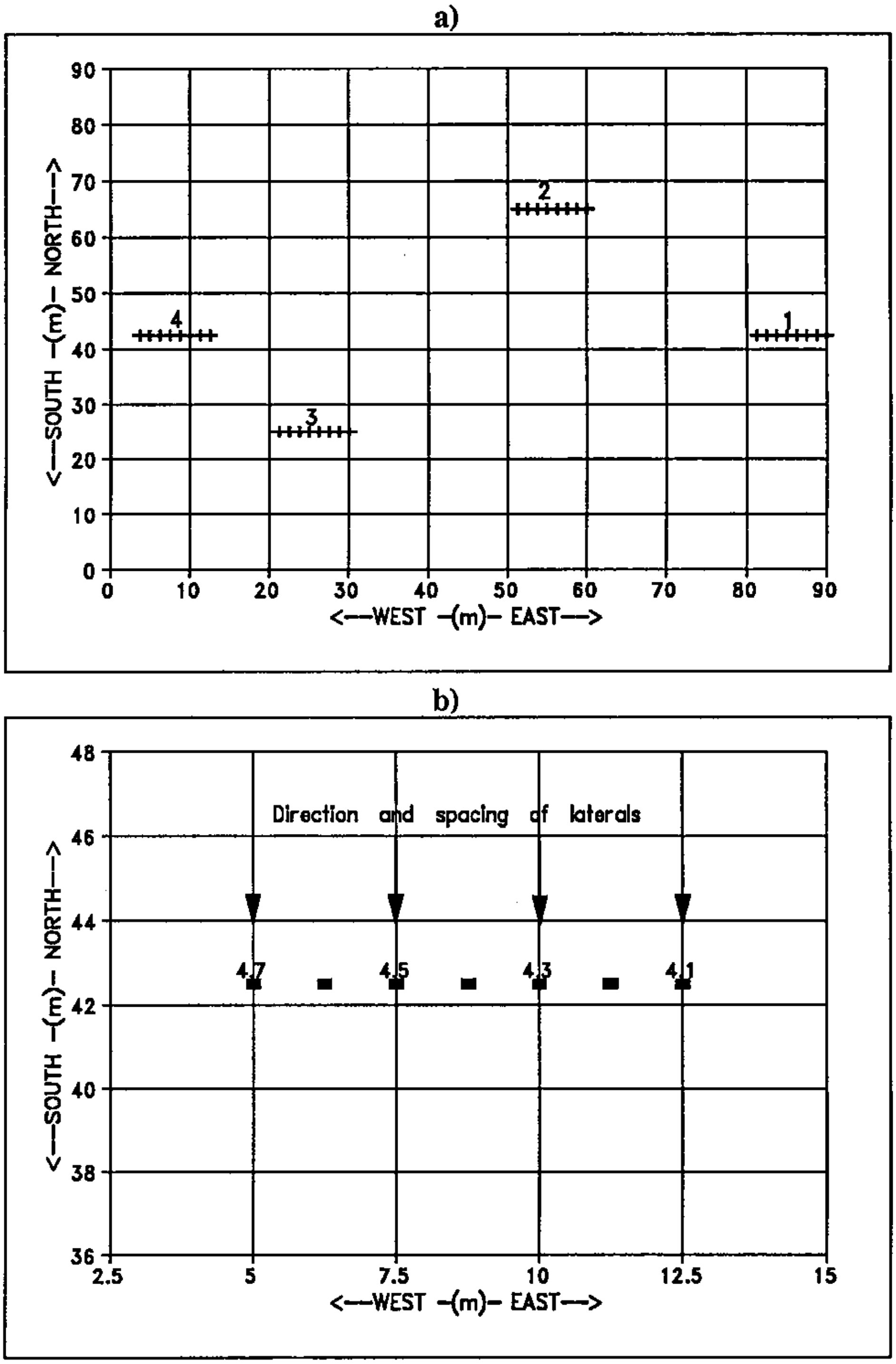
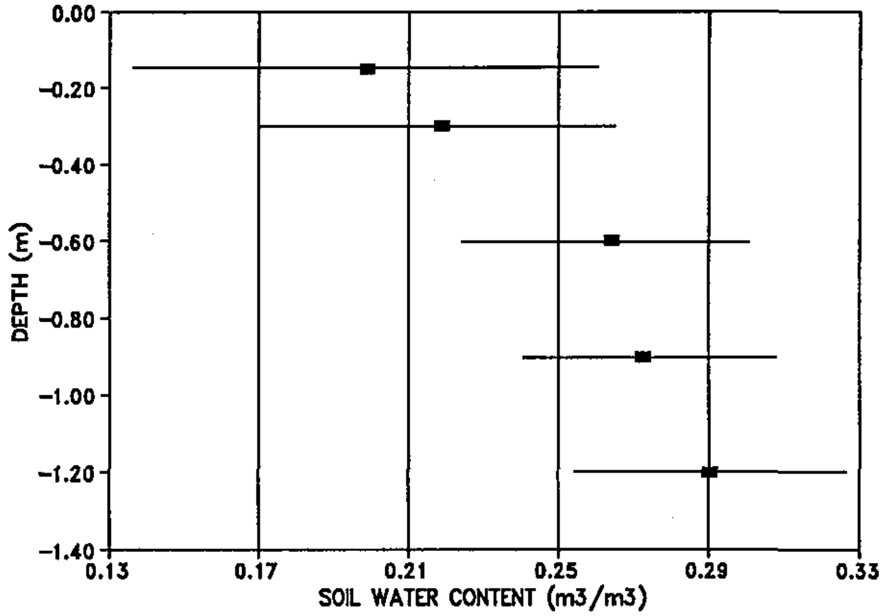


Figure 4.1 Location of: a) the 15 neutron access tubes distributed as four groups within the drip irrigated field, and b) spacing, location and identification within group 4.

4.3 RESULTS AND DISCUSSION

The mean and standard error of the water content of the 10 summer and 5 winter measurements are given in Figure 4.2. The standard error of the summer values for the depths shallower than 0,3 m are substantially larger than the winter values and must be attributed to the effect of differences in crop water uptake between the various sites. The increase in soil water content with depth is also much steeper during summer than during winter.

a)



b)

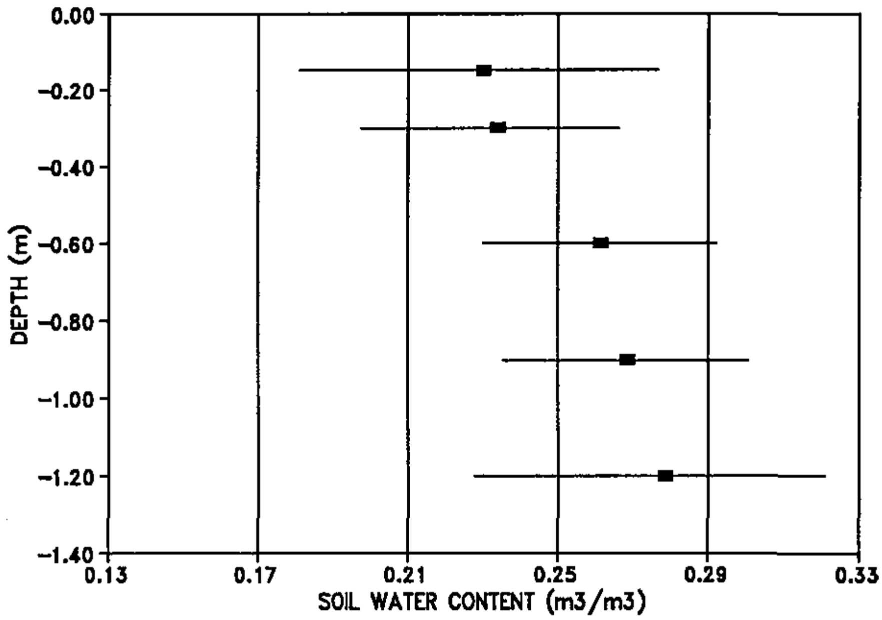


Figure 4.2. Mean and standard error of the volumetric soil water content at 14 monitoring sites in a drip irrigated vineyard near Robertson: a) Summer measurements (n=10), and b) Winter measurements (n=5).

The probability density function of the soil water content established during the initial survey of May 1987 when gravimetric samples were taken, is given in Figure 4.3. Although the total sample size of 14 was too small to test for normality, the shape of the cumulative probability curve (P) suggests a normal distribution. It should be borne in mind that for a normal distribution the numerical values of the 50 percentile, median and arithmetic mean are the same. Sampling positions 2.1 and 2.5 are both very close to the 50 percentile value, with positions 1.5 and 1.7 slightly further away from the median position. Positions 1.1 (P=81%) and 4.3 (P=19%) are approximately one standard deviation from the median (or mean), while positions 2.7 and 3.7 represent the driest and wettest sampling locations respectively. According to this result any one of positions 2.1 or 2.5, or even 1.5 and 1.7 can be used to represent the mean soil water content of the 14 sampling positions, and hence, this particular drip irrigated vineyard. The soil water information of these sites can therefore be used to regulate irrigation applications.

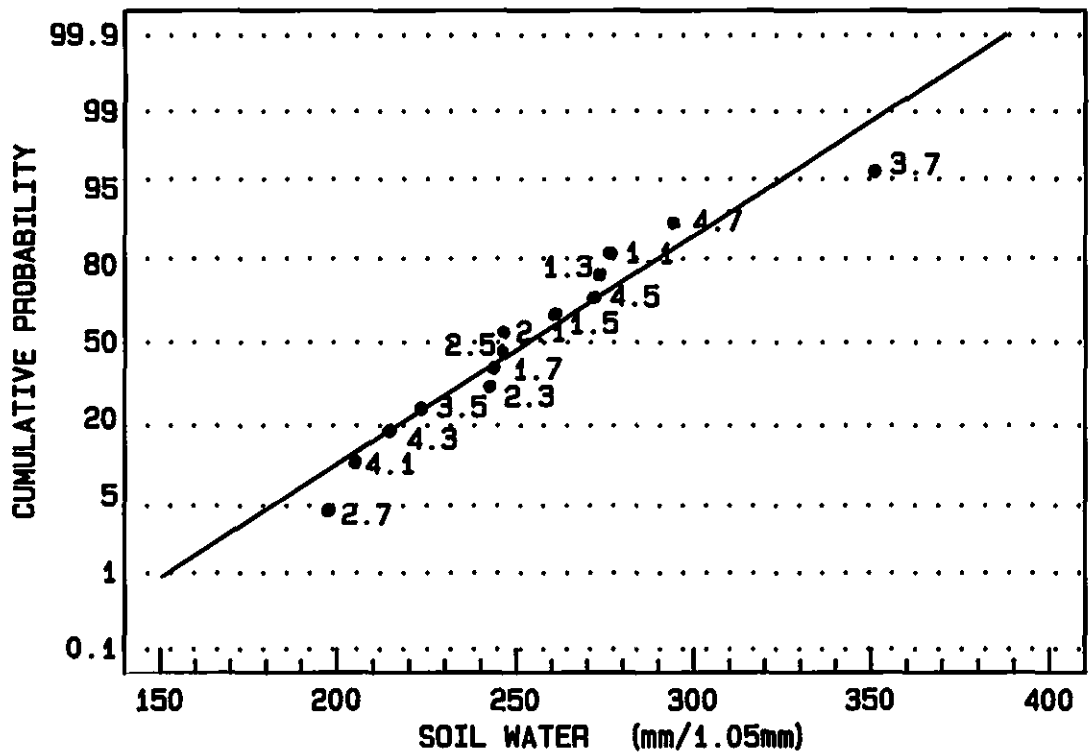


Figure 4.3 Cumulative probability density curve of the soil water content that was gravimetrically determined at 14 sites in a drip irrigated vineyard in May 1987. The numbers are the identification codes for the sampling sites

The intertemporal relative deviation from the mean soil water content, calculated using all 15 measurements (Figure 4.4) however, gives a slightly different rank order than Figure 4.3. According to Figure 4.4, position 4.5 should be a better approximation of the field mean (=0 in Figure 4.4) because on average it is only 0,4% (±6,6%) higher than the field mean at any one time. The water content at position 2.5 is 4,6% (±4,2%) lower than the field average, while position 2.1, in spite of its smaller domain of uncertainty, is 8,2% higher than the temporal field average. Of importance, however, is the fact that compared to the rank position obtained with the initial survey, 13 of the 14 sampling locations maintained their positions relative to the 50 percentile. The only exception is location 2.3 which moved from a position below the 50 percentile to one that is 5,5% (±5,1%) above the temporal mean field average (Fig. 4.3 and 4.4).

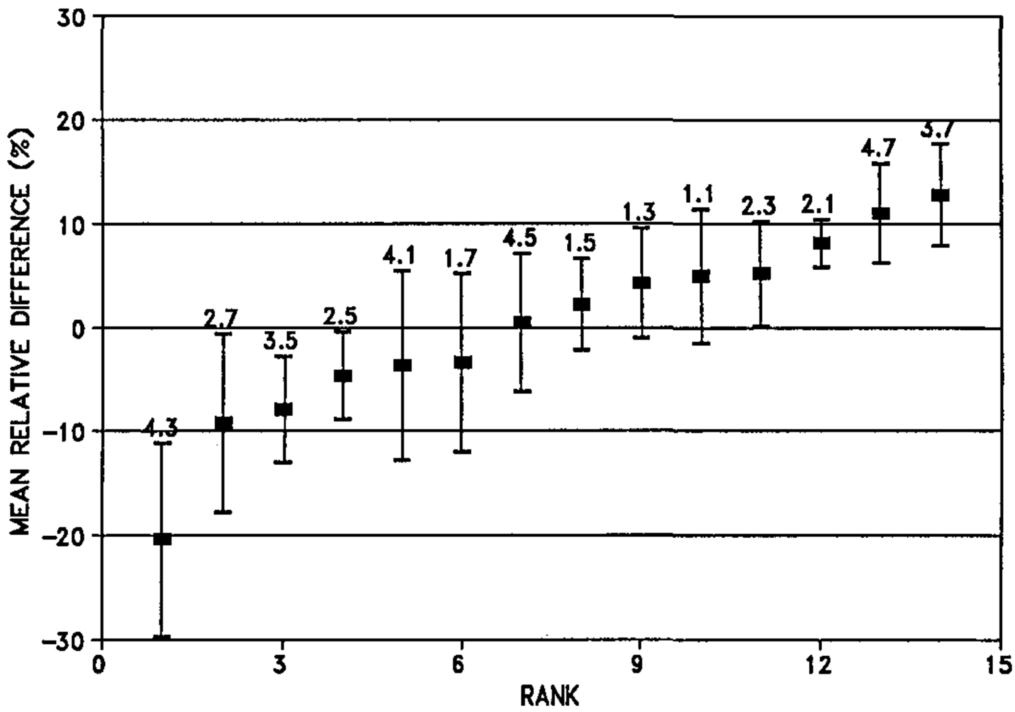


Figure 4.4 Ranked intertemporal relative deviation from the mean profile (0-1,05 m) soil water content based on 15 measurements made during summer and winter. The vertical bars indicate the associated time standard deviation, while the numbers refer to the 14 sampling sites.

It is not clear what the cause for this change in the rank order between gravimetric samples and the neutron probe collected soil water data is. A possible explanation is that the volume of soil sampled with the gravimetric technique is considerably smaller than the volume measured by the neutron probe. The volume of each of the 0,3 m depth increments of the gravimetric samples was 498 cm_3. By assuming a radius of 0,15 m as the zone of influence of the neutron probe, it can be shown that for a 0,3 m depth increment the volume of soil measured by the neutron thermalization method, is 14 137 cm^3. This is 28 times larger than the volume of the gravimetric samples. Hawley *et al.* (1982), found that the size of the sample influences the degree of measured variability of field soil water content. In his study the water content of the smaller samples were more variable than the larger ones. In another study of volume-accuracy relationships, Lauren *et al.* (1986), found that an increase in the physical size of a sample produced a general decrease in the mean and variance of the measured saturated hydraulic conductivity values. It therefore seems as if the size of the gravimetric sample might influence the variability and hence the probability density function and ultimately the selection of representative sites for soil water monitoring.

When the soil measurements are split into summer and winter values, most of the sampling locations maintain their rank positions on the relative scale of mean differences (Fig. 4.5 and 4.6). Locations 4.3 and 3.7 remain the driest and wettest of the 14 sampling sites, while 4.5 and 1.5 stay within 3% of the field average during summer and winter. The biggest difference caused by splitting the data into two sets of seasonal values is the smaller temporal standard deviation of each location during winter. In view of the measured high statistical uniformity coefficient of emitter flow (i.e. 93%), the significant reduction in the domain of uncertainty must for the most part be attributed to spatial differences in crop water uptake. It seems as if the intrinsic variability in the soil water retention properties of the soil is substantially smaller than the variability imposed by the crops and method of irrigation. Wagenet (1985), referred to this variability imposed by external factors as the extrinsic variability. It furthermore seems that location 2.5 which, based on the results of the initial sampling, would have been a logical choice to monitor the soil water content for irrigation scheduling purposes, moves further away from the field mean during winter. During summer it was 3,7% (±4%) lower (Fig. 4.5) and in winter 5,8% (±3,2%) lower than the field mean (Fig. 4.6.).

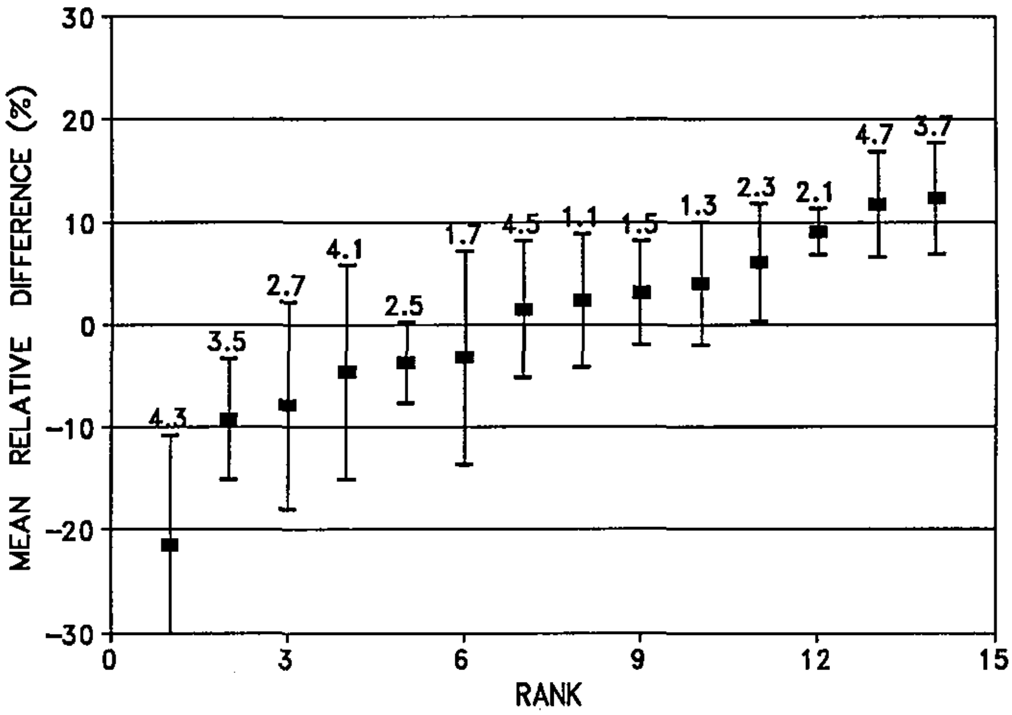


Figure 4.5 Ranked intertemporal relative deviation from the mean profile (0-1,05 m) soil water content based on 10 different measuring dates during summer. The vertical bars indicate the associated time standard deviation, while the numbers refer to the 14 sampling sites.

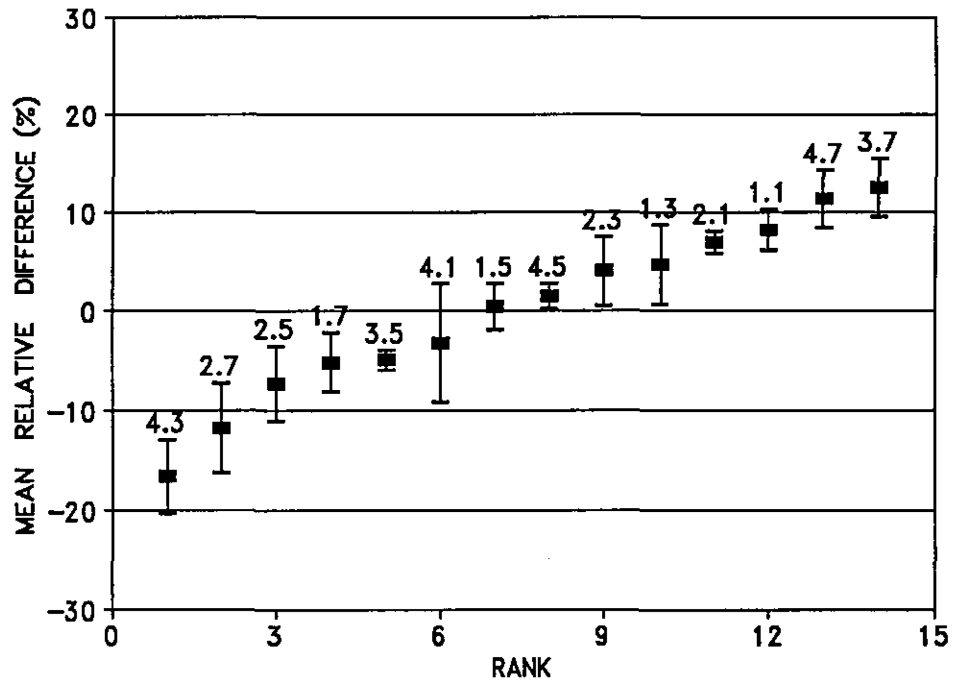


Figure 4.6 Ranked intertemporal relative deviation from the mean profile (0-1,05 m) soil water content based on 5 different measuring dates during winter. The vertical bars indicate the associated time standard deviation, while the numbers are the identification code for the 14 sampling sites.

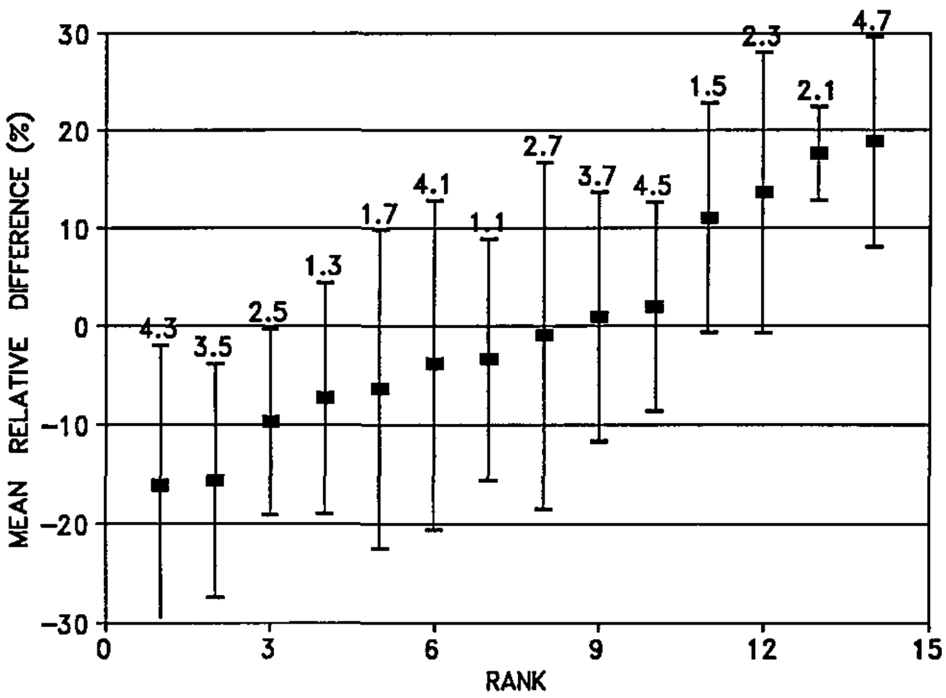


Figure 4.7 **Ranked intertemporal relative deviation from the mean topsoil (0-0,45 m) water content based on all 15 measurements made during summer and winter. The vertical bars indicate the associated time standard deviation, while the numbers are the identification code for the 14 sampling sites.**

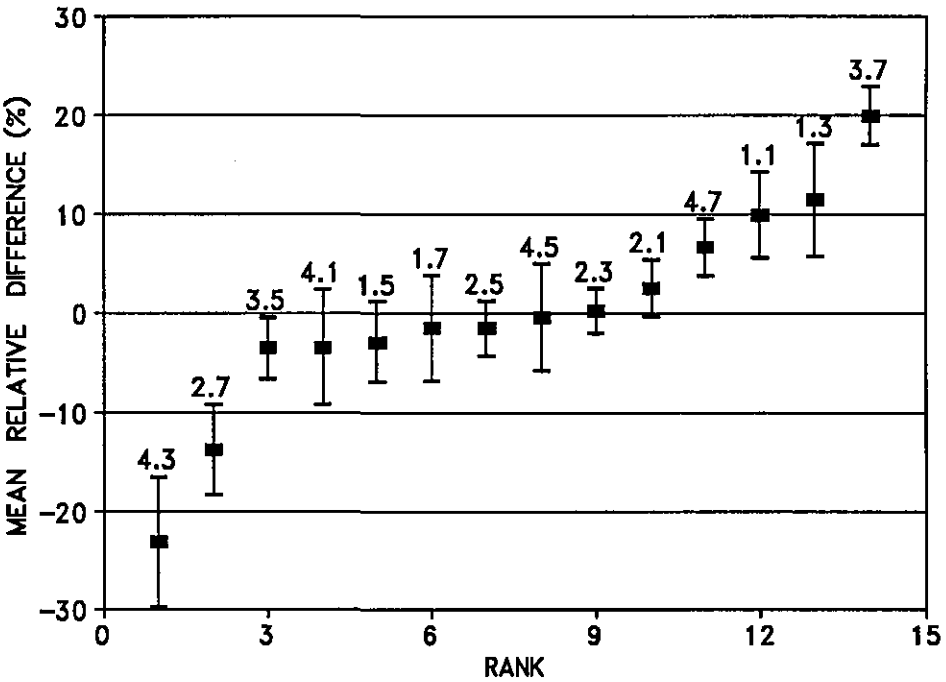


Figure 4.8 **Ranked intertemporal relative deviation from the mean subsoil (0,45-1,05 m) water content based on all 15 measurements made during summer and winter. The vertical bars indicate the associated time standard deviation, while the numbers are the identification code for the 14 sampling sites.**

The rank order of several of the sampling locations changes drastically when the water content of the topsoil only (i.e. 0-0,45 m), is considered (Fig. 4.7). Based on the total profile water content, locations 3.7 and 2.7 are 12,8% (±4,9%) above and 9,2% (±8,6%) below the field mean respectively. However, the topsoil data show that both sites are within 1% from the mean. Therefore, if soil water content of the topsoil (0-0,45 m) only was determined during the initial survey, the probability density function and ultimate selection of a representative soil water monitoring site would have been markedly different. The ranking of the sampling locations on the scale of mean relative differences (Fig. 4.7) also show that the temporal mean of each location is associated with a large measure of uncertainty. For example, location 2.7 is only 0,5% smaller than the field mean, but it is associated with a standard error which exceeds 11%. In contrast, the standard errors of the subsoil water contents are much less. The subsoil water measurements yielded a ranking order which is more similar to that of the profile water content (Fig. 4.4 and 4.8). This indicates the degree to which the subsoil dominates the total profile water conditions. On a temporal basis the soil water content of the 0,45-1,05 m layer in this vineyard is also less variable.

The rank of each measurement location based on the interannual deviation from the temporal relative mean of all 15 observations of the profile soil water content, i.e. 0-1,05 m, is listed in Table 4.1. Also indicated are the depth weighted mean clay (<0,002 mm) and silt plus clay (<0,02 mm) percentages, as well as the field capacity values determined as described before. In the study of Vachaud *et al.* (1985), the wettest location had a higher silt and clay content than the driest position. They consequently explained the time stability of particular locations by the relationship between soil texture and water content. In the present study, the location with the lowest clay content, namely site 4.3, was also the driest of the 14 locations (Table 4.1). However, the converse is not true, because the wettest location, i.e. site 3.7, was not the position with the highest clay content. The location with the highest clay content, site 1.1, had a rank number of 10. The relationship between the rank order and total silt plus clay was equally vague. The association between the apparent field capacity and the rank order is more clear. The wettest and driest sampling locations had the highest (344,5 mm/1,05 m) and lowest (259,0 mm/1,05 m) field capacity water contents, with the positions closest to the mean, i.e. locations 1.7, 4.5 and 1.5, having values close to the arithmetic mean of the wettest and driest positions. The Spearman's rank correlation test also shows that the field capacity values correlate better with the temporally based rank order than the textural variables. The r-coefficients are 0,86, 0,27 and 0,21 for the field capacity water content, clay, and silt plus clay contents respectively (Table 4.1).

Table 4.1 Rank of each sampling location in terms of the relative deviation δ'_{ij} from the relative temporal mean soil water content with the corresponding field capacity, depth weighted mean clay and silt plus clay contents

Location %	Rank	Field Cap.[a] mm/1,05 m	Clay % <0,002 mm	Silt+clay <0,02 mm
11	10	313,6	23,5	70,6
13	9	313,9	21,5	67,1
15	8	296,3	23,1	69,3
17	6	297,6	22,5	70,7
21	12	291,3	19,0	49,1
23	11	297,8	17,9	49,4
25	4	286,4	18,8	47,5
27	2	239,9	19,9	46,6
35	3	285,5	20,1	52,0
37	14	344,5	22,0	63,1
41	5	268,0	19,3	63,1
43	1	259,0	18,0	61,1
45	7	293,2	22,1	65,8
47	13	315,2	20,3	53,4
Spearman r		0,86**	0,27	0,21

[a] Field Cap = field capacity
** = Statistically significant at P=0,001

4.4 CONCLUSIONS

In a 0,5 ha drip irrigated soil with a highly variable soluble salt content, it was found that certain sampling locations conserve the property to represent the mean and extreme values of the field water content over time. The presence of the vines and irrigation increased the variability of the measured values without any big influence on the ranking position of the various monitoring sites as they initially appear on the probability density curve. The locations that were identified as being representative of the field mean water content during summer, also represented the mean during winter when irrigation and transpiration were absent.

If the soil water content is split into top- (0-0,45 m) and subsoil (0,45-1,05 m) components, *different ranking orders on the probability density curve are obtained.* Positions representing the field mean and extreme water contents of the topsoil differ significantly in space from the corresponding subsoil positions. This indicate that the sampling depth will have a profound effect on the actual selection of monitoring sites and that the rooting depth of the particular crop will have to be carefully considered if this technique of an initial field scale sampling and computed probability density function are used to identify the mean and extreme values.

Another factor that might influence the selection of the soil water monitoring sites, is the physical size of the soil sample. In this study it was found that a set of physically smaller sized gravimetric samples had a probability density function on which the rank order of certain locations differed from that of soil water contents measured with a neutron probe. It is speculated that these volume differences had an effect on the rank order of locations. This aspect will have to be investigated in greater detail.

It is concluded that, because of the temporal stability of the ranking position of the measuring sites, the probability density curve of one sampling only can be used to identify representative sites (e.g. the median), that can be used for soil water monitoring and irrigation scheduling. However, cognizance should be taken of the confounding effects that are likely to occur with depth and sample size.

4.5 REFERENCES

Bralts, V.F. and D.M. Edwards, 1987. Drip irrigation design and evaluation based on statistical uniformity concept. *Adv. Irrig.* 4:67-117

Campbell, G.S. and M.D. Campbell, 1982. Irrigation scheduling using soil moisture measurements: Theory and Practice. *Adv. Irrig.* 1:25-42

Hawley, M.E., A.H. McCuen, and T.J. Jackson. 1982. Volume - accuracy relationship in soil moisture sampling. J. Irrig. and Drainage Div., Proc. ASCE. 108:1-11

Lauren, J.G., R.J. Wagenet, J. Bouma, and J.H.M. Wosten. 1986. Variability of saturated hydraulic conductivity in a glossaquic hapludalf with macropores. *Soil Sci.* 145:20-28

MacVicar, C.N., J.M. De Villiers, R.F. Loxton, E. Verster, J.J.N. Lambrechts, F.R. Merryweather, J. le Roux, T.H. van Rooyen and H.J. von M. Harmse. 1977. Soil classification. A binomial system for South Africa. Dep. Agric. Tech. Serv. Pretoria, Sci. Bull. 390, 150 pp.

Moolman, J.H. 1989. Effect of spatial variability on the estimation of the soluble salt content in a drip- irrigated saline loam soil. *Agric Water Management*, 15:361-376.

Nielsen, D.R., J.W. Biggar, and K.T. Erh. 1973. Spatial variability of field-measured soil-water properties. *Hilgardia* 42:215-259.

Vachaud, G., A. Passeret de Silans, P. Balabanis, and M. Vauclin. 1985. Temporal stability of spatially measured soil water probability density function. *Soil Sci. Soc. Am. J.* 49:822-828

Wagenet, R.J. 1985. Measurement and interpretation of spatially variable leaching processes. In: D.R. Nielsen and J. Bouma (Ed.) Soil spatial variability. Proc. Workshop ISSS and SSSA, Las Vegas, NV. 30 Nov.-1 Dec. 1984. PUDOC, Wageningen, Netherlands

CHAPTER 5
THE DESIGN AND USE OF A TIPPING BUCKET FLOW GAUGE FOR THE MEASUREMENT OF SURFACE- AND SUBSURFACE DRAINAGE

DIE ONTWERP EN GEBRUIK VAN 'n KANTELBAKVLOEIMETER VIR DIE METING VAN DREINERINGS- EN OPPERVLAKAFLOOPWATER.*

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ABSTRACT

The design and use of a tipping bucket flow gauge for the measurement of subsurface- and surface drainage water.

A tipping bucket flow gauge was designed for direct measurement of flow rates in subsurface drains of agricultural lands. The free-board problem in a manhole was overcome by using two reservoirs and pump system. The flow gauge was connected to a standard data logger with low power consumption. The flow gauge can also be easily adapted for measuring surface runoff. Results obtained with the flow gauge in irrigated vineyards in the Breede River Valley show a positive correlation between irrigation applications and flow rates in subsurface drains.

5.1 INLEIDING

Dit is dikwels nodig om die hoeveelheid en vloeitempo van dreinerings- en oppervlakafloopwater van gronde te meet. Weens die groot volumes water wat gemeet moet word, moeilike toeganklikheid (van ondergrondse dreineringspype) en lae hidrouliese drukke (wat die gebruik van gewone vloeimeters uitskakel), is die fisiese uitvoering van sulke bepalings egter moeilik en tydrowend. Die doel van hierdie artikel is om te rapporteer oor die tegniese detail van 'n kantelbakvloeimeter wat vir die ondergrondse meting van dreineringswater ontwerp is. Daar word verder aangetoon hoe dieselfde instrument ook vir die meting van oppervlakafloopwater gebruik kan word. Enkele resultate van metings wat met hierdie vloeimeter in besproeide wingerde in die Breëriviervallei gemaak is, word ook aangebied.

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*Paper originally delivered at the 17th Conference of the Soil Science Society of South Africa, January 1992, Stellenbosch 7600, South Africa

5.2 MATERIALE EN METODE

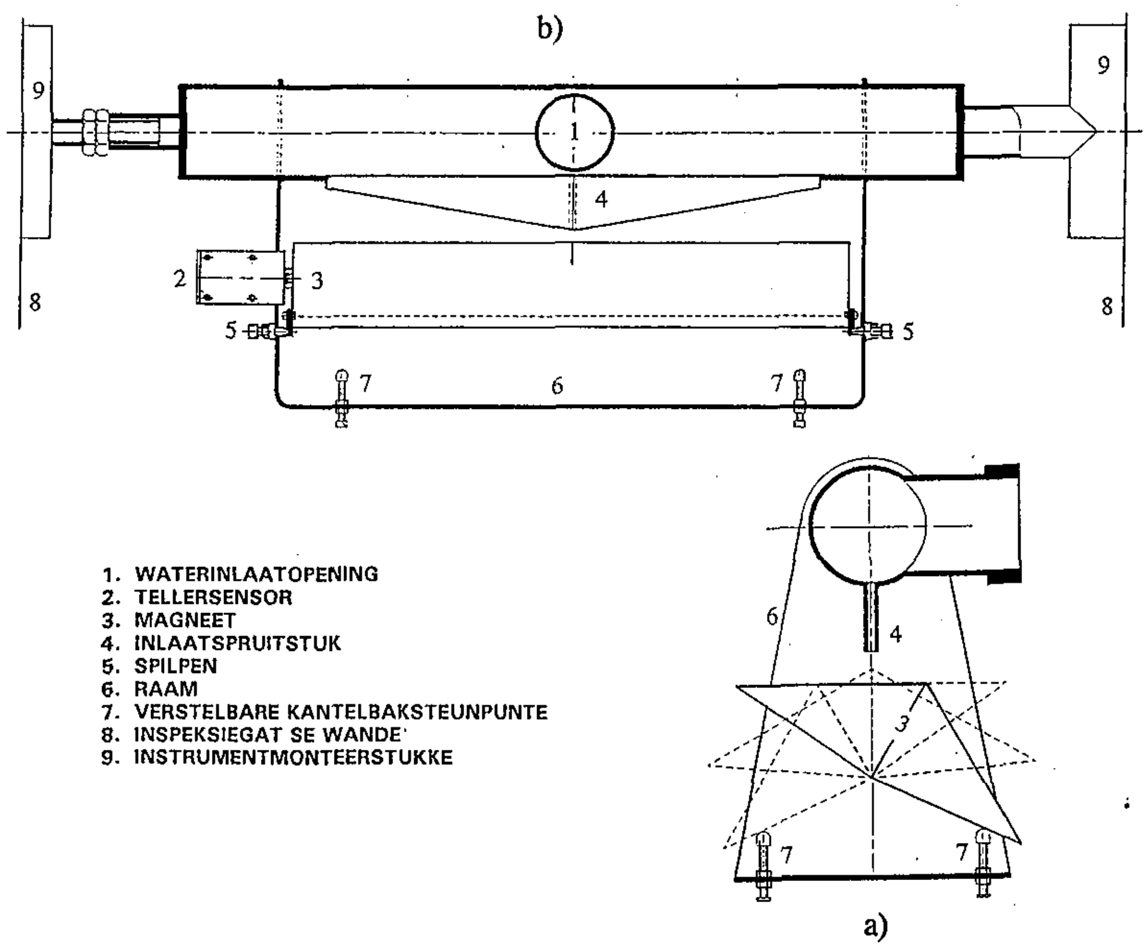
5.2.1 Ontwerp van die meter

'n Kantelbakvloeimeter van vlekvrye staal is in samewerking met die Buro vir Meganiese Ingenieurswese van die Universiteit Stellenbosch ontwerp. Die vloeimeter bestaan uit 'n inlaatspruitstuk, kantelbak, instrumentraam en 'n tellersensor, met laasgenoemde wat aan meeste dataregistreerders kan verbind. 'n Skematiese uiteensetting van twee aansigte van die apparaat word in Figuur 5.1 aangegee.

Die vorm van die inlaatspruitstuk is sodanig dat dit die water egalig oor die hele lengte van die kantelbak kan versprei. Sodoende word turbulensie tot 'n minimum beperk wat voorkom dat die krag van die inlopende water self 'n kanteling sal veroorsaak. Die spesiaal ontwerpte vorm (Figuur 5.1) verseker dat die water nie as 'n enkele straal die kantelbak tref nie, maar as 'n gordyn van water. Die vorm verseker verder dat 'n kanteling nie sal plaasvind alvorens die massa van die water in die bak groot genoeg is nie.

Die kantelbak is so ontwerp dat wanneer die bak gevul word, verskuif die swaartepunt van die massa terug oor die spilpenlyn tot die teenkantelmassa oorwin word. Hierdie aksie word deur die vorm van die bak bepaal. Die verhouding tussen sylengtes op die dwarssnit van die kantelbak is 4:6:7. 'n Verdere eienskap van die kantelbak is dat dit kalibreerbaar is sodat beide kompartemente daarvan, d.w.s. die bakke, presies eweveel water stort. As gevolg van die naald-tipe montering van die bak is die kantelaksie gevoelig en baie vinnig. Die raam huisves vier kantelbak steunpunte, wat gebruik word om die kantelbak mee te kalibreer. Dit dien ook om die momentum van die valslag tydens die kanteling effens te absorbeer.

'n Magnetiese tellersensor is plaaslik ontwerp om eerstens sensitief genoeg te wees en tweedens so 'n klein stroom as moontlik te trek. Aan die kantelbak is 'n klein magneet geheg en die tellersensor tel die aantal kere wat die magneet verby beweeg. Die tellersensor bestaan uit 'n wipskakelaar ("*Reed switch*") wat horisontaal gemonteer is, en 'n weerstand. Die horisontale montering verseker dat net een telling geregistreer word as die magneetveld verby beweeg terwyl die weerstand die kragverbruik beperk. Die tellersensor word aan 'n digitale dataregistreerder verbind. Die registreerder akkumuleer die pulse tot aan die einde van 'n registreerperiode en stoor dan die totale telling in die geheue. Die keuse van die lengte van registreerperiodes berus by die sensitiwiteit en tydsresolusie wat die gebruiker verlang.



Figuur 5.1 Skematiese voorstelling van die kantelbakvloeimeter van vlekvrye staal: (a) dwarssnit en (b) vooraansig

5.2.2 Kalibrasie

Tydens opstelling van die apparaat, word die kantelbak gebruik om die meter waterpas op te stel op die volgende wyse. Naastenby 0,5 dm_3 water word in die kantelbak gegooi en die meter word dan verskuif totdat hierdie water egalig oor die hele lengte van die bak versprei lê. Om die meter in die rigting loodreg op die kantelbak waterpas te kry, word die instrument in die rigting van kantelling (oor sy breedte) geroteer met die kantelbak wat balanseer tussen die twee kantelposisies, sodat die skeidingsplaat tussen die twee bakke, met balansering, presies onder die inlaatspruitstuk staan. Die instrument moet dan op hierdie posisie geanker word. Om te sorg dat die instrument presies 1 dm_3 per kanteling stort, word 1 dm_3 water in 'n bak gegooi en die verstelbare steunpunte opgedraai totdat die bak spontaan kantel.

5.2.3 Wyses van opstelling

Normaalweg kan die meter sonder moeite in 'n inspeksiegat opgestel word. Die inlaatpyp van die meter word direk aan die dreineringspyp verbind en nadat dit waterpas gestel is, word die twee arms van die meter gebruik om dit stewig teen die kante van die inspeksiegat te laat vasskop. Soms bestaan die beperking dat die valhoogte tussen die inlaat en uitlaat van die inspeksiegat te klein, of op dieselfde vloeihoogte is. In een spesifieke opstelling in 'n besproeide wingerd is hierdie probleem m.b.v. 'n dubbele reservoirsisteem oorkom. Hierdie resevoirsisteem bestaan uit twee opgaartenks, (die een ondergronds in die inspeksiegat en die ander bogronds), pype, 'n kraan en 'n elektriese dompelpomp.

Met opstelling word 'n vlekvryestaal drom onder in die inspeksiegat gemonteer terwyl die kantelbakmeter direk bokant hierdie drom in die inspeksiegat geplaas word. Die tweede drom word buite die inspeksiegat opgestel. Omdat daar gevaar bestaan dat die onderste drom sal dryf as die vlak van die water in die inspeksiegat te hoog styg, is 'n spesiale deksel met drie stabiliseerderarms ontwerp wat die drom stewig op die bodem vasdruk. Die drom is so ontwerp dat dit nie die vloei van water in die inspeksiegat sal blokeer as die pomp buite werking is nie. Dit is bewerkstellig deur 'n oorloop in die drom aan te bring en dan die drom so te installeer dat die oorloop net hoër as die mond van die inloopopening asook die vlak van die staande water om die drom is. Die dompelpomp word binne die drom opgestel en met 'n pyp verbind aan die tweede drom wat buite op die inspeksiegat se opening staan. Hierdie tweede drom kan gebruik word om die deksel van die inspeksie-opening te vervang. Wanneer die water in die onderste drom 'n sekere kritiese hoogte beriek, skakel die domelpomp outomaties aan en word die water na die tweede, bogrondse drom verplaas. Aangesien hierdie drom op 'n hoër vlak as die kantelbak staan en dit met pype daaraan verbind is, sal dit weens gravitasiekrag spontaan deur die vloeimeter terug in die inspeksiegat loop.

Die pomp tans in gebruik is 'n Kyokuto L/LA50-40S wat oor 'n 400 watt 240 volt motor beskik en in staat is om water twee meter hoog teen 'n tempo van 350 L min_{-1} te pomp. Die pomp beskik oor twee hoogte regulerende skakelaars wat dit moontlik maak om die volume in die drom na willekeur aan te pas.

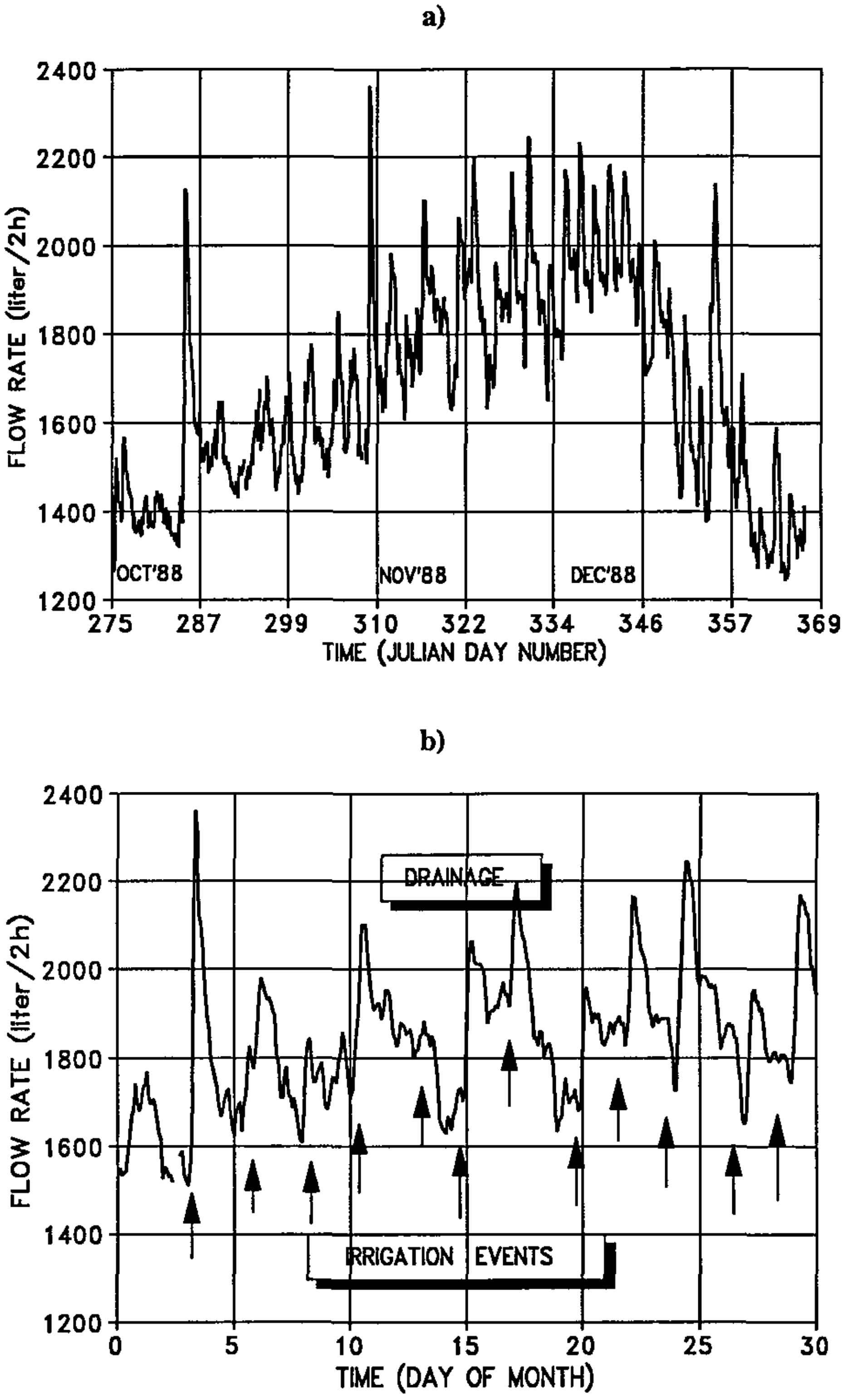
Deur die kantelbakvloeimeter op 'n yster- of beton basis te monteer, kan die meter ook op die grondoppervlak opgestel word om afloop uit 'n drein wat bogronds eindig, of oppervlakafloop te meet. Indien daar 'n behoefte bestaan om 'n groter stroom te meet as wat die kantelbakmeter kan hanteer, kan twee of meer van hierdie meters in serie verbind word. Met die byvoeging van elke meter word die meetbare tempo met 90 liter per minuut vergroot.

5.2.4 Dataregistrering en herwinning

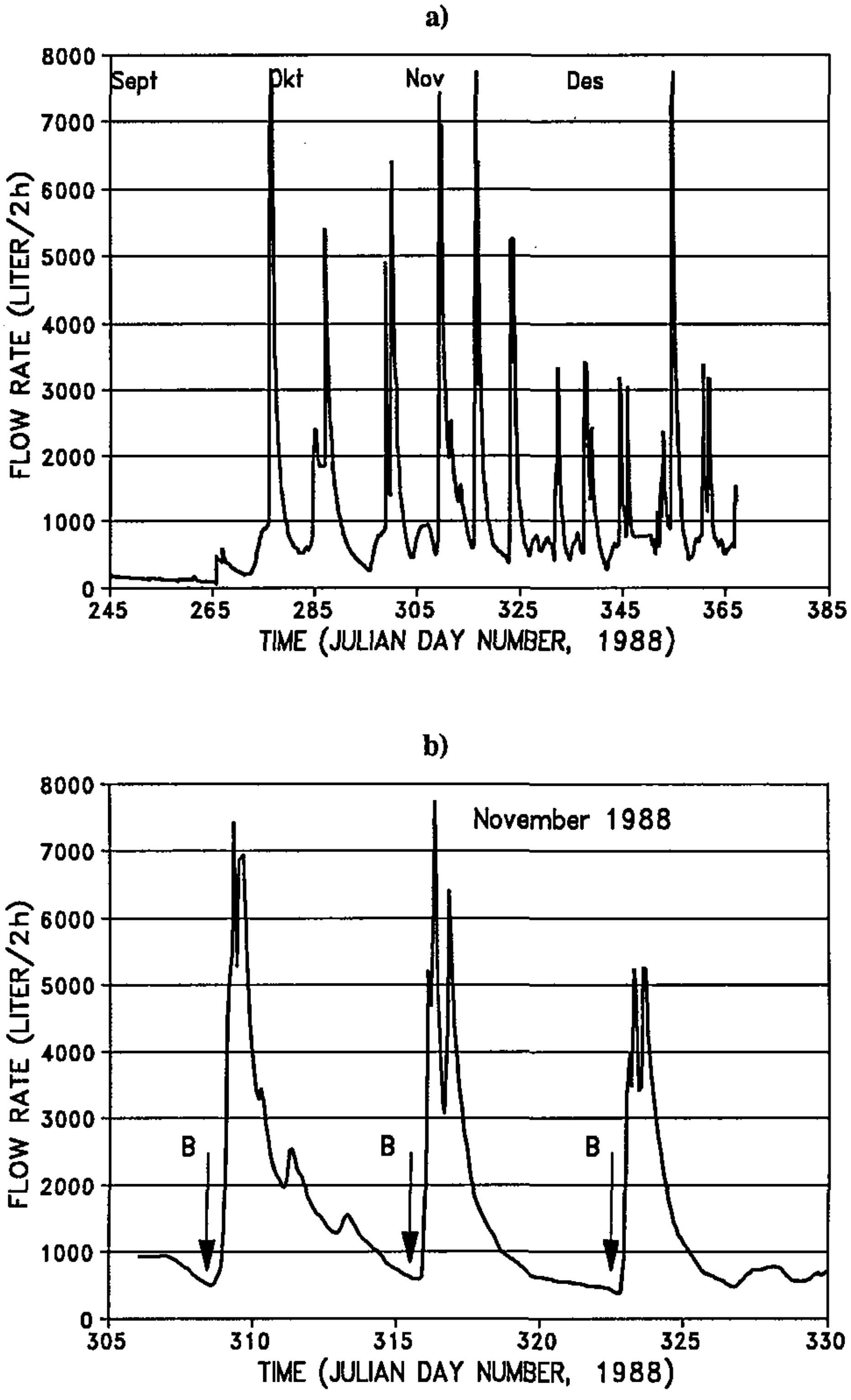
'n Plaaslik ontwikkelde dataregistreerder en terugleesapparaat (*"MCS 120-02 Environmental logger" en "MCS-420 Data Point Reader"*, M. C. Systems, Kaapstad) word tans gebruik. Die terugleesapaaraat kan aan enige IBM-versoenbare rekenaar gekoppel word. Hierdie registreerder maak gebruik van verwyderbare geheue modules (EPROM) waarop die data gestoor word. Gevolglik is 'n leë EPROM al apparaat wat saamgeneem hoef te word as die meetstasie besoek word. Die koste van geheue modules is laag en dit is baie gerieflik om te gebruik. Nadat die data m.b.v. die terugleesapparaat herwin is, kan die EPROM m.b.v. UV strale weer skoon gevee word vir latere hergebruik. Verdere voordele van die sisteem is dat dit vir lang tye geen diens verg nie, asook dat die data maklik herwin kan word met 'n klein of geen risiko t.o.v. verlies daarvan.

5.3 RESULTATE

Twee kantelbakvloeimeters is in verskillende wingerde op kommersiële plase in die BreërivierVallei opgestel om die verwantskap tussen besproeiingstoedienings en drieneringsvloeitempos te karakteriseer. In die een geval is 'n vloeimeter in die inspeksiegat van 'n ondergrondse dreineringstelsel wat 'n drupbesproeide wingerd op 'n fynsandleem onderlê, geinstalleer. In die ander geval is die vloeimeter op die oppervlak opgestel en aan 'n afsnydrein van 'n mikrobesproeide wingerd wat teen 'n klipperige skaliehang lê (Knight, 1991), verbind. Die resultate vir September tot Desember 1988 word in Figure 5.2 en 5.3 onderskeidelik vir die drup- en mikrobesproeide wingerd aangetoon.



Figuur 5.2 Die dreineringstempo as 'n funksie van tyd in 'n drupbesproeide wingerd op 'n fynsandleem grond: a) September - Desember 1988; b) November 1988. Die aanvang van elke besproeiing gedurende November word met B aangedui



Figuur 5.3 Die dreineringstempo as 'n funksie van tyd in 'n mikrobesproeide wingerd op 'n skalieryke grond: a) September - Desember 1988; b) November 1988. Die aanvang van elke besproeiing gedurende November word met B aangedui.

Die aanvang van elke besproeiing gedurende November 1988 word in Figure 5.2b en 5.3b aangedui. In beide gevalle is 'n verbasende vinnige deurlooptempo geregistreer wat toegeskryf word aan voorkeur-vloeiweë in die grond. Dit was veral opmerklik in die geval van die mikrobesproeide wingerd dat die vloeitempo binne een uur na die aanvang van 'n besproeiing, vinnig toegeneem het. Direk na afloop van die besproeiing het die vloeitempo weer skerp afgeneem. Hierdie twee waarnemings bevestig die feit dat die kantelbakvloeimeter 'n nuttige instrument is wat op 'n baie fyn tydsresolusie, vloeimetings en tempos kan bepaal.

5.4 BESPREKING EN GEVOLGTREKKINGS

Ten spyte van die feit dat die kantelbakbeginsel al relatief oud is (Edwards *et al*, 1974; Schrale, 1982), bly dit steeds een van die mees akkurate metodes waarmee vloeivolumes en vloeitempos gemeet kan word. 'n Belangrike eienskap van hierdie plaaslik ontwerpte meter is die groot variasie in vloeitempos (0 - 90 dm_3 min_{-1}) wat dit akkuraat (3%) kan meet. Die vloeimeter kan maklik gekalibreer word en besit die vermoë om, tesame met 'n versoenbare dataregistreerder, oor lang periodes onafhanklik te werk. Afhangende van die tipe dataregistreerder kan daar beide totale vloei (d.w.s. volume) of vloeitempo gemeet word. Weens die fisiese dimensies van hierdie apparaat kan dit met min moeite en relatief klein kostes in 'n inspeksiegat of op die grondoppervlak opgestel word.

Hierdie betrokke kantelbalvloeimeter is so ontwerp dat dit 'n nuttige instrument is wat gebruik kan word om die effek van landbou, en spesifiek besproeiing, op die waterbronne van 'n omgewing mee te kan kwantifiseer. Die vloeimeter is van groot waarde in die bepaling van water- en soutbalanse in besproeiingslandbou. Resultate wat met die vloeimeter op twee besproeide wingerde in die Breëriviervallei ingewin is, toon aan dat daar 'n aansienlike hoeveelheid besproeiingswater weens voorkeur- en kortpadvloei verlore gaan (Moolman & De Clercq, 1992). 'n Beter kennis van die water- en soutbalans kan tot beter besproeiingsbestuur lei. Die gevolg is dat dreineringsafloop ook beter bestuur en beheer kan word om sodoende 'n kleiner impak op die riviersisteme te hê wat dikwels as lewensslagaar vir 'n groot gemeenskap dien. Inligting wat met hierdie tipe kantelbakvloeimeter versamel is, stel die wetenskaplike in staat om alternatiewe bestuuropsies te toets, wat 'n groter mate van harmonie tussen grondbenutting en die omgewing kan bewerkstellig.

5.5 VERWYSINGS

EDWARDS, I.J., JACKSON, W.D. & FLEMING, P.M., 1974. Tipping bucket gauges for measuring run-off from experimental plots. *Agric. Meteorol.* 13: 189-201.

KNIGHT, F.H., 1991. Die beweging en bestuur van water in klipryke besproeiingsgronde. M.Sc. Agric-tesis, Universiteit Stellenbosch.

MOOLMAN, J.H. & DE CLERCQ, W.P., 1992. Water balance studies in a drip irrigated vineyard in the Breede River Valley: a comparison of different methods. 17e Kongres van die Grondkundevereniging van Suid-Afrika, Stellenbosch, Januarie 1992 (Hierdie uitgawe).

SCHRALE, G. 1982. An improved tipping bucket gauge for monitoring tile drain flows. Division of land use and protection, Soil and Water Management Report 11/81 (Australië)

WATER BALANCE STUDIES IN A DRIP IRRIGATED VINEYARD IN THE BREEDE RIVER VALLEY: A COMPARISON OF DIFFERENT METHODS.

WATER BALANCE STUDIES IN A DRIP IRRIGATED VINEYARD IN THE BREEDE RIVER VALLEY: A COMPARISON OF DIFFERENT METHODS.*

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ABSTRACT

The evapotranspiration, irrigation, soil water content and drainage flow rates of three irrigation seasons were used to estimate the water balance of a drip irrigated vineyard. The five different methods employed to calculate the leaching fraction, gave widely varying results. From the field capacity of the soil, class A-pan estimated evapotranspiration data and measured irrigation quantities, it was inferred that with the exception of 1987/88, the amount of water that will percolate through the root zone of the drip irrigated vines, will be insignificant. However, quantitative measurement of the soil water content and the applied irrigation amounts during two individual events, suggest significant losses of water out of the root zone, probably due to macropore- and preferential flow. The drainage hydrograph and chloride distribution in the soil volume in the immediate vicinity of the emitters, provide further evidence of significant losses due to macropore- and preferential flow. It is concluded that a water balance based on irrigation and evapotranspiration amounts alone, might lead to spurious conclusions regarding the harmful, e.g. salinization, effects of irrigated agriculture on the water resources of an environment.

6.1 INTRODUCTION

Agriculture and in particular, irrigation, can have a marked effect on the ecology of on environment. Irrigation return flow has been speculated to be the cause of the increase in the salt content of local rivers such as the Breede River (Moolman et al, 1983) and the Great Fish- and Sundays Rivers (Hall & Du Plessis, 1981). Similar results have been reported by Oster & Rhoades (1975) for some rivers in the western states of the U.S.A. Accurate information about the water and salt balance of irrigated lands are required to obtain reliable estimates of the, often deleterious, effect of irrigated agriculture on water resources. Such information, furthermore, should be the basis on which alternative irrigation management strategies are to be formulated.

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Hillel (1980b, p197) defines the field-water balance as *"an account of all quantities of water added to, subtracted from, and stored within a given volume of soil during a given period of time"*. Various methods have been proposed to quantify the water balance of irrigated lands. In its simplest form, the water balance states that the difference between the amount of water added and the amount of water withdrawn during a period is equal to the change in water content during the same period. The amount of water withdrawn can be inferred from indirect calculation or direct measurement of the evapotranspiration amounts. Alternatively, fluxes of water through the soil can be obtained by detail monitoring of both the soil water content and matric potential. It can also be estimated in lysimeters and other measuring devices. These different techniques are all estimates of the water balance and might yield markedly different results. Moolman (1991) has found, that uncertainties concerning the irrigation and evapotranspiration amounts have a far greater effect when predicting the water and salt fluxes of irrigated lands than any other soil property such as hydraulic conductivity, soil water retention and cation exchange capacity. The purpose of this study is to report on the results of a water balance study conducted using the same set of data, but with different methods of calculating the change in water content during a certain period of time.

6.2 METHODS AND MATERIALS

6.2.1 Experimental conditions

Between September 1987 and March 1990 various components of the soil-plant-air-continuum were studied on commercial farm located in the Breede River Valley. In this particular case, vines on a saline sandy loam soil (Moolman, 1989) were irrigated with a drip irrigation system with an emitter and row spacing of 1 m and 2,5 m respectively. A water table which fluctuates between approximately 1,5 and 2,0 m is present and as a consequence this vineyard is underlain by a tile drainage system located at 2 m depth (Fig. 6.1). Various aspects of the soil, irrigation water and atmospheric conditions were monitored but only those pertaining to the present study will be mentioned here. The flow rate in one drain pipe and the irrigation quantities applied to the area (0,475 ha) directly overlying the drain, were recorded every two hours with a datalogger and custom designed tipping bucket flow gauge (De Clercq & Moolman, 1992, this issue) and tipping bucket rain gauge respectively. The flow gauge is situated in an inspection man hole. Unfortunately, during the first season, i.e. 1987/88, the system that was used to monitor the flow in the subsurface drain failed frequently which led to a considerable loss of data. Consequently the flow record of this particular season is incomplete and discontinuous and was therefore not used in this study. The drain in which the flow rates were monitored are bordered on all sides by other drains and the assumption was therefore made that the drain under consideration intercepts the deep percolate of the irrigated area (0,475 ha) overlying this particular pipe only. The tipping bucket rain gauge was placed below the dripper line directly underneath one emitter (Fig. 6.1). Because of the high coefficient of uniformity (0,93) of the irrigation system in this vineyard, (Moolman & De Clercq, 1991), the volume of water recorded at this one emitter could be used to calculate the total amount of water applied on the 0,475 ha area by multiplying with the number (1850) of emitters. A class A-pan, read every morning at 08h00, and the appropriate crop factors for vines i.e. Sept 0,20; Oct 0,27; Nov 0,37; Dec 0,42; Jan 0,42; Feb 0,46; March 0,44; were used to estimate daily evapotranspiration (ET) depths. The total wetted area in this vineyard is estimated to be 1850 m^2 and was obtained from inspection of the salt distribution around the emitters (Moolman, 1989).

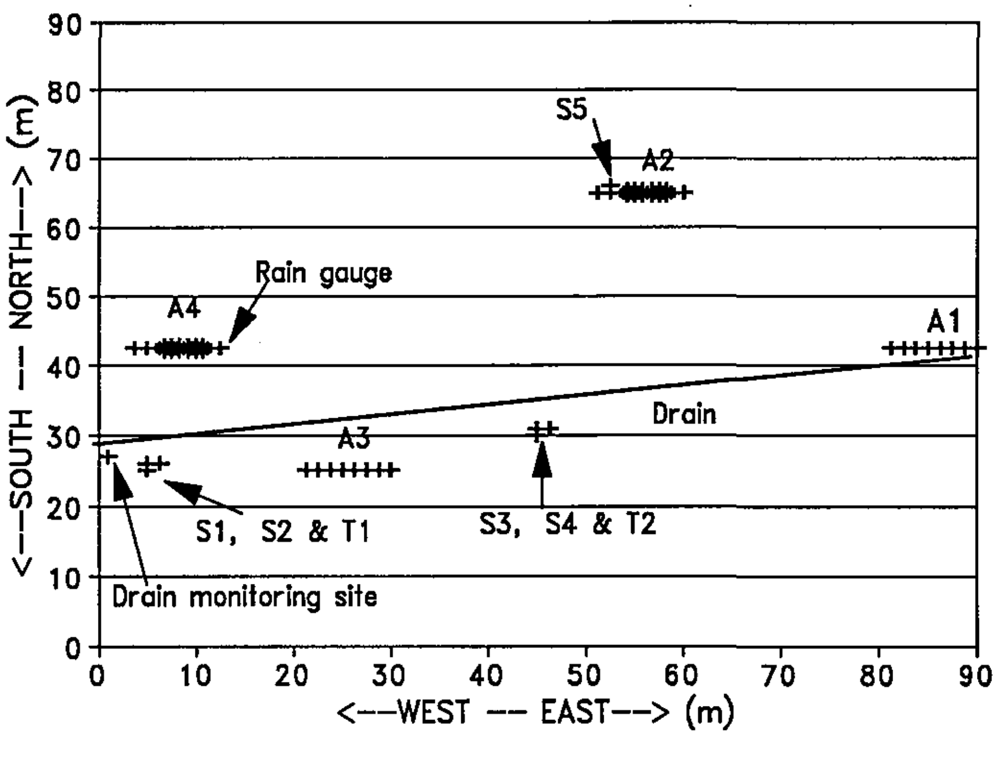


Figure 6.1 Map of the drip irrigated vineyard indicating the location of the drain pipe and various monitoring positions. (A=neutron access tubes and soil sampling sites, T=tensiometer site, S=porous cup sampler)

In this study all calculations were made in volumetric units. Consequently, the ET depths (mm) were converted to a volume by multiplying with the total cultivated area, i.e. 4750 m^2. The soil water content was determined with the neutron moderation technique (Hillel, 1980a, p128) at 30 different locations in the vineyard (Fig. 6.1). At each of these 30 sites, the field capacity, FC, (*viz.* drained upper limit) was determined *in situ* in May 1987. The mean FC per 0,9 m depth was 254 mm, which is equivalent to 469,9 m^3 per 1665 m^3 of wetted soil. Subsequent to the determination of FC, one emitter at each of four of these soil water monitoring sites were selected and equipped with an additional 14 neutron access tubes. These tubes were installed at various distances and directions from the emitters. The layout of this battery of neutron access tubes at two of the emitters where measurements were made, are given in Figure 6.2. The surface area allocated to each monitoring site are listed in Table 6.1. The soluble salt content of the soil to a depth of 1,2 m at different distances from the emitters were obtained by taking soil samples at sites A1 to A4 (Figure 6.1) in May 1987, August 1988 and July 1989.

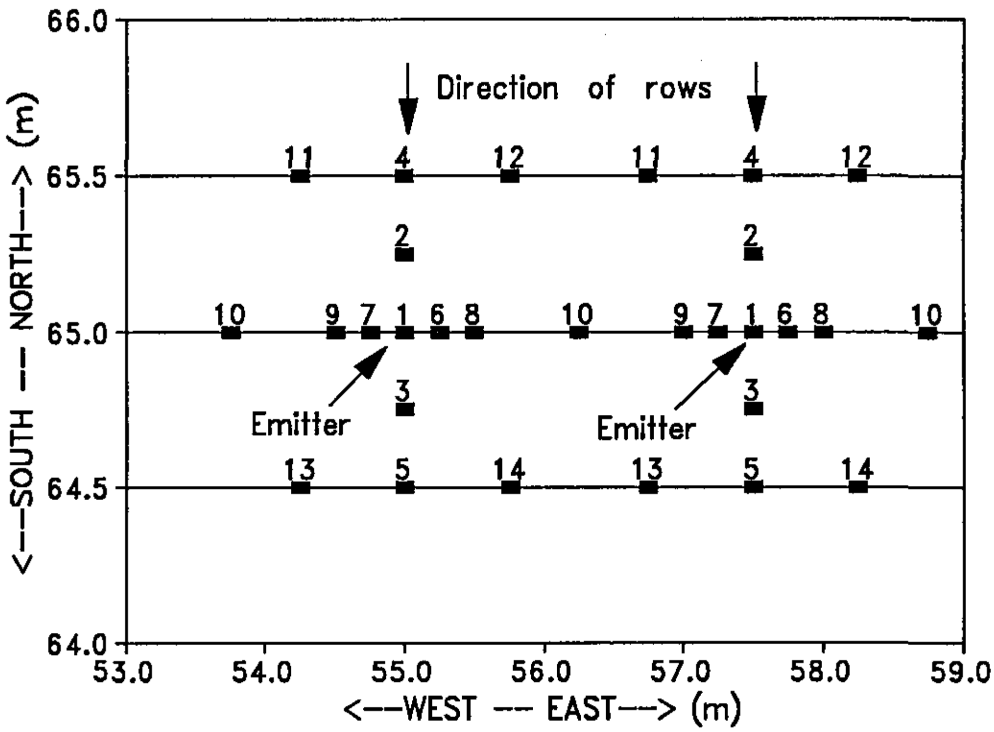


Figure 6.2 Diagram indicating the 14 positions at different directions and distances from two emitters where the soil water content was monitored during November 1988 and 1989

Table 6.1 Areas assigned to each of the soil water monitoring sites around the four emitters that were studied (Figure 6.2)

Position	Area (m^2)	Position	Area (m^2)
1	0,068	7	0,109
2	0,116	8	0,315
3	0,116	9	0,315
4	0,081	10	0,500
5	0,081	11-14	0,173
6	0,109	TOTAL	2,500

6.2.2 Calculating the water balance

Five different methods were used to estimate the various components of the water balance. In all cases the results were expressed in terms of the leaching fraction (LF), i.e. the volume of the deep percolate (below the root zone) as a fraction of the volume of applied irrigation water (Hillel, 1980a, p255).

With the first approach, the leaching fraction (LF1) was calculated using the difference between the measured irrigation and rain amounts and calculated evapotranspiration, as follows:

$$LF1 = [(I+R)-ET]/(I+R) \qquad (1)$$

where

I = irrigation (L^3)

R = rain (L^3)

ET = evapotranspiration (L^3)

= CF * Pan evaporation * area (L^3)

CF = crop factor

In the case of the vineyard under study, LF1 was calculated on a monthly basis for September to March for the 1987/88, 1988/89 and 1989/90 irrigation seasons. In this approach, the capacity of the soil to retain water, is not considered. This method will for the ease of discussion be referred to as the macro approach.

If the field capacity, FC, (or drained upper limit) of the soil is considered to be the maximum amount of water that a soil can retain, a theoretical estimate of the volume of the deep percolate and therefore, LF can be obtained. By using the measured irrigation and rain amounts and by calculating ET on a daily basis as above, and by furthermore assuming that the soil water content is at field capacity at the start of the growing (or irrigation) season, a record can be kept of the theoretical daily fluctuation in soil water content. If the antecedent soil water content plus irrigation exceeds field capacity, deep percolation will occur (Burns, 1974). The leaching fraction (LF2) for each irrigation and rainfall event is then calculated as follows:

$$LF2 = DP/(I+R) \quad (2)$$

where

DP = deep percolation

= (antecedent soil water + I + R) - FC

This approach will be referred to as the soil capacity method, i.e. the soil drains every time field capacity is exceeded. It was assumed that, because of the presence of the tile and interceptor drains, once the deep percolate has left the root zone it will be removed out of the vineyard and that the amount of water that might re-enter the root zone through capillary action, is negligible. It follows that a LF value can be obtained only for those events where DP>0. For comparative purposes, LF2 was also expressed as monthly mean values.

A third estimate of the water balance was obtained by accurate measuring of the amount of applied water and the soil water content prior to and following two individual irrigation events. The leaching fraction (LF3) was calculated as follows:

$$LF3 = [I-(SW_a-SW_b)]/I \quad (3)$$

where

SW_a = profile soil water content after irrigation (L^3)

SW_b = profile soil water content before irrigation (L^3)

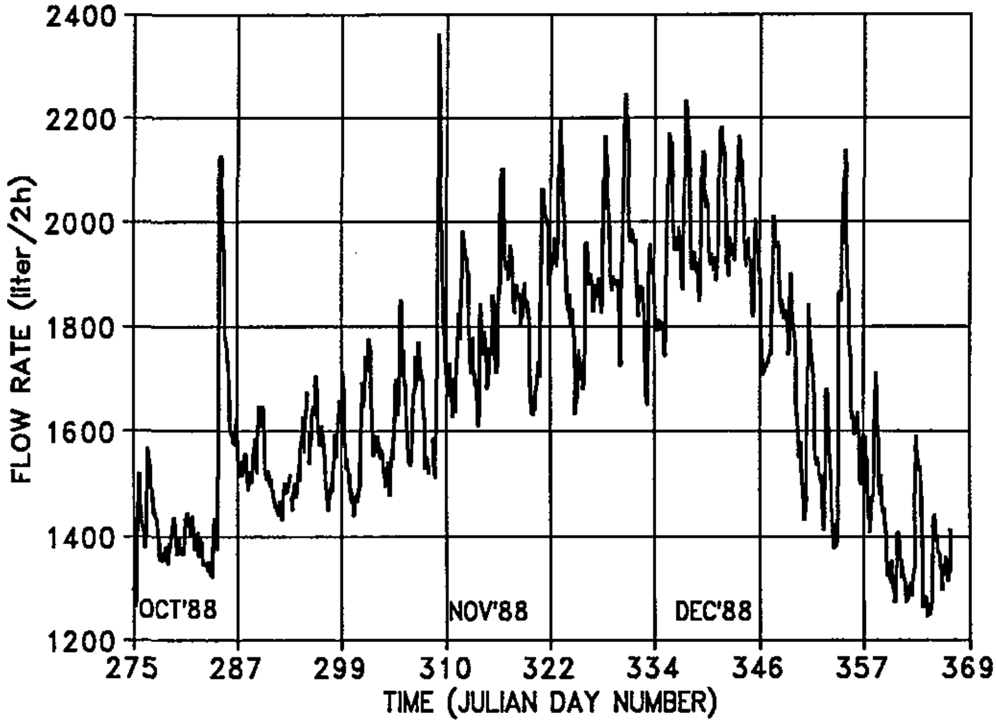
Because of time and manpower constraints, a limited number only of these detailed measurements were be made. The results of two events (29/11/1988 and 30/11/1989) at four emitters (Fig. 6.2), will be presented here.

The fourth estimate of LF was obtained by measuring the increase in the volume of flow in subsurface drains from the onset, up to 12 hours after the cessation of an irrigation event. This volume was then expressed as a fraction of the applied water for that particular event.

$$LF4 = \text{Increase in drainage volume}/I \quad (4)$$

The drainage hydrograph for the 1988/89 season (Figure 6.3a) shows an increase in the flow rate from September to December after which it decreases again. Superimposed on this graph are daily fluctuations, which upon inspection, shows a positive correlation with individual irrigations events (Figure 6.3b). For the 1988/89 season, LF4 was calculated for all irrigation events from October to December, but for the 1989/90 season the irrigation and flow events of November 1989 only were studied.

a



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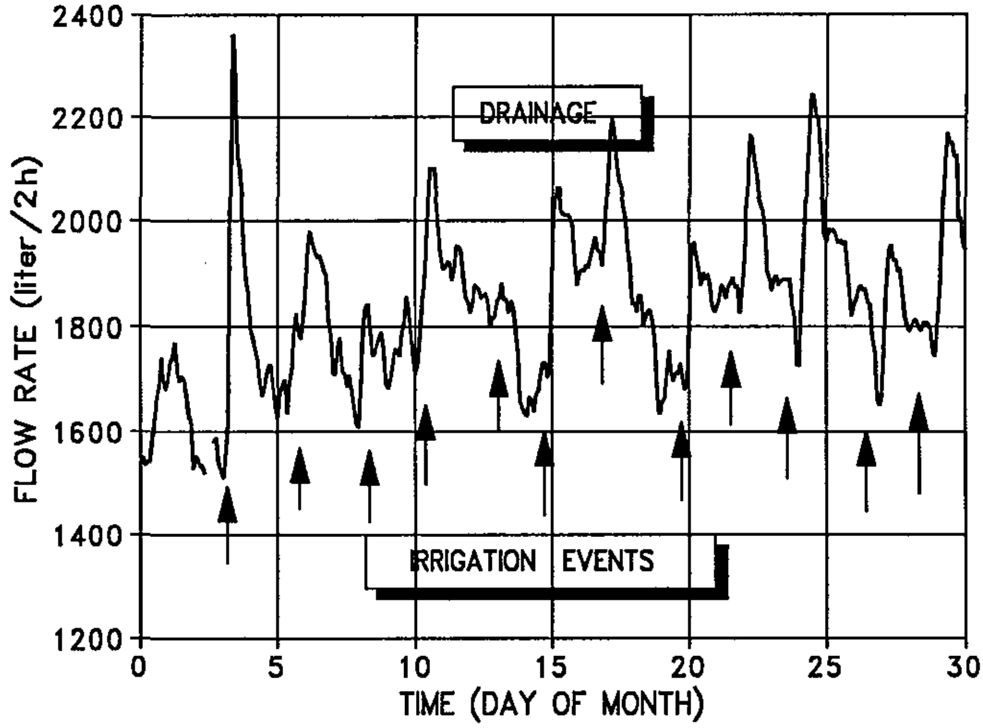

Figure 6.3 Flow rate in the tile drain for the period a) October to December 1988, and b) November 1988. The start of each irrigation event is indicated by the arrow

The leaching fraction can also be estimated from the increase in the concentration of a conservative ion, such as chloride, from the irrigation water value to that in the deep percolate at the bottom of the root zone (Oster, 1984, p187). This approach assumes steady state conditions in the chemistry of the soil and is calculated as follows:

$$LF5 = Cl_{irr}/Cl_{sw} \qquad (5)$$

where

Cl_{sw} = chloride concentration of the soil solution

Cl_{irr} = chloride concentration of the irrigation water.

The analytical data of the 1,0 m soil depth of the three sampling times were pooled and LF5 calculated as a function of distance and direction (N-S, E-W, Figure 6.2) from the emitter. The LF5 values were used only to verify the LF values obtained with the soil water and irrigation water mass balances, i.e. LF1 to LF4, and as estimates of the temporal mean leaching fractions.

6.3 RESULTS AND DISCUSSION

The monthly totals of the measured irrigation, rain and the calculated evapotranspiration values are summarized in Table 6.2. The totals varied significantly on both a monthly and annual basis. Despite comparable ET losses, the farmer applied significantly more water during the 1987/88 season than during any of the other two seasons. The result is that, according to equation 1 and with the exception of October 1987, deep percolation losses in excess of 10% of the applied water should have occurred during every month of the irrigation season. During the 1988/89 and 1989/90 seasons less water was applied with the LF1 values being commensurately smaller than the 1987/88 season (Table 6.2). According to this macro approach of calculating the water balance, a nett water shortage could have occurred during the 1988/89 and 1989/90 seasons. However, the vines did not show any visual stress symptoms.

Compared to the macro approach, the soil capacity approach of calculating leaching fractions, in most cases yielded comparable, but different values. The biggest discrepancy between the LF1 and LF2 values occurred during September and November (1987, 1988, 1989), January (1989) and March (1990). It can be deduced from Table 6.2 that equation 1 will show deep percolation to occur whenever $I+R > ET$. This will be true even for those cases where the soil water content is low, i.e. after prolonged periods during which ET exceeded $I+R$. In contrast, equation 2 (soil capacity approach) might reveal that the soil has a large enough capacity to absorb the excess of irrigation over evapotranspiration, e.g. March 1990. The converse can also occur, i.e. ET > I but the soil is too wet to retain all of the applied irrigation water at any particular time, e.g. September 1987, 1988 and 1989 and December 1989.

Table 6.2 Summary of monthly totals of measured irrigation, rain and estimated evapotranspiration volumes, and the calculated leaching fractions

Month	Total (m^3)			Leaching Fraction	
	I	R	ET	LF1	LF2
1987/88 season					
Sept	134,1	86,4	133,7	0,394	0,549
Oct	223,7	12,6	262,3	0,000	0,000
Nov	558,4	12,6	478,9	0,161	0,083
Dec	710,4	28,8	611,5	0,173	0,199
Jan	705,3	0,0	552,6	0,217	0,227
Feb	678,5	0,0	463,2	0,317	0,278
March	612,3	23,4	353,2	0,444	0,444
1988/89 season					
Sept	129,5	25,2	159,3	0,000	0,540
Oct	268,9	48,6	287,3	0,112	0,160
Nov	480,2	7,2	424,4	0,131	0,075
Dec	584,2	61,2	585,5	0,102	0,110
Jan	530,1	21,6	504,7	0,089	0,140
Feb	380,5	45,9	417,3	0,024	0,033
March	238,6	63,0	336,5	0,000	0,000
1989/90 season					
Sept	62,8	48,6	143,9	0,000	0,129
Oct	125,7	88,2	217,7	0,000	0,000
Nov	337,3	55,8	330,9	0,158	0,050
Dec	591,0	6,3	544,1	0,089	0,142
Jan	No data available				
Feb	198,3	61,2	405,3	0,000	0,038
March	488,3	31,5	360,5	0,306	0,000

LF1, LF2 = leaching fraction according to equations 1 and 2 respectively.

Table 6.3 Mean values of four soil water measurements at different distances and positions relative to an emitter measured prior to and following a 19,5 dm^3 per emitter irrigation event on 30 November 1989

Position	Area (m^2)	30/11/89 18h00 (dm^3)	1/12/89 06h00 (dm^3)	Δ	Position	Area (m^2)	30/11/89 18h00 (dm^3)	1/12/89 06h00 (dm^3)	Δ
1	0,068	20,1	21,4	1,23	8	0,315	104,2	105,1	0,82
2	0,116	35,0	35,7	0,75	9	0,315	98,5	98,3	-0,25
3	0,116	37,0	38,1	1,17	10	0,500	152,1	151,5	-0,63
4	0,081	24,2	25,5	1,27	11	0,173	55,6	56,9	1,34
5	0,081	24,6	25,0	0,41	12	0,173	53,2	54,0	0,80
6	0,109	35,2	35,8	0,61	13	0,173	57,2	57,2	0,03
7	0,109	32,1	32,9	0,87	14	0,173	55,4	55,5	0,05
Change in water content per total area					8,5 dm^3				
Change in water content at positions 1-9 only					9,1 dm^3				
Leaching fraction LF3					0,53				

The difference in soil water content prior to and following an irrigation application of 19,5 dm^3 per emitter on 29 November 1989 are given in Table 6.3. The increase in the volume of soil water per wetted volume was significantly less than the applied amounts. A mass balance show that, on 1 December 1989 at 06h00 between 10,4 dm^3 and 11,0 dm^3 of water that flowed through the emitter could not be accounted for within the root zone (0,9 m). This unaccounted water must have percolated through the root zone and is equivalent to a mean leaching fraction of 0,53 (Table 6.3). A similar observation was made on 29 November 1988 when the LF3 was measured to be 0,43 (data not shown). Both of these values are one order of magnitude higher than the equivalent LF1 and LF2 values for November 1988 and 1989 (Table 6.2). The fourteen neutron access tubes covered the whole 2,5 m^2 area served by one emitter (Figure 6.2). These high values can therefore not be attributed to incomplete measurement of the soil water in the area surrounding an emitter. The low recovery of the applied water within the root zone is furthermore not caused by evapotranspiration because the irrigation was applied at night. Runoff during an irrigation event has also never been observed in this vineyard. The depth distribution of the volumetric soil water content at field capacity, the spatial mean water content after irrigation and the water content before and after the irrigation at a position below the emitter (position 1, Figure 6.2), is illustrated in Figure 6.4. It can be seen that the mean water content after the irrigation application was less than the field capacity values to a depth of 0,9 m, but at the deeper depths (>0,9 m) field capacity was exceeded by approximately 0,02 m^3 m^{-3}. Even directly below the emitter, which immediately after an irrigation event, should be the wettest part of the area surrounding an emitter, the water content for the depths < 0,9 m did not exceed field capacity. The only logical explanation for this excessive water losses is macropore flow, especially in the immediate environment of the emitter where the application rate is at a maximum. The small increase in water content directly below the emitter (Figure 6.4 and Table 6.3) supports this conclusion.

It is possible that the big difference between the LF1, LF2 and LF3 values is the result of inaccurate crop factors and/or class A-pan evaporation data that were used to calculate the LF1 and LF2 values. However, the class A-pan data of other weather stations situated in the same region gave similar results. The particular crop factors that were used in this study are widely accepted as being realistic for the particular environment. Even if the factors are slightly wrong, the differences and resulting effect will be marginal. It is therefore unlikely that inaccurate crop factors are the cause of the big discrepancies between the various estimates of the leaching fraction.

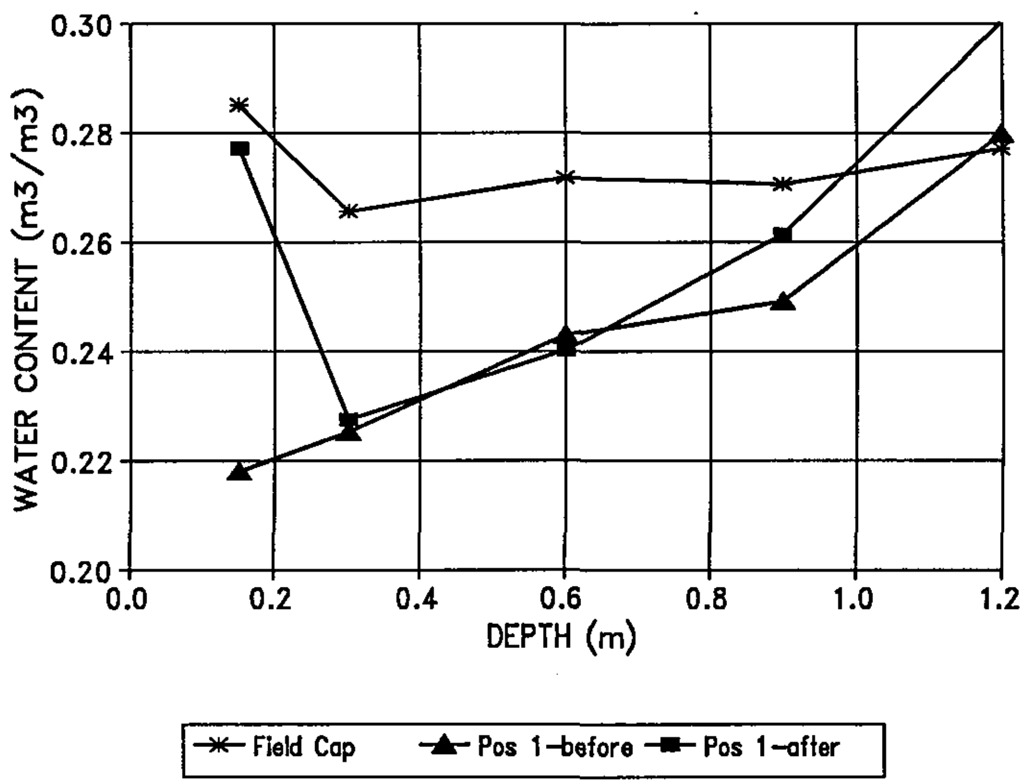

Figure 6.4 Depth distribution of soil water content at field capacity, before and after an irrigation event on 30/12/89. (FC = mean value for field capacity at site A2 and A4; spatial mean = of total area per emitter; Pos 1 = monitoring position below an emitter)

The relationship between the drainage hydrograph and the irrigation events of October to November 1988 and November 1989 that were used to calculate the LF4 values, are summarized in Table 6.4. The mean values for the four months under consideration are all less than 0,10. However, the standard deviations show that for some events LF4 was in excess of 0,10. The values furthermore decreased progressively from October to December 1988. With the exception of November 1988 they are all less than the equivalent LF1, LF2 and LF3 values. It is unlikely that the deep percolate will be intercepted quantitatively by the drain. It is therefore reasonable to accept that the LF4 will be less than any of the other leaching fractions. However, the quick response between the drainage flow rate after each irrigation event, is evidence of non-D'Arcian type macropore- or preferential flow and supports the deduction based on the LF3 values (Table 6.3) that macropore flow might be the principle reason for the large volume of water that could not be accounted for within the root zone during the irrigation events that were monitored during November 1988 and 1989 (Table 6.3).

Table 6.4 Monthly values of the total and mean applied irrigation water, the monthly increases in the drainage flow volumes and the concomitant leaching fractions

	Oct88	Nov88	Dec88	Nov89
Number of events	10	11	13	13
Total irrigation (m^3)	268,91	468,22	622,74	352,53
Mean irrigation (m^3)	24,45	39,02	38,92	27,11
Total flow increase (m^3)	20,75	28,04	19,86	4,53
Mean flow increase (m^3)	0,11	0,13	0,08	0,57
Mean LF4	0,086	0,079	0,041	0,019
Std dev LF4	0,092	0,055	0,023	0,014

The temporal mean depth distribution of chloride (Table 6.5) yield leaching fractions that are more comparable to the LF3 than to any of the other leaching fractions. It also suggests that the deep percolation losses are spatially dependent with deep percolation losses becoming less distinct with distance from the emitters.

Table 6.5 Temporal mean and standard deviation of the chloride concentration at 1 m depth at different distances and positions relative to the emitter

Distance (m)	Code [a]	Chloride ($mg\ l^{-1}$) Mean	StdDev	Leaching fraction LF5 Mean	StdDev	n
0,00	1	312	351	0,530	0,393	4
0,25	1	415	386	0,241	0,142	9
0,50	1	532	452	0,201	0,181	21
0,50	2	669	453	0,212	0,238	8
1,25	2	1237	490	0,059	0,029	19

a: 1 = within the vineyard row (N-S); 2 = perpendicular to the vineyard row (E-W)

6.4 CONCLUSIONS

The five different methods of calculating the water balance and the amount of water that will drain out of the root zone of irrigated lands, gave results that differ widely. From the class A-pan estimated evapotranspiration data and recorded irrigation quantities of three seasons, it was inferred that, with the exception of 1987/88, the amount of water that will percolate through the root zone of the drip irrigated vines, will be insignificant. A similar result was obtained even when the water holding capacity of the soil was considered. Based on these two easy, but simplistic approaches, it seems justifiable to conclude that similar irrigation practices elsewhere in the Breede River Valley will have a minimal effect on the quality and ecology of the environment and the river itself. However, quantitative measurement of the soil water content and the applied irrigation amounts, suggest significant losses of water out of the root zone, probably due to macropore- and preferential flow. The drainage hydrograph and chloride distribution in the soil volume in the immediate vicinity of the emitters are further evidence of significant losses due to macropore- and preferential flow. It is inevitable that a certain portion of this water will eventually surface again as irrigation return flow which will invariably add to the salt burden of the Breede River. It therefore seems logical to conclude that a water balance based on irrigation and evapotranspiration amounts alone, might lead to spurious conclusions regarding the harmful, e.g. salinization, effects of irrigated agriculture on the water resources of an environment.

6.5 REFERENCES

BURNS, I.G., 1974. A model for predicting the redistribution of salt applied to fallow soils after excess rainfall or evaporation. *J. Soil Sci.* 25:165-178.

DE CLERCQ, W.P. & MOOLMAN, J.H. 1992. Die ontwerp en gebruik van 'n kantelbakvloeimeter vir die meting van dreinerings- en oppervlakafloopwater. 17th Congress of the Soil Science Society of South Africa, Stellenbosch, January 1992

HALL, G.C. & DU PLESSIS, H.M., 1981. Studies of mineralization in the Great Fish and Sundays Rivers. Volume 2: Modelling river flow and salinity. C.S.I.R Special report WAT 63, National Institute for Water Research, C.S.I.R., Pretoria.

HILLEL, D., 1980a. Fundamentals of soil physics. Academic Press, New York.

HILLEL, D., 1980b. Water balance and energy balance in the field. In: D. Hillel (ed) Applications of soil physics. Academic Press, New York.

MOOLMAN, J.H. 1989. Effect of spatial variability on the estimation of the soluble salt content in a drip-irrigated saline loam soil. *Agric. Water Management* 15:361-376.

MOOLMAN, J.H. 1991. A sensitivity analysis of the effect of some input parameters on the water and salt flux of irrigated lands predicted with two contrasting hydrosalinity models. pp. 3A-3-1 to 3A-3-11 In: Proc. of the Fifth South African National Hydrological Symposium, Stellenbosch, November 1991.

MOOLMAN, J.H. & DE CLERCQ, W.P. 1991. Using the probability density function to locate representative soil water monitoring sites in a drip irrigated vineyard. Accepted for publication in: Proc. Southern African Irrigation Symposium, Durban, June 1991.

MOOLMAN, J.H., VAN ROOYEN, P.C. & WEBER, H.W. 1983 The effect of irrigation practices in the Breë River Valley on the salt content of a small river. *Irrig. Sci.* 4:103-116

OSTER, J.D. & RHOADES, J.D., 1975. Calculated drainage water compositions and salt burdens from irrigation with river waters in the Western United States. *J. Environ Qual.* 4:73-79

OSTER, J.D., 1984. Leaching for salinity control, p175-189 In: Shainberg, I., & Shalhevet, J.: Soil salinity under irrigation. Springer-Verlag, Berlin.

CHAPTER 7
SUMMARY AND CONCLUSIONS

7.1 GENERAL

The purpose of the field study was to accumulate a data base of field information that can be used as reference data against which the predicted quantity and quality of water leaving the root zone of irrigated lands, calculated with water and solute transport models, can be evaluated. In order to achieve this, for a period of three years, various hydrological and hydrochemical soil processes in a 0,5 ha drip irrigated vineyard in the Breede River Valley were comprehensively monitored in time and in space. Aspects that were monitored are:

i) the soluble salt and exchangeable cation composition within and just below the root zone of vines (Colombar wine grapes),

ii) the soil water content and spatial distribution from the surface to a depth of 1,05 m,

iii) the rate, quantity and chemical composition of drainage water leaving the irrigated area,

iv) certain hydrological parameters such as irrigation, precipitation and Class A-pan evaporation,

v) certain physical and chemical soil properties.

7.2 SPATIAL VARIABILITY OF FIELD DATA

The field study again emphasised the variable nature of water and solute transport processes even over small distances. This can best be illustrated by a summary of the arithmetic means and standard deviations of a selection of soil properties all measured at the 0,3 m depth of 32 different spatial positions in May 1987. These two statistics are given in Table 7.1 and were calculated based on the assumption of a normal distribution*. As was shown in chapter 3, a property like the soluble salt content of the soil, does not have a normal distribution which implies that in such cases, the arithmetic mean is a rather meaningless statistic. However, for the sake of comparison, arithmetic means were used throughout.

The results indicate that dynamic processes (e.g. the rate of water movement through the soil) exhibit significantly more variation than static soil properties. For example, the coefficients of variation (CV's) of the clay content and bulk density at 0,3 m depth are approximately 0,1. The soluble salt content (EC) and infiltration rate in contrast have CV's of 0,50 and 1,20 respectively (Table 7.1).

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*(NB. All time dependant measurements for a particular sample, e.g. infiltration rate and soil water content, were made at exactly the same spatial coordinate.)

Table 7.1 Summary of the central statistics of certain parameters that were determined during the course of the study in the drip irrigated vineyard at Robertson. Except for water content and infiltration rate, the data are all from the 0,30 m depth layer.

Parameter	Units	n_1	Mean	StdDev	CV	n_2 (Δ=10%)	n_2 (Δ=5%)
Clay	%	32	20,3	2,2	0,11	12	51
BulkDens	kg/m^3	32	1606,5	152,3	0,09	10	38
FieldCap	mm/1,05m	31	293,6	22,7	0,08	7	26
Infil(2h)	mm/h	32	59,8	72,0	1,21	1514	6053
Water(14/1/88)	mm/1,05m	29	227,4	28,2	0,12	17	65
Water(28/07/88)	mm/1,05m	29	242,6	24,3	0,10	11	43
EC	mS/m	32	668,8	333,9	0,50	262	1044
Cl(sol)	mg/dm^3	32	1196,5	939,8	0,79	648	2587
CEC	cmol(+)/kg	32	9,3	1,0	0,11	13	66
ESP	%	32	12,7	8,1	0,64	408	1915

n_1=actual sample size; n_2=theoretical sample size; BulkDens=bulk density; FieldCap=field capacity; Infil(h)=infiltration rate after two hours of continuous ponding; Water(14/1/88)=profile soil water content measured in Jan. 1988 (summer); Water(28/07/88)=profile soil water content measured in Jul. 1988 (winter); EC=electrical conductivity of saturated paste extract; Cl(sol)=chloride concentration in the saturated paste extract; CEC=cation exchange capacity; ESP=exchangeable sodium percentage.

In order to demonstrate that the 32 samples per 0,5 ha that were collected in May 1987 (Table 7.1), and the 32 sites at which the water content were subsequently monitored, might still not be sufficient to detect temporal changes in the population mean, the theoretical number of samples for not erroneously accepting or rejecting the null hypothesis at $\alpha = 0,05$ and $\beta = 0,10$ (levels at which type I and type II errors of the null hypothesis can be tolerated), were calculated. This was done by assuming that all the soil properties listed in Table 7.1 have a normal distribution and that the calculated sample means and standard deviations are unbiased estimates of the true field means. *(It should be emphasised that assumption of normality is not correct in all cases. This will have an effect on the theoretical sample size).* In this particular 0,5 ha irrigated field, 12 samples are required to declare a 10% deviation from the sample mean as being statistically different from the one listed in Table 7.1 and 51 samples for the 5% case. However, the equivalent cases for electrical conductivity are 262 and 1044 samples respectively. The practical implication is that in order to accept temporal changes in the field mean of soil properties such as infiltration rate and the soluble salt content as being statistically significant, a great number of samples have to be collected.

7.3 VALIDATION OF WATER AND SALT TRANSPORT MODELS

The large spatial variability and non-normality of certain soil properties also have important implications when the quantity and quality of the deep percolate of irrigated (and rainfed) lands have to be predicted. In deterministic models the input parameters are considered to be single valued, which, as was shown in this and other studies, is not the case. It would seem appropriate that in deterministic modelling, the sample mean of a specific parameter (e.g. hydraulic conductivity or EC) is the obvious value that should be used as input for the model. However, if a particular variable is subjected to spatial variability, the calculation of the mean and the level of confidence that can be attached to that value as being the true mean, becomes a function of the sampling strategy that was used. The greater the variability, the more samples should be collected to obtain a true representation of the mean. The variable nature of soil properties and processes will also effect the validation of models. If the sampling strategy that was used is not correct at all stages of the study, the process of validation and the results obtained in itself might be spurious.

Water and solute transport models are often validated against calculated or measured water balances. An important finding of the field study was that in drip irrigated lands (i.e. partially wetted surfaces) different methods of calculating the water balance will yield divergent answers. It was found that a water balance based on measured irrigation and indirectly measured evapotranspiration amounts alone, might lead to incorrect conclusions with regard to the effects of irrigated agriculture on the environment.

7.4 CONCLUSIONS

The field study was successful in accumulating a data base suitable for the validation of water and salt transport models at the micro- (10 m^2) and meso (1 ha) scale. However, the fact that all measurements were made in a drip irrigated field where three dimensional processes predominate, might mean that the data base is not suitable for the validation of one-dimensional water and solute transport models.