SITUATION ANALYSIS OF PROBLEMS FOR WATER QUALITY MANAGEMENT IN THE LOWER ORANGE RIVER REGION WITH SPECIAL REFERENCE TO THE CONTRIBUTION OF THE FOOTHILLS TO SALINIZATION.

by

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EXECUTIVE SUMMARY

Introduction

Sustainable and efficient use of water is implicit in the 1998 National Water Act of South Africa. The most feasible manner in which to achieve this is by integrated water resource management through licensing water and allowing larger user participation in management of the water resource. Water resource management is to be performed by two types of institutions, namely a Catchment Management Agency (CMA) and a Water User Association (WUA). The function of the CMA is integrated catchment management according to a catchment management strategy (CMS). One CMA is foreseen for each of the 19 water management areas (WMAs) in South Africa. The WUA will form at a more local level than the CMA to coordinate different users in the day-to-day management of an irrigation scheme, a river or a catchment.

Water quality is related to water quantity and should form a part of integrated water resource management. The national water quality management framework policy is therefore aligned with the National Water Act. Integrated water quality management comprises several facets, but water quality planning ultimately determines its principles of action. Catchment assessment studies continually serve to provide information regarding the physical and socio-economic cause-and-effect relationships underlying the principal water related problems in the WMA and its sub-catchments. Such studies enable the water quality manager to formulate a catchment water quality management strategy. The strategic management of water quality at the WMA and sub-catchment level is collectively governed through 19 CMSs. This is to facilitate alignment between WMAs, or sub-catchments within a WMA, where water quality impacts on downstream-users. Such joint management of catchments is considered a necessity in the case of the Orange River which is the largest and most strategic water resource in South Africa.

One of the most comprehensive river assessment studies performed in South Africa namely, the Orange River Replanning Study, indicated potential for water quality related problems in the Lower Orange WMA, particularly in the river reach between Boegoeberg and Onseepkans. The lower Orange WMA is located in an arid area with limited rainfall that is characterized by high evaporation losses. The tributary inflows in the area are intermittent, and only contribute to river flow during periods of unusually high precipitation in the Lower Orange River basin. The salt contribution of these rivers and natural streamlets to the Orange River during such events is unknown. The bulk of the surface water of the Lower Orange WMA is found in the main stem of the Orange River and almost all of its surface water originates from Lesotho, the Vaal WMAs and the Upper Orange WMA. Both the water flow and water quality in the Orange River have been severely affected by extensive upstream developments due to transfer of good quality water out of the Orange River in Lesotho and the Upper Orange WMA, high salinity irrigation return flows along the Orange River and inflow of poor quality water from the Vaal River. Furthermore, a considerable amount of salt (*ca.* 3 million tons) originating from irrigation water has been withheld from the Vaal River, and subsequently the Orange River, by the Vaalharts irrigation scheme since its inception in 1935. It is feared that this salt may cause serious problems for irrigation farmers downstream if the storage capacity of its ultimate sink is exceeded, resulting in highly saline groundwater flows.

In the Lower Orange WMA, irrigation is the dominant water use and comprises 94% of the total water requirement compared to 3%, 2% and 1% thereof, respectively, for urban, rural and mining purposes. Nearly all irrigation developments are dependent on water from the river. More than 35 000 ha of land are cultivated between Boegoeberg and Onseepkans, with grapes (60%) and cotton (*ca.* 20%) constituting the main crops. Other crops include lucerne (8.2%), wheat (7.9%) and maize (3.5%). Most of the irrigation water is applied to high value orchard type crops of which yield and quality may be negatively affected by water deficits or excessive salinity. The irrigation water is therefore needed with a relatively high assurance of supply and should be of acceptable quality.

Irrigation return flow constitutes an important part of the overall water balance of the Orange River and may be as high as 30% of water applied to the land. In comparison, urban and industrial return flows are minimal. Water quality of the return flow is generally poor. The magnitude and salinity of irrigation return flow to the river and canal systems, the extent and salt load of irrigation-induced recharge of groundwater, as well as the possible inflow of groundwater to surface water along the river are important factors dictating river salinization, especially in arid areas. Such information is still unknown for the Lower Orange WMA, but its availability is considered essential to devise appropriate strategies for sustainable management of catchments.

Both surface water degradation and salt retention are considered to be potential problems in the Lower Orange WMA which may impact on sustainability of agriculture. A study of water quality of the Orange River confirmed increases in salt concentration downstream from the Gariep Dam (121 mg L^{-1}) to the Orange River Mouth (326 mg L^{-1}) in 1995 and expressed special concern about the increase in salinity between Boegoeberg and Kakamas. Simulation using the Water Quality Model for the Orange River Catchment furthermore projected that by 2030, salt concentration would increase by about 25% at Boegoeberg Dam and Kakamas. This is ascribed to the effect of irrigation return flow from the Boegoeberg area on the reduced flow in the river. In the river reach from Boegoeberg Dam to Onseepkans, where grapes represent 90% of the crop value, the actual salt concentration regularly exceeds 500 mg L^{-1} (0.77 dS m^{-1}), but remains below 750 mg L^{-1} (1.15 dS m^{-1}) on all but a few occasions. From an interpretation of available salinity guidelines, this study concluded that since the periods when salt concentration increases beyond 750 mg L^{-1} are of short duration, this should not have a long-term effect on permanent crops.

Salinity research on grapevines in the Breede River Valley, however, indicated that grapevines are more sensitive to salinity than suggested by international salinity guidelines. This is important information to consider when evaluating the effect of salinity on crop production. The water quality situation downstream of Vioolsdrift was furthermore identified as a definite cause for concern and may have international implications as the Orange River is shared between South Africa and Namibia over hundreds of kilometers. Several development opportunities identified in both Namibia and South Africa, including the recommended construction of a dam at Vioolsdrift, can lead to increased water requirements in future and/or impact on the water quality.

Salt is furthermore, according to DWAF's (Department of Water Affairs and Forestry's) salinity model output, retained in the river system from Kakamas to Vioolsdrift, a situation that cannot continue indefinitely. A recommendation was therefore made that further investigations into salt retention on irrigated lands should be conducted as a matter of priority in order to validate this effect. Despite the presentation of viable solutions to the water table problem and resulting salinization in the Lower Orange River Area *ca.* 10 years ago, grape producers in 2002 still rated problems related to salinity of water and soils as high and requested research in this regard. Yield decrease due to waterlogging and/or salinization is not really an option for producers as the production of deciduous fruit and grapes is already becoming increasingly difficult due to the combined effect of several constraints. Salinization of semi-arid areas throughout the world is furthermore seen as a threat to long-term production of perennial fruit that is particularly sensitive to salinity and ion toxicities. Salt build-up beyond certain limits will be extremely costly to rectify and can irreversibly harm agriculture in the region.

Expansion of the table grape industry in the upper part of the Lower Orange River system (below Vanderkloof Dam to Augrabies) with water already allocated, water for irrigation of 4000 ha earmarked for resource poor farmers and future irrigation water requirements of Namibia, could furthermore put additional pressure on the system by decreasing the available volume of water and increasing irrigation return flow to the river. The water resources of the Integrated Orange River System of which the Lower Orange WMA forms part, are despite a current surplus, effectively in balance and should be carefully managed to ensure sustainable use.

A knowledge base to design a sound management plan is thus of utmost importance to ensure a competitive agricultural industry in the Region. A situation-analysis is necessary to assess the current situation with regard to problems with management of water quality in the Lower Orange WMA. This assessment could be used to identify future research or technology transfer needs which will aid in design of a management plan. The management plan should then be used as a directive for the sustainable usage of natural resources along the river, and should form part of the bigger development plan of the Region including protection of the ecosystem.

Objectives

The objectives of the project were as follows:

- To assess the land use, soil salinity and water quality, as well as salinity management practices, from a synthesis of existing information and by utilizing satellite imagery and field surveys in selected areas.
- To evaluate the present situation and likely future trends with regard to water quality and soil salinity management.
- Based on the situation assessment above, to identify the need for policy development, and the need for research on which further policy development may be based, in order to protect soil and water resources in this area.

Research approach

In order to achieve the project objectives, and specifically to permit a situation analysis, the report had to address several aspects of salinity in the study area, namely surface water quality, soil salinity, soil salt generation potential, drainage water quality and current, as well as alternative water and soil salinity management practices (Figure 1). The general research approach was to use existing studies and data as far as possible and supplement it, where necessary, by additional research and sampling on a limited scale to enable a situation analysis.

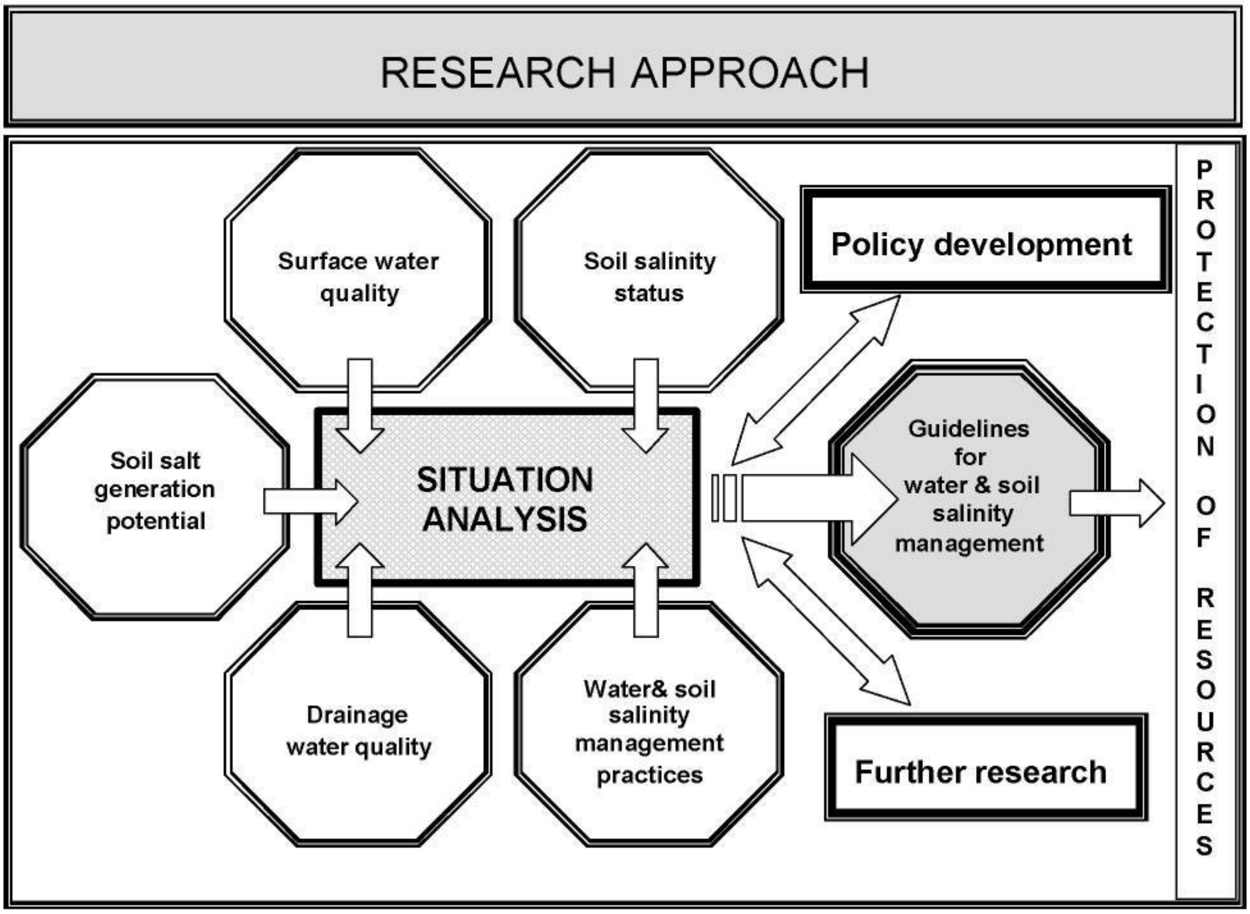

Figure 1. Aspects of salinity included in the situation analysis of problems in water quality management.

The water quality status of surface water was assessed through a desktop study of water quality data made available by the Directorate of Resource Quality Services of DWAF. The soil salinity status for the study area was determined initially through identification of the potentially salinized cultivated area by means of an aerial survey, which was followed by a process of selective soil sampling and chemical analyses. The potential for salt leaching for three different soil types that frequently occur in the area was determined through more detailed research utilizing soil surveys and leaching experiments. An indication of drainage water quality for the region was obtained by monitoring drains from irrigated vineyards at selected sites, while water and soil salinization management practices currently employed by important role players in the region were assessed through a group discussion. Other possible water and soil salinization management practices were obtained from the literature. The situation analysis served to provide a knowledge base for decision making to refine guidelines for water and soil salinity management and to identify future research and policy development needs.

Report structure

In the report, the role of irrigation development in and general irrigation-induced mechanisms underlying river salinization are reviewed from the literature, followed by an assessment of water quality and trends in water quality. The salt generation potential of soils in three contrasting areas under irrigation and the chemical composition of drainage water of selected areas are reported. The identification and classification of cultivated areas utilizing satellite imagery and aerial survey imagery, as well as the identification of the potentially salinized cultivated area and the verification thereof are also addressed. Guidelines for management of water quality related problems are proposed, with the need for research and policy development being illuminated in the conclusions of the report.

Water quality and salt retention

Although the proposed study area was the Boegoeberg to Onseepkans river reach, selected water quality results for the river reach from Onseepkans to Alexander Bay were included to enhance data interpretation. The situation analysis indicated that surface water quality according to the long-term electrical conductivity (EC), sodium adsorption ratio (SAR) and cation and anion concentrations, is of good quality and is not expected to pose any serious problems regarding salinity, sodicity or toxicity. Prerequisites, however, are that a leaching fraction of at least 0.1 is applied for low frequency irrigation systems and that foliage of sensitive crops is not wetted. For low flow years the EC may be more than double the long-term value for certain months and this increase in salinity could become important if consecutive years of low flow occur and if the ameliorating effect of precipitation in summer and autumn remains negligible. An appropriate increase in leaching fraction could be applied to avoid a reduction in production or quality of crops during such scenarios.

Trends downstream from Boegoeberg to Alexander Bay indicated a significant increase in salinity and sodicity, with the EC in the Boegoeberg to Onseepkans reach increasing by *ca.* 57% and from Onseepkans to Alexander Bay by 95%, relative to that in the Orange River reach upstream from Hopetown. Trends over time indicated a general increase in the annual mean for the EC, SAR and almost all cation and anion concentrations in the water after 1992, with the EC increasing by *ca.* 0.1 dS m^{-1}. Based on the current trend and mean flow, all EC values between Boegoeberg and Onseepkans could exceed the EC Class 1 threshold of 0.4 dS m^{-1} after the next 40 years. The increase in irrigation water pH may be of concern, with the water at Vioolsdrift running the highest risk of causing problems with crop production and encrustation of irrigation equipment or clogging of drip irrigation systems. The increasing trend in pH over time seems to have levelled off, but it is uncertain how sustainable the production of crops will be should the irrigation water pH rise further at other monitoring sites. The water quality data base for the lower Orange River region was surprisingly incomplete and the importance of collecting monthly data for the interpretation of trends in salinization over the long term cannot be overemphasized. Steps should be taken immediately to ensure a reliable water quality data base for the lower Orange River region in the future.

Concerns regarding salt retention in the Boegoeberg to Onseepkans river reach appear to be valid, but should be seen in context. The longitudinal annual average river salinity profiles and salt balance for the river reach between Boegoeberg and Onseepkans for high and low flow years, respectively, indicated that the river oscillates between a salinization profile and an equilibrium, or even a mobilization profile. It is hypothesized that salt retention occurs in the Boegoeberg to Onseepkans reach during periods following extremely high or relatively high flow in the river. The salt retention in the river reach occurs due to waterlogged conditions in low lying soils, which make effective leaching of salt periodically unfeasible. The presence of high water tables promotes salinization of these soils under conditions of high evaporative demand that are typical for the lower Orange River region. During years with low water flow salts can be effluxed from the river reach as low water tables allow salts to be effectively leached from the salinized soils.

Drainage water originating from over irrigation of foothill soils may aggravate the situation during high flow years or prolong the period of waterlogging and potential for salinization. It also has potential to mobilize salts which can have devastating effects for the crops cultivated on low lying alluvial soils, and to cause deterioration in surface water quality through groundwater seepage. Return flow from irrigated fields and leaking canals between Boegoeberg and Onseepkans is estimated to constitute between 15 and 20% of the irrigation requirement per year and as such may contribute *ca.* 7% of the water if the mean annual water flow in the river is 200 x 10^6 m^3. It was, however, impossible to determine any effect of the extensive irrigation developments on foothill soils during the 1990s on the river water quality due to the myriad factors that influence the river water quality and the lack of a reliable database. A simultaneous increase in EC at Boegoeberg and Onseepkans after 1992, however, indicated that irrigation return flows from the irrigation development on the foothills, which occurred mainly beyond Boegoeberg, cannot be the main source for the salinity increase in the river reach from Boegoeberg to Onseepkans.

Salt contribution from soils

Laboratory research on the salt leaching potential of shallow saprolitic soils, deep Kalahari sands and calcareous terrace soils from the foothills indicated that these soils are not particularly saline in their virgin state, although some local spots of exceptionally high salinity and sodicity were also found. The sources of salt in these soils are both soluble salts as well as accelerated weathering of primary minerals such as feldspar and biotite. It is estimated that the earlier stages of vineyard development could release several times more salt than that which would be applied through irrigation water alone. Where annual application of 1000 mm of 0.3 dS m^{-1} irrigation water could result in accumulation of 2 ton of salt per hectare per metre, irrigation could release on average between 3 and 8, and even 10 additional tons per hectare per metre of soil drained within the first decade of vineyard development. For some localised spots the salt generation potential could be as low as 2 or as high as 48 tons/ha.m. Where salt release of the latter magnitude represents the majority of soils in a small primary catchment, severe consequences for crop production on the low lying alluvial soils and/or impact on river water quality could be expected if drainage water from the foothills is not intercepted and responsibly disposed of.

The EC of drainage water emanating from small catchments dominated by calcareous alluvium, weathered gneiss and Kalahari windblown sands was 1.5 dS m^{-1}, 2 to 4 dS m^{-1} and *ca.* 10 dS m^{-1}, respectively. Drainage water quality can be affected by various factors and these values are therefore not necessarily indicative of the salts generated in such catchments. It provides, however, an indication of the drainage water salinity that can be encountered in the area. The total salt contribution to the river by these waters could not be estimated as the volume of drainage water is not known.

According to the salt leaching potential scenario above, one would expect the salinity status of irrigated vineyards to decrease if salt mobilization occurred. It was therefore surprising to find the contrary, namely, that there is no indication of a drop in salinity when virgin lands are converted to irrigated vineyards, but rather some indications of a slight increase in salinity. There was also evidence of local saline patches within vineyards. To counter the development of such salinity in vineyards, sophisticated drainage should be a prerequisite for any new irrigation development on the foothills, while review of regular gypsum and fertilizer applications are strongly advocated. The prospect of localized salinization within vineyards on foothill soils is probably of more immediate concern than the issue of river water quality deteriorating through salt generation. It should, however, be kept in mind that this conclusion was based on results from a limited dataset.

Soil salinity and management practices

The procedure used to assess the area of saline soils in the region indicated that a mere 1.7% of the sampled area was too saline for grapevine production without yield loss (i.e. soils had a saturated soil water extract EC > 0.75 dS m^{-1}). For the whole area this represents 436 ha of 25 843 ha under cultivation. The small percentage of saline soils found may be partially attributed to the fact that sampling occurred during a period of lower river flow, which is characterized by desalination. What this survey also indicated is that only *ca.* 14% of the area displaying poor growth (potentially salinized area) was actually saline. This indicates that vegetation stress on about 2000 ha in the lower Orange River area was induced by causes other than salinity, such as water deficits and localized waterlogging. Based on these results, technology transfer regarding irrigation scheduling and water table management at farm level appears to be essential.

Specific management actions are recommended to curtail water quality deterioration and development of soil salinization in the lower Orange River region, as well as to maintain optimum production of grapevines. Management actions are proposed for national government, local authorities, local extension services and farmers, respectively. The management actions focus on reduction of the amount of leached water and improved drainage management and include aspects of water delivery management, irrigation efficiency (scheduling, leaching and system efficiency), and reuse and disposal of drainage water. The most important management actions proposed for the region include improvement of irrigation efficiency, application of adequate leaching, revision of irrigation practices in severely salinized areas, lining of water delivery and storage structures, maintenance of drainage systems already installed, installation of drainage in basin lands ("*hollande*") and foothill soils and well-judged installation of cut-off drains between the irrigated foothill soils and the basin lands to intercept drainage water, which is to be disposed of in the river.

The grape industry is important to the economy of the area as vineyards constitute 68% of the cultivated area and a yield decrease due to salinity is not considered an option. Irrigation water with a maximum salinity of 0.55 dS m^{-1} is considered suitable for use during low, and 0.75 dS m^{-1} during high frequency irrigation, provided a leaching fraction of *ca.* 0.2 is maintained. The salt concentration in the river at Onseepkans reached levels equal to an EC of almost 0.7 dS m^{-1} in the irrigation water during years with low flow, which indicates that the potential exists for excessive salt accumulation during such years, especially where low frequency irrigation systems are used.

The absence of a drainage management strategy for the area, as well as lack of appropriate policy to enforce installation of drainage or to retire land where excessive salinization occurs, almost certainly hampered the management of surface water and soil salinization. The development of such policy and integration with the water quality management strategy of DWAF is therefore seen as necessary to protect water and soil resources in the Lower Orange River WMA. Possible constraints for implementation of the management actions include the rate of the integrated water resource management transformation process by DWAF, the level of communication between relevant institutions and the availability of resources to provide, alter and maintain water delivery and storage infrastructure.

Recommendations for further research and technology transfer

To effect more efficient water use and to prevent salinization problems at farm level, technology transfer on irrigation scheduling as well as drainage and water table management is needed.

To ensure sustainable use of the water resource and to support future management decisions, there is a need for ongoing collection and interpretation of information and research on specific aspects, including the following:

- For monitoring of water quality trends and salt balance calculations or systems modelling to support salinity management decision making, consistent monthly data collection, verification, processing and interpretation of surface water quality and water flow data are crucial.
- For estimation of the impact of drainage water quality on surface water quality, collection of data on drainage water quality and quantity is necessary. Such information can be included in and managed similarly to the surface water database as described above.
- For judicious installation of cut-off drains, detailed information on geo-hydrological characteristics of the catchments and sub-catchments is required.
- For estimation of the potential effect of catchment or sub-catchment characteristics on irrigation-induced ground water recharge, more research is necessary especially regarding soil water retaining properties and recharge rates.
- Recharge rate is affected by water consumption of the irrigated crop and research is needed on the minimum water requirement of all crops produced in the lower Orange River WMA. The effect of netting covers on water consumption should also be researched.
- In order to obtain a better understanding of the salinization mechanism operating in the lower Orange WMA, the contribution of salt by tributaries of the Orange River (e.g. the Sout and Hartebeest rivers) during periods of unusually high precipitation needs to be quantified.

- Effective methods of technology transfer need to be developed to ensure that producers adopt a best practices approach with respect to irrigation scheduling and salinity management.
- For an improved method to identify salinized irrigated areas from aerial survey images, an object-oriented approach should be researched.

The full version of this report is available on CD from the Water Research Commission.

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The Steering Committtee responsible for this project consisted of the following persons:

Mr HM du Plessis	:	Water Research Commission (Chairperson)
Mr PJS Strumpher	:	National Department of Agriculture
Mr H Gerber	:	Northern Cape Department of Agriculture and Land Reform
Mr JHH Joubert	:	Northern Cape Agricultural Union
Prof ATP Bennie	:	University of the Free State
Prof M Fey	:	University of Stellenbosch
Mr PJE Louw	:	ARC Infruitec-Nietvoorbij (2002 to June 2004)
Dr PA Myburgh	:	ARC Infruitec-Nietvoorbij (June 2004 to April 2005)

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1 INTRODUCTION

Sustainable and efficient use of water is implicit in the 1998 National Water Act of South Africa. The proclamation of this Act resulted in comprehensive reform of the water resource management of the country, endeavoring at creating a more efficient system through licensing water and allowing larger user participation in management of the water resource (Faysse, 2003). Water resource management is to be performed by two types of institutions, namely a Catchment Management Agency (CMA) and a Water User Association (WUA). The function of the CMA is integrated catchment management according to a catchment management strategy (CMS). The CMA itself is responsible for definition of the CMS and organizing the funding for its implementation. One CMA is foreseen for each of the 19 water management areas (WMAs) in South Africa. The WUA will form at a more local level than the CMA to coordinate different users in the day-to-day management of an irrigation scheme, a river or a catchment and will replace the function of already existing Irrigation Boards.

Water quality is related to water quantity and should form a part of integrated water resource management. The national water quality management framework policy (DWAF, 2002) is therefore aligned with the National Water Act and an integrated water quality management (IWQM) model was proposed to address water quality management related issues (Van Wyk *et al.*, 2003). Van Wyk *et al.* (2003) defined IWQM as a "dynamic, but systematic process for continual management improvement, based on the principle that you need to understand a situation before you can improve it". Integrated water quality management comprises several facets, but water quality planning ultimately determines the principles of action for the IWQM (Van Wyk *et al.*, 2002; Van Wyk *et al.*, 2003). Catchment assesment studies continually serve to provide information regarding the physical and socio-economic cause-and-effect relationships underlying the principal water related problems in the WMA and its sub-catchments. Such studies enable the water quality manager to determine Resource Quality Objectives and to formulate a catchment water quality management strategy. The strategic management of water quality at the WMA and sub-catchment level is collectively governed through 19 CMSs. This is to facilitate alignment between WMAs or sub-catchments within a WMA where water quality impacts on downstream-users. Such joint management of catchments is considered a necessity in the case of the Orange River which is the largest and most strategic water resource in South Africa (DWAF, 1999a; DWAF, 2004a). The Orange River is of great importance to South Africa since the natural flow represents more than 22% of the country's surface water resources.

Lower Orange water management area

One of the most comprehensive river assessment studies performed in South Africa namely, the Orange River Replanning Study (DWAF, 1999a), indicated potential for water quality related problems in the Lower Orange WMA, particularly in the river reach between Boegoeberg and Onseepkans, which is indicated in Figure 1.1. Water quality in a specific river reach is determined by various factors, including precipitation, the quality of water entering the river reach, the salt contribution of tributary and groundwater inflows, river losses through evaporation and surface as well as subsurface return flows (Tanji & Hanson, 1990). The quantity and quality of return flows is not only affected by the distribution

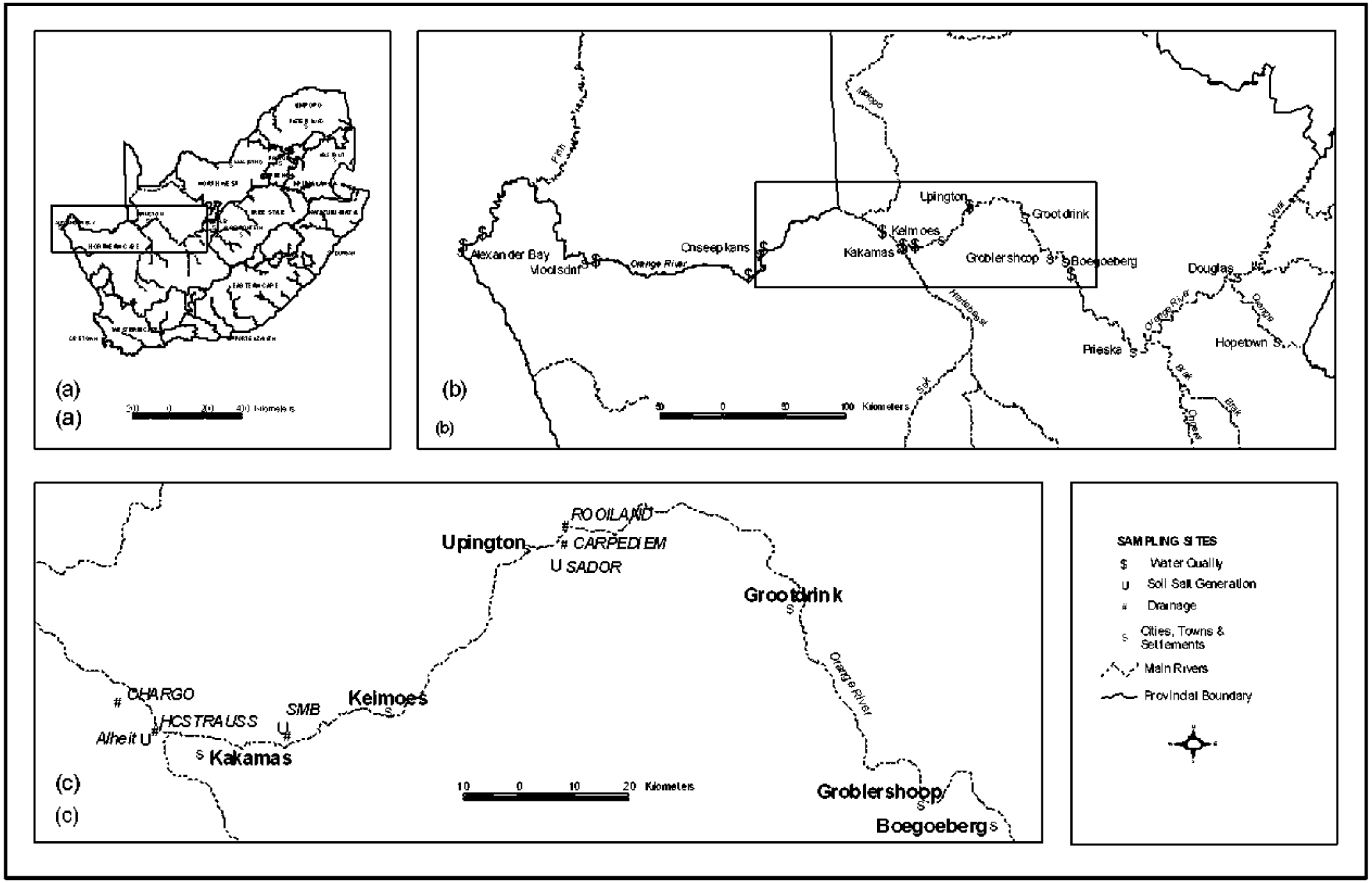

Figure 1.1. Location of the study area within South Africa (a), the water quality sampling sites and location of the river reach between Boegoeberg and Onseepkans (b) and drainage water and soil sampling sites for salt generation potential studies within the Boegoeberg to Onseepkans river reach (c).

pattern of precipitation, but also by the activities of domestic, industry, mining and agricultural groups along the river reach.

The Lower Orange WMA is arid as the annual rainfall varies between *ca.* 400 mm and *ca.* 200 mm from Vanderkloof to Boegoeberg dams and rainfall tends to decrease westwards until it becomes less than 50 mm per annum (Chutter *et al.*, 1996). Some tributaries of the Orange River relevant for the Lower Orange WMA include the Vaal River which has it confluence with the Orange River *ca.* 13 km west of Douglas, the Ongers and Hartebeest rivers draining from the south and the Molopo and Fish rivers (Namibia) draining from the north (Fig. 1.1b, DWAF, 2004b). The Ongers, Hartebeest and Molopo rivers are ephemeral and only contribute to river flow during periods of unusually high precipitation in the Lower Orange River basin. The salt contribution of these rivers and natural streamlets to the Orange River during such events is unknown. The Fish River in Namibia only contributes to flows in the last reach of the Orange River from Onseepkans to Alexander Bay (DWAF, 2004b). Evaporation losses in the Lower Orange WMA are high, with the maximum mean annual evaporation amounting to between 2000 mm to 2400 mm from above Boegoeberg Dam to upstream of Vioolsdrift, thereafter decreasing in the direction towards the coast (Chutter *et al.*, 1996).

The Lower Orange WMA is in the unenviable position that the bulk of its surface water is found in the main stem of the Orange River and that almost all of its surface water originates from Lesotho, the Vaal WMAs and the Upper Orange WMA (DWAF, 2004a; DWAF, 2004b). Both the water flow and water quality in the Orange River have been severely affected by extensive upstream developments (DWAF, 1999a; DWAF, 2004b). Factors contributing to increased salinization include: transfer of good quality water out of the Orange River in Lesotho and the Upper Orange WMA, high salinity irrigation return flows along the Orange River and inflow of poor quality water from the Vaal River (DWAF, 2004b). Furthermore, a considerable amount of salt (*ca.* 3 million tons) originating from irrigation water has been withheld from the Vaal River, and subsequently the Orange River, by the Vaalharts irrigation scheme since its inception in 1935 (Anon, 1997). It is speculated that the groundwater may have been serving as sink and that it may cause serious problems for irrigation farmers downstream if its capacity is exceeded, resulting in highly saline groundwater flows. The exact mechanism of salt diversion or retention and ultimate salt sink remains unknown.

In the Lower Orange WMA, irrigation is the dominant water use and comprises 94% of the total water requirement compared to 3%, 2% and 1% thereof, respectively, for urban, rural and mining purposes (DWAF, 2004b). Nearly all the irrigation developments are located along the main stem of the Orange River and are dependent on water from the river for their crop production. According to Loxton Venn & Associates (1998), more than 35 000 ha of land is cultivated between Boegoeberg and Onseepkans, with approximately 60% of the land being utilized for production of grapes, and cotton occupying *ca.* 20% of the cultivated area. Other crops produced in the area include lucerne, wheat and maize, which represented 8.2%, 7.9% and 3.5 % of the crop area, respectively. Approximately 47% of the irrigation requirement is supplied through canal systems and the remaining 53% is abstracted directly from the river (DWAF, 2004b). Most of the irrigation water is applied to high value orchard type crops (DWAF, 2004b). Yield and quality of these crops may be negatively affected by water deficits (Fereres & Goldhamer, 1990; Shalevet & Levy, 1990; Williams & Matthews, 1990; Myburgh, 2003a; Myburgh, 2003b) or excessive salinity (Maas & Hoffman, 1977; Bernstein, 1980; Abrol *et al.*, 1988; Moolman *et al.*, 1999; De Clercq *et al.*, 2001). Irrigation water is therefore needed at a relatively high assurance of supply and should be of acceptable quality.

Irrigation return flow constitutes an important part of the overall water balance of the Orange River and may be as high as 30% of water applied to the land (Rossouw, 1997). Urban and industrial return flows are minimal compared to irrigation return flow. According to Rossouw (1997), water quality of the return flow is generally poor. The magnitude and salinity of irrigation return flow to the river and canal systems, the extent and salt load of irrigation-induced recharge of groundwater, as well as the possible inflow of groundwater to surface water along the river are important factors dictating river salinization, especially in arid areas (Smedema, 2000). Such information is still unknown for the Lower Orange WMA (DWAF, 2004b), but its availability is considered essential to devise appropriate strategies for sustainable management of catchments.

Potential salinity problems and its implications

Surface water degradation: A study on water quality aspects of the Orange River on expected water quality changes (Van Veelen & Van Heerden, 1998) confirmed increases in salt concentration downstream from the Gariep Dam (121 mg L^{-1}) to the Orange River Mouth (326 mg L^{-1}) in 1995. A noticeable change in concentration occurred especially between Boegoeberg and Kakamas in 1995, and simulation using the Water Quality Model for the Orange River Catchment furthermore projected that by 2030, salt concentration would increase by about 25% at Boegoeberg Dam and Kakamas. This is ascribed to the effect of the irrigation return flow from the Boegoeberg area on the reduced flow in the river. In order to allow for different climatic and other conditions along the length of the Orange River, the river was divided into three reaches i.e. Vanderkloofdam to Boegoebergdam, Boegoebergdam to Onseepkans and Downstream of Onseepkans (Van Veelen & Van Heerden, 1998). In the second reach, where grapes represent 90% of the crop value, the actual salt concentration regularly exceeds 500 mg L^{-1} (0.77 dS m^{-1}), but remains below 750 mg L^{-1} (1.15 dS m^{-1}) on all but a few occasions. They concluded according to available salinity guidelines that since periods when the salt concentration increases beyond 750 mg L^{-1} are of short duration, this should not have a long-term effect on permanent crops.

Moolman *et al.* (1999), however, concluded from salinity research on grapevines in the Breede River Valley that grapevines were more sensitive to salinity than suggested by international salinity guidelines. This is important information to consider when evaluating the effect of salinity on crop production. Irrigation farmers in the lower reaches of the Vaal and Riet Rivers are experiencing substantial yield reductions in certain crops and more profitable crops have been withdrawn from production as a result of generally poor, but especially fluctuating, water quality (Armour & Viljoen, 2000). The water quality situation downstream of Vioolsdrift was furthermore identified as a definite cause for concern (Van Veelen & Van Heerden, 1998). This could also have international implications as the river is shared between South Africa and Namibia over hundreds of kilometers. Several development opportunities identified in both Namibia and South Africa can lead to increased water requirements in future (Becker & Luger, 2004) and also impact on the water quality. One such development that will be affected by water quality issues is the recommended construction of a dam at Vioolsdrift.

Salt retention: A disturbing result from DWAF's salinity model output was a decrease in salt load downstream from Kakamas to Vioolsdrift (Van Veelen & Van Heerden, 1998). This indicated that salt is retained in the system, a situation that cannot continue indefinitely. Limited water resources and increasing soil salinization in arid and semi-arid regions are universally considered to be important limitations for agricultural production (Abrol *et al.*, 1988; Orcutt & Nilsen; 2000; Rosegrant, Cai & Cline, 2002). It is estimated that 4% of the irrigated land in the Northern Cape is severely affected by salinity or waterlogging, while an additional 20% is moderately affected by these phenomena (Water Research Commission, 1996, cited in Backeberg, 2000). Salinization of semi-arid areas throughout the world is accordingly seen as a threat to long-term production of perennial fruit, which is particularly sensitive to salinity and ion toxicities (Bernstein, 1980).

A recommendation was therefore made that further investigations into salt retention on irrigated lands should be conducted as a matter of priority (Van Veelen & Van Heerden, 1997). During identification of research priorities for the Lower Orange River Valley (Winetech, 6 April 2000), grape producers rated problems related to salinity of water and soils as high (2^{nd} from 8 priorities). This request for research came despite the presentation of viable solutions to the water table problem and resulting salinization in the Lower Orange River Area approximately 10 years ago (Viljoen, Van der Ryst & Le Roux, 1991). High water tables and salinization has been a problem in irrigated areas along the Orange River since 1948 (Van Gardenen & Klintworth, 1948). Salt build-up beyond certain limits will be extremely costly to rectify and can irreversibly harm agriculture in the region.

Accepting yield decrease due to waterlogging and/or salinization is not really an option for producers as the production of deciduous fruit and grapes is already becoming increasingly difficult due to the combined effect of several constraints. Constraining factors include competition from other Southern Hemisphere suppliers (e.g. Chile, Argentina), high interest rates, lower internal rate of return and meeting the specific requirements of European markets that have stringent quality standards and demand an increasing variety of cultivars to select their products from (Huyshamer, 1997). The national GDP of table grapes alone amounts to more than 2.2 billion rand (DFPT, 2005). Expansion of the table grape industry in the upper part of the Lower Orange River system (below Vanderkloof Dam to Augrabies) with water already allocated, water for irrigation of 4000 ha earmarked for resource poor farmers (DWAF, 2004b) and future irrigation water requirements of Namibia (Becker & Luger, 2004) could furthermore put additional pressure on the system by decreasing the available volume of water and increasing irrigation return flow to the river. The water resources of the Integrated Orange River System of which the Lower Orange WMA forms part, are despite a current surplus, effectively in balance (DWAF, 2004a; DWAF, 2004b) and should be carefully managed to ensure sustainable use.

A knowledge base to design a sound management plan is thus of utmost importance to ensure a competitive agricultural industry in the region. A situation-analysis is necessary to assess the current situation with regard to problems with management of water quality in the Lower Orange WMA. This assessment could be used to identify future research or technology transfer needs which will aid in design of a management plan. The management plan should then be used as a directive for the sustainable usage of natural resources along the river, and should form part of the bigger development plan of the region including protection of the ecosystem.

1.1 Objectives

The objectives of the project were as follows:

- To assess the land use, soil salinity and water quality, as well as salinity management practices, from a synthesis of existing information and by utilizing satellite imagery and field surveys in selected areas.
- To evaluate the present situation and likely future trends with regard to water quality and soil salinity management.
- Based on the situation assessment above, to identify the need for policy development, and the need for research on which further policy development may be based, in order to protect soil and water resources in this area.

1.2 Structure of the report

The role of irrigation development in and general irrigation-induced mechanisms underlying river salinization are reviewed in Chapter 2. An assessment of water quality and trends in water quality is made in Chapter 3, while the salt generation potential of soils in three contrasting areas under irrigation and the chemical composition of drainage water of selected areas are discussed in Chapter 4 The identification and classification of cultivated areas utilizing satellite imagery and aerial survey imagery are reported in Chapters 5 and 6, respectively. The identification of the potentially salinized cultivated area and the verification thereof are also addressed in Chapter 6. Guidelines for management of water quality related problems are proposed in Chapter 7, with the need for research and policy development being illuminated in the conclusions of the report. Drainage water quality analysis data as well as soil chemical analysis data are attached in Appendices A and B, respectively, for future reference, while the potential effect of irrigation water salinity on grapevine and its leaching requirements is specifically reported on in Appendix C.

2 LITERATURE

Introduction

The sustainability of agriculture in a river basin requires a strategy, as well as the implementation of appropriate management practices, to control salinity at the irrigated field, river reach, catchment and basin scale. Otherwise, irrigation may not result in prosperity, but in demise, as was the case for several ancient civilizations where once-productive areas later turned into saline wastelands (Pillsbury, 1981). A prerequisite for a successful water and salinity management strategy in arid areas is an understanding of the processes underlying river salinization, the basics of which are described by several authors (Fourie, 1976; Tanji & Hanson, 1990; Smedema; 2000). This literature review depicts especially the role of irrigation development in the salinization process and describes general irrigation-induced mechanisms underpinning river salinization.

Sources of salt in arid zone river basins

Salinization appears to be a common feature of river basins in the arid zone, including the Aral Sea Basin in Central Asia, Colorado Basin in the western USA, the Indus Basin in Pakistan, the Murray-Darling basin in south eastern Australia and the Nile Basin in Egypt (Smedema, 2000). High evaporative demand, limited rainfall and restricted leaching are characteristics of arid areas which promote salt accumulation.

The salts found in the waters and soils in a river basin may differ in origin (Abrol *et al.*, 1988; Smedema, 2000). Salts may be released from rocks and soils by mineral weathering and dissolution (*primary salts*). In addition, sedimentary rock strata formed during previous geological periods (*fossil salts*) may become exposed through geological uplifting or erosion and, if released and mobilized by natural processes or through actions such as irrigation, may contribute substantially to the salt load in an irrigated basin. *Salts carried by wind* may be a significant source in coastal areas (100-200 kg $ha^{-1}a^{-1}$) or originate from nearby desert areas (10-100 kg $ha^{-1}a^{-1}$). *Irrigation water* also contains salt, and as plants assimilate only a small percentage thereof, it may remain in the soil when the water evapotranspires. The salt load depends on the volume and salinity of the applied irrigation water, but may amount to *ca.* 2 to 3 tons ha^{-1} for an annual application of 1000 mm water with a salinity of between 0.31 dS m^{-1} and 0.47 dS m^{-1}. *Fertilizers* which generally contain between 65% and 75% salt may contribute an additional *ca.* 200-300 kg salt $ha^{-1}a^{-1}$ where modern farming practices are applied, provided at least half of the salt is taken up by the crops (Smedema, 2000). *Salts from residential and industrial development* may also import or mobilize salts in the basin, but are generally considered to be a minor source.

Irrigation, the hydrological cycle and salinization

Resident salt storage in arid zone soils may be substantial and it may become a major problem when the salts are mobilized and become part of the salt dynamics of the basins (Abrol *et al.*, 1988; Smedema, 2000). Although the abovementioned arid zone river basins are all different and the factors contributing to their salinization vary, irrigation constitutes the main water user, generally consuming more than *ca.* 80% of the water resources in each of these respective basins (Smedema, 2000). The situation in the lower

Orange River area is not an exception, as irrigation represents 94% of the total water requirements for the Lower Orange WMA (DWAF, 2004b).

The general mechanisms by which irrigation development contributes to increase river salinity include: reduction of the dilution capacity of the river system due to abstraction and consumptive use of the river water for irrigation; the use of the river system as a means of disposal for saline drainage water generated by regular leaching and drainage of irrigated lands or reclamation of salinized land and last, but not least, loading of the river system by primary, fossil, and other types of resident salts mobilized by irrigation-induced seepage flows or by some other irrigation-induced mechanisms (Smedema, 2000).

Regular leaching of soils in arid areas is a prerequisite to prevent salinization of soils. Irrigation water contain some salts which accumulate within the irrigated root zone as soil water is used by plant transpiration or lost through evaporation (Rhoades & Loveday, 1990). High evaporative demand can create the potential for upward flow of water into the root zone through capillary rise processes. The root zone and soil surface may become salinized by this process as water is lost and the salt remains in the soil. Although groundwater is not accessible for most agricultural pastures and crops until the water table is at least 2 m from the surface, capillary rise due to high evaporative demand may bring salt from the water table to the soil surface where it concentrates (Abrol *et al.*, 1988; Pengelly & Fishburn, 2002).

Land salinization can be classed according to causal factors as dryland salinity or irrigation salinity (Pengelly & Fishburn, 2002). Dryland salinity is created by interruption of one of the natural paths (i.e. evapotranspiration) through which ground water is removed from the water table, while irrigation salinity is caused by increasing groundwater inputs. Land use decisions basically underlie the formation of dryland salinity (Pengelly & Fishburn, 2002). Replacement of deeply rooted vegetation by shallow-rooted plants and the effect of the resultant decreased evapotranspiration on the hydrological cycle results in a rise of the water table which mobilizes large quantities of salt previously stored deep within the soil. The rise in the water table resulting in irrigation-induced salinity is, however, due to irrigation water applied in excess of plant evapotranspiration as well as leakages from supply canals and water storage structures which percolate into the groundwater, and may become enough to raise the water table, and with it the salt.

Salt removal from the soil profile can be achieved by applying water in excess of the evapotranspiration requirements. The fraction of water that passes through the root zone is called the leaching fraction (Rhoades & Loveday, 1990). By varying the leaching fraction, the concentration of salts in the drainage water and soil water in the profile can be controlled within certain limits for fields irrigated to steady state conditions (Rhoades & Loveday, 1990). The latter assumes no appreciable contribution of salts from the dissolution of soil minerals or salts or removal of salts by precipitation or plants, uniform aerial application of water in the field and a water table depth sufficient to prevent introduction of salts into the root zone from capillary rise processes. Under such conditions, the leaching/drainage water becomes more concentrated with a lower leaching fraction (increased irrigation efficiency) and less concentrated with a higher leaching fraction (decreased irrigation efficiency) (Rhoades & Loveday, 1990; Smedema, 2000). Sometimes equilibrium conditions may not exist, or the relationships may be disturbed by the leaching/

drainage water having picked up resident or other salts, being partly generated by rainfall or containing significant other flow components (surface irrigation waste, drainage flows from non-irrigated land, etc.).

Excessive drainage of irrigation water may also change the prevailing geohydrological flow regimes in a catchment by induction of previously non-existing groundwater flows which may load the rivers with formerly harmless, deeply stored resident salts (Smedema, 2000). The lag time before groundwater salinity levels start to increase following the introduction of irrigation to an area will be approximately proportional to the rate of irrigation drainage (Leany, 2000). The lag time and maximum salinity level of the groundwater are mainly determined by soil texture (clay content), gravimetic water content, recharge/drainage rates after clearing and after irrigation, and the amount of salt storage. The rate of irrigation drainage is largely controlled by irrigation efficiency, the surface soil properties and the irrigated crop type. Research on groundwater salinization in the Tintinara area of South Australia, based on a modelling approach, predicted lag times for areas with 30 m deep water tables of between 20 and 60 years if drainage rates are *ca.* 200 mm a^{-1} and *ca.* 100 mm a^{-1}, respectively. These drainage rates are typical of that expected from irrigation of olive trees using micro-spray irrigation systems. Lag time for areas with 60 m deep water tables was estimated to vary between 30 to 90 years, depending on the drainage rate (Leany, 2000). Although the soil physical characteristics and drainage rates are more important to determine the recharge rate, salinity levels of the groundwater in the study area may largely be determined by the amount of salt storage in the overlying soil. According to Leany (2000), predictions for areas in the Tintinara region that are irrigated over the time frames given above, indicate that salinity levels of the groundwater may rise from less than 1000 mg L^{-1} to between 1500 and 6000 mg L^{-1}.

River salinization and its management

Although salinity naturally tends to increase downstream in rivers, irrigation may exacerbate these trends through the processes described above. This occurs where rivers in irrigated basins serve as sources of irrigation water as well as sinks for drainage water and the salinity of the river water tends to increase especially downstream as the drainage water returns to the lower river reaches. South African examples in this regard are ample and include amongst others, the Lower Vaal River (Du Preez *et al.* 2000), Fish/ Sundays rivers (Hall & Du Plessis, 1979), the Berg River (Fourie, 1976) and the Breede River (Fourie, 1976; Greeff, 1990). The water quality deterioration in these rivers, however, cannot solely be attributed to irrigation effluent as urban and industrial effluent may also contribute.

Longitudal annual average salinity profiles of the main stems of river systems reflect the combined impacts of water abstraction and salt loading and can be related to a particular status of the salt balance (Smedema, 2000). The profiles are most representative of rivers where flow is highly regulated, but for other basins the salinity values may be considerably lower during the wet season and higher during the dry season. Although several generic profile types may be conceived, three basic profiles are defined namely an equilibrium, a salinization and a mobilization profile. The *equilibrium profile* develops when all the salts diverted from the river with the irrigation water return to the river with the drainage flows and there is no salt-loading of the river by primary, fossil, or other resident salts already present in the basin, *i.e.* the salt balance is in equilibrium (salt input = salt output). A *salinization profile* forms where not all of the diverted salt returns to the river, but is partly retained in the irrigated land and underlying groundwater.

Salt retention results in a positive salt balance (salt input > salt output) with the salt load of the river decreasing downstream and lower river salinity values occur along the length of the river compared to the equilibrium profile scenario. The *mobilization profile* occurs when fossil, primary or other resident salts in the basin are being mobilized and are entering the river system. This profile represents a negative salt balance (salt input < salt output) and is the most common for irrigated basins in the arid zone. The salinity level of the profile is higher compared to that of the equilibrium profile and has steep gradients particularly in the mobilization reaches of the river. The shapes of the profiles are all dependant on the abstraction/return flow ratio and the irrigation/drainage water salinity ratio, while surplus loading of the river is an additional factor affecting the mobilization profile (Smedema, 2000). Irrigation management can therefore significantly affect the river profile, especially through increased water use efficiency and reduced drainage volumes (Rhoades & Loveday, 1990; Tanji & Hanson, 1990; Ayars & Tanji, 1999).

Control measures to deter the downstream increase in river salinity are difficult to adopt in a developed river basin where the water resources have been almost fully allocated and used (Smedema, 2000). Management options basically lies between decreasing water abstraction or alternatively increasing fresh river flows, and reducing the salt loading of the river while maintaining the salt balance of the land and preventing the salinization of land by disposal of salts by means other than via the river (Rhoades & Loveday, 1990; Tanji & Hanson, 1990; Madramootoo *et al.*, 1997; Smedema, 2000). Such measures generally either place restrictions on the water use or on the disposal of saline water, or add to the water use or disposal costs (Smedema, 2000).

The water resources in the Lower Orange WMA are nearly all allocated (DWAF, 2004a; DWAF, 2004b), which may restrict possibilities for water quality management in the area (Smedema, 2000). The literature confirms that, in order to devise an appropriate water quality management strategy, knowledge of the current salinity status and salinity management of the water resource, as well as a clear understanding of the catchment specific mechanisms which contribute to river salinization, is necessary. It is in this context that research results on surface and drainage water quality (Chapter 3), the salt generation potential of selected soils under irrigation (Chapter 4), the soil salinity status of the irrigated area (Chapters 5 and 6) and water quality management practices (Chapter 7) in the Lower Orange WMA are presented.

3 WATER QUALITY OF THE LOWER ORANGE RIVER

3.1 Introduction

An assessment of water quality or trends in water quality is a necessity if problems for water quality management are to be identified. Water quality in the lower Orange River region is of importance for mainly five user groups namely recreational, domestic, industries, agriculture and the environment. The focus of this report, however, will be on crop farming, which is one of the most important economic activities in the lower Orange River.

Water quality is generally categorized according to its potential effects on crop yield and quality, soil physical properties and irrigation equipment (Ayers & Westcot, 1985). The main criteria used to establish if irrigation water has potential to cause soil conditions injurious to crop growth are salinity, sodicity and specific ion concentrations (Shainberg & Letey, 1984). Salinity refers to total salt concentration and is most commonly measured and reported as electrical conductivity (EC), while the sodium adsorption ratio (SAR = $Na^+/(Ca^{2+} + Mg^{2+})^{½}$ with Na^+, Ca^{2+} and Mg^{2+} in mmol dm^{-3}) is frequently used to quantify the irrigation water sodium hazard.

In this chapter the water quality of the lower Orange River downstream from Boegoeberg (Fig. 1.1b) will be assessed and patterns of downstream deterioration of water quality and trends in water quality over time discussed. The quality of drainage water from selected small primary catchments is reported and an attempt made to estimate the degree of salt efflux from the river reach between Boegoeberg and Onseepkans. An assessment is also made of the *status quo* regarding management of salinization in the region.

3.2 Data collection, retrieval and processing

Water quality data for the lower Orange River was obtained from the chemical database of the Directorate of Resource Quality Services of the Department of Water Affairs and Forestry (DWAF) in South Africa. All available data for all the water quality monitoring sites between Boegoebergdam and Alexander Bay (Fig. 1.1b, Table 3.1) were requested electronically. Monitoring sites beyond the river reach between Boegoeberg to Onseepkans in the direction of the river mouth were included to aid in data interpretation. The water quality variables researched included pH, electrical conductivity (EC, dS m^{-1}), the concentration (mg L^{-1}) of dissolved sodium (Na), potassium (K), magnesium (Mg), calcium (Ca,) chloride (Cl), nitrogen as ammonium (NH_4-N), nitrogen as nitrate and nitrite (NO_3-N), phosphorus as phosphate (PO_4-P), sulphur as sulphate (SO_4) and total alkalinity as calcium carbonate. The SAR for each sampling site was also obtained.

To get an initial indication of the water quality situation in the lower Orange River all available data per monitoring site were classed for salinity, sodicity as well as for sodium and chloride toxicity according to the South African Water Quality Guidelines (DWAF, 1996). Datasets for many monitoring sites were incomplete as the samples for certain periods of time were not taken continuously. The values of water quality variables in general vary throughout the season due to changes in river water flow, evaporative demand and the volume and quality of irrigation return flows. Annual means based on data limited to single or certain months in a year may therefore result in erroneous trends in water quality. The data were therefore sorted according to sampling date into four seasons, namely spring (Sep to Nov), summer (Dec to Feb), autumn (Mar to May) and winter (Jun to Aug). Annual means for each water quality variable were only calculated if at least one measurement per season and all four seasons per year had data available.

Analysis of variance was done per monitoring site and for the river reaches from Boegoeberg to Onseepkans and Onseepkans to Alexander Bay, respectively, to assess if there were differences in water quality variables between seasons over the long term. Water quality monitoring sites for which the data set contained at least four annual mean data points per variable were selected for evaluation of long-term trends in water quality. Data for the Onseepkans site were only available until 1998 and since data compared well to that of Pella during 1996 to 1998, data from the Pella monitoring site was used to continue the annual mean data set for Onseepkans from 1999 to 2003 for evaluation of trends over time.

Table 3.1 Water quality monitoring sites of the South African Department of Water Affairs and Forestry between Boegoeberg and Alexander Bay in the lower Orange River region. The estimated distance downstream (DD) is relative to Boegoeberg reserve/ Zeekoebaart

Monitoring site	Description	DD (km)	Latitude	Longitude	Drainage region	Date of first samples	End date of record on 06/05/2004	No. of samples
D7H008	Boegoeberg reserve/ Zeekoebaart	0	-29.029722	+22.187778	D73	01/04/1966	26/01/2004	827
D7H005	Upington	95	-28.460833	+21.248889	D73	03/10/1952	20/10/2003	3869
D7H003	Kakamas	155	-28.755278	+20.621111	D73	01/10/1965	10/12/1993	201
D7H014	Kakamas South/ Neusberg left side	155	-28.768056	+20.720556	D73	02/01/1995	16/02/2004	249
D8H002	Kakamas South/ Renosterkop island	155	-28.641111	+20.428889	D81	30/06/1968	03/11/1972	7
D8H004	Onseepkans	275	-28.735556	+19.306111	D81	22/08/1971	23/04/2000	943
D8H008	Pella Mission	318	-28.963056	+19.152500	D81	28/04/1980	31/01/2004	572
D8H003	Vioolsdrift	470	-28.760833	+17.730278	D82	16/02/1959	30/10/2003	1237
D8H007	Brand Kaross	643	-28.486111	+16.695556	D82	08/08/1971	16/04/2002	414
D8H012	Alexander Bay	683	-28.566111	+16.508056	D82	16/05/1995	17/04/2002	280

The quality of drainage water from irrigated vineyards on foothill soils was monitored from July 2003 to April 2004 at five small catchments selected in co-ordination with personnel of the Nothern Cape Department of Agriculture. The sites included soils typical of the lower Orange River region that predominated either in gneiss, windblown Kalahari sands or calcrete. Two of the catchments were located in an eastern and three in a western direction from Upington (Fig. 1b; Table 3.2). The drainage water was analyzed for pH, EC, all the cations and anions as described above for the river water, as well as carbonate (CO_3), bicarbonate (HCO3), boron (B) and silica (Si).

Table 3.2 The location of drainage water quality monitoring sites and dominant features of the associated foothill soils in the lower Orange River region

Drainage water monitoring site	Latitude	Longitude	Location	Dominant soil feature
Rooiland	-28.415403343	+21.323547161	±13 km from Upington on Olifantshoekroad (N14)	Calcrete
Carpe Diem	-28.447805000	+21.318630000	±14 km from Upington on Groblershoop road	Calcrete
SMB	-28.756243230	+20.784749826	± 20 km from Keimoes to Kakamas	Windblown sand
Strauss	-28.743912847	+20.530209862	±12 km from Kakamas to Augrabies, near Alheit	Gneiss
Chargo Trust	-28.693328253	+20.463467094	±20 km from Kakamas, near Marchand.	Gneiss

Monthly river flow data was obtained from the hydrology website of DWAF (http://www.dwaf.gov.za/Hydrology) for the Boegoeberg/Zeekoebaart, Upington and Onseepkans river water quality monitoring sites and the annual mean river flow was calculated for January to December per site. Linear regression relationships were used to relate the annual mean flow of each of the monitoring sites to that of the others to enable estimation of flow for years with missing data. The flow data were used in combination with EC data to estimate the annual mean salt efflux from the reach between Boegoeberg to Onseepkans at Onseepkans as follows:

$$\text{Salt load}_{\text{Boegoeberg}} = EC_{\text{Boegoeberg}} \times 650 \times 10^{-9} \times \text{Flow}_{\text{Boegoeberg}} \quad (3.1)$$

$$\text{Salt load}_{\text{Onseepkans}} = EC_{\text{Onseepkans}} \times 650 \times 10^{-9} \times \text{Flow}_{\text{Onseepkans}} \quad (3.2)$$

$$\text{Annual salt efflux}_{\text{Onseepkans}} = \text{Salt load}_{\text{Onseepkans}} - \text{Salt load}_{\text{Boegoeberg}} \quad (3.3)$$

where

EC = annual mean EC of the irrigation water (dS m^{-1} at 25°C)

Flow = annual mean water flow ($m^3 \times 10^6$)

The average conversion factor to estimate total dissolved solids from EC (dS m^{-1} at 25°C) is 650 mg L^{-1} (DWAF, 1996) and salt load is reported in units of tons.

The annual mean river flow of the river reach between Boegoeberg and Onseepkans was calculated as the mean of the annual mean flow of that at Boegoeberg, Upington and Onseepkans.

3.3 Results and discussion

3.3.1 Status of water quality monitoring sites

The water quality and flow data available for the monitoring sites in the lower Orange River were in general discontinuous and long-term means may therefore not present an accurate picture regarding the salinity status of the river. The number of samples available for analysis varied between monitoring sites and ranged between 7 and *ca.* 3870, with the largest data sets available being that for Boegoeberg reserve/ Zeekoebaart (referred to as Boegoeberg from here on), Upington and Vioolsdrift (Table 3.1). The data set for Kakamas was limited with no data at all for 1994 and the data for monitoring sites D7H003, D7H014 and D8H002 were combined for statistical analyses purposes. Onseepkans marks the end of the intensely irrigated area which starts at Boegoeberg. Monitoring of water quality at Onseepkans was terminated in 2000 despite recommendations of the Orange River Development Project Replanning Study for it to be continued on a monthly basis (Van Veelen & Van Heerden, 1998).

Downstream of the study area between Boegoeberg and Onseepkans a relatively complete dataset was collected from 1980 until 2004 at Pella (Table 3.1). The latest data available for Brand Kaross and Alexander Bay were April 2002, which renders Vioolsdrift as the only remaining monitoring site that is currently active beyond Pella in the direction of the river mouth. The importance of collection of monthly water quality data for the interpretation of trends in river salinization over the long term cannot be overemphasized and steps should be taken immediately to ensure a reliable water quality data base for the lower Orange River region in the future. In this regard, the recommendations of the Orange River Development Project Replanning Study for the publishing of an annual water quality report (Van Veelen & Van Heerden, 1998) should be seriously considered.

3.3.2 General classification of river water quality

Classification of water quality of the Orange river in the lower Orange river region according to the South African Water Quality Guidelines (DWAF, 1996) indicated that the water is of good quality. Approximately 75% of all available EC values were assigned to Class I which include EC values of less than 0.4 dS m^{-1} (Tables 3.3 & 3.4). No yield decreases are expected if salt sensitive crops are irrigated with Class I water provided a leaching fraction of 0.1 is applied for low frequency irrigation systems and that wetting of foliage is avoided (DWAF, 1996).

Class II quality water includes water with EC values of equal to or more than 0.4 dS m^{-1} but less than 0.9 dS m^{-1}. The percentage of water quality values in EC Class II in general increased downstream from Boegoeberg to Brand Kaross, with an abrupt increase at the river mouth (Table 3.3) where the water quality is affected by variations in tidal flow. The percentage of values in EC Class II at Alexander Bay was approximately tenfold compared to that at Boegoeberg and nearly threefold that at Brand Kaross. The percentage of EC values in Class II remained less than 14% for the values between Boegoebergdam and Onseepkans and increased to *ca.* 32% for the values of the river reach from Onseepkans to Alexander Bay. Electrical conductivity values exceeding the boundaries of Class II amounted to less than 1% and were restricted to Alexander Bay, except for one EC value of 0.92 dS m^{-1} at Boegoebergdam (Table 3.3). A 95% relative yield of moderately salt sensitive crops such as grapevine can be maintained by using EC Class II water with a low frequency irrigation system and by applying a leaching fraction of 0.1 (DWAF, 1996). Wetting of foliage of sensitive crops should be avoided (DWAF, 1996).

Table 3.3 Classification of irrigation water salinity measured as electrical conductivity (EC) of all the available data for selected monitoring sites for the lower Orange River region during the period 1960 to 2003 (n = the number of observations)

Water quality monitoring site	Salinity class (%)			n
	I (EC< 0.4 dS m^{-1})	II ($0.4 \leq$ EC < 0.9 dS m^{-1})	III ($0.9 \leq$ EC < 2.7 dS m^{-1})	
Boegoeberg	92.7	7.2	0.1	790
Upington	80.4	19.6	0.0	240
Kakamas	87.6	12.4	0.0	314
Onseepkans	82.0	18.0	0.0	943
Pella	64.0	36.0	0.0	411
Vioolsdrift	74.7	25.3	0.0	1203
Brand Kaross	74.0	26.0	0.0	412
Alexander Bay	27.8	71.1	1.1	263

Table 3.4 Classification of irrigation water salinity measured as electrical conductivity (EC) of all the available data for selected river reaches in the lower Orange River region during the period 1960 to 2003 (n = the number of observations)

River reach	Salinity class (%)			n
	I (EC< 0.4 dS m^{-1})	II ($0.4 \leq$ EC < 0.9 dS m^{-1})	III ($0.9 \leq$ EC < 2.7 dS m^{-1})	
Boegoeberg to Onseepkans	86.3	13.7	0.0	2287
Onseepkans to Alexander Bay	67.7	32.2	0.1	2339
Boegoeberg to Alexander Bay	76.9	23.0	0.1	4626

The potential of water to cause infiltration problems is determined by mutually evaluating the SAR and EC values of the water as increasingly saline water tends to counter the negative effects of sodium on infiltration of water into the soil. More than *c.* 90% of all available SAR values classed for potential soil infiltration problems, were assigned to Class I that include SAR values of less than 1.5 (Tables 3.5 & 3.6). The exception was at Alexander Bay where less than 75% of SAR values were of Class I. Nearly all the SAR values in class II and III may, according to the associated EC values of the water, cause moderate infiltration problems, especially at Onseepkans, Pella, Vioolsdrift and Alexander Bay (Table 3.5).

The percentage SAR values that is expected to cause moderate soil infiltration problems remained less than 5% of the values between Boegoebergdam and Onseepkans and increased to *c.* 11% of the values for the river reach from Onseepkans to Alexander Bay (Table 3.6). The adjusted SAR may be a better indicator of the sodicity danger regarding infiltration of water into the soil, especially where sufficient calcium and enough carbonate, bicarbonate and sulphates are present in the water to result in precipitation of calcium as calcium carbonate or calcium sulphate (Ayers & Westcot, 1985). However, a very limited adjusted SAR dataset was available for selected monitoring sites (Table 3.7) and the necessary bicarbonate data for calculation of the index not obtainable from DWAF. The adjusted SAR values were between 51% and 80% higher compared to that of the SAR, with the ratio of adjusted SAR to

SAR increasing downstream from Boegoeberg. Furthermore, the percentage of adjusted SAR values exceeding a value of 1.5 was greater than 60% for all the monitoring sites except Boegoeberg. Based on these results it is recommended that the adjusted SAR be used for evaluation of potential infiltration problems of water from the lower Orange River downstream of Boegoeberg. The data set on which the recommendation is based, however, represents a very limited period during 1999 and 2000 and the sample size for some sites was very small.

Table 3.5 Classification of water sodicity of all the available sodium adsorption ratio (SAR) data for selected monitoring sites for the lower Orange River region during the period 1960 to 2003 (n = the number of observations). The SAR and electrical conductivity (EC) are evaluated together to establish the potential for problems with infiltration of water into the soil (IP). The SAR is measured in units of (mmol $L^{-1})^{0.5}$ and EC in dS m^{-1}

Water quality monitoring site	Sodicity class (%)							n
	I SAR < 1.5	II 1.5 ≤ SAR < 3.0			III 3.0 ≤ SAR < 6.0			
	0.2 > EC ≥ 0.2	EC < 0.2	0.2 ≤ EC ≤ 0.9	EC > 0.9	<0.25	0.25 ≤ EC ≤ 1.3	>1.3	
	No IP	IP Likely	Moderate IP	No IP	IP Likely	Moderate IP	No IP	
Boegoeberg	97.9	0.0	1.9	0.2	0.0	0.0	0.0	583
Upington	95.8	0.0	4.2	0.0	0.0	0.0	0.0	240
Kakamas	98.1	0.0	1.4	0.0	0.0	0.5	0.0	215
Onseepkans	93.0	0.0	7.0	0.0	0.0	0.0	0.0	545
Pella	94.1	0.0	5.9	0.0	0.0	0.0	0.0	405
Vioolsdrift	90.8	0.0	9.0	0.0	0.0	0.1	0.0	768
Brand Kaross	95.0	0.0	4.3	0.0	0.0	0.7	0.0	141
Alexander Bay	73.0	0.0	25.1	0.4	0.0	1.5	0.0	263

Table 3.6 Classification of water sodicity of all the available sodium adsorption ratio (SAR) data for selected river reaches in the lower Orange River region during the period 1960 to 2003 (n = the number of observations). The SAR and electrical conductivity (EC) are evaluated together to establish the potential for problems with infiltration of water into the soil (IP). The SAR is measured in units of (mmol $L^{-1})^{0.5}$ and EC in dS m^{-1}

River reach	Sodicity class (%)							n
	I SAR < 1.5	II 1.5 ≤ SAR < 3.0			III 3.0 ≤ SAR < 6.0			
	0.2 > EC ≥ 0.2	EC < 0.2	0.2 ≤ EC ≤ 0.9	EC > 0.9	<0.25	0.25 ≤ EC ≤ 1.3	>1.3	
	No IP	IP Likely	Moderate IP	No IP	IP Likely	Moderate IP	No IP	
Boegoeberg to Onseepkans	96.0	0.0	3.9	0.1	0.0	0.1	0.0	1524
Onseepkans to Alexander Bay	89.4	0.0	10.2	0.1	0.0	0.4	0.0	1624
Boegoeberg to Alexander Bay	92.6	0.0	7.1	0.1	0.0	0.2	0.0	3207

Table 3.7 The relative increase of the adjusted SAR (SARa) over the SAR and the percentage of SARa values exceeding a value of 1.5 for selected monitoring sites in the lower Orange River for a variety of dates during the period 1999 and 2000

Monitoring site	SARa: SAR ratio	SARa values > 1.5 (%)	n	Begin date	End date
Boegoeberg	1.51	24.0	50	10/04/1999	26/12/2000
Upington	1.67	75.0	8	08/08/2000	26/09/2000
Onseepkans	1.62	62.5	8	27/02/2000	23/04/2000
Pella	1.69	67.8	59	07/03/1999	02/12/2000
Vioolsdrift	1.70	62.7	51	20/02/1999	16/12/2000
Alexander Bay	1.80	100.0	32	17/08/1999	10/10/2000

Classification of water for sodium toxicity through root uptake confirmed the low potential for problems regarding water quality in the lower Orange River region. Less than 2.5% of all SAR values per monitoring site were classed SAR toxicity Class II, except at Alexander Bay where *ca.* 10% of the values exceeded an SAR value of 2 (Table 3.8). Only *ca.* 1% of SAR values exceeded a value of 2 for the river reach between Boegoeberg and Onseepkans while 2.6% of the SAR values between Onseepkans and Alexander Bay ranged between 2 and 3.9 (data not shown) (Table 3.9). The maximum SAR values remained less than 3 for water from monitoring stations from Boegoeberg to Pella. The exception was one SAR value of 5.1 recorded at Kakamas. Grapevine yield may be reduced if the SAR exceeds a value of 3 in the saturated soil water extract (Myburgh & Howell, unpublished final report, ARC Infruitec-Nietvoorbij, Project WW04/13). The classification of the SAR data for the lower Orange River water therefore indicated that the probability that sodium toxicity will develop in plants sensitive to sodium through root uptake is limited, provided that the leaching fraction is such that the SAR does not exceed a value of 3 in the saturated soil water extract. Monitoring sites that presented the highest risk for development of sodium toxicity were Onseepkans and Alexander Bay.

Table 3.8 Sodium toxicity classification according to the sodium adsorption ratio (SAR) for conditions where foliage is not wetted (that is, through root uptake) and the number of observations (n) used to calculate the long-term mean SAR from all available SAR data for different monitoring sites during the period 1960 to 2003 for the lower Orange River region

Monitoring site	Sodium toxicity class (%)		n
	I (SAR < 2)	II ($2 \leq$ SAR< 8)	
Boegoeberg	99.5	0.5	583
Upington	99.2	0.8	240
Kakamas	99.5	0.5	215
Onseepkans	97.8	2.2	545
Pella	99.8	0.2	405
Vioolsdrift	98.4	1.6	765
Brand Kaross	98.6	1.4	141
Alexander Bay	89.7	10.3	263

Table 3.9 Sodium toxicity classification according to the sodium adsorption ratio (SAR) for conditions where foliage is not wetted (that is, through root uptake) and the number of observations (n) used to calculate the long-term mean SAR from all available SAR data for different river reaches during the period 1960 to 2003 for the lower Orange River region

River reach	Sodium toxicity class (%)		n
	I	II	
	(SAR < 2)	(2 ≤ SAR< 8)	
Boegoeberg to Onseepkans	98.9	1.1	1583
Onseepkans to Alexander Bay	97.4	2.6	1624
Boegoeberg to Alexander Bay	98.1	1.9	3207

Classification of water for sodium toxicity through foliar absorption and root uptake, respectively, rendered similar results, namely that the probability for the development of sodium toxicity is minimal with the highest risk being at Alexander Bay (Tables 3.10 & 3.11). The maximum sodium concentration from Class II was 102 mg L^{-1} at Alexander Bay, while single values of 123 mg L^{-1} and 147 mg L^{-1} at Brand Kaross and Kakamas, respectively, were assigned to Class III. Foliar injury of grapevine may occur if the sodium concentration in sprinkler water exceeds 115 to 230 mg L^{-1} (Ayers & Westcot, 1985), indicating that Class II water may still be used for overhead irrigation of vineyard. This guideline, however, is only applicable for daytime sprinkling under conditions that are not too hot or too dry (DWAF, 1996).

Table 3.10 Sodium toxicity classification for foliar absorption and the number of observations (n) used to calculate the long-term mean sodium from all available sodium concentration data for different monitoring sites during the period 1960 to 2003 for the lower Orange River region

Monitoring site	Sodium toxicity class (%)			n
	I	II	III	
	Na ≤ 70 mg L^{-1}	70 < Na < 115 mg L^{-1}	115 ≤ Na < 230 mg L^{-1}	
Boegoeberg	99.5	0.5	0.0	583
Upington	99.6	0.4	0.0	240
Kakamas	99.5	0.0	0.5	215
Onseepkans	98.7	1.3	0.0	545
Pella	99.8	0.2	0.0	405
Vioolsdrift	99.0	1.0	0.0	768
Brand Kaross	99.3	0.0	0.7	141
Alexander Bay	93.5	6.5	0.0	263

The classification of chloride concentration data indicated that the probability for chloride toxicity was even less than that for sodium toxicity (Tables 3.12 & 3.13). Less than 1% of the chloride values for all monitoring stations and river reaches exceeded 100 mg L^{-1}, which is the maximum chloride concentration that is expected not to cause chloride accumulation in all but the most sensitive plants, even when chloride uptake is through foliar absorption when crop foliage is wetted. The chloride concentration did not exceed 103 mg L^{-1} except at Boegoeberg where it ranged between 106 mg L^{-1} and 135 mg L^{-1}, and at

Kakamas, where the chloride concentration reached 124 mg L^{-1}. Foliar injury of grapevine through foliar absorption of chloride may be expected at chloride concentrations of between 175 mg L^{-1} and 350 mg L^{-1} (Ayers & Westcot, 1995). This guideline, however, is only applicable for daytime sprinkling under conditions that are not too hot or too dry. The South African water quality guidelines class grapevine as sensitive, indicating that water with chloride concentrations of less than 175 mg L^{-1} may cause foliar injury (DWAF, 1996).

Table 3.11 Sodium toxicity classification for foliar absorption and the number of observations (n) used to calculate the long-term mean sodium from all available sodium concentration data for different river reaches during the period 1960 to 2003 for the lower Orange River region

River reach	Sodium toxicity class (%)			n
	I	II	III	
	$Na \leq 70$ mg L^{-1}	$70 < Na < 115$ mg L^{-1}	$115 \leq Na < 230$ mg L^{-1}	
Boegoeberg to Onseepkans	99.2	0.7	0.1	1583
Onseepkans to Alexander Bay	98.3	1.6	0.1	1627
Boegoeberg to Alexander Bay	98.8	1.2	0.1	3210

Table 3.12 Chloride toxicity classification of the water and the number of observations (n) used to calculate the long-term mean chloride concentration in the water from all available chloride concentration data for different monitoring sites during the period 1960 to 2003 for the lower Orange River region

Monitoring site	Chloride toxicity class (%)		n
	I	II	
	($Cl \leq 100$ mg L^{-1})	($100 < Cl < 140$ mg L^{-1})	
Boegoeberg	99.5	0.5	582
Upington	99.6	0.4	240
Kakamas	99.5	0.5	215
Onseepkans	99.8	0.2	545
Pella	100.0	0.0	405
Vioolsdrift	100.0	0.0	768
Brand Kaross	100.0	0.0	141
Alexander Bay	99.2	0.8	263

Table 3.13 Chloride toxicity classification of the water and the number of observations (n) used to calculate the long-term mean chloride concentration in the water from all available chloride concentration data for different river reaches during the period 1960 to 2003 for the lower Orange River region

Monitoring site	Chloride toxicity class (%)		n
	I	II	
	($Cl \leq 100$ mg L^{-1})	($100 < Cl < 140$ mg L^{-1})	
Boegoeberg to Onseepkans	99.6	0.4	1583
Onseepkans to Alexander Bay	99.9	0.1	1624
Boegoeberg to Alexander Bay	99.8	0.2	3209

3.3.3 Trends in river water quality

The long-term mean gives a better indication of the long-term magnitude of the different water quality variables for some monitoring sites compared to that of others in the lower Orange River, as the number of years on which the long-term mean was based varied between 5 and 25 years. Monitoring sites for which more than ten years of annual average data were available included Boegoeberg, Upington, Onseepkans and Vioolsdrift. The long-term mean EC data for the lower Orange River region indicated that the salinity of the water at all monitoring stations except Alexander Bay is such that salt sensitive crops can be grown without suffering a yield decrease when using low frequency irrigation systems (Table 3.14). However, a leaching fraction of 0.1 may be required and wetting of foliage of sensitive crops should be avoided (DWAF, 1996). The long-term mean EC for the river reach from Boegoeberg to Onseepkans was less than 0.3 dS m^{-1} and from Onseepkans to Alexander Bay less than 0.4 dS m^{-1} (Table 3.15). According to the long-term mean SAR, irrigation water sodicity should not pose any problems regarding the infiltration of water into soils as the SAR values for the water remained below 1.5 from Boegoeberg to the river mouth (Tables 3.14 & 3.15). An adequate infiltration rate may therefore be expected even for soils sensitive to the formation of infiltration rate reducing surface seals under conditions of rainfall during the irrigation season (DWAF, 1996).

Table 3.14 Long-term mean values (1960 to 2003) of the water quality variables for the monitoring sites in the lower Orange River. Only years with at least one data point available for each of the four seasons were included in long-term means (n = minimum number of years used to calculate the long-term mean)

Water quality monitoring site	pH	EC	Cation/anion concentration (mg L^{-1})										SAR	n
		(dS m^{-1})	Na	K	Mg	Ca	Cl	SO_4	PO_4-P	NH_4-N	NO_3-N	TAL[1]		
Boegoeberg	8.0	0.26	14	2.3	10	23	14	21	0.03	0.05	0.3	89	0.63	17
Upington	7.9	0.30	17	2.0	10	23	18	21	0.02	0.04	0.4	92	0.74	11
Kakamas	7.6	0.29	17	1.9	10	25	13	17	0.04	0.04	0.2	104	0.70	5
Onseepkans	7.9	0.32	22	2.1	12	26	18	24	0.02	0.04	0.2	106	0.87	19
Pella	8.2	0.37	24	2.8	13	29	22	36	0.03	0.03	0.2	113	0.92	8
Vioolsdrift	7.9	0.35	23	2.3	12	28	20	28	0.02	0.04	0.2	112	0.90	25
Brand Kaross	7.4	0.35	24	2.0	12	28	20	25	0.02	0.04	0.1	108	0.96	8
Alexander Bay	8.4	0.46	36	3.5	15	34	33	47	0.04	0.03	0.2	134	1.25	6

[1] Total alkalinity as calcium carbonate

Table 3.15 Long-term mean values (1960 to 2003) of the water quality variables for selected river reaches in the lower Orange River. Only years with at least one data point available for each of the four seasons were included in long-term means (n = minimum number of years used to calculate the long-term mean)

River reach	pH	EC	Cation/anion concentration (mg L^{-1})										SAR	n
		(dS m^{-1})	Na	K	Mg	Ca	Cl	SO_4	PO_4-P	NH_4-N	NO_3-N	TAL[1]		
Boegoeberg to Onseepkans	7.9	0.29	18	2.1	11	24	16	22	0.03	0.04	0.3	97	0.74	52
Onseepkans to Alexander Bay	8.0	0.36	25	2.5	13	29	22	31	0.02	0.04	0.2	114	0.96	47
Boegoeberg to Alexander Bay	7.9	0.32	21	2.3	11	26	19	26	0.03	0.04	0.2	105	0.84	99

[1] Total alkalinity as calcium carbonate

Ion concentrations in the water in general decreased as follows: Ca, SO_4, Na, Cl, Mg, K, NO_3-N, NH_4-N and PO_4-P (Tables 3.14 & 3.15). Sodium and Cl concentrations in the water remained below toxic levels, provided the leaves of sensitive crops are not wetted. Sodicity problems may be aggravated if Mg is present in higher concentrations than Ca (Ayers & Westcot, 1985). The ratio of Ca to Mg, however, was more than 2, indicating that Mg concentrations in the Lower Orange river water will not increase sodicity related problems. The PO_4 concentration remained below 0.05 mg L^{-1}, which is considered low. The highest long-term SO_4 levels were found in the water at Pella and Alexander Bay and the concentration remained less than 50 mg L^{-1}, which is near the lower end of its usual concentration range in irrigation water (Ayers & Westcot, 1985). Ammonium-nitrogen levels higher than 1 mg L^{-1} are seldom found in irrigation water and the concentration of NO_3-N found in most surface water is less than 5 mg L^{-1} (Ayers and Westcot, 1985). The NH_4-N concentration was less than 0.1 mg L^{-1} and NO_3-N less than 0.5 mg L^{-1} at all monitoring sites and it was therefore not considered problematic over the long term. The long-term mean pH value of the water remained below 8.0 for the river reach from Boegoeberg to Onseepkans, with higher pH values recorded only at Pella and Alexander Bay. The pH at the river mouth reached the upper boundary of the acceptable pH range for irrigation water.

3.3.3.1 Trends downstream

The long-term mean EC and SAR for the period 1960 to 2003 at Boegoeberg (Table 3.14) was slightly higher compared to the long-term means downstream of the Vaal/Orange confluence calculated for the period 1971 to 1997. The long-term mean EC at the Prieska and Irene monitoring sites was 0.23 dS m^{-1} and the SAR equaled 0.53 (Du Preez et al., 2000). The Na, Mg and Ca concentrations in the water increased by approximately 2 mg L^{-1}, while the K, Cl and SO_4 concentration, respectively, increased by *ca.* 0.5 mg L^{-1}, *ca.* 3 mg L^{-1} and *ca.* 6 mg L^{-1} at Boegoeberg compared to the Prieska and Irene monitoring sites. The nitrogen and PO_4 concentrations remained approximately the same for Boegoeberg and the Prieska and Irene monitoring sites. The pH at Boegoeberg, however, was 8.0 compared to the 7.6 at Prieska and Irene and the total alkalinity increased by 11 mg L^{-1}.

The EC tended to increase with increasing distance from Boegoeberg to the river mouth (R^2 = 0.72, p = 0.008). Statistically significant linear regression relationships at a 95% confidence level were found for several ions with the distance downstream to Alexander Bay, including Ca (R^2 = 0.75, p = 0.005), Mg (R^2 = 0.67, p = 0.014), Na (R^2 = 0.78, p = 0.004) and Cl (R^2 = 0.60, p = 0.024). The linear regression relationship between total alkalinity and the distance downstream rendered a coefficient of determination of 0.71 (p=0.008). In contrast, the NO_3-N concentrations tended to decrease downstream (R^2 = 0.61, p = 0.023). No significant trend downstream was found for K, SO_4, NH_4-N, PO_4 and pH at a 95% confidence level. The variation in the concentrations of these ions downstream may be due to the influence of effluent from industries and mines or fertilizers in irrigation return flows. Sodium increased at a significantly higher rate downstream compared to Ca and Mg (data not shown), resulting in an increase of SAR downstream (R^2 = 0.82, p = 0.002).

If the relationships between the respective water quality variables and the distances downstream from Boegoeberg to Onseepkans were considered, the linear regression relationships improved for EC

(R^2 = 0.91, p = 0.048), Na (R^2 = 0.89, p = 0.015), Mg (R^2 = 0.97, p = 0.057) and Ca (R^2 = 0.91, p = 0.048) and became poorer or not significant a 95% significance level for the other water quality variables. There was no significant change in the rate of Na increase for the river reach from Boegoeberg to Onseepkans compared to that for the reach from Boegoeberg to Alexander Bay (data not shown). No significant linear regression relationships were found between any of the water quality variables and the distances downstream from Onseepkans in the river reach from Onseepkans to Alexander Bay.

The long-term means for all the water quality variables except that for nitrogen and PO_4, were lower for the river reach between Boegoeberg to Onseepkans compared to the river reach between Onseepkans and Alexander Bay (Table 3.15). The change in EC and ion content for selected cation and anions downstream in the Orange River confirmed the trend of increasing salinity to the river mouth (Table 3.16). The EC increased by *ca.* 25% for each consecutive river reach, with the EC for the river reach between Boegoeberg and Onseepkans being *ca.* 57%, and that between Onseepkans and Alexander Bay *ca.* 95%, respectively, higher compared to the EC for river reach that ends at Hopetown (data not shown). The ions that increased most downstream included Na, Cl and SO_4 (Table 3.16).

Table 3.16 The long-term downstream change in electrical conductivity (EC, dS m^{-1}) as well as cation and anion content (mg L^{-1}) in the Orange River. Data upstream from Boegoeberg was obtained from Du Preez *et al.* (2000)

From river reach	To river reach	EC	Na	Mg	Ca	Cl	SO_4
Upstream of Hopetown	Between Hopetown and the Vaal-Orange confluence	0.02	1.4	0.1	2.7	-0.8	1.8
Between Hopetown and the Vaal-Orange confluence	Downstream of the Vaal-Orange confluence to Prieska	0.05	4.6	1.5	1.4	7.4	5.5
Downstream of the Vaal-Orange confluence to Prieska[1]	Boegoeberg to Onseepkans	0.06	5.9	2.3	3.8	5.3	7.0
Boegoeberg to Onseepkans	Onseepkans to Alexander Bay	0.08	7.2	2.1	4.4	6.0	9.3

3.3.3.2 Trends over time

Long-term trends

The concentration of ions in the water is largely influenced by the amount of water flow, which can vary much between years. In order to establish and interpret the change in water quality over time, the annual mean water flow for the water quality monitoring sites from Boegoeberg to Vioolsdrift were graphed over calendar years (Fig. 3.1). Flow data for most monitoring sites were available for the period between 1965 and 2003 and the overall annual means did not always include data from all the sites. Water flow fluctuated between 30 x 10^6 m^3 and *ca.* 2500 x 10^6 m^3, with extremely high flow restricted to the years 1976 and 1988. In contrast, the mean annual flow remained less than 175 x 10^6 m^3 during 1970, 1973, 1983 to 1985, 1993, 1995 and 1999. The lowest mean annual water flow for all monitoring sites was recorded for 1993 and 1995 when flow amounted to 88 x 10^6 m^3 and 102 x 10^6 m^3, respectively. Flows of less than 85 x 10^6 m^3 were recorded at Onseepkans, Vioolsdrift and Pella, respectively, during 1993, 1994 and 1995.

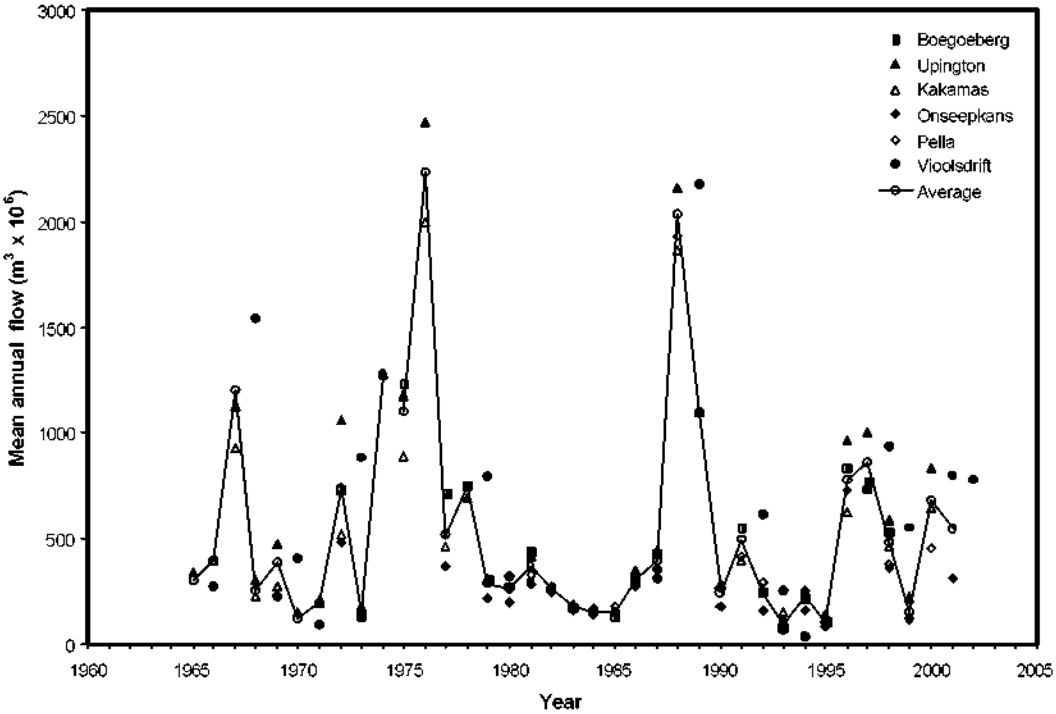

Figure 3.1. The mean annual water flow at selected monitoring sites in the lower Orange River during the period 1965 to 2003.

Approximately 60 years of mean monthly flow data were available for the Upington monitoring site and the variation in river flow patterns for the different seasons indicated that the highest flow occurred during summer and autumn, with the lowest flow during spring and winter (Fig. 3.2A to D). Low flow occurred more frequently from approximately 1980 onwards. The lowest water flow recorded at this site between 1980 and 2003 was during September 1993 and it amounted to 61 x 10^6 m^3.

The annual means for EC, SAR, the soluble cations and anions as well as pH were graphed over calendar years (Figs. 3.3 to 3.9). The water quality monitoring sites from Boegoeberg to Vioolsdrift weres collectively graphed to display the general downstream trend. The available data sets were limited and water quality data for the period from 1975 to 2003 were the most continuous and suitable to be graphed.

The EC in general increased from Boegoeberg to Onseepkans within the study area, with the highest EC at Vioolsdrift. The EC fluctuated with water flow and generally increased during periods of low flow and decreased during periods of high flow (Figs. 3.1 & 3.3). The extremely high flow in 1976 was followed by several years of relatively low flow, especially during 1983 to 1985 (Fig. 3.1). The water, however, returned to its previous minimum salinity levels at Boegoeberg in the first, and at Onseepkans and Vioolsdrift in the second year after 1985 when annual mean water flow of between 300 x 10^6 m^3 and 400 x 10^6 m^3 occurred (Figs. 3.1 & 3.3).

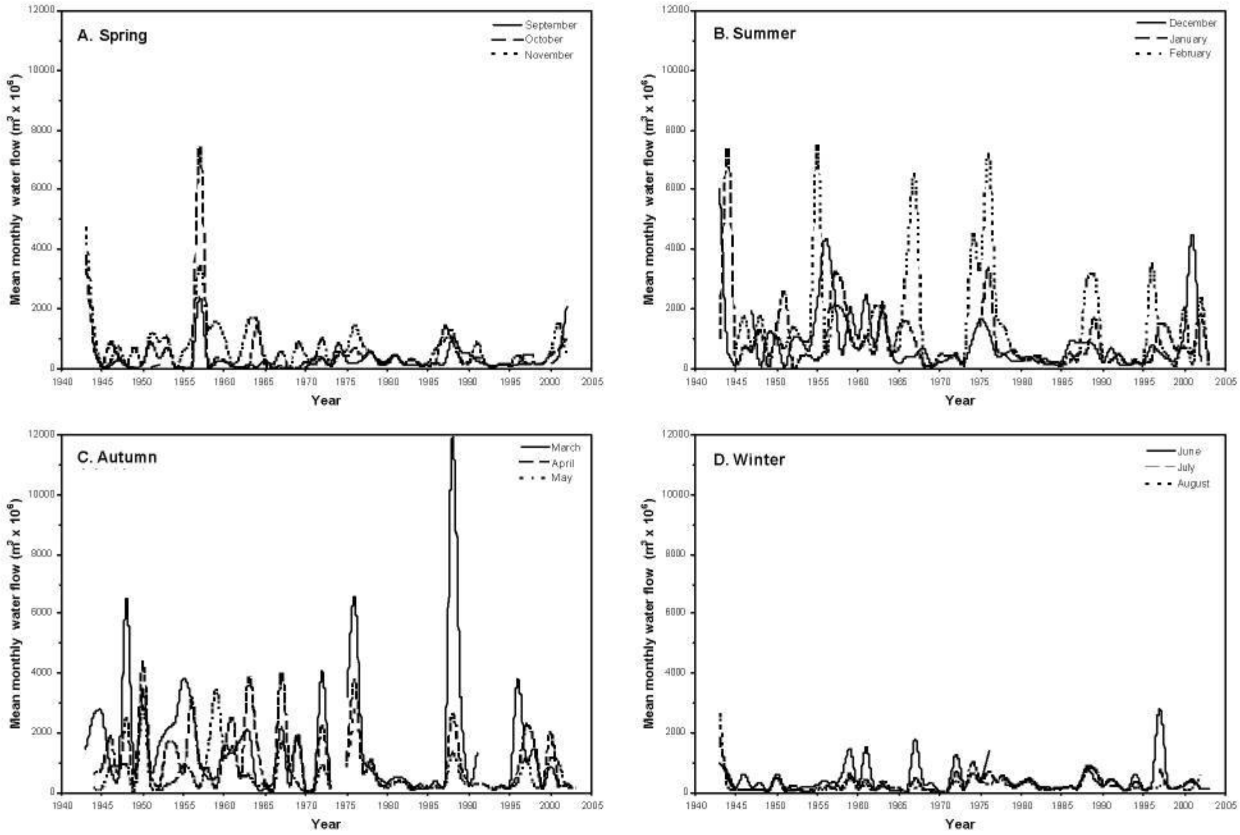

Figure 3.2. The mean monthly water flow for the Upington water quality monitoring site in the lower Orange River during spring (A), summer (B), autumn (C) and winter (D) for the years 1943 to 2003.

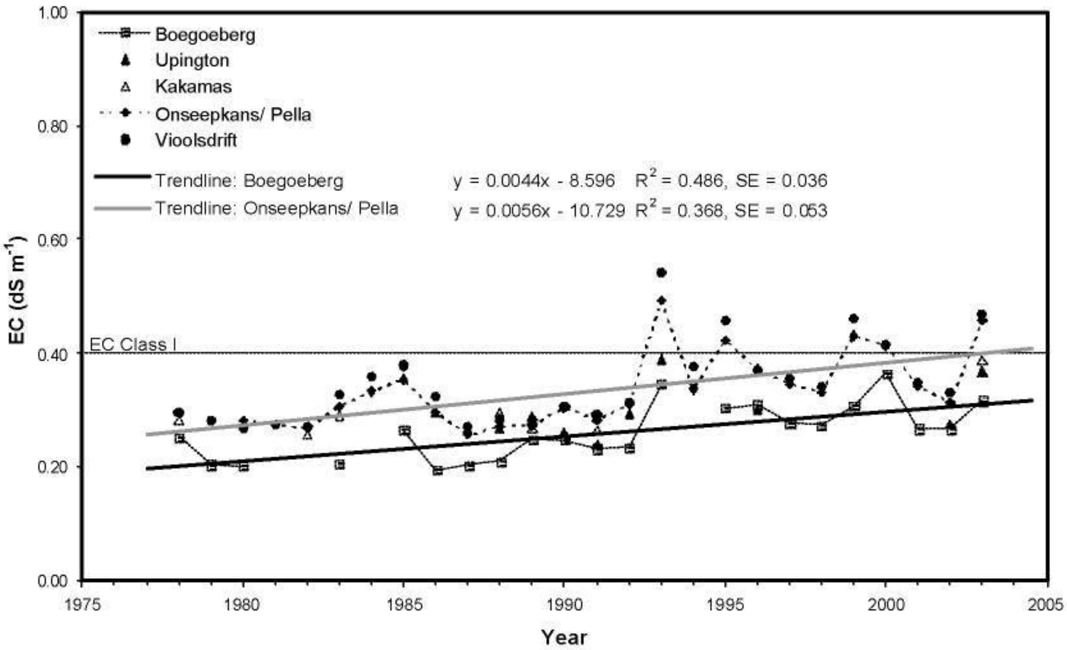

Figure 3.3. The annual mean electrical conductivity (EC) of the water for several monitoring sites along the lower Orange River during the period 1975 to 2003. The upper limit for EC Class I is 0.4 dS m^{-1}.

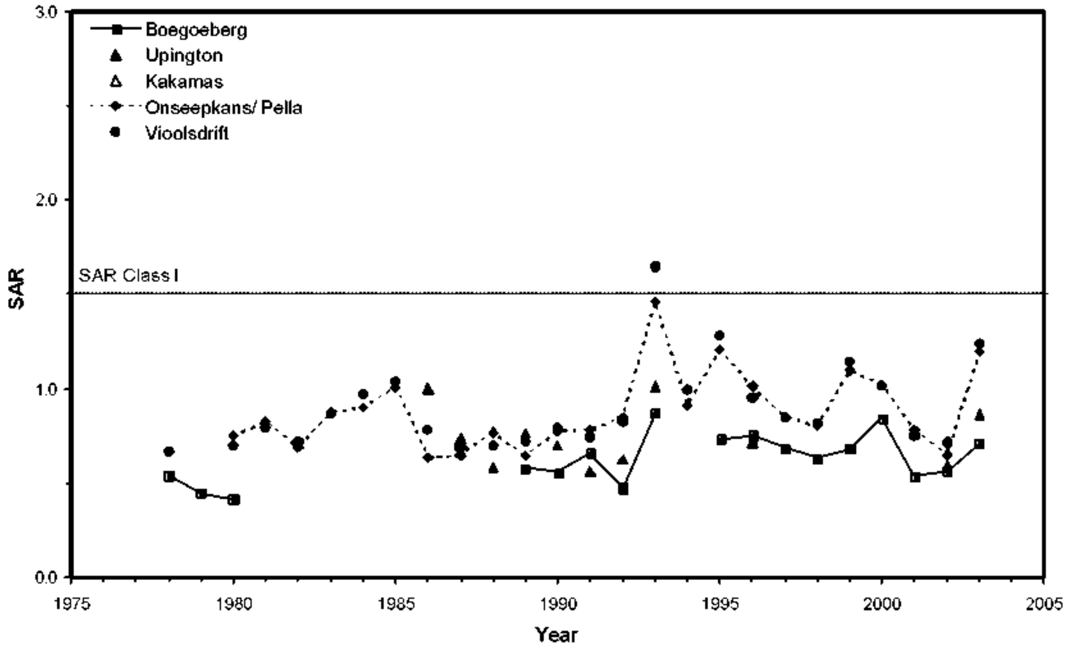

Figure 3.4. The annual mean sodium adsorption ratio (SAR) of the water for several monitoring sites in the lower Orange River region during the period 1975 to 2003. The upper limit for SAR Class I is 1.5.

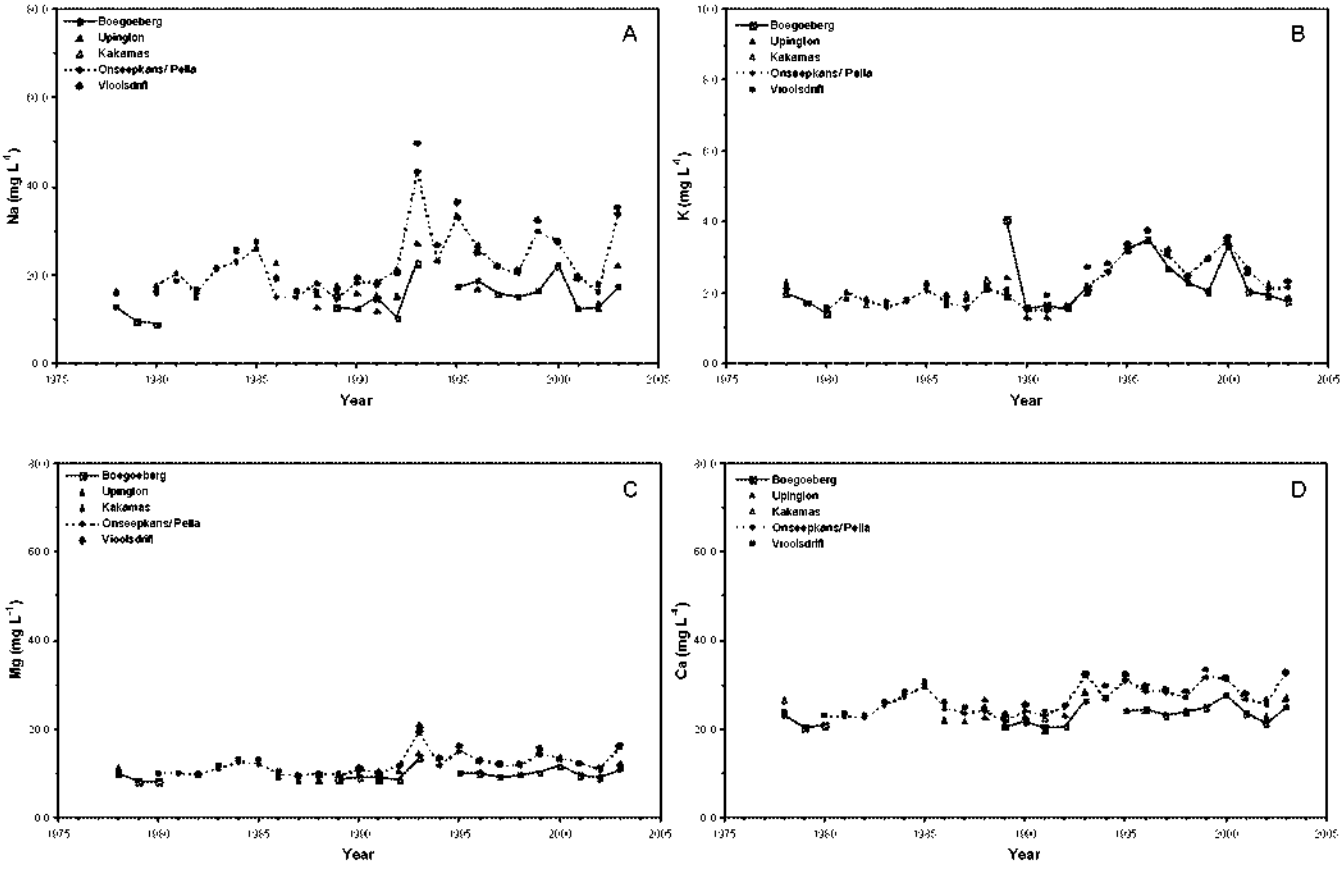

Figure 3.5. The annual mean concentration of (A) sodium (Na), (B) potassium (K), (C) magnesium (Mg) and (D) calcium (Ca) in the water at selected monitoring sites along the lower Orange River during the period 1975 to 2003

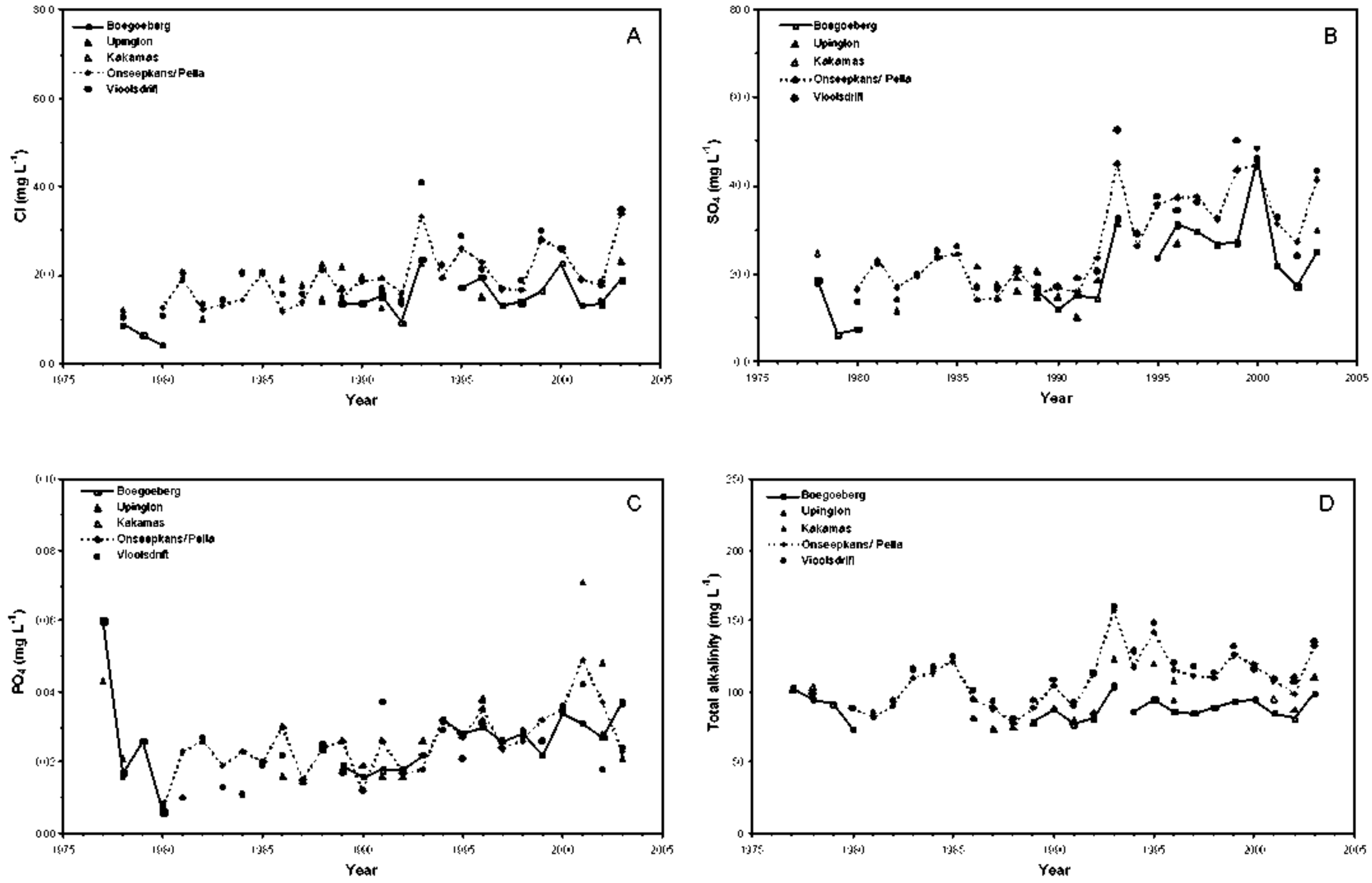

Figure 3.6. The (A) chloride (Cl), (B) sulphate (SO_4), (C) phosphate (PO_4) and (D) total alkalinity as calcium carbonate in the water of selected monitoring sites in the lower Orange River during the period 1975 to 2003.

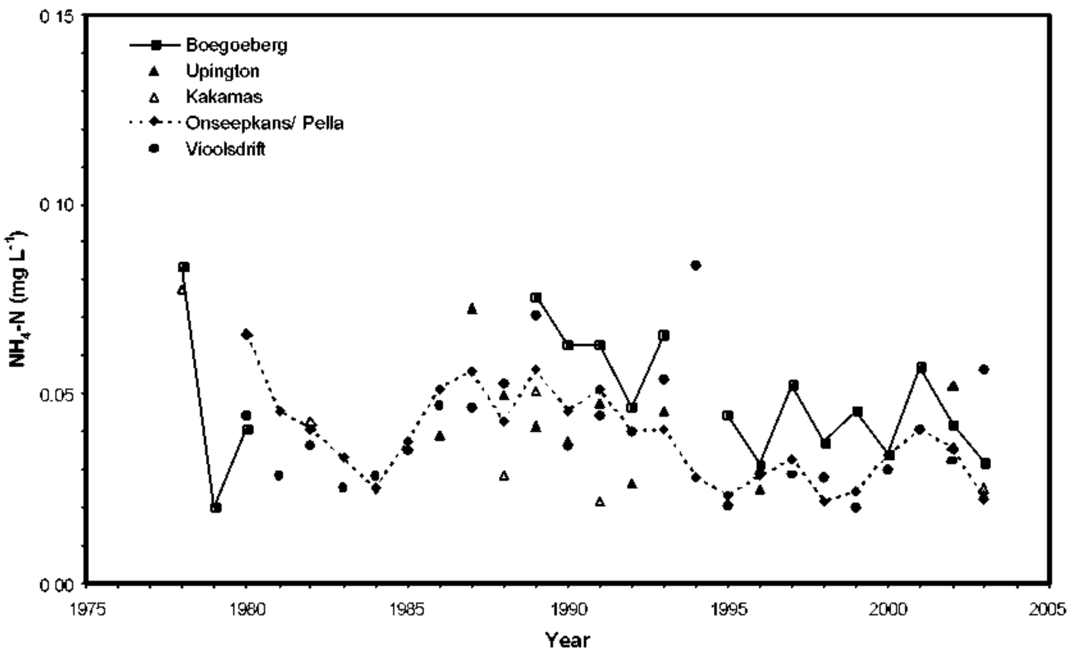

Figure 3.7. The annual mean ammonium (NH_4) concentration of the water for several monitoring sites in the lower Orange River region during the period 1975 to 2003.

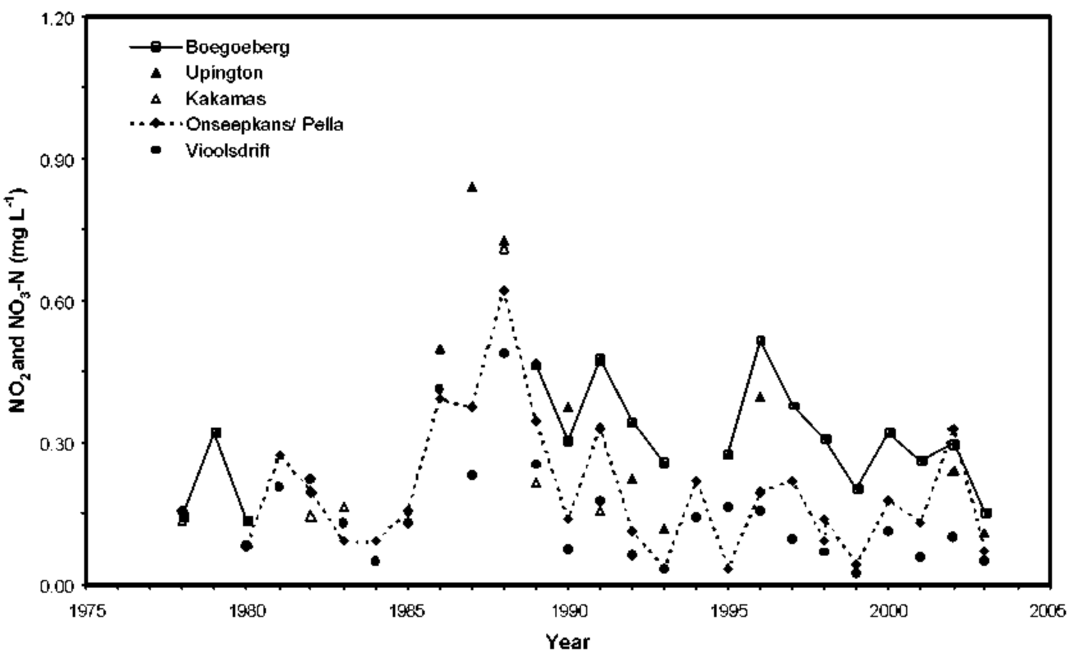

Figure 3.8. The annual mean nitrite and nitrate concentration of the water for several monitoring sites in the lower Orange River region during the period 1975 to 2003.

After the period of high flow in 1988, however, a period of relatively low flow followed during 1990 to 1995 (Fig. 3.1). This period included years with the lowest flow recorded yet between 1965 and 2003, namely 1993 and 1995. The EC at Boegoeberg did not decrease to the low salinity levels of *ca.* 0.2 dS m^{-1} recorded before 1989, despite the low flow period being followed by an annual mean water flow in excess of 750 x 10^6 m^3 during 1996 and 1997 (Fig. 3.3). The EC at Onseepkans/ Pella was higher than, but followed approximately the same pattern as, that for Boegoeberg. The mean annual EC at Onseepkans/Pella and Vioolsdrift deteriorated to EC Class II water during low flow years, which was for approximately a third of the period between 1993 and 2002. The increase in EC during 2000 only at Boegoeberg was related to a sharp increase in nearly all cation and anion concentrations at this specific monitoring site (Figs. 3.5 & 3.6). This increase in EC and ion concentrations was not associated with a low flow period and the salts were most likely contributed by the Vaal and upper Orange Rivers from outside the study area.

Linear regression relationships between time and EC for Boegoeberg and Onseepkans, respectively, were statistically significant at a 95% significance level (Fig. 3.3). The estimated EC for Boegoeberg and Onseepkans, respectively, for the year 2020 is 0.29 dS m^{-1} and 0.49 dS m^{-1}. The estimated EC for Boegoeberg is similar to the 0.31 dS m^{-1} estimated by Du Preez *et al.* (2000) for the Orange river reach downstream of the Vaal-Orange confluence to Prieska for the year 2020. It was furthermore predicted that after the next 40 years all EC values in Figure 3.3 would be above the EC Class 1 threshold line should the trend continue and the mean flow remain the same. The slopes of the regression equations increased from 0.0025 for the Orange river reach downstream of the Vaal-Orange confluence to Prieska (Du Preez *et al.*, 2000) to 0.0044 for Boegoeberg and 0.0056 for Onseepkans (Fig. 3.3), indicating a tendency for accelerated salinization downstream.

The SAR also fluctuated between years with low and high water flow, remaining less than 1.5 except for the low water level during 1993 at Vioolsdrift (Figs. 3.1 & 3.3). Water with such a low SAR has, according to the South African water quality guidelines, no potential for causing problems regarding the infiltration of water into the soil or for development of toxicity through root absorption by sensitive crops (DWAF, 1996). The SAR record for Boegoeberg was incomplete and difficult to derive a trend from, but the minimum of the fluctuating SAR values tended to be higher after 1993 compared to that during 1978 to 1980 (Fig. 3.3). Likewise, there was an upward shift of the available fluctuating minimum and maximum SAR values for Onseepkans/ Pella after 1992. However, the SAR for Onseepkans in 2002 was comparable to the SAR values for 1987 and 1989.

The ion concentrations were in general lower at Boegoeberg compared to that at Onseepkans/ Pella and Vioolsdrift (Figs. 3.5 & 3.6). Exceptions were K (Fig. 3.5B) and PO_4 (Fig. 3.6C) where no clear trend could be found between the concentrations of these ions at different monitoring sites, and the NH_4 and NO_3 concentrations which tended to be higher at Boegoeberg compared to Onseepkans/ Pella and Vioolsdrift (Figs. 3.7 & 3.8). The annual mean data for the cations and anions except the nitrogen compounds all tended, in agreement with the EC and SAR data, to show a general increase in concentration after 1992 (Figs. 3.5 & 3.6). The gradual increase in phosphates and sulphates (Fig. 3.6B & C) could be due to agricultural activity and it is of concern that the sulphate concentration has nearly doubled during the last decade (Fig. 3.6B). This increase could be attributed to the application of gypsum or ammonium sulphate fertilizers outside the study area as there had been a significant increase in irrigation development between the Van der Kloof Dam and Boegoeberg, while activities along the Vaal River also could have had an impact. The concentration of K at nearly all monitoring sites exceeded 2 mg L^{-1}, which is considered the normal level thereof in irrigation water, for the majority of the period between 1992 and 2000 (Fig. 3.5B).

Water pH tended to rise rapidly initially, which then leveled off (Fig. 3.9), probably due to a change in anion dominance. The pH remained above 8 for all monitoring sites since 1993, with that at Vioolsdrift exceeding the upper pH limit for irrigation water of 8.4 from time to time (Fig. 3.9). According to the long-term mean, however, the pH remained less than 8 at all monitoring sites between Boegoeberg and Onseepkans. Water with pH in excess of 8.4 may cause foliar damage or decrease the visual quality of marketable products if they are wetted during irrigation, affect the availability of several micro and macronutrients and increase problems with encrustation of irrigation pipes and clogging of drip irrigation systems (DWAF, 1996). The Langelier index of the water for the period 1999 to 2003 in general indicated a tendency towards increasing scaling problems downstream from Boegoeberg (Fig. 3.10). The Langelier index, however, does not account for calcium-sulphate ion pairing and may be an exaggerated indicator of scaling potential. Further research utilizing a modeling approach is necessary to enable better understanding of the chemical interactions and to determine the true scaling potential of the water.

Seasonal variation

Although long-term trends are important to establish the salinity status for an area, shorter term water quality data is necessary for within season management decisions regarding crop production. Water

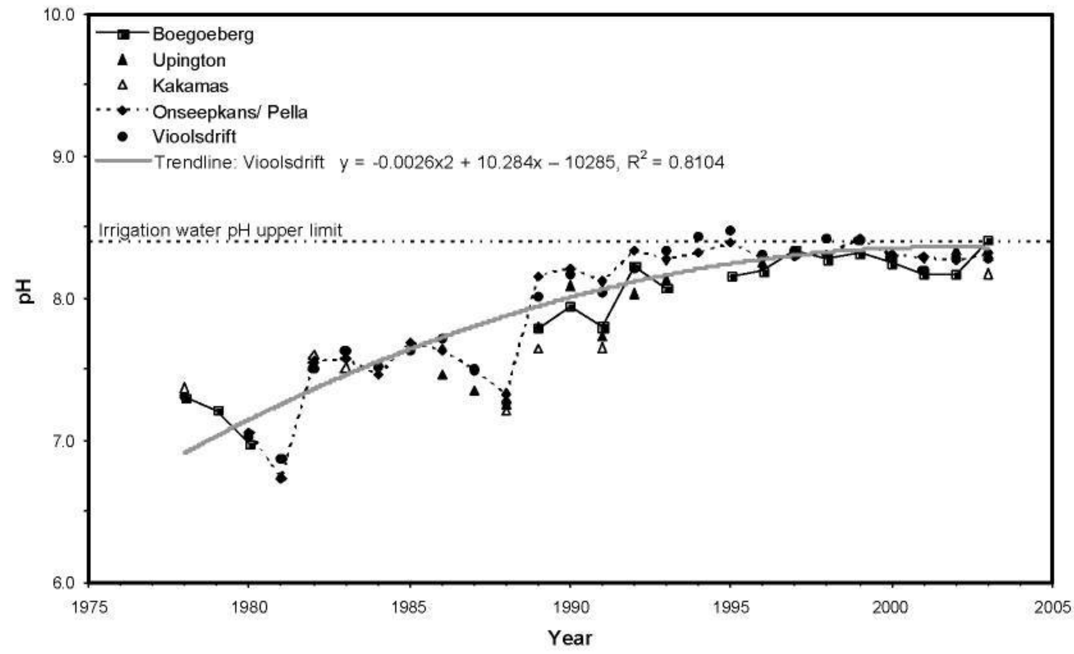

Figure 3.9. The annual mean pH of the water for several monitoring sites in the lower Orange River region during the period 1975 to 2003.

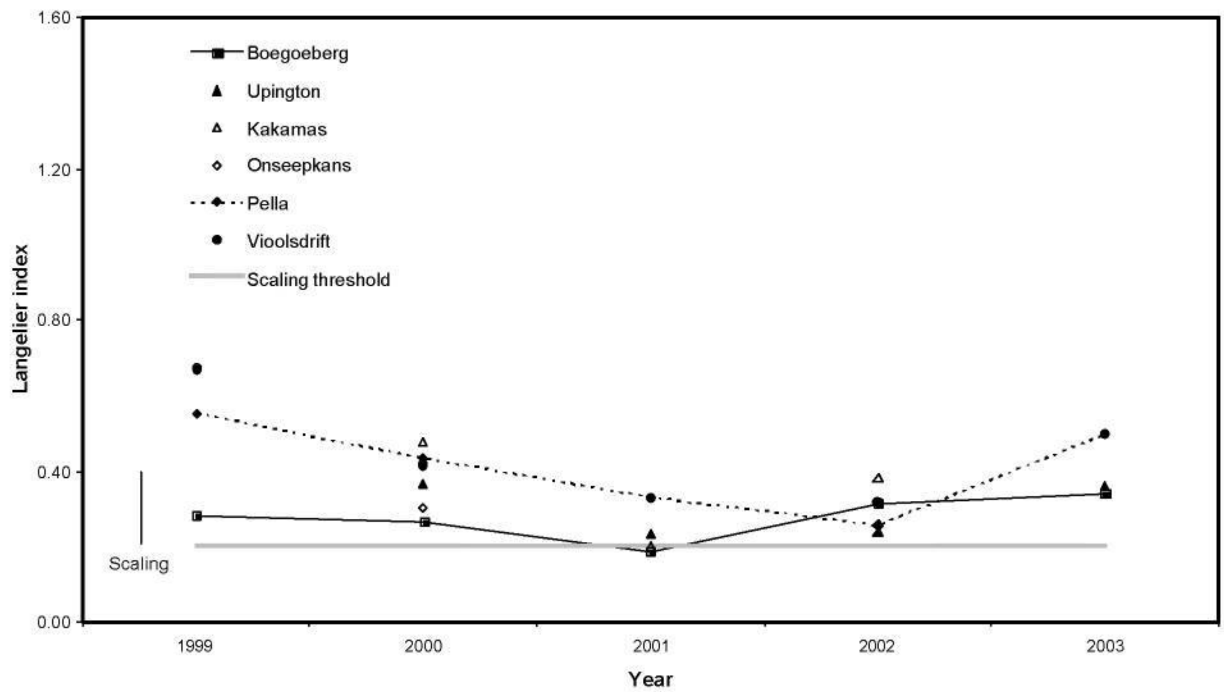

Figure 3.10. The annual mean Langelier index of the water for several monitoring sites in the lower Orange River region during the period 1999 to 2003. Scaling occurs if the Langelier index exceeds the threshold value 0.2 (DWAF, 1996).

quality may vary considerably, not only between years, but also within years due to seasonal variation in precipitation, quantity and quality of irrigation return flows and the effect of hydro-electric power plants on river flow. In the lower Orange River region, the EC is the water quality variable that has the most extended database and it was therefore used to illustrate the seasonal variation in salinity. The annual average EC, for example, for a high flow year (1988) was 0.21 dS m^{-1} and 0.27 dS m^{-1}, and for a low flow year (1993), 0.35 dS m^{-1} and 0.49 dS m^{-1} at Boegoeberg and Onseepkans, respectively.

Crops may vary in sensitivity to salinity during different phenological development stages. If the time of the year when salinity reach maximum levels and the magnitude of the salinity is known, producers will be able to decide which crops are suitable, or to dilute the irrigation water to ensure that water quality does not affect production or product quality negatively. Although the EC was in general higher in spring and lower in autumn, the long-term mean EC during all seasons was still less than 0.4 dS m^{-1} at all monitoring sites, except at Alexander Bay where the EC exceeded 0.5 dS m^{-1} in spring (Table 3.17). Based on EC values of less than 0.4 dS m^{-1}, no serious water quality related problems are to be expected for the crops in the lower Orange River region if adequate leaching is applied to prevent the excessive accumulation of salt in the soil profile.

Table 3.17 The long-term mean electrical conductivity (EC) of water from selected water quality monitoring sites for the Lower Orange River region during spring, summer, autumn and winter. Values within seasons designated by the same symbol do not differ significantly (p=0.05) and seasons were tested separately

Water quality monitoring site or river reach	**EC (dS m^{-1})**			
	Spring	**Summer**	**Autumn**	**Winter**
Boegoeberg	0.23 ^{b}	0.28 ^{a}	0.27 ^{a}	0.26 ^{a}
Upington	0.28 ^{ab}	0.30 ^{ab}	0.27 ^{b}	0.33 ^{a}
Kakamas	0.32 ^{a}	0.27 ^{a}	0.28 ^{a}	0.29 ^{a}
Onseepkans	0.34 ^{a}	0.31 ^{b}	0.31 ^{b}	0.32 ^{ab}
Pella	0.39 ^{a}	0.37 ^{ab}	0.32 ^{b}	0.39 ^{a}
Vioolsdrift	0.37 ^{a}	0.34 ^{ab}	0.33 ^{b}	0.34 ^{ab}
Brand Kaross	0.36 ^{a}	0.35 ^{a}	0.34 ^{a}	0.33 ^{a}
Alexander Bay	0.52 ^{a}	0.49 ^{a}	0.39 ^{b}	0.46 ^{ab}
Boegoeberg to Onseepkans	0.29 ^{a}	0.29 ^{a}	0.28 ^{a}	0.29 ^{a}
Onseepkans to Alexander Bay	0.39 ^{a}	0.37 ^{b}	0.33 ^{c}	0.36 ^{b}

The monthly average data for years with high and low water flow, however, indicated that the EC may be more than double the long-term average EC for certain months in low flow years. This increase in salinity could become important if consecutive years of low flow occur and if the ameliorating effect of precipitation in summer and autumn remains absent. The EC at Boegoeberg exceeded 0.5 dS m^{-1} during February and reached 0.46 dS m^{-1} in July 1993 (Fig. 3.11). The situation at Onseepkans was more serious, with the EC being more than 0.4 dS m^{-1} for ten months of the low flow year (Fig. 3.12). The EC at Onseepkans was 0.56 dS m^{-1} at the start of the grapevine growing season during August and increased to almost 0.7 dS m^{-1} during October 1993. Months with low EC values included December to March 1993 with the lowest EC recorded in March 1993 as 0.36 dS m^{-1}.

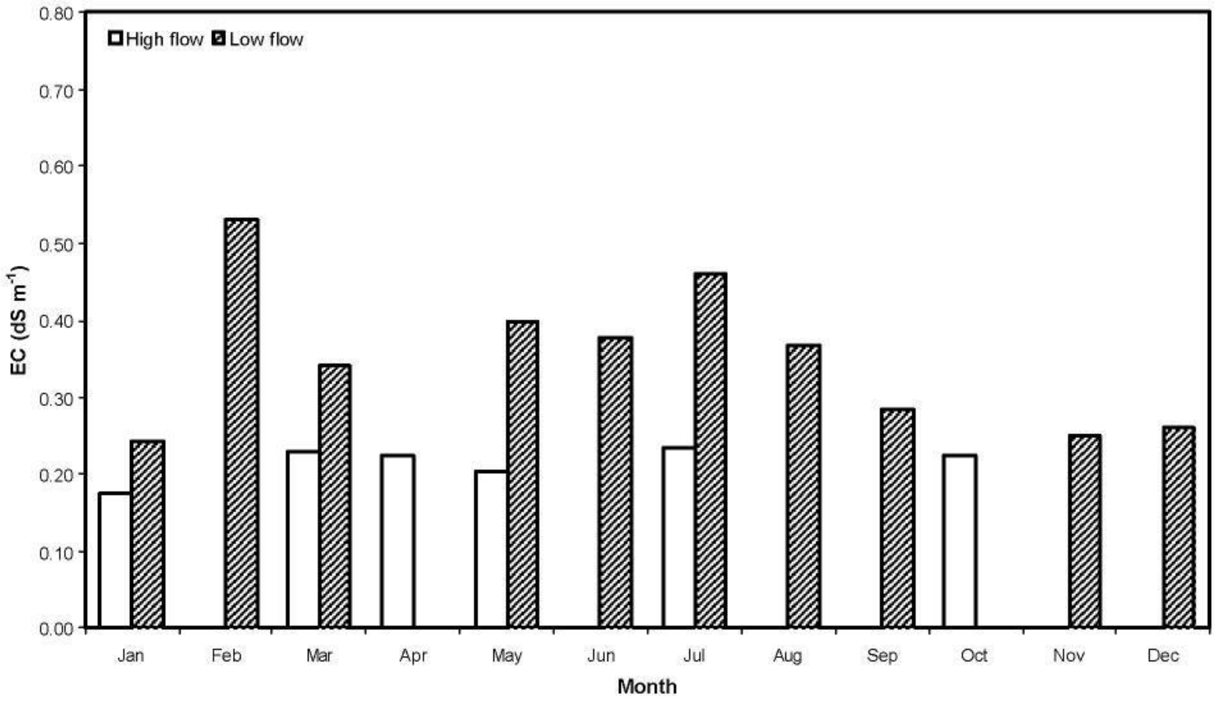

Figure 3.11. The monthly variation in electrical conductivity (EC) of the water at the Boegoeberg water quality monitoring site during years of high (1988) and low (1993) water flow, respectively.

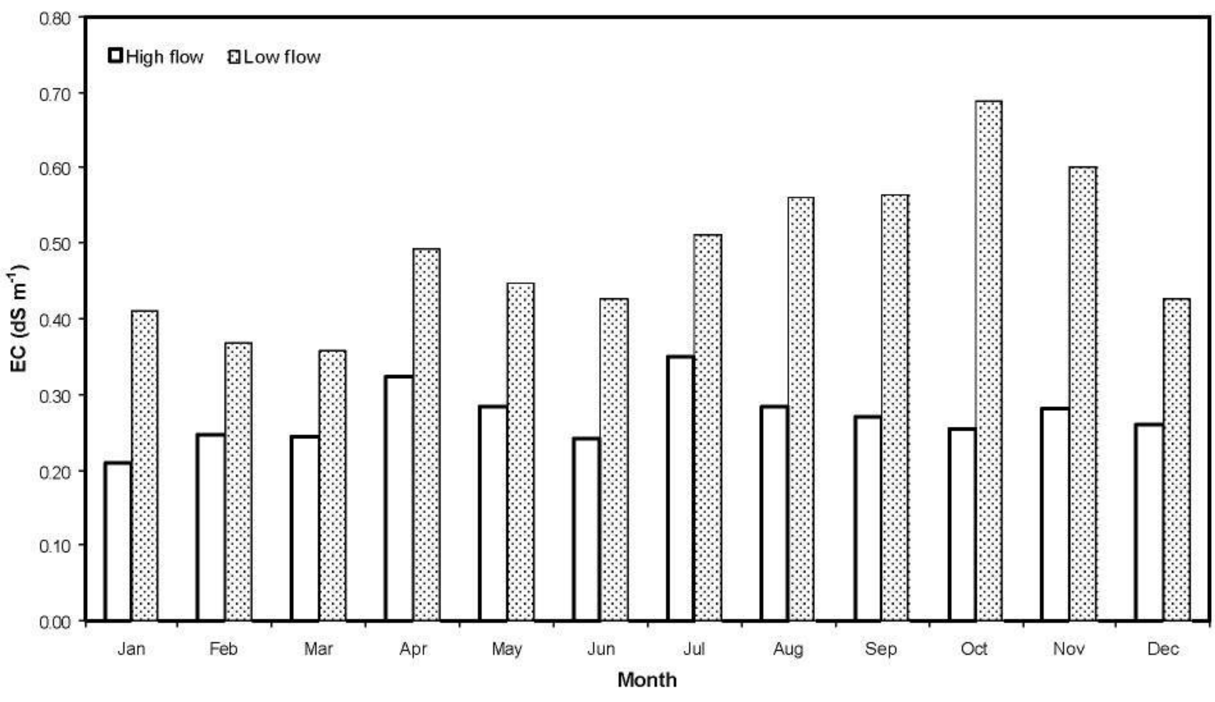

Figure 3.12. The monthly variation in electrical conductivity (EC) of the water at the Onseepkans water quality monitoring site during years of high (1988) and low (1993) water flow, respectively.

3.3.4 Trends in drainage water quality

The mean pH, EC, as well as cation and anion content of the drainage water for the five small primary catchments are summarized in Table 3.18. The EC of the drainage water from the catchments dominated in calcrete containing soils at Carpé Diem and Rooiland was the lowest of that for the small catchments monitored, with the EC remaining less than 1.5 dS m^{-1}. There were large differences in the EC of the drainage water from small catchments where gneiss soils frequently occurred with the EC of the drainage water at Strauss being approximately double that at Chargo Trust, where the EC of the drainage water remained below 2 dS m^{-1}. The highest EC, however, was found downstream from Upington in the drainage water from SMB where windblown sands pre-dominated the small-catchment.

The pH of the drainage water remained within the limits for irrigation water, being higher in the water originating from the calcrete rich catchments (Table 3.18). Sodium levels exceeded 200 mg L^{-1} (Table 3.18) and the adjusted SAR exceeded 5 (data not shown) for all catchments except that at Rooiland. Care should be taken if the water is re-used for irrigation purposes as most of the cation and anion concentrations in the drainage water were high enough to cause moderate to severe salinity, infiltration or toxicity problems (Ayers & Westcot, 1985).

Table 3.18 The mean chemical composition (July 2003 to April 2004) of water samples collected from the drainage water monitoring sites in the lower Orange River region

Drainage water quality monitoring site	pH	EC (dS m^{-1})	Cation/anion concentration (mg L^{-1})											
			Na	K	Ca	Mg	Cl	CO3[1]	HCO3	SO_4	B	PO_4-P	NH_4-N	NO_3-N
Carpé Diem	8.0	1.4	239	1.2	50	24	65	55	363	185	0.5	0.1	0.1	12.9
Rooiland	8.0	1.0	69	12.5	61	53	76	55	322	77	0.1	0.0	0.2	7.2
SMB	7.8	9.9	1909	6.8	238	176	1991	52	295	2317	6.1	0.2	0.9	34.3
Strauss	7.4	3.6	460	4.1	336	40	542	25	294	935	0.9	0.1	0.3	4.7
Chargo Trust	7.8	1.7	209	1.3	106	45	214	41	347	246	0.3	0.1	0.3	3.0

The application of different fertilizer programs by producers and the limited number of monitoring sites complicated the comparison of the drainage water quality for small primary catchments predominated by calcrete, gneiss and windblown sand soils. No definite trends were present for most of the drainage water quality variables over the ten month period that it was monitored (Figs. 3.13 to 3.14) and the monthly drainage water quality data for all five catchments were attached in Appendix A for future reference. The quality of the drainage water at SMB and Strauss was of the poorest (Table 3.18, Figs. 3.13 to 3.14). Electrical conductivity values of between 2 dS m^{-1} to 10 dS m^{-1} are considered typical for many drainage waters (Rhoades, 1999) and the EC of the drainage water at SMB (Fig. 3.13A) exceeded the maximum value several times. Also, the SAR of the drainage water at SMB (Fig. 3.13B) exceeded values of between 5 and 15, which is regarded as the general range of sodicity for several drainage waters (Rhoades, 1999), by far (Fig. 3.13B). The composition of the drainage water from these small catchments is discussed in more detail in the chapter reporting on the salt generation potential of different soils in the Lower Orange River region (section 4.3.6).

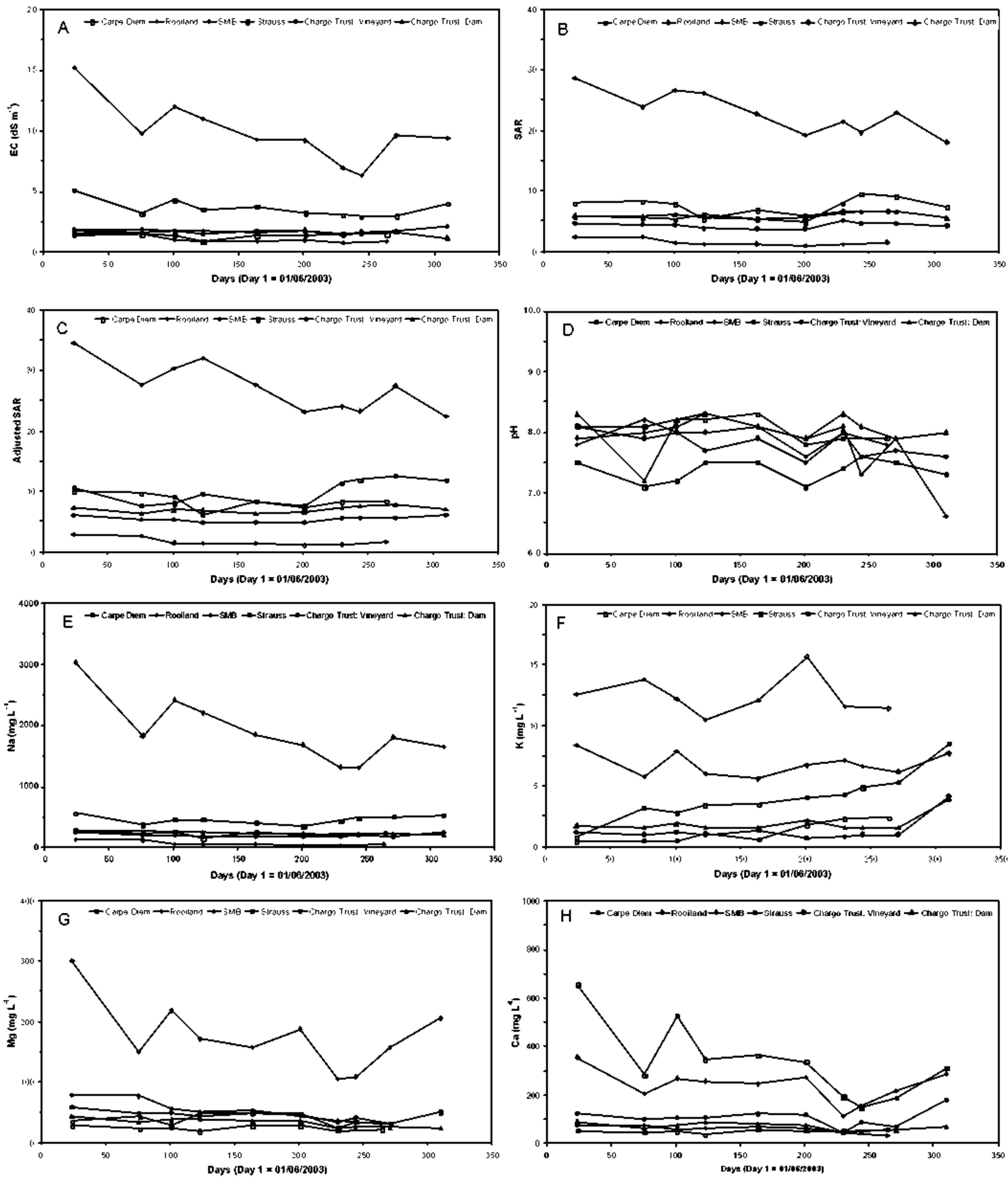

Figure 3.13. Variation in (A) electrical conductivity (EC), (B) the sodium adsorption ratio (SAR), (C) the adjusted SAR and (D) the pH as well as the (E) sodium (Na), (F) potassium (K), (G) magnesium (Mg) and (H) calcium (Ca) concentration in drainage water sampled at Carpé Diem, Rooiland, SMB, Strauss and Chargo Trust at selected stages from June 2003 to April 2004. Chargo Trust: Vineyard refers to drainage water intercepted fom a vineyard, while Chargo Trust: Dam is drainage water intercepted from below a leaking dam.

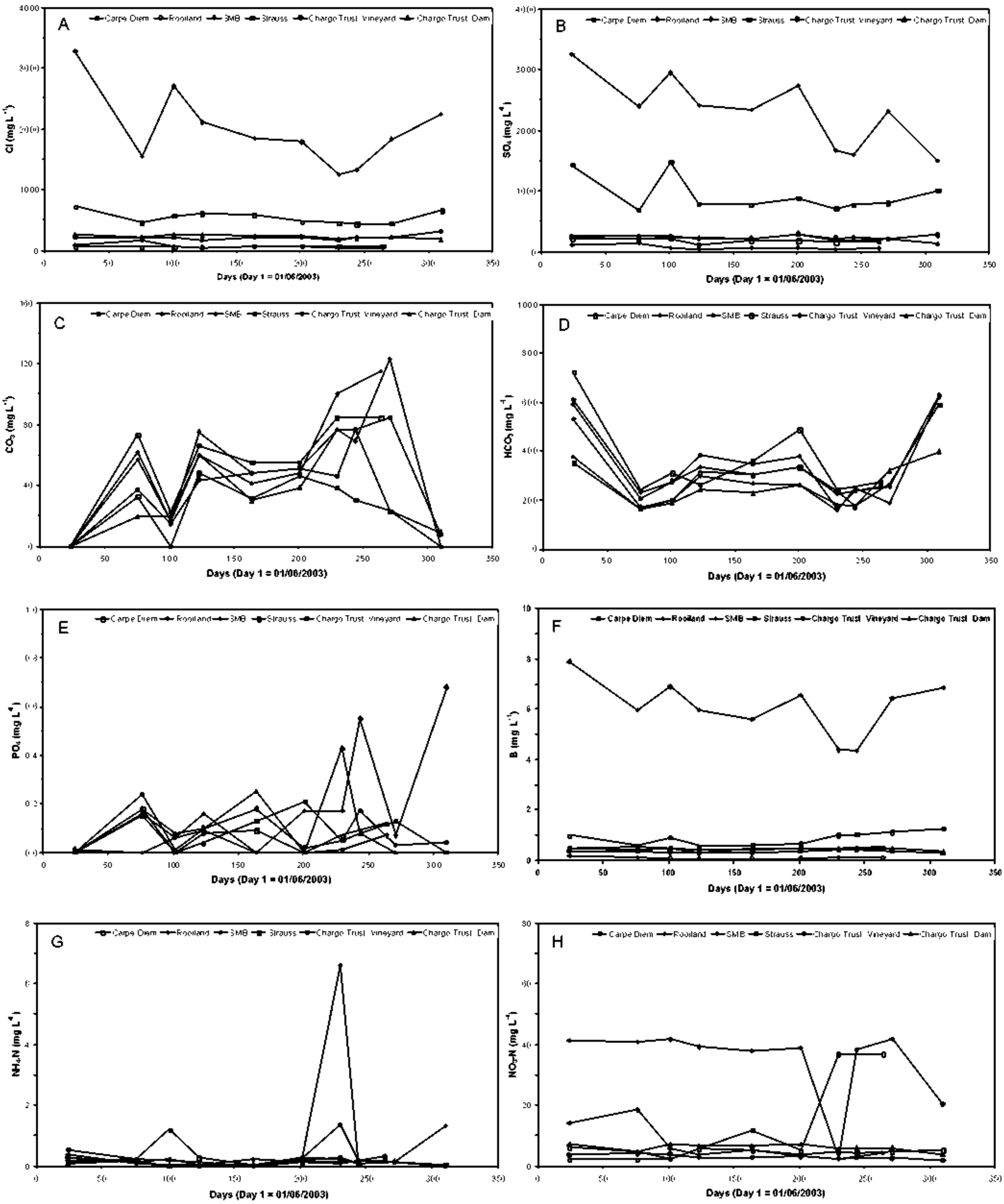

Figure 3.14. Variation in (A) chloride (Cl), (B) sulphate (SO_4), (C) carbonate (CO_3), (D) bicarbonate (HCO_3), (E) phosphate (PO_4), (F) boron (B), (G) ammonium (NH_4) and (H) nitrate (NO_3) concentration in drainage water sampled at Carpé Diem, Rooiland, SMB, Strauss and Chargo Trust at selected stages from June 2003 to April 2004. Chargo Trust: Vineyard refers to drainage water intercepted from a vineyard, while Chargo Trust: Dam is drainage water intercepted from below a leaking dam.

3.3.5 Salt retention in the Boegoeberg to Onseepkans river reach

The salinity status of the lower Orange River (Table 3.14) is still less than that of most of the rivers from the other arid river basins explored by Smedema (2000). The exception is the Indus River basin, where the river has lower salinity, but extensive soil salinization problems are experienced due to salt retention (Smedema, 2000). Close inspection of the long-term longitudal salinity profile of the lower Orange River (Fig. 3.15A) indicates that, besides the increase at Alexander Bay due to tidal flows, the EC tends to increase in two sections, namely from Boegoeberg to Upington, and from Kakamas to Onseepkans, with a steep rise at Pella. Steep increases in the river salinity profile may be associated with the mobilization of salts, but it may also be a result of increased water abstraction (Smedema, 2000). During 1988 a flood occurred, resulting in an EC lower than the long-term values and despite an initial steep increase in the EC from Boegoeberg to Kakamas, the EC became slightly lower between Kakamas to Pella and Vioolsdrift (Fig. 3.15A). This may indicate periodic salt retention in the soils or groundwater for that specific river reach, as persistent low salinity downstream may, according to Smedema (2000), be indicative of such salt retention. During low flow years such as 1993 and 2003, the EC not only became higher compared to 1988 and the long-term EC (Fig.3.15A), but the longitudal river salinity profile became more of exponential form (Fig. 3.15B), which is theoretically typical of an equilibrium profile (Smedema, 2000). A similar exponential profile at even higher salinity levels may also indicate salt mobilization, provided the total salt load of the river increases, especially in a downstream direction (Smedema, 2000).

The longitudal annual average salinity profiles discussed above reflect the combined impacts of water abstraction and salt loading on the river. The salt load of the water at Boegoeberg and Onseepkans varied between years and ranged between *ca.* 20 and *ca.* 260 tons per year during the period 1980 to 1998 (Fig. 3.16). The salt load of the water was in general higher at Onseepkans compared to that at Boegoeberg during the years with low water flow between 1980 and 1987 (Figs. 3.1 & 3.16). In contrast, the salt load became lower at Onseepkans than that at Boegoeberg during periods of extremely high flow such as in 1988 and in the following years until extremely low flows occurred again in 1993. The salt load at Onseepkans remained higher than that at Boegoeberg until 1996 and became lower in 1997, which was the second year that water flow exceeded 700 x 10^6 m^3 after the extremely low flows that occurred in the period between 1993 and 1995.

The salt balance for the river reach between Boegoeberg and Onseepkans likewise fluctuated, with smaller amounts of salt effluxing at Onseepkans during periods of low water flow, and larger amounts of salt being retained in the river reach during periods of high water flow (Fig. 3.17). It took several years after the 1988 flood event for the salt balance to change from negative to positive. It is hypothesized that, during flood periods, especially the lower lying soils along the river (known locally as *binnegronde*) become inundated and that salinization of these waterlogged soils proceeds until excess water has drained. Effective leaching of salts from soils only becomes possible after water tables subsided adequately. The time frame needed for the water level to drop depends on the magnitude of flow in consecutive years. Excessive amounts of drainage water originating from over irrigation of foothill soils may further delay drainage of the lower lying soils after flood periods. There are several locations where

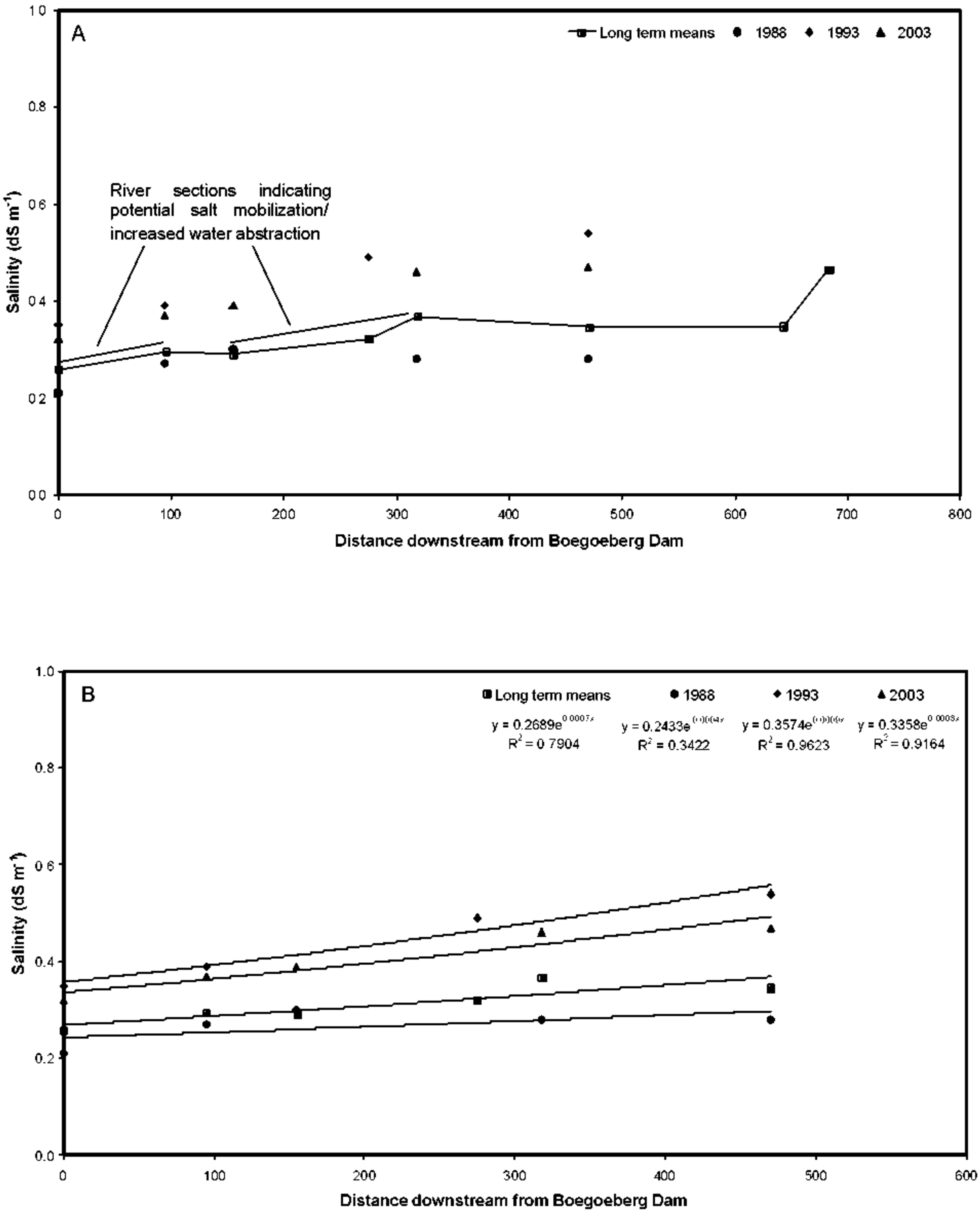

Figure 3.15. Longitudal salinity profiles for the lower Orange River for the long-term as well as for high flow (1988) and low flow (1993, 2003) years indicating (A) sections along the river between Boegoeberg Dam and Alexander Bay where salt mobilization or increased water abstraction potentially occurs and (B) differences in exponential fit of salinity profiles for the river between Boegoeberg Dam and Vioolsdrift.

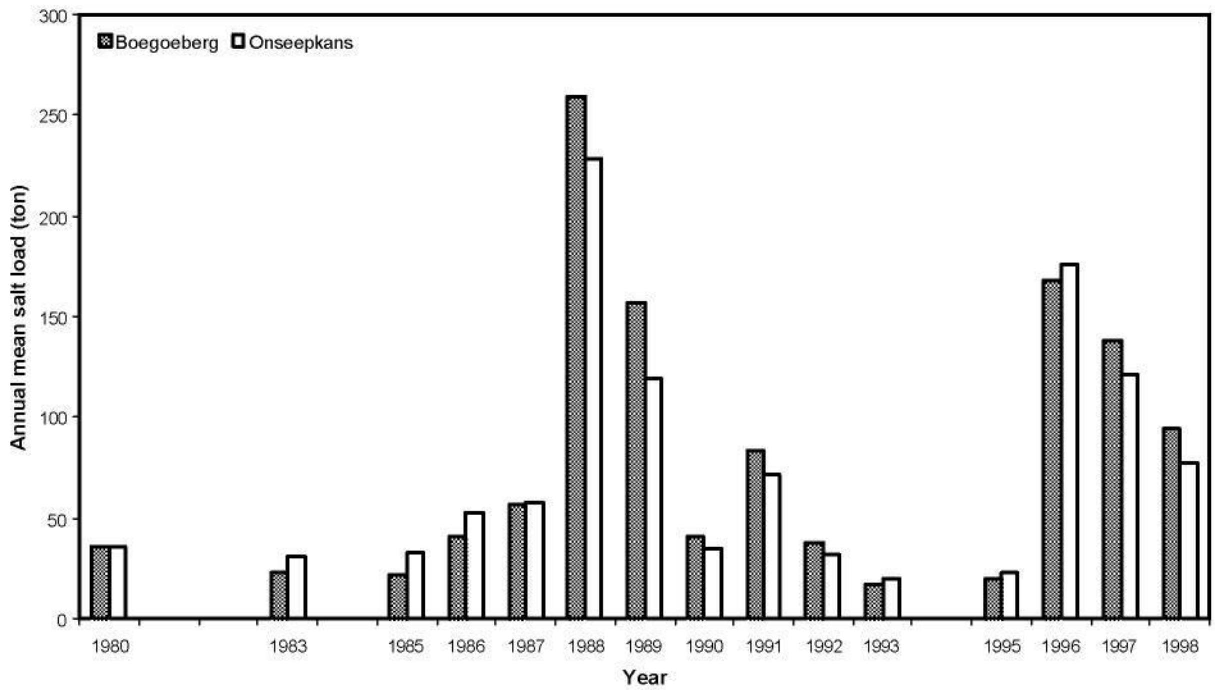

Figure 3.16. The mean annual salt load at Boegoeberg and Onseepkans for selected years during 1980 to 1998.

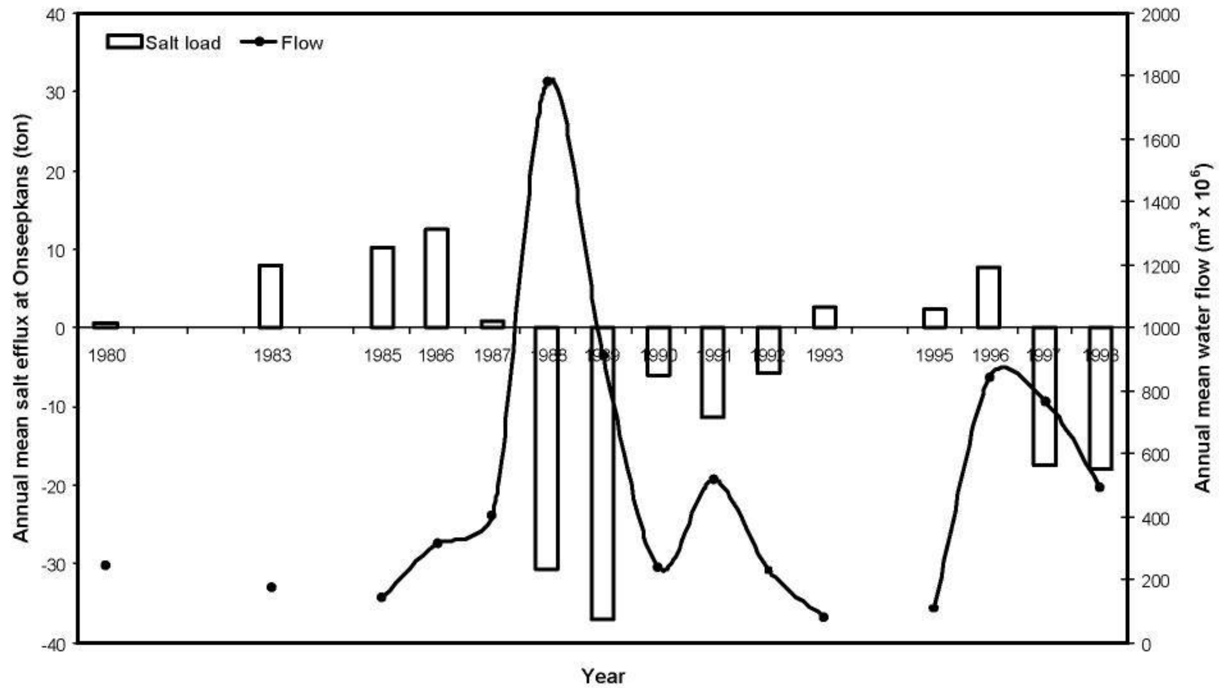

Figure 3.17. The mean annual salt efflux at Onseepkans for selected years during 1980 to 1998. The annual mean flow includes flow at Boegoeberg, Upington and Onseepkans.

the water table of the lower lying soils had risen after development and irrigation of the foothill soils (known locally as *buitegronde)* occurred for the first time (data not shown). According to Rossouw (1997), irrigation return flow (field as well as canal losses) may constitute between 15 to *ca.* 20% of the irrigation requirement for certain irrigation schemes within the Boegoeberg to Onseepkans river reach. In volumetric terms the return flow may amount to between 1.7 x10^6 m^3 and 25.6 x10^6 m^3 per year for certain irrigation schemes, resulting in an average return flow of 14.5 x10^6 m^3 for the Boegoeberg to Onseepkans river reach.

Comparison of the salt balance for years of comparable flow furthermore indicated that more salt was retained in the river reach from Boegoeberg to Onseepkans in 1990 compared to 1980, and in 1998 compared to 1991 (Table 3.19). This does not necessarily indicate an accumulation of salts in the river reach over time, as the time frame after a significant flood event and its effect on the water table level should be taken into account. The years 1980 and 1991 were 4 years after an extremely high, and 3 years after a relatively high water flow event, respectively. The years 1990 and 1998, however, were 2 and 1 years after an extremely high and relatively high water flow event, respectively. One could therefore expect higher salt retention for the years 1980 and 1998, which followed sooner after a flood compared to the years 1980 and 1991.

Table 3.19 The mean annual flow, salt load at Boegoeberg and Onseepkans and the amount of salt effluxed from or retained in the Boegoeberg to Onseepkans river reach in the lower Orange River for selected years between 1980 and 1998

Year	Mean annual flow (m^3 x 10^6)	Salt load (ton)		Salt effluxed (+)/ retained (-) (ton)
		Boegoeberg	Onseepkans	
1980	246	35.5	36.2	0.7
1990	238	41.3	35.3	-6.1
1991	517	83.4	72.0	-11.5
1998	494	95.0	77.1	-17.9

3.4 Conclusions

The water in the lower Orange River is, according to the long-term EC, SAR and cation and anion concentrations, of good quality and not expected to pose any serious problems regarding salinity, sodicity or toxicity. Prerequisites, however, are that a leaching fraction of at least 0.1 is allowed for low frequency irrigation systems and that foliage of sensitive crops is not wetted. The occurrence of salinity related problems, however, may be overlooked if only the long-term mean data or annual mean data are considered.

During years with low water flow, salts are able to be effluxed from the river reach as low water tables allow salts to be effectively leached from the salinized soils. The impact of the drainage water on river salinization, however, remains unknown. The results indicated that irrigation return flow from the irrigation development on the foothills, which occurred mainly beyond Boegoeberg, cannot be the main source for the salinity increase in the river reach from Boegoeberg to Onseepkans. Careful regulation of flow in the river as well as a drainage management strategy for the region is necessary to deter increased salinization of the river and soils.

Trends downstream from Boegoeberg to Alexander Bay indicated a significant increase in salinity and sodicity. Based on the current trend and mean flow, all EC values between Boegoeberg and Onseepkans could exceed the EC Class 1 threshold after the next 40 years. The data base for the lower Orange River region was surprisingly incomplete and the importance of collecting monthly water quality data for the interpretation of trends in river salinization over the long term cannot be overemphasized. Steps should be taken immediately to ensure a reliable water quality data base for the lower Orange River region in the future.

4 SALT GENERATION POTENTIAL OF SOILS IN THREE CONTRASTING AREAS UNDER IRRIGATION

4.1 Introduction

New land is increasingly being converted to irrigated vineyards on sloping terrain adjoining the Orange River floodplain. This has given rise to concern over additional salts that may be discharged into the river system, or at least towards lower-lying, established vineyards. Water provision for new development is being held back until a satisfactory understanding has emerged of how serious the consequences may be.

The soils in question (known locally as *buitegronde*, meaning "exterior soils" because they lie above the irrigation canal), unlike their alluvial counterparts, are shallow, stony aridisols and show minimal weathering from the country rock which in most cases is granite-gneiss. The geological circumstances are described in detail in a study by Eloff *et al.* (1985), who addressed the interesting phenomenon of accelerated weathering as a result of irrigation in this hyperthermic environment. There appears to be some evidence indicating that within a short period of time - no more than a decade or two - there has been a significant breakdown of more weatherable minerals such as biotite and feldspar and neoformation of clay minerals and iron oxides giving rise to a quite dramatic alteration in soil physical properties. Although in its natural state the granite-gneiss saprolite is superficially unaltered in general appearance from fresh rock, it has been altered sufficiently to have lost much of its integrity and when it is ripped and cultivated it converts quite rapidly to a loose, gravelly texture which allows water penetration from the outset. This coupled with the copious application of irrigation water and the exceptionally high summer temperatures might be expected to produce acceleration in weathering that is probably unprecedented in agricultural lands.

Although there are indications of natural salinity along dry watercourses and in low-lying areas, the soils in question are surprisingly poor in free salts. Many of them are calcareous, however, with hardpan calcrete having developed in some soils. Nevertheless, because of the possibility that weathering may generate a fast release of salts and because of the exceptionally high potential evaporation, salinity problems could develop, especially given the moderate concentration of salts that already occurs in the irrigation water of these lower reaches of the Orange River.

The objective of this chapter is to present the results of a study into the salinity generation potential of three pedologically contrasting areas where vineyards have been established above the floodplain of the Lower Orange River. In each area it was possible to compare vineyard soils with adjacent virgin soils.

4.2 Materials and methods

The three areas selected for study were as follows: Alheit and SMB Boerdery in the Kakamas-Keimoes district, and the SADOR farm near Upington (Fig. 1.1c). At Alheit, the soils are derived from biotite gneiss and typify the shallow soils that prevail over much of the terrain bordering the Orange River floodplain. An extensive area, established to irrigated table grapes during the last ten years, is bordered by virgin land where comparative sampling of undisturbed soils can readily be accomplished. At SMB Boerdery the soils are derived from wind-blown Kalahari sands, referred to locally as *duinegronde* (dune soils). While not as extensive as the shallow soils on granite-gneiss, such areas are understandably favoured for intensive development because of easier land preparation and the probably greater simplicity of irrigation management. The SADOR farm was selected to cover a third common feature of the *buitegronde*, namely the occurrence of secondary limestone pans (calcrete) as a dominant soil feature. There was ample opportunity at both SMB and SADOR to sample virgin soils immediately adjacent to the vineyards. A summary of all sampling sites and their geographic co-ordinates (obtained by means of a global position system or GPS) is presented in Tables 4.1 to 4.3.

At Alheit, six soil profiles were selected in established vineyards, three in a young vineyard and twelve on adjacent virgin land (Table 4.1). The pits were opened by hand- or mechanical digging to a depth of between one and two metres and in each pit three samples were taken representing upper, middle and lower layers in the soil profile. In vineyards, additional samples were taken to compare the soil beneath the irrigation dripper lines and dry soil midway between rows. The twelve profiles in virgin land were sited along a transect crossing the natural dendritic drainage pattern so that soils in lower concave and higher, convex portions of the landscape could be compared.

Table 4.1 Soil sampling locations on the farm Alheit

Block no.	Row no.	Vine no.	Sample ID			Coordinates				Elevation	SE
						South		East			
						Deg	Min	Deg	Min	(m)	(±)
4	10	7	A	W	1	28	45.404	20	30.755	667.4	5.9
4	22	18	A	W	2	28	45.381	20	30.744	665.0	5.6
4	48	7	A	W	3	28	45.358	20	30.700	666.7	12.4
5	6	8	A	W	4	28	45.339	20	30.673	669.3	11.7
5	21	6	A	W	5	28	45.328	20	30.657	673.8	14.3
5	41	7	A	W	6	28	45.293	20	30.620	668.3	9.8
6C	6	16	A	JW	1	28	45.473	20	30.798	670.4	5.0
6C	17	11	A	JW	2	28	45.457	20	30.782	666.6	4.8
6C	30	13	A	JW	3	28	45.442	20	30.761	667.6	5.1
Virgin soil			A	B	1	28	45.425	20	30.727	674.7	5.4
Virgin soil			A	B	2	28	45.413	20	30.714	672.7	5.0
Virgin soil			A	B	3	28	45.401	20	30.699	668.9	5.8
Virgin soil			A	B	4	28	45.397	20	30.693	667.5	5.7
Virgin soil			A	B	5	28	45.391	20	30.682	669.8	5.8
Virgin soil			A	B	6	28	45.382	20	30.662	672.7	8.9
Virgin soil			A	B	7	28	45.378	20	30.637	675.0	5.0
Virgin soil			A	B	8	28	45.37	20	30.615	669.8	5.0
Virgin soil			A	B	9	28	45.365	20	30.574	665.4	5.4
Virgin soil			A	B	10	28	45.358	20	30.555	670.0	5.5
Virgin soil			A	B	11	28	45.346	20	30.527	669.7	5.2
Virgin soil			A	B	12	28	45.321	20	30.501	673.0	5.7

Legend. A: Alheit; **W**: Wingerd (vineyard); **B**: Buitegrond (virgin); **JW**: Young vineyard

At SMB, three different blocks of vineyards and adjacent virgin land were identified (lowest X, middle Y and uppermost Z; Table 4.2). One of the blocks (Y) was selected because of clear evidence in the field of a salt build-up under irrigation. These soils are mostly very deep reddish sands or loamy sands. Only those virgin soils marked BW are strictly comparable with adjacent vineyard soils, the others (B) being located some distance away. Establishment of the vineyards in some cases has involved considerable moving and leveling of the Kalahari sands, which in their natural state occur as elevated dunes. On this farm a rigorous program of soil amendment with manure and gypsum is pursued and samples of these materials from stockpiles on the farm were collected for laboratory tests.

Table 4.2 Soil sampling locations on SMB Boerdery

Block	Slope direction	Sample ID				Coordinates South		East		Elevation (m)	SE (±)
						Deg	Min	Deg	Min		
1	Bottom	S	X	W	1	28	44.810	20	46.390	702.9	5.7
1		S	X	W	2	28	44.806	20	46.409	700.0	5.7
1	to	S	X	W	3	28	44.800	20	46.419	706.3	6.2
1		S	X	W	4	28	44.792	20	46.431	706.1	16.7
Virgin soil	Top	S	X	BW	5	28	44.776	20	46.421	701.8	5.9
Virgin soil	Bottom	S	X	B	1	28	44.771	20	46.330	703.1	5.9
Virgin soil	to	S	X	B	2	28	44.753	20	46.332	705.7	5.0
Virgin soil		S	X	B	3	28	44.741	20	46.335	707.1	6.2
Virgin soil	Top	S	X	B	4	28	44.730	20	46.337	706.4	4.6
24,25	Bottom	S	Y	W	1	28	44.297	20	46.361	688.2	6.5
24,25		S	Y	W	2	28	44.294	20	46.376	715.9	5.2
24,25	to	S	Y	W	3	28	44.284	20	46.392	727.3	6.6
24,25		S	Y	W	4	28	44.277	20	46.411	728.7	4.9
Virgin soil	Top	S	Y	BW	5	28	44.271	20	46.421	724.3	5.5
Virgin soil	Bottom	S	Y	B	1	28	44.178	20	46.324	725.3	4.6
Virgin soil	Middle	S	Y	B	2	28	44.171	20	46.335	723.5	5.5
Virgin soil	Top	S	Y	B	3	28	44.168	20	46.347	724.6	5.4
37B	Bottom	S	Z	W	1	28	44.375	20	46.595	737.3	5.2
37B	to	S	Z	W	2	28	44.385	20	46.593	742.9	6.4
37B		S	Z	W	3	28	44.391	20	46.592	748.7	6.3
Virgin soil	Top	S	Z	BW	4	28	44.402	20	46.588	757.8	4.5

Legend. S: SMB Boerdery; **X, Y, Z**: separate blocks; **W**: Wingerd;
B Buitegrond (virgin); **BW**: Buite wingerd (virgin)

At SADOR (Table 4.3) three profiles were excavated within a well established vineyard and another three in adjacent ground. The calcrete horizon in these soil profiles varies in depth and its upper part consists of more nodular rather than continuously cemented material, with nodules up to the size of a fist or more being interspersed with sandy soil. It is believed that these soils developed on an old, elevated terrace of the Orange River. The topography is almost flat.

Table 4.3 Soil sampling locations on the SADOR farm, Upington

Block no.	Sample ID			Coordinates				Elevation	SE
				South		East			
				Deg	Min	Deg	Min	(m)	(±)
1000A	U	W	1	28	28.990	21	18.067	813.4	13.0
	U	W	2	28	28.922	21	18.067	815.1	19.9
	U	W	3	28	28.879	21	18.067	811.3	14.3
Virgin	U	B	1	28	28.990	21	18.086	810.4	4.7
	U	B	2	28	28.925	21	18.090	809.6	6.7
	U	B	3	28	28.882	21	18.089	812.7	5.5

Legend. U: Upington; **W**: Wingerd (vineyard); **B**: Buitegrond (virgin)

Soil samples were collected by channeling down the freshly exposed profile, taking care to ensure a representative slice of soil, rock and saprolite fragments. The fragments were broken with a hammer where necessary. After air-drying the material was crushed with a large steel pestle and mortar to pass a 2mm screen. Individual as well as composite samples for different blocks were then subjected to laboratory analysis and leaching experiments.

Salinity, pH and exchangeable cation content were determined on all samples. For salinity determination the EC (electrical conductivity) of a 1:5 soil:water extract was measured after shaking overnight (16h). Using composite samples prepared from top, middle and bottom layers on each of the three farms, a correlation was made of EC in the 1:5 extract with the EC of a saturated paste extract (EC_e). On selected composite samples a full cation and anion analysis of the 1:5 soil:water extract was also performed. Exchangeable cations were determined by extraction with 1M ammonium acetate (pH7). Cations were determined by flame atomic absorption spectroscopy and anions by ion liquid chromatography.

Salt-generation potential was assessed in three ways. Firstly, the 1:5 soil:water suspensions used for salinity assessment were shaken again after allowing them to stand for a two month period, and EC and pH was measured in the supernatant. Secondly, on a sub-set of soils selected to give a representative cross section of salinity levels from each field area, a leaching experiment was conducted, over a five day period, in which 1:5 soil:water suspensions were equilibrated overnight (16h), EC and pH were measured in the supernatant after centrifugation, then the supernatant was discarded and replaced with distilled water and the extraction process continued. Thirdly, on a set of composite samples the effects of gypsum and manure addition, at rates similar to those applied in vineyard management, on salinity and pH, was also assessed by shaking 1:5 soil:water suspensions of treated and untreated soils overnight for 16h.

4.3 Results and discussion

4.3.1 Field soil properties and exchangeable cation content

The samples taken from each profile, thickness of each contiguous horizon sampled (cm), effervescence with HCl (Y, as an indication of calcareousness), a brief description of each horizon and the ammonium acetate-extractable cations and exchangeable sodium percentage (ESP) are summarized for all soils in

Tables 4.4 to 4.6 (where gaps exist in the tables this indicates that samples or data went missing). The ESP for the purposes of this report is the ratio of ammonium acetate-extractable Na to total extractable cations, expressed as a percentage.

Table 4.4 Soil description and exchangeable cation content: Alheit

Farm: Land use	Profile No		Sampled horizon	(cm)	HCl	Description	Exchangeable cations ($mmol_c$ kg^{-1}) Ca	Mg	Na	K	ESP %
Alheit:	AB	1	A Top	10	Y	Red soil	190.5	13.8	6.1	2.9	2.9
Virgin soil			B Middle	20	Y	Calcrete/saprolite	194.3	11.0	6.6	1.5	3.1
			C Bottom	40	Y	Saprolite	163.8	10.4	4.2	1.4	2.3
	AB	2	A Top	10		Red soil	71.1	41.4	4.7	3.8	3.9
			B Middle	30		Red soil/layered saprolite	168.7	52.9	13.7	3.5	5.8
			C Bottom	20		Saprolite	73.3	18.2	1.8	1.2	1.9
	AB	3	A Top	10		Red soil	41.5	25.8	0.7	3.2	1.0
			B Middle	30		Saprolite	185.5	28.9	0.5	1.8	0.2
			C Bottom	50		Saprolite (less weathered)	167.6	18.8	0.6	1.4	0.3
	AB	4	A Top	10		Red soil	111.8	19.8	0.8	4.6	0.6
			B Middle	30		Saprolite	161.0	10.8	3.0	1.8	1.7
			C Bottom	50		Saprolite (less weathered)	189.1	6.8	6.3	1.1	3.1
	AB	5	A Top	10	Y	Red soil	102.0	6.4	0.6	6.4	0.5
			B Middle	30	Y	Red soil, blocky	182.0	6.8	0.9	2.8	0.5
			C Bottom	50	Y	Calcareous saprolite	203.0	5.6	0.9	1.8	0.4
	AB	6	A Top	10		Red soil	195.5	15.8	2.6	2.0	1.2
			B Middle	30		Red soil, blocky	45.4	18.8	0.7	4.7	1.0
			C Bottom	30	Y	Calcareous soil	182.3	10.3	4.0	0.8	2.0
	AB	7	A Top	10		Red soil	30.3	13.5	0.7	4.3	1.3
			B Middle	30		Saprolite	52.0	28.2	0.7	2.6	0.9
			C Bottom	30		Saprolite (less weathered)	46.6	26.1	0.8	1.6	1.0
	AB	8	A Top	10		Red soil	46.5	16.6	0.7	5.3	1.0
			B Middle	30	Y	Calcareous saprolite	132.6	14.6	1.1	3.1	0.7
			C Bottom	40	Y	Saprolite (less weathered)	159.4	16.8	2.1	2.1	1.2
	AB	9	A Top	10		Red soil	182.0	16.8	2.0	19.5	0.9
			B Middle	30	Y	Saprolite	168.8	13.9	1.2	21.4	0.6
			C Bottom	40	Y	Saprolite (less weathered)	158.2	13.4	1.0	23.2	0.5
	AB	10	A Top	10		Red soil	28.8	9.3	0.4	4.0	1.0
			B Middle	30		Saprolite	34.7	4.9	0.7	1.9	1.6
			C Bottom	30	Y	Calcareous saprolite	83.4	9.3	2.0	2.6	2.0
	AB	11	A Top	10		Red soil	41.9	3.9	0.4	1.9	0.9
			B Middle	30		Saprolite	123.8	5.5	0.7	2.1	0.5
			C Bottom	30		Saprolite (less weathered)	155.5	5.6	0.7	2.4	0.5
	AB	12	A Top	10		Red soil	44.0	26.3	1.2	4.0	1.6
			B Middle	30		Red soil, blocky/ saprolite	69.0	31.2	2.0	2.2	2.0
			C Bottom	30		Saprolite (layered)	72.8	29.3	2.5	1.8	2.3

Arrowed column indicates thickness in cm of each horizon (profile depth is the sum of horizon thicknesses).
HCl test for calcareousness: Y indicates clear effervescence

Table 4.4 Soil description and exchangeable cation content: Alheit (continued)

Farm: Land use	Profile No		Sampled horizon	(cm)	HCl	Description	Exchangeable cations ($mmol_c\ kg^{-1}$) Ca	Mg	Na	K	ESP %
		(D: dripper line; M: mid-point between vine rows)									
Alheit: Young Vineyard	AJW	2D	A Top	10		Red soil					
			B Middle	30		Red soil, blocky					
			C Bottom	30		Red soil, blocky, hard					
		2M	A Top	10		Red soil	84.5	8.3	4.6	2.1	4.6
			B Middle	30		Red soil, blocky	109.1	6.8	8.8	1.1	7.0
			C Bottom	30		Red soil, blocky, hard	192.6	7.3	7.0	1.1	3.3
Alheit: Vineyard	AW	1D	A Top	10		Red soil, sandy	91.4	23.3	2.4	4.5	2.0
			B Middle	30		Saprolite; more roots 0-60cm	205.0	16.0	2.5	2.1	1.1
			C Bottom	30		Saprolite (less weathered)	183.0	12.6	2.5	2.4	1.3
	AW	1M	A Top	10		Red soil, sandy	213.5	10.9	1.2	4.3	0.5
			B Middle	30		Saprolite; no roots	219.4	8.9	1.2	2.5	0.5
			C Bottom	30		Saprolite (less weathered)	207.5	6.5	1.0	1.9	0.5
	AW	2D	A Top	10	Y	Red soil	200.9	16.6	4.9	3.3	2.2
			B Middle	40	Y	Saprolite; more roots 0-50cm	199.5	12.8	2.6	2.2	1.2
			C Bottom	25	Y	Saprolite (less weathered)	213.6	10.8	2.1	1.8	0.9
	AW	2M	A Top	10	Y	Red soil	222.8	6.9	2.1	1.7	0.9
			B Middle	15	Y	Saprolite; very few roots	214.7	5.0	2.1	1.3	1.0
			C Bottom	50	Y	Saprolite (less weathered)					
	AW	3D	A Top	10		Red soil	185.9	20.9	3.6	3.7	1.7
			B Middle	20		Red soil, blocky	198.4	12.8	3.9	3.2	1.8
			C Bottom	30		Red soil, blocky, hard, on rock	173.3	5.8	3.1	4.0	1.7
	AW	3M	A Top	10		Red soil	214.3	7.5	2.9	5.7	1.2
			B Middle	20		Red soil, blocky	199.7	5.4	19.7	3.2	8.7
			C Bottom	30		Red soil, blocky, hard, on rock	191.1	6.4	15.8	2.6	7.3
	AW	4D	A Top	10		Red soil	105.2	18.9	3.2	6.4	2.4
			B Middle	20	Y	Calc. saprolite; roots 0-40cm	85.8	17.3	2.1	4.0	2.0
			C Bottom	30	Y	Calcareous saprolite	171.5	12.6	2.4	3.4	1.3
	AW	4M	A Top	10		Red soil	204.3	10.6	1.2	4.7	0.5
			B Middle	20	Y	Calc.saprolite; no roots	196.3	10.4	1.5	2.5	0.7
			C Bottom	30	Y	Calcareous saprolite	192.1	9.2	1.3	2.3	0.6
	AW	5D	A Top	10		Red soil	79.1	7.1	2.4	1.9	2.7
			B Middle	20	Y	Calc.saprolite; roots 0-25cm	143.4	17.7	3.2	1.6	1.9
			C Bottom	20	Y	Calcareous saprolite	170.3	18.1	2.1	1.4	1.1
	AW	5M	A Top	10		Red soil					
			B Middle	20	Y	Calc. saprolite; no roots	99.0	15.9	3.4	2.3	2.8
			C Bottom	20	Y	Calcareous saprolite	86.9	14.8	2.7	1.9	2.5
	AW	6D	A Top	10		Red soil; roots 0-60 cm	43.8	10.7	2.6	4.4	4.2
			B Middle	20		Red soil/ saprolite	17.8	7.8	1.7	1.3	5.9
			C Bottom	40	Y	Red soil, blocky/saprolite	138.0	5.0	2.9	2.3	2.0
	AW	6M	A Top	10		Red soil; very few roots	114.0	5.7	1.8	3.6	1.5
			B Middle	20		Red soil/saprolite	40.2	2.6	0.8	1.5	1.8
			C Bottom	40	Y	Red soil, blocky/saprolite					

Table 4.5 Soil description and exchangeable cation content: SMB Boerdery

Farm: land use	Profile No		Sampled horizon	(cm)	HCl	Description	Exchangeable cations (mmol$_c$ kg^{-1}) Ca	Mg	Na	K	ESP %
SMB farm: Block X Virgin soil	SXB	1	A Top	40	Y	Sandy soil	52.1	9.5	4.3	1.7	6.3
			B Middle	40	Y	Sandy soil	75.2	6.4	3.0	1.5	3.5
			C Bottom	40	Y	Sandy soil (stony below)	159.5	9.7	1.2	2.0	0.7
	SXB	2	A Top	40	Y	Sandy soil	47.8	6.2	0.5	3.1	0.8
			B Middle	40	Y	Sandy soil	80.1	6.8	3.6	7.3	3.7
			C Bottom	40	Y	Sandy soil (stony below)	77.0	7.5	12.7	5.1	12.4
	SXB	3	A Top	40		Sandy soil	8.1	5.1	0.4	1.7	2.8
			B Middle	40		Sandy soil	17.7	6.4	0.4	2.6	1.6
			C Bottom	40		Sandy soil (stony below)	33.1	7.8	0.5	2.4	1.2
	SXB	4	A Top	40		Sandy soil	9.5	5.8	0.4	2.3	2.2
			B Middle	40		Sandy soil	9.0	7.5	0.6	1.8	3.2
			C Bottom	40		Sandy soil (stony below)	12.9	7.8	0.7	1.7	3.0
	SXBW	5	A Top	30		Sandy soil	27.4	6.9	3.0	2.9	7.4
			B Middle	30		Sandy soil	12.1	8.6	1.0	1.6	4.1
			C Bottom	30		Sandy soil	43.4	8.7	1.9	1.1	3.5
SMB farm: Block X Vineyard	SXW	1	A Top	40		Sandy soil	33.3	9.7	1.1	3.7	2.4
			B Middle	40		Sandy (stoneline at 70cm)	68.5	9.1	1.2	2.2	1.5
			C Bottom	40		Sandy soil	45.9	5.8	2.8	1.8	5.0
			D Lowest	30		Sandy soil	178.4	16.3	3.7	3.2	1.8
	SXW	2	A Top	40		Sandy soil	19.8	8.3	3.3	3.4	9.4
			B Middle	40		Sandy soil (stoneline again)	81.5	10.4	4.1	2.0	4.2
			C Bottom	40		Sandy soil	88.3	9.3	3.1	2.1	3.0
	SXW	3	A Top	40		Sandy soil	23.6	8.9	4.0	2.4	10.3
			B Middle	40		Sandy soil	50.2	8.0	3.2	2.5	5.0
			C Bottom	40		Sandy soil	91.1	10.3	3.5	2.6	3.2
	SXW	4	A Top	40		Sandy soil	23.4	9.0	3.7	2.9	9.6
			B Middle	40		Sandy soil	48.1	8.9	3.7	1.5	5.9
			C Bottom	40		Sandy soil	90.8	9.4	3.3	1.1	3.2
SMB farm: Block Y Virgin soil	SYB	1	A Top	40	Y	Sandy soil	191.2	20.2	6.0	10.8	2.6
			B Middle	40	Y	Sandy calcareous, stony soil	187.5	38.5	62.4	10.9	20.9
			C Bottom	40	Y	Sandy calc, on calcrete	184.4	33.5	49.4	4.5	18.2
	SYB	2	A Top	40	Y	Sandy soil	223.9	13.4	3.6	6.7	1.5
			B Middle	40	Y	Sandy calcareous	198.7	24.3	17.1	14.4	6.7
			C Bottom	40	Y	Sandy calcareous	218.8	22.2	17.4	10.8	6.5
	SYB	3	A Top	40	Y	Sandy soil	84.1	12.5	2.9	7.4	2.7
			B Middle	40	Y	Sandy calcareous	177.7	17.0	4.0	9.4	1.9
			C Bottom	40	Y	Sandy calcareous	200.6	37.7	30.8	13.7	10.9

Arrowed column indicates thickness in cm of each horizon (profile depth is the sum of horizon thicknesses).
HCl test for calcareousness: Y indicates clear effervescence

Table 4.5 Soil description and exchangeable cation content: SMB Boerdery (continued)

Farm: land use	Profile No		Sampled horizon	(cm)	HCl	Description	Exchangeable cations (mmol$_c$ kg^{-1}) Ca	Mg	Na	K	ESP %
SMB farm: Block Y Vineyard	SYW	1	A Top	30	Y	Sandy soil	216.4	19.1	4.7	4.6	1.9
			B Middle	30	Y	Sandy soil	245.3	18.0	5.0	5.8	1.8
			C Bottom	40	Y	Sandy soil	262.9	23.6	3.7	7.5	1.3
			D Lowest	40	Y	Sandy/calcrete (poor drainage)	218.6	35.4	3.3	10.0	1.3
	SYW	2	A Top	30	Y	Sandy soil	257.8	22.6	5.7	6.3	1.9
			B Middle	30	Y	Sandy soil	218.8	36.2	4.5	5.2	1.7
			C Bottom	40	Y	Sandy soil	221.2	37.6	4.3	6.3	1.6
	SYW	3	A Top	30	Y	Sandy soil	182.9	13.7	3.2	4.7	1.6
			B Middle	30	Y	Sandy soil	194.8	13.9	3.6	5.1	1.7
			C Bottom	40	Y	Sandy soil	192.6	20.1	3.6	4.8	1.6
	SYW	4	A Top	30	Y	Sandy soil	172.7	12.4	3.2	3.7	1.7
			B Middle	30	Y	Sandy soil	173.8	11.9	3.7	4.0	1.9
			C Bottom	40	Y	Sandy soil	181.5	14.6	3.8	4.9	1.9
SMB farm: Block Y Virgin soil	SYBW	5	A Top	30		Sandy soil	158.5	11.6	3.3	5.3	1.9
			B Middle	30		Sandy soil	129.8	11.9	4.1	4.8	2.7
			C Bottom	40		Sandy soil	153.7	11.8	4.3	4.5	2.4
SMB farm: Block Z Vineyard	SZW	1	A Top	40	Y	Sandy soil	120.7	6.4	3.2	3.0	2.4
			B Middle	40	Y	Sandy soil	121.0	6.6	3.3	1.8	2.5
			C Bottom	40	Y	Sandy soil	133.2	6.8	4.0	0.9	2.7
			D Lowest	30	Y	Sandy soil	121.1	7.7	3.2	1.0	2.4
	SZW	2	A Top	40	Y	Sandy soil	61.0	8.7	2.8	4.5	3.7
			B Middle	40	Y	Sandy soil	156.6	8.8	3.7	1.5	2.1
			C Bottom	40	Y	Sandy soil	76.0	7.1	4.0	1.5	4.5
	SZW	3	A Top	40		Sandy soil	17.7	6.7	3.4	3.1	11.2
			B Middle	40		Sandy soil	16.6	6.8	3.5	2.1	12.0
			C Bottom	40		Sandy soil	28.9	9.0	4.9	1.1	11.2
SMB farm: Block Z Virgin soil	SZBW	4	A Top	40		Sandy soil	8.7	5.3	2.8	1.6	15.4
			B Middle	40		Sandy soil	10.4	6.8	3.7	1.2	16.9
			C Bottom	40		Sandy soil	13.5	8.7	2.7	1.7	10.1

Arrowed column indicates thickness in cm of each horizon (profile depth is the sum of horizon thicknesses).
HCl test for calcareousness: Y indicates clear effervescence

Table 4.6 Soil description and exchangeable cation content: SADOR

Farm: land use	Profile No		Sampled horizon	(cm)	HCl	Description	Exchangeable cations (mmol$_c$ kg^{-1}) Ca	Mg	Na	K	ESP %
SADOR farm, Upington: Virgin soil	UB	1	A Top	40	Y	Red soil, sandy	115.8	6.7	1.1	4.2	0.9
			B Middle	40	Y	Sandy/calcareous nodules	203.0	6.2	1.0	1.5	0.5
			C Bottom	40	Y	Calcrete/calcareous nodules	202.2	8.3	2.4	1.1	1.1
	UB	2	A Top	40	Y	Red soil, sandy	188.9	6.4	2.1	5.3	1.0
			B Middle	40	Y	Sandy/calcareous nodules	213.5	11.9	16.5	2.3	6.8
			C Bottom	40	Y	Calcrete/calcareous nodules	219.1	14.8	22.1	2.0	8.6
	UB	3	A Top	40	Y	Red soil, sandy	117.5	5.9	0.7	5.0	0.6
			B Middle	40	Y	Red soil, harder	219.3	6.3	3.1	3.9	1.3
			C Bottom	40	Y	Calcrete/calcareous nodules	203.6	6.2	1.6	2.5	0.8
SADOR farm, Upington: Vineyard	UW	1	A Top	40	Y	Red soil, sandy	47.1	17.0	2.9	3.6	4.1
			B Middle	40	Y	Red soil/calcareous nodules	174.1	12.0	3.7	2.7	1.9
			C Bottom	40	Y	Calcareous nodules	235.3	11.3	3.5	1.6	1.4
	UW	2	A Top	40	Y	Red soil, sandy	137.7	15.8	3.7	7.2	2.2
			B Middle	40	Y	Red soil/calcareous nodules	231.9	10.9	5.5	2.3	2.2
			C Bottom	40	Y	Calcareous nodules	244.7	14.7	3.3	2.2	1.2
	UW	3	A Top	40	Y	Red soil, sandy	109.5	15.6	4.6	5.5	3.4
			B Middle	40	Y	Red soil/calcareous nodules	230.5	14.3	4.2	3.7	1.7
			C Bottom	40	Y	Calcareous nodules	239.4	14.0	4.0	3.2	1.5

Arrowed column indicates thickness in cm of each horizon (profile depth is the sum of horizon thicknesses).
HCl test for calcareousness: Y indicates clear effervescence

The great majority of the soils are dominated by Ca with relatively small amounts of Mg, K and Na. The ESP is generally much lower than that which would be expected to cause a deterioration of physical properties under irrigation. The few exceptionally high ESP values are invariably associated with more saline soils, as will be seen from a comparison with salinity data reported later. The more sandy soils of SMB (or at least those that are non-calcareous) are generally far less rich in basic cations than those of Alheit and SADOR, as would be expected. No attempt was made with the cation analyses to distinguish between exchangeable and free salts or to make corrections for dissolution of calcium carbonate during the extraction.

4.3.2 Laboratory weathering by equilibration

Of more direct interest in the assessment of salt generating potential is the extent to which salts are readily washed out of the soil by irrigation water. This will be influenced partly by the hydrolysis of exchangeable cations (especially Na), partly by the presence of free soluble salts (e.g. halite and gypsum) and, perhaps as importantly in these minimally weathered soils, by the dissolution of the more weatherable primary (e.g. biotite, feldspar) and secondary (e.g. calcite) minerals that would normally not be considered important sources of solutes.

The first experiment, conducted on all the soil samples, consisted of equilibrating an aqueous soil suspension for an extended period and determining EC and pH at intervals to monitor the course of solute build-up in solution. Tables 4.7 to 4.9 report the results. The EC values in these tables are calculated, based on the correlation between EC_e and the EC of the 1:5 soil:water suspension, obtained for 9 representative composite samples made up from A, B and C horizons of all the soils in each of the three study areas. In performing the regression, the linear relationship

$$\mathbf{EC_e = 14.2EC_{1:5} - 72}$$

was discarded ($R^2 = 0.77$; lower still with zero intercept forcing), in favour of the following power function which gave $R^2 = 0.84$:

$$\mathbf{EC_e = 2.42(EC_{1:5})^{1.47}}$$

This relationship, from which the originally measured values in a 1:5 extract can be calculated, is strong enough to allow the salinity values in Tables 4.7-4.9 to be reliably compared, for convenience, with EC_e values in the salinity literature. It should be noted that the calculated EC_e is reported in dS m^{-1} (multiply these values by 100 to obtain mS m^{-1}).

The sequence of five measurements in Tables 4.7-4.9 (numbers 1-5 in column headings) refer to 1, 2, 7, 20 and 30 days equilibration, respectively. For pH the final measurement was on day 20 (hence there are only four pH columns). Blank spaces appear where samples or data went missing.

The first noteworthy trend to observe in the EC data is that soils with an initially high EC (> 3 or 4 dS m^{-1}, indicating a significant concentration of freely soluble salts), exhibit a much smaller difference between the first and final EC values than soils with an initially low EC. This simply reflects the dominant influence of readily soluble salts in the former case, masking the effect of sparingly soluble minerals which dominate the dissolution behaviour in the latter. It emphasizes the marked difference in rate of dissolution from free salts (e.g. halite) compared with primary weatherable minerals such as feldspar and biotite.

Table 4.7 Salinity and pH changes in 1:5 soil:water suspensions (1=16h; 5=2 months): Alheit

Farm: land use	Profile No		Sampled Horizon		EC_e (dS m^{-1}, calculated) (y=2.42x(exp1.47), R^2=0.84)					pH			
				(cm)	1	2	3	4	5	1	2	3	4
Alheit: Virgin soil	AB	1	A Top	10	0.6	1.1	1.6	3.0	3.2	9.2	8.9	8.4	7.7
			B Middle	20	0.6	0.9	1.1	1.5	1.8	9.3	9.4	9.0	8.5
			C Bottom	40	0.6	0.8	1.0	1.2	1.3	9.5	9.4	9.1	8.7
	AB	2	A Top	10	0.9	2.1	1.4	1.9	2.1	9.0	8.9	8.6	8.1
			B Middle	30	0.5	4.9	5.2	5.6	6.0	8.5	8.3	8.2	8.0
			C Bottom	20	1.3	1.6	1.8	2.1	2.1	8.9	8.6	8.4	8.2
	AB	3	A Top	10	0.5	1.0	1.3	1.8	2.0	8.6	8.5	8.2	7.7
			B Middle	30	0.6	1.0	1.2	1.6	2.0	9.0	9.0	8.6	8.3
			C Bottom	50	0.5	0.7	0.9	1.2	1.4	9.4	9.2	8.9	8.5
	AB	4	A Top	10	0.7	0.9	1.2	1.8	2.4	9.2	9.0	8.7	8.2
			B Middle	30	0.8	1.1	1.2	1.5	1.7	9.4	9.3	9.1	8.7
			C Bottom	50	1.2	1.6	1.7	1.9	2.0	9.5	9.4	9.2	8.9
	AB	5	A Top	10	0.7	1.0	1.4	2.0	2.7	9.3	9.1	8.6	8.1
			B Middle	30	0.6	1.0	1.3	1.8	2.2	9.2	9.2	8.8	8.4
			C Bottom	50	0.6	0.9	1.1	1.4	1.6	9.3	9.3	9.0	8.7
	AB	6	A Top	10	0.8	1.3	1.4	1.8	2.1	9.1	9.1	8.8	8.4
			B Middle	30	0.5	0.9	1.1	1.5	1.9	8.5	8.5	8.1	7.8
			C Bottom	30	0.9	1.2	1.4	1.6	1.9	9.5	9.5	9.2	8.8
	AB	7	A Top	10	0.4	0.8	1.1	1.8	1.7	8.0	8.6	7.4	7.3
			B Middle	30	0.4	0.6	0.7	1.0	1.0	7.9	8.1	7.5	7.2
			C Bottom	30	0.3	0.4	0.5	0.7	0.8	7.8	7.9	7.5	7.2
	AB	8	A Top	10	0.5	0.8	1.0	1.4	1.6	8.8	8.8	8.5	8.1
			B Middle	30	0.7	0.9	1.2	1.5	1.7	9.3	9.2	9.0	8.6
			C Bottom	40	0.9	1.3	1.5	1.8	1.9	9.3	9.0	8.9	8.6
	AB	9	A Top	10	1.5	2.1	2.3	2.7	3.0	10.0	9.9	9.6	9.1
			B Middle	30	4.7	5.3	5.4	6.2	6.7	9.1	9.2	8.9	8.3
			C Bottom	40	5.7	6.2	6.2	6.6	6.6	9.0	9.0	8.8	8.5
	AB	10	A Top	10	0.7	1.1	1.5	2.1	2.4	9.0	9.0	8.3	7.8
			B Middle	30	0.5	1.2	0.9	1.2	1.4	9.4	8.7	8.9	8.5
			C Bottom	30	2.7	0.7	3.5	4.1	3.9	8.7	9.3	8.5	8.1
	AB	11	A Top	10	0.5	0.7	0.8	1.1	1.4	9.3	9.3	9.0	8.5
			B Middle	30	0.6	0.8	0.9	1.3	1.5	9.2	9.2	9.0	8.6
			C Bottom	30	0.6	0.9	1.0	1.3	1.5	9.2	9.3	9.0	8.7
	AB	12	A Top	10	0.8	1.0	1.2	1.4	1.4	8.3	8.3	8.0	7.8
			B Middle	30	1.5	2.0	2.1	2.6	2.5	8.5	8.7	8.4	8.2
			C Bottom	30	0.7	1.2	1.5	2.1	2.1	8.7	8.8	8.6	8.1
Mean					1.0	1.4	1.7	2.1	2.3	9.0	9.0	8.6	8.2

Numbers 1-5 in column headings refer to 1, 2, 7, 20 and 30 days equilibration, respectively

For pH the final measurement was on day 20 (hence there are only four pH columns)

Blank spaces appear where samples or data went missing

Table 4.7 Salinity and pH changes in1:5 soil:water suspensions (1=16h; 5=2 months): Alheit (continued)

Farm: land use	Profile No		Sampled horizon		EC_e (dS m^{-1}, calculated) (y=2.42x(exp1.47), R^2=0.84)					Ph			
				(cm)	1	2	3	4	5	1	2	3	4
		(D: dripper line; M: mid-point between vine rows)											
Alheit: Young Vineyard	AJW	2D	A Top	10	1.5	2.0	2.2	3.0	3.7	9.2	9.0	8.6	8.0
			B Middle	30	0.7	1.0	1.1	1.4	1.5	9.3	9.3	9.0	8.7
			C Bottom	30	0.9	1.1	1.1	1.3	1.4	9.4	9.3	9.1	8.9
		2M	A Top	10	4.1	4.1	4.2	4.5	4.9	8.6	8.7	8.4	8.1
			B Middle	30	6.7	6.5	6.3	7.0	7.3	8.5	8.6	8.4	8.0
			C Bottom	30	3.5	3.6	3.7	3.8	3.9	8.8	8.9	8.8	8.5
Alheit: Vineyard	AW	1D	A Top	10	1.2	1.9	2.5	3.7	4.1	8.9	8.4	8.0	7.6
			B Middle	30	1.0	1.3	1.6	2.2	2.5	9.2	9.0	8.7	8.2
			C Bottom	30	0.6	0.9	1.0	1.4	1.5	9.6	9.4	9.1	8.6
	AW	1M	A Top	10	1.2	1.7	2.1	3.1	3.7	9.1	8.9	8.5	7.9
			B Middle	30	1.1	1.3	1.8	2.2	2.4	9.2	9.1	8.8	8.4
			C Bottom	30	1.0	1.4	1.6	1.9	2.0	9.3	9.2	8.9	8.5
	AW	2D	A Top	10	1.1	1.6	2.0	3.0	3.4	9.2	8.9	8.4	7.8
			B Middle	40	0.9	1.4	1.7	2.3	2.7	9.3	9.2	8.8	8.2
			C Bottom	25	0.7	1.0	1.2	1.4	1.5	9.4	9.3	9.0	8.6
	AW	2M	A Top	10	2.5	2.9	2.9	3.3	3.4	8.9	8.8	8.7	8.3
			B Middle	15	1.0	1.4	1.6	1.9	2.1	9.2	9.2	8.9	8.5
			C Bottom	50	0.0	0.0	0.0	0.0	0.0				
	AW	3D	A Top	10	1.3	2.2	2.9	4.0	4.4	9.0	8.6	8.1	7.7
			B Middle	20	1.7	2.3	2.5	3.3	4.0	9.1	8.9	8.7	8.1
			C Bottom	30	0.9	1.4	1.5	1.7	1.8	9.6	9.4	9.2	8.9
	AW	3M	A Top	10	9.8	10.7	10.7	11.6	11.7	8.8	8.6	8.4	8.0
			B Middle	20	4.5	5.2	5.2	5.4	5.7	9.3	9.2	9.0	8.6
			C Bottom	30	3.3	3.9	4.0	4.2	4.2	9.6	9.5	9.2	8.9
	AW	4D	A Top	10	1.6	2.6	3.4	4.8	5.1	9.0	8.4	7.9	7.5
			B Middle	20	1.0	1.5	1.9	3.0	3.2	9.0	8.7	8.3	7.8
			C Bottom	30	0.9	1.4	1.7	2.4	2.9	9.3	9.1	8.7	8.1
	AW	4M	A Top	10	0.9	1.6	2.3	3.7	4.2	9.2	8.7	8.1	7.6
			B Middle	20	1.3	1.5	1.7	2.1	2.3	9.3	9.2	8.9	8.5
			C Bottom	30	0.9	1.3	1.5	2.0	2.3	9.4	9.3	8.9	8.5
	AW	5D	A Top	10	0.7	0.9	1.0	1.5	1.8	9.6	9.4	9.1	8.4
			B Middle	20	1.0	1.3	1.5	1.8	1.9	9.2	9.0	8.8	8.5
			C Bottom	20	0.6	1.0	1.1	1.4	1.5	9.4	9.2	9.0	8.6
	AW	5M	A Top	10									
			B Middle	20	1.0	1.0	1.2	1.6	1.6	9.1	8.9	8.7	8.3
			C Bottom	20	0.6	1.0	1.1	1.6	1.7	9.1	9.0	8.7	8.4
	AW	6D	A Top	10	1.1	1.6	2.0	2.9	3.3	9.4	9.1	8.6	7.9
			B Middle	20	0.6	0.8	0.9	1.2	1.3	9.3	9.3	9.0	8.3
			C Bottom	40	0.9	1.1	1.3	1.7	1.8	9.4	9.4	9.1	8.6
	AW	6M	A Top	10	2.4	2.7	2.9	3.7	3.7	8.9	8.8	8.5	8.0
			B Middle	20	1.0	1.2	1.4	1.8	1.8	9.1	9.1	8.9	8.5
Mean					1.7	2.1	2.3	2.9	3.1	9.2	9.0	8.7	8.3

Numbers 1-5 in column headings refer to 1, 2, 7, 20 and 30 days equilibration, respectively

For pH the final measurement was on day 20 (hence there are only four pH columns)

Blank spaces appear where samples or data went missing

Table 4.8 Salinity and pH changes in1:5 soil:water suspensions (1=16h; 5=2 months): SMB

Farm: land use	Profile No		Sampled horizon		EC_e (dS m^{-1}, calculated) (y=2.42x(exp1.47), R^2=0.84)					pH			
				(cm)	1	2	3	4	5	1	2	3	4
SMB farm: Block X Virgin soil	SXB	1	A Top	40	0.6	0.8	1.1	1.4	1.9	9.2	9.2	8.9	8.5
			B Middle	40	0.6	0.9	1.0	1.2	1.3	9.2	9.1	9.0	8.7
			C Bottom	40	0.8	1.0	1.1	1.3	1.8	9.3	9.2	9.0	8.7
	SXB	2	A Top	40	0.6	0.8	0.9	1.3	1.4	9.4	9.2	9.1	8.6
			B Middle	40	1.2	0.2	1.5	1.6	1.7	9.8	9.7	9.6	9.3
			C Bottom	40	2.9	3.2	3.1	3.1	3.0	10.4	10.2	10.2	10.0
	SXB	3	A Top	40	0.2	0.4	0.5	0.7	0.9	8.7	8.6	8.4	7.7
			B Middle	40	0.4	0.7	0.8	1.1	1.3	9.2	9.2	9.0	8.6
			C Bottom	40	0.5	0.8	0.8	1.1	1.1	9.4	9.3	9.1	8.7
	SXB	4	A Top	40	0.2	0.4	0.5	0.7	0.8	8.6	8.4	8.3	7.8
			B Middle	40	0.3	0.5	0.6	0.9	1.0	8.9	8.9	8.6	7.9
			C Bottom	40	0.7	1.0	1.0	1.3	1.4	9.0	9.0	8.9	8.6
	SXBW	5	A Top	30	0.6	0.8	1.0	1.5	1.9	9.3	9.2	8.9	8.3
			B Middle	30	0.3	0.5	0.6	0.9	1.1	9.1	9.0	8.8	7.9
			C Bottom	30	0.7	0.8	0.9	1.2	1.2	9.5	9.4	9.2	8.8
SMB farm: Block X Vineyard	SXW	1	A Top	40	1.1	1.4	1.9	2.9	3.2	8.5		8.2	7.6
			B Middle	40	1.3	1.8	1.7	2.1	2.4	8.9		8.7	8.3
			C Bottom	40	0.7	0.8	1.1	1.4	2.0	9.1		9.0	8.5
			D Lowest	30	1.1	1.3	1.6	1.8	2.0	8.9		8.8	8.5
	SXW	2	A Top	40	0.6	0.9	1.2	1.6	1.7	8.5		7.9	7.5
			B Middle	40	0.7	1.0	1.3	1.6	1.9	9.1		8.8	8.3
			C Bottom	40	1.7	1.7	2.0	2.2	2.4	8.7		8.7	8.3
	SXW	3	A Top	40	0.7	0.8	1.1	1.6	1.7	8.8		8.6	8.2
			B Middle	40	0.8	0.9	1.1	1.4	1.6	9.0		8.8	8.4
			C Bottom	40	0.9	1.0	1.2	1.6	1.7	9.0		9.0	8.5
	SXW	4	A Top	40	0.7	0.9	1.3	1.9	2.1	8.7		8.3	7.6
			B Middle	40	0.9	0.9	1.1	1.4	1.5	9.2		9.0	8.6
			C Bottom	40	1.0	1.1	1.4	1.8	2.1	9.1		8.9	8.5
SMB farm: Block Y Virgin soil	SYB	1	A Top	40	1.8	1.9	2.1	2.3	2.2	9.8		9.6	9.3
			B Middle	40	12.6	12.2	12.3	12.5	13.4	10.0		9.7	9.4
			C Bottom	40	12.9	12.7	12.5	12.7	13.5	10.0		9.7	9.5
	SYB	2	A Top	40	1.5	1.7	2.0	2.5	2.9	9.1		8.9	8.4
			B Middle	40	7.8	7.8	8.1	8.4	8.7	9.1		8.9	8.6
			C Bottom	40	16.2	16.0	16.3	16.6	16.5	8.7		8.6	8.3
	SYB	3	A Top	40	1.2	1.3	1.6	2.3	2.6	9.0		8.6	8.1
			B Middle	40	1.0	1.1	1.4	1.8	2.0	9.4		9.1	8.7
			C Bottom	40	21.2	20.7	20.6	21.0	21.9	9.0		8.7	8.3
Mean					2.7	2.8	3.0	3.3	3.6	9.1	9.2	8.9	8.5

Numbers 1-5 in column headings refer to 1, 2, 7, 20 and 30 days equilibration, respectively
For pH the final measurement was on day 20 (hence there are only four pH columns)
Blank spaces appear where samples or data went missing

Table 4.8 Salinity and pH changes in1:5 soil:water suspensions (1=16h; 5=2 months): SMB (continued)

Farm: land use	Profile No		Sampled horizon	(cm)	EC_e (dS m^{-1}, calculated) 1	2	3	4	5	pH 1	2	3	4
SMB farm:	SYW	1	A Top	30	2.1	2.4	2.7	3.2	3.5	8.9		8.7	8.4
Block Y			B Middle	30	7.4	7.6	7.6	7.9	8.6	8.4		8.4	8.1
Vineyard			C Bottom	40	10.8	10.9	10.7	11.1	11.7	8.3		8.3	8.1
			D Lowest	40	4.8	5.3	5.7	6.4	7.2	8.7		8.5	8.1
	SYW	2	A Top	30	5.5	5.6	5.9	6.7	7.2	8.4		8.2	7.7
			B Middle	30	2.1	2.4	2.6	3.0	3.2	8.9		8.8	8.5
			C Bottom	40	2.0	2.3	2.5	2.8	3.0	9.0		9.0	8.7
	SYW	3	A Top	30	1.3	1.6	2.0	3.1	3.3	8.8		8.5	7.9
			B Middle	30	1.7	1.8	2.2	2.6	2.5	9.0		8.8	8.4
			C Bottom	40	1.6	1.7	1.9	2.2	2.2	9.1		9.0	8.7
	SYW	4	A Top	30	0.9	1.1	1.4	2.3	2.6	9.0		8.7	8.0
			B Middle	30	1.1	1.3	1.6	2.4	2.7	9.1		8.9	8.3
			C Bottom	40	1.6	1.7	2.0	2.3	2.4	9.2		9.0	8.6
SMB farm:	SYBW	5	A Top	30	0.8	1.1	1.2	1.6	1.6	9.4	9.3	9.2	8.7
Block Y			B Middle	30	0.8	1.1	1.2	1.4	1.5	9.5	9.4	9.3	8.9
Virgin soil			C Bottom	40	1.2	1.5	1.6	1.8	2.0	9.6	9.5	9.4	8.9
SMB farm:	SZW	1	A Top	40	1.0	1.7	2.2	3.0	3.5	9.6	8.8	8.5	7.8
Block Z			B Middle	40	0.9	1.1	1.3	1.6	1.9	9.3	9.2	9.0	8.4
Vineyard			C Bottom	40	0.9	1.1	1.3	1.6	1.7	9.1	9.2	9.1	8.6
			D Lowest	30	0.9	1.1	1.2	1.6	1.8	9.5	9.2	9.1	8.5
	SZW	2	A Top	40	1.9	2.0	2.5	3.3	3.7	8.5		8.2	7.5
			B Middle	40	0.7	0.8	1.0	1.4	1.6	9.2		9.0	8.5
			C Bottom	40	0.9	1.0	1.3	1.6	1.9	9.0		8.9	8.3
	SZW	3	A Top	40	0.4	0.5	0.7	1.1	1.2	8.4		8.1	7.4
			B Middle	40	0.3	0.4	0.5	0.8	0.9	8.4		8.2	7.5
			C Bottom	40	0.8	0.9	1.0	1.3	1.5	9.0		8.9	8.5
SMB farm:	SZBW	4	A Top	40	0.2	0.4	0.5	0.7	0.8	8.5	8.5	8.3	7.7
Block Z			B Middle	40	0.2	0.3	0.4	0.6	0.7	8.8	8.8	8.5	7.8
Virgin soil			C Bottom	40	0.1	0.2	0.3	0.4	0.5	8.4	8.6	8.5	7.7
Mean					1.9	2.1	2.3	2.7	3.0	8.9	9.0	8.7	8.2

Numbers 1-5 in column headings refer to 1, 2, 7, 20 and 30 days equilibration, respectively
For pH the final measurement was on day 20 (hence there are only four pH columns)
Blank spaces appear where samples or data went missing

Table 4.9 Salinity and pH changes in1:5 soil:water suspensions (1=16h; 5=2 months): SADOR

Farm: land use	**Profile No**		**Sampled horizon**	**(cm)**	**EC_e ($dS\ m^{-1}$, calculated) 1**	**2**	**3**	**4**	**5**	**pH 1**	**2**	**3**	**4**
SADOR farm, Upington: Virgin soil	UB	1	A Top	40	0.5	0.8	1.0	1.6	1.9	9.3	9.2	9.0	8.3
			B Middle	40	0.8	1.0	1.2	1.5	1.8	9.2	9.2	9.1	8.5
			C Bottom	40	0.8	1.0	1.2	1.4	1.7	9.4	9.3	9.2	8.7
	UB	2	A Top	40	0.8	1.0	1.2	1.7	2.0	9.4	9.2	9.1	8.5
			B Middle	40	8.5	8.7	8.6	8.7	9.5	8.7	8.6	8.4	8.0
			C Bottom	40	11.7	12.1	12.2	12.5	13.2	8.6	8.5	8.4	7.8
	UB	3	A Top	40	0.6	0.8	1.0	1.5	1.8	9.4	9.2	9.0	8.3
			B Middle	40	1.0	1.1	1.4	1.8	2.0	9.1	9.0	8.9	8.4
			C Bottom	40	1.4	1.6	1.8	2.1	2.4	9.1	9.1	8.8	8.4
SADOR farm, Upington: Vineyard	UW	1	A Top	40	0.6	1.1	1.5	1.8	2.1	8.6	8.3	8.0	7.6
			B Middle	40	0.7	0.9	1.1	1.7	2.0	9.1	8.9	8.7	8.2
			C Bottom	40	0.9	1.2	1.5	2.0	2.4	9.1	9.0	8.8	8.2
	UW	2	A Top	40	1.5	2.2	2.8	3.2	3.5	8.6	8.1	7.9	7.7
			B Middle	40	1.1	1.4	2.0	2.8	3.4	9.2	9.0	8.4	7.9
			C Bottom	40	1.1	1.5	1.7	2.0	2.3	9.2	9.1	8.9	8.5
	UW	3	A Top	40	1.9	2.5	3.0	3.6	4.0	8.7	8.3	8.0	7.7
			B Middle	40	1.1	1.5	1.8	2.6	2.9	9.1	8.8	8.6	8.6
			C Bottom	40	1.2	1.4	1.6	1.9	2.3	9.2	9.1	8.9	8.5
Mean					2.0	2.3	2.6	3.0	3.4	9.1	8.9	8.7	8.2

The virgin soils at Alheit from our study (Table 4.7), however, are generally not conspicuously saline, with a mean EC_e value (16h equilibration) of 1.0 $dS\ m^{-1}$ (although increasing to a mean of 2.3 $dS\ m^{-1}$ after 30 days equilibration) and with the most saline profile (AB 9) having an EC_e of 5.7 $dS\ m^{-1}$ in the C horizon. The adjacent vineyard soils have a mean EC_e of 1.7 $dS\ m^{-1}$ (initially) increasing to 3.1 $dS\ m^{-1}$ after 30 days, which is about 50 percent higher than the salinity in the virgin soils. That this is not merely due to the sampling procedure having intercepted higher concentrations of salts because of redistribution through drip irrigation is indicated by the comparison between D (dripper) and M (mid-point) samples from each pit, which suggests that although in two profiles (AJW 2 and AW 3) there has been a marked migration of salts into the drier zone (M) between the vine rows, as might be expected, there is generally no significant difference in salinity with sampling position in the profile. There is some indication then, that the vineyard soils (no vineyards here are more than a decade old) may have become more saline than their virgin counterparts, although this cannot be stated with complete certainty. Irrigation with slightly saline water (EC typically 0.3 to 0.5 $dS\ m^{-1}$), use of soil amendments (especially gypsum) and the weathering of minerals would all have contributed to such an increase in salinity. It should be noted that, because of some confusion over sample labeling, the other AJW (young vineyard) profiles listed in Table 4.1 were not included in these analyses. Another aspect worth noting is that there does not appear, in either virgin or vineyard soils at Alheit, to be a consistent stratification of salinity with depth. In most cases the profiles show surprisingly little variation in salt distribution with depth.

The calculated mean salinity values for the SMB soils in Table 4.8 suggest a more saline condition than in the Alheit soils (Table 4.7) although the means are heavily weighted, especially in Table 4.8, by a few exceptionally saline soils (particularly some of the soils, both virgin and vineyard, in block Y). Actually the salinity levels in the majority of these deep, sandy soils are probably lower than those at Alheit, as might be expected. Again, the tendency for EC in the less saline soils to more than double over the 30 day equilibration period suggests an important contribution to salinity from the dissolution of sparingly soluble minerals. Except for the BW profiles, the virgin soils at SMB were not sampled adjacent to vineyards and so it is more difficult to draw conclusions about the effect of vineyard establishment on soil salinity. Nevertheless, if the three virgin BW profiles (SXBW, SYBW and SZBW) are compared with their adjacent vineyard profiles (SXW, SYW and SZW), there does seem to be a consistent increase in salinity of the vineyard soils, confirming the trend observed in the Alheit data.

The SADOR data are shown in Table 4.9. Here the mean salinity values are again heavily influenced by the saline subsurface horizons in virgin profile UB 2. If one discounts these as anomalous, then the overall trend with equilibration time is similar to that of the Alheit soils and the effect of vineyards (it should be noted too that these are much older vineyards than those at Alheit and SMB) may again have been to increase soil salinity by a small margin.

The alkaline character of all the soils is evident in the pH data (Tables 4.7 to 4.9), with initial values of around 9 (rarely nearer 10), typically being associated with base cation hydrolysis, decreasing to nearer 8 or less after 20 days reaction (pH column 4), probably as a result of equilibration with atmospheric CO_2 and the precipitation of calcium carbonate. A few soils (notably SXB2 C and SYB1 B and C) displayed buffering at these high pH levels, which remained between 9.5 and 10 after 20 days equilibration, suggesting that some of the salts in these more saline soils may consist of carbonates more soluble than calcite (i.e. these might be classified as true alkali soils). Such soils are certainly among the most sodic, as can be verified from ESP data in Tables 4.4 to 4.6.

4.3.3 Soluble salt composition

The general composition of the soil solution was assessed from saturated paste extract analyses of composite samples made up by mixing equal quantities of all samples from A, B and C horizons of the profiles from each of the three study areas (Table 4.10). Calcium and Na are the dominant cations with slightly less Mg and minor K concentrations, the most sodic (and saline) soils being the subsurface composites from SMB. Chloride is the dominant anion at Alheit and SADOR, whereas sulphate is dominant in the SMB soils (possibly as a result of more intensive use of gypsum as a soil amendment). Although never dominant, nitrate levels are exceptionally high and suggest that fertilizer application rates need to be reviewed. In general, there is sufficient correspondence between the totals of cations and anions to suggest that bicarbonate is not a dominant anion, although in the less saline composites (Alheit C and SADOR A and C) it is likely to constitute a significant fraction of the anion content. Based on a mean cation content of 22 and mean anion content of 23 $mmol_c\ L^{-1}$, and assuming a water content at saturation of 40%, the salt content in the saturated paste extracts would translate, very approximately, into an average soil profile soluble salt content in the field of between 4 and 5 tons ha^{-1} to a depth of 1m. This figure can be born in mind for later comparison with salt generation estimates based on leaching experiments.

Table 4.10 Cation and anion analysis of saturated paste extracts of composite soils

Cations									
Composite sample	**Ca**	**Mg (mg/l)**	**Na**	**K**	**Ca**	**Mg**	**Na ($mmol_c\ kg^{-1}$)**	**K**	**Total**
Alheit A	139	50	219	9	7.0	4.2	9.5	0.2	20.9
Alheit B	170	29	127	12	8.5	2.4	5.5	0.3	16.7
Alheit C	126	19	105	9	6.3	1.6	4.6	0.2	12.7
SMB A	210	50	130	45	10.5	4.2	5.7	1.2	21.5
SMB B	263	74	452	65	13.2	6.2	19.7	1.7	40.6
SMB C	206	63	340	46	10.3	5.3	14.8	1.2	31.5
SADOR A	85	21	110	28	4.3	1.8	4.8	0.7	11.5
SADOR B	320	75	311	20	16.0	6.3	13.5	0.5	36.3
SADOR C	55	14	87	7	2.8	1.2	3.8	0.2	7.9
Anions									
Composite sample	**F**	**Cl (mg/l)**	**NO_3**	**SO_4**	**F**	**Cl**	**NO_3 ($mmol_c\ kg^{-1}$)**	**SO_4**	**Total**
Alheit A	0.1	482	535	172	0.0	13.6	8.8	3.6	25.9
Alheit B	0.1	239	220	136	0.0	6.7	3.6	2.8	13.2
Alheit C	0.6	152	132	147	0.0	4.3	2.2	3.1	9.5
SMB A	0.8	135	100	627	0.0	3.8	1.6	13.1	18.5
SMB B	2.7	468	305	1313	0.1	13.2	5.0	27.4	45.5
SMB C	2.4	349	106	1147	0.1	9.8	1.7	23.9	35.5
SADOR A	0.1	104	175	96	0.0	2.9	2.9	2.0	7.8
SADOR B	0.1	1510	40	133	0.0	42.5	0.7	2.8	46.0
SADOR C	0.5	92	73	54	0.0	2.6	1.2	1.1	4.9

4.3.4 Laboratory weathering by leaching

The equilibration experiments described in section 4.3.2 are inadequate for calculating the quantity of salt that may be released with the application of successive leaching fractions as normally occurs in vineyard irrigation. This is particularly the case when solute content is governed mainly by the dissolution of sparingly soluble minerals that subtend a low equilibrium concentration, but may dissolve at measurable rates if the equilibrium is disturbed.

The results of the leaching experiment are shown in Table 4.11. The five columns (Leach 1 to 5) represent the daily removal of salts with successive shaking extractions of distilled water at a soil:solution ratio of 1:5. The amount of salt removed decreased exponentially, becoming relatively constant on the fifth day. This smallest quantity of salt released on the fifth day probably represents the steady-state weathering of sparingly-soluble minerals as opposed to more readily dissolved salts which dominate the earlier washings. As a conservative estimate of salt-generating potential it was therefore decided to subtract the final value from the preceding four values and then sum these to give total salt release, calculated in field units of kg/ha for a soil depth of 1m (column c). Potential leaching, on the other hand, is calculated as the sum of all five values (column d). Mean and median values are presented for these estimates at the base of Table 4.11. It should be stressed that these are crude estimates of salt-generation potential, to give some indication of what order of magnitude of salinity can be expected in drainage waters from vineyards on these soils. Much depends on temperature, leaching rate and other factors such as the solute load applied in the irrigation water. The figures also give no indication of what concentration of salts will emerge in drainage water, but they do give some indication of how much salt can potentially be mobilized. An appropriate model such as the soil-water-balance (SWB) model could make use of these data as input, together with relevant meteorological data, to compute the likely discharge rate of salts from catchments.

Table 4.11 Salinity in daily leachates of selected soils (Leach 1 to 5 represents successive leaching at 1:5 soil:water ratio; 16h shaking with distilled water, then centrifugation and decantation)

Soil			EC (dS m^{-1})					Total salt leached (less background)			Potential
no.			Leach 1	Leach 2	Leach 3	Leach 4	Leach 5	dS m^{-1} 1:5	mg kg^{-1}	kg ha^{-1}.m	leaching
								a	b	c	d
AB	4	C	0.20	0.10	0.08	0.07	0.05	0.22	448	4478	9838
AB	5	B	0.10	0.08	0.07	0.07	0.05	0.12	246	2458	7248
AB	6	B	0.09	0.03	0.02	0.02	0.01	0.11	211	2110	3341
AB	7	A	0.10	0.05	0.03	0.02	0.02	0.13	256	2556	4286
AB	7	C	0.04	0.02	0.02	0.01	0.01	0.06	116	1161	1831
AB	9	B	0.39	0.12	0.08	0.07	0.06	0.42	845	8446	14376
AB	9	C	0.53	0.14	0.09	0.07	0.06	0.58	1160	11604	17684
AB	10	A	0.08	0.03	0.02	0.01	0.01	0.11	215	2146	2881
AB	11	C	0.08	0.06	0.05	0.05	0.04	0.07	149	1486	5526
AJW	2M	A	0.41	0.10	0.06	0.05	0.04	0.46	913	9134	13304
AJW	2M	C	0.35	0.10	0.07	0.06	0.04	0.40	805	8054	12344
AW	1M	A	0.17	0.10	0.08	0.07	0.06	0.19	389	3892	9502
AW	3D	B	0.23	0.11	0.08	0.07	0.06	0.27	531	5306	10876
AW	3M	A	1.05	0.20	0.09	0.08	0.05	1.21	2414	24142	29492
AW	3M	B	0.54	0.15	0.09	0.07	0.05	0.64	1279	12788	17998
AW	4M	B	0.15	0.09	0.07	0.06	0.05	0.17	334	3340	8350
AW	6M	A	0.22	0.08	0.06	0.06	0.05	0.24	475	4752	9302
SXB	2	C	0.22	0.09	0.09	0.05	0.04	0.28	557	5568	9638
SXB	3	C	0.07	0.06	0.04	0.05	0.04	0.05	96	958	5058
SXBW	5	B	0.05	0.02	0.01	0.02	0.02	0.02	44	440	2470
SXW	2	A	0.08	0.03	0.02	0.02	0.01	0.11	210	2103	3077
SXW	2	C	0.16	0.07	0.05	0.05	0.04	0.17	333	3326	7456
SXW	4	B	0.10	0.06	0.05	0.05	0.04	0.09	187	1872	5882
SYB	1	B	1.14	0.37	0.17	0.11	0.08	1.46	2910	29104	37544
SYB	1	C	0.79	0.29	0.13	0.09	0.07	1.01	2026	20258	27238
SYB	2	A	0.17	0.09	0.07	0.07	0.05	0.18	358	3584	8824
SYB	3	A	0.14	0.08	0.06	0.05	0.04	0.15	306	3060	7330
SYB	3	B	0.07	0.06	0.05	0.05	0.04	0.05	106	1060	5210
SYB	3	C	1.76	0.34	0.14	0.10	0.08	2.00	4006	40058	48458
SYW	1	B	1.01	0.29	0.13	0.05	0.05	1.28	2567	25670	30750
SYW	2	B	0.23	0.13	0.13	0.12	0.09	0.26	511	5108	13728
SYBW	5	A	0.10	0.07	0.06	0.05	0.05	0.09	182	1818	6378
SZBW	4	A	0.03	0.02	0.01	0.01	0.01	0.04	87	873	1587
SZBW	4	C	0.04	0.01	0.02	0.01	0.01	0.05	106	1062	1782
UB	2	A	0.10	0.09	0.11	0.06	0.05	0.17	343	3430	8210
UB	2	B	0.77	0.17	0.09	0.07	0.05	0.89	1779	17790	22870
UB	3	A	0.08	0.07	0.06	0.05	0.04	0.10	194	1938	5988
UB	3	C	0.14	0.07	0.06	0.05	0.05	0.14	278	2778	7408
UW	1	C	0.11	0.08	0.07	0.06	0.05	0.14	273	2730	7300
UW	3	C	0.13	0.08	0.07	0.06	0.05	0.15	292	2920	7760
Mean			0.31	0.10	0.07	0.06	0.04	0.36	713	7134	11503
Median										3333	7985

Calculations: **a**: Sum of 5 leachate EC values after subtracting background (leach 5 value) from each; **b**: a*2000 (accommodating 1:5 soil water ratio and assuming salt conc. in $mmol_c/L$ is EC*10, and that 1 $mmol_c$ salt is 40mg); **c**: b*10; **d**: as in c, but with no background subtraction

Suffice it to say that something like 3-8 tons and possibly as much as 10 tons per ha of salt can be expected to be released *on average* from vineyards in these areas during the earlier stages of vineyard development (this estimate applies to the case where water from only 1m of soil is drained). If we assume that sufficient water is applied to remove the more soluble salts, then the background release of salts might be much lower. A quantitative estimate, however, is impossible because the rate of salt release from weathering is not known. For comparison, if we assumed a river water salinity of 0.3 dS m^{-1} and an irrigation application of 1000 mm per year, this would amount to applying about 2 ton ha^{-1} of salt. The earlier stages (say the first decade) of vineyard development could therefore be expected to release several times more salt that which would be applied in irrigation water.

4.3.5 Effect of gypsum and manure applications on soil salinity

Slightly saline irrigation water is not the only way the natural salt content of the soil can be augmented when vineyards are established. Information from farmers in the area suggests that gypsum application is widely recommended and that a rate of as much as 5 tons ha^{-1} per annum is applied in order to maintain infiltration rate. In addition, kraal manure is regularly applied to some of the soils, especially on the sandy soils at SMB. Although gypsum itself is not soluble enough to have a damaging effect on osmotic potential and crop yields, it will react with exchangeable cations, increasing the Ca saturation of the exchange surfaces and generating additional soluble salts of Mg, Na and K in the process. Regular gypsum application could therefore be expected to boost salinity in the drainage water. To the extent that organic manures may contain some soluble salts, a similar consideration might apply here as well. These effects would be superimposed on those of routine NPK fertilizer applications which mostly consist of readily soluble salts.

The results of amending six composite soils with gypsum and manure (obtained from stockpiles at SMB) at rates comparable with those that are applied in vineyard establishment are shown in Table 4.12. The increase in salinity is substantial (3- to 4-fold) with gypsum and even with manure at 20 tons/ha, salinity is nearly doubled. Given that most of the soils are dominated by exchangeable Ca and are at a very low risk in terms of sodicity hazard, **the necessity for gypsum application should be carefully reviewed. Not only is it costly, but it might also be environmentally undesirable from a return-flow water quality standpoint. It follows that gypsum should only be applied if soils have a high sodium content and there is a good drainage system in place to catch the run-off.**

4.3.6 Composition of drainage water from selected catchments

Earlier in this report a summary was presented of water quality data for drainage from selected small catchments. It was evident that an exceptionally saline condition is reached in some of these drains. Data for two of the monitoring sites are relevant to the study of salt generation potential since the drainage water emanates from areas that have been investigated for soil salinity. One monitoring station, labeled Strauss, involves the sampling of drainage water from the Alheit catchment area. The other, SMB, relates to the main drain which captures most of the return flow from SMB Boerdery.

Table 4.12 Salinity and pH response of composite soils from top, middle and bottom horizons to addition of gypsum and manure

Treatment	Soil composite	EC (dS m^{-1})	EC increase	pH	pH decrease
Nil (control)	Alheit A	0.23		8.4	
	Alheit B	0.24		8.3	
	Alheit C	0.16		8.8	
	SMB A	0.18		8.6	
	SMB B	0.23		9	
	SMB C	0.30		8.7	
Gypsum (10t/ha)	Alheit A	0.70	0.47	7.9	0.5
	Alheit B	0.67	0.43	8	0.3
	Alheit C	0.64	0.48	8.1	0.7
	SMB A	0.62	0.45	8	0.6
	SMB B	0.69	0.46	8.3	0.7
	SMB C	0.75	0.45	8.3	0.3
Gypsum (20t/ha)	Alheit A	1.11	0.88	7.6	0.7
	Alheit B	1.03	0.80	7.8	0.5
	Alheit C	1.05	0.89	7.8	0.9
	SMB A	1.04	0.86	7.8	0.8
	SMB B	1.07	0.84	8.1	0.9
	SMB C	1.12	0.82	8.1	0.6
Manure (20t/ha)	Alheit A	0.38	0.15	7.8	0.5
	Alheit B	0.36	0.12	7.9	0.4
	Alheit C	0.32	0.16	7.9	0.9
	SMB A	0.34	0.16	7.9	0.7
	SMB B	0.40	0.17	8.2	0.8
	SMB C	0.48	0.18	8.2	0.5
Gypsum (10t/ha) + Manure (20t/ha)	Alheit A	0.82	0.59	7.4	0.9
	Alheit B	0.78	0.55	7.5	0.8
	Alheit C	0.73	0.57	7.6	1.2
	SMB A	0.73	0.56	7.5	1.1
	SMB B	0.81	0.58	7.7	1.3
	SMB C	0.83	0.53	7.8	0.9
Gypsum (10t/ha)	No soil	0.58		6	
Gypsum (20t/ha)	No soil	1.00		5.9	
Manure (20t/ha)	No soil	0.25		7.5	
Gypsum (10t/ha) + manure (20t/ha)	No soil	0.72		6.9	

Salinity and pH measured in the supernatant of 1:5 soil suspensions after 16h shaking

EC and pH also measured in water shaken with equivalent quantitiesof the amendments to those used in treatments

It is tempting to conclude from the extreme salinity of some of the drainage water that the salt discharge is a serious problem. Without flow data, however, the drainage analyses cannot be used to calculate salt flux. The high salinity of the drainage suggests that substantial concentration has taken place through evapotranspiration. The composition of the drainage water may only be indirectly related to soil solution composition in the catchment area because evaporative concentration will result in carbonate precipitation, while the passage of leachate through a subsurface environment of different redox and CO_2 concentration will also affect the status of some solutes (e.g. bicarbonate and nitrate). In this section the relative concentrations of major cation and anions in drainage water is compared with those in saturated paste extracts of soils in the drainage catchment.

The analyses of 10 samples taken monthly from the two drains are shown in Table 4.13. The SMB drainage is acutely saline and the exceptionally high concentrations of Na, Cl and B (the most conservative of the ions) suggest that evaporation is the main cause of the elevated salinity. The Strauss drainage (from the Alheit catchment) is also saline, but much less so than that at SMB.

Table 4.13 Chemical composition of water samples collected from two drainage monitoring stations (Day 1 = 1 July 2003)

Drain	Day	EC	pH	Na	K	Ca	Mg	Cl	CO_3	HCO_3	SO_4	B	P	NH_4-N	NO_3-N
		(dS m^{-1})								(mg L^{-1})					
SMB	24	15.2	7.8	3029	8	356	300	3280	0	531	3255	7.90	0.01	0.19	42
	76	9.8	8.2	1833	6	205	149	1553	62	172	2399	5.96	0.00	0.25	41
	101	12.0	8.0	2417	8	269	218	2700	16	202	2948	6.89	0.06	0.18	42
	123	11.0	8.0	2203	6	257	171	2106	75	297	2406	5.97	0.16	0.14	39
	164	9.3	8.1	1857	6	246	157	1841	48	268	2346	5.60	0.00	0.01	38
	201	9.2	7.9	1685	7	273	188	1786	52	264	2742	6.55	0.17	0.15	39
	230	6.9	8.1	1320	7	113	106	1256	77	157	1679	4.39	0.17	6.61	3
	244	6.4	7.3	1300	7	155	109	1322	69	250	1593	4.35	0.55	0.10	38
	271	9.6	7.9	1807	6	215	157	1831	123	188	2308	6.44	0.07	0.16	42
	310	9.4	6.6	1643	8	288	206	2233	0	621	1498	6.84	0.68	1.31	20
Strauss (Alheit)	24	5.1	7.5	562	1	655	35	726	0	354	1431	0.98	0.00	0.55	6
	76	3.2	7.1	378	3	283	43	462	33	166	694	0.56	0.18	0.21	5
	101	4.3	7.2	460	3	529	30	572	0	202	1479	0.91	0.00	1.20	2
	123	3.5	7.5	455	3	346	49	608	48	314	790	0.57	0.04	0.28	6
	164	3.8	7.5	411	4	364	50	582	32	302	771	0.59	0.13	0.03	5
	201	3.2	7.1	354	4	338	48	475	46	334	888	0.67	0.21	0.20	4
	230	3.1	7.4	444	4	193	25	452	39	235	716	0.99	0.05	0.28	5
	244	2.9	7.6	493	5	148	35	437	31	175	774	1.03	0.08	0.07	4
	271	3.0	7.5	510	5	189	32	448	23	266	804	1.11	0.13	0.16	5
	310	4.0	7.3	530	9	313	51	658	0	591	1007	1.27	0.00	0.06	5

It is instructive to compare the drainage water in terms of relative concentration of major ions with the composition of the saturated paste extracts of composite samples from SMB and Alheit which were reported in Table 4.10. The comparison is presented in Table 4.14.

Table 4.14 Major ion fractions (means) in soil solutions and drainage waters

Source	Cation fraction			Anion fraction			
	Ca	Mg	Na	Cl	SO4	NO3	HCO3
SMB soil solution	0.38	0.17	0.41	0.26	0.66	0.08	0.00
SMB drainage water	0.11	0.13	0.76	0.50	0.44	0.01	0.06
Alheit soil solution	0.45	0.16	0.38	0.50	0.23	0.28	0.00
Alheit drainage water	0.25	0.11	0.64	0.44	0.46	0.01	0.10

The proportion of Na to Ca and Mg is markedly higher in drainage from both areas than in the soil solution. This can probably be attributed to the sequestration of both Ca and Mg as insoluble carbonates as the solution becomes concentrated through evaporation. Chloride is clearly dominant in Alheit soils whereas sulphate becomes co-dominant with Cl in the drainage water. Conversely, sulphate dominance in SMB soils becomes reduced in SMB drainage. The very high concentration of sulphate in SMB drainage suggests that gypsum may also have precipitated during evaporative concentration. Nitrate accounts for 28% of the anions in Alheit soils and 8% in SMB soils. These fractions reduce to less than 1% in both drainage waters, suggesting that denitrification also affects drainage water evolution. The relative concentration of total alkalinity, reported as bicarbonate, is negligible in soils from both areas, but becomes significant (10% and 6% from Alheit and SMB, respectively) in the drainage water. Reaction of CO_2, which is more concentrated in the soil atmosphere, with alkalinity derived from mineral weathering would possibly account for the increased proportion of bicarbonate in the drainage water.

These explanations of how chemical composition may have evolved in the passage from soil water to groundwater are presented with caution because it is not certain to what extent the mean values for the composite soils are representative of the drainage catchments, what the intermediate influence of the vadose zone might have been and also to what extent the drainage water emanates from the areas where the samples were taken. They are offered, however, because they do make geochemical sense and it may provide a basis for interpreting similar data in future cases where there is more certainty about the hydrological continuity between sampled soils and the drainage emanating from them.

4.4 Conclusions

This investigation has provided a preliminary basis for quantifying the salt increment that will develop when new lands along the lower Orange River are developed for irrigated crops. The quantity of salt has been estimated to be on average several times greater than if irrigation water alone, with a conductivity of about 0.3 dS m^{-1}, was the sole source of salinity in return flow.

In general, the soils in three contrasting areas representing shallow saprolitic soils, deep Kalahari sands and calcareous terrace soils are not particularly saline in their virgin state (although some local spots of high salinity were recorded). There is no indication of a drop in salinity when virgin lands are converted to irrigated vineyards; in fact, there are some indications of a slight increase in salinity. Although it was not consistently observed, there were some instances of a marked redistribution of salts, migrating from dripper zones to drier soil between vine rows, and also of salinity build-up in the lower parts of some vineyards. The prospect of local saline patches developing and expanding within vineyards is probably of more immediate concern than the issue of river water quality deteriorating through salt generation. Installation of sophisticated drainage should be a prerequisite for any new development of the virgin *buitegronde*.

Although the use of manure as a soil amendment can probably be justified on the grounds of vineyard nutrition, the widespread use of regular gypsum applications to maintain healthy infiltration rates should be carefully reviewed. The soils are generally well endowed with exchangeable calcium, have a very low exchangeable sodium percentage and have sufficient electrolyte levels to ensure minimal soil structural deterioration when irrigated with water from the Orange River. Not only may the expensive use of gypsum be unnecessary, but it will probably also increase salinization, both locally in soils within vineyards and more widely in irrigation return flow. Exceptionally high nitrate concentrations in some of the soils suggest that fertilizer application rates might also be beneficially reviewed.

The intense evapotranspiration that characterizes irrigated lands in the lower Orange River means that the threat of salinity will always be more serious than elsewhere, and hopefully this report will contribute to the further sophistication in production practices that will be needed to ensure sustainability.

5 IDENTIFICATION AND CLASSIFICATION OF CULTIVATED AREAS UTILIZING SATELLITE IMAGERY

The project required statistics on the area under cultivation and the area affected by salinization. A literature search on satellite remote sensing techniques used for identifying irrigated and salinized areas was conducted. The literature on using satellite imagery for mapping irrigated land confirmed that it was very feasible to obtain accurate land cover statistics, especially of cultivated areas in arid and semi-arid regions (Campbell 1996; Lewis 1998; Wang *et al.* 2001; Campbell 2002). The spectral differences between healthy and vigorously growing crops and those of sparsely distributed natural vegetation are large. These broad land cover classes are easily separated, either manually by visual interpretation or digitally by statistical methods such as cluster analysis or by density slicing of a Normalized Difference Vegetation Index (NDVI) image (Lenney *et al.*, 1996). Satellite imagery had also been successfully used to map vegetation stress. Cultivated areas severely affected by soil salinity are expected to suffer impaired growth and therefore should be identifiable using multi-spectral image analysis techniques (Jamieson *et al.* 1995; Walker & Jolly 1995; Penuelas *et al.* 1997; Thornburn, Wang *et al.* 2002). Consequently it was decided to test whether available Landsat imagery could meet the requirements of the research project.

Two Landsat ETM + scenes were acquired free of charge from the Department of Water Affairs and Forestry (DWAF) in Kimberley. These were: 174/80 2001-02-17 and 175/80 2000-11-0. Both these are summer images. Summer images are expected to show the greatest spectral differences between the irrigated areas and adjacent uncultivated natural vegetation areas. Foliage of vines and other summer crops under irrigation will be maximally developed at this time of the year, giving strong reflectance in the near-infrared portion of the electromagnetic spectrum. This should be advantageous for automated digital identification of the irrigated and cultivated crops along the Orange River *vis a vis* the natural vegetation of the surrounding semi-arid land.

The Landsat images were imported into ERDAS Imagine Version 8.6 for image analysis. No radiometric and geometric corrections were done. The systematically corrected images had been supplied to DWAF by the USGS and were already in the Transverse Mercator projection. These images were merged. Figure 5.1 shows the lower reaches from Upington to Keimoes.

5.1 Unsupervised image classification

At this stage of the research project no detailed ground truth data were available, consequently supervised image classification techniques were not feasible. An unsupervised approach was thus dictated. Unsupervised classification with ERDAS Imagine uses the ISODATA algorithm (ERDAS, 2002). To execute this method the user is required to specify the number of clusters *a priori*. As this is not known in advance, four separate analyses were done with 10, 20, 30 and 40 classes, respectively.

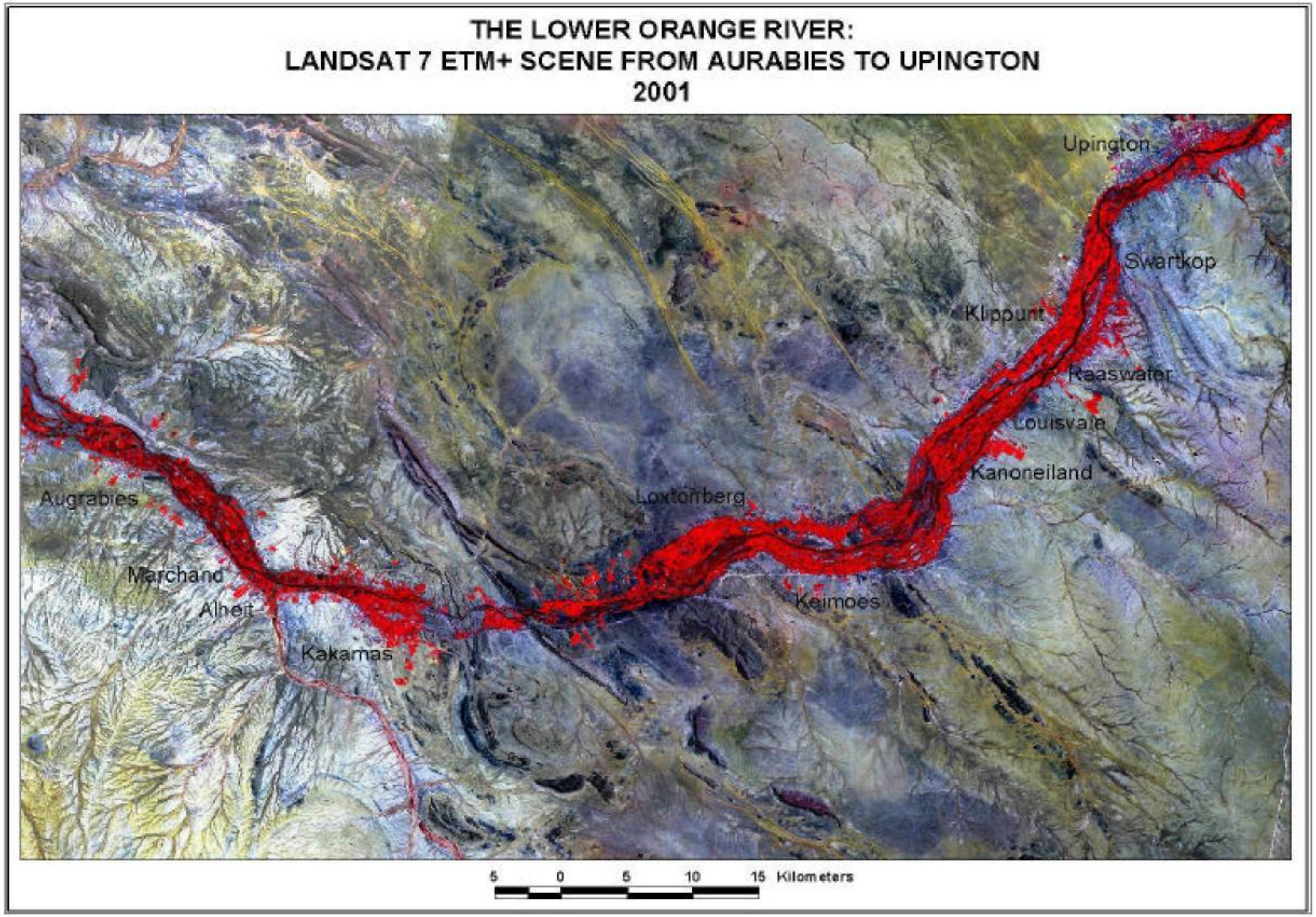

Figure 5.1. Mosaiced Landsat 7 ETM+ imagery showing cultivated land along the lower Orange River from Augrabies to Upington in 2001.

The resultant classifications were visually inspected to decide which was most easily interpretable and had sufficient informational content to demarcate different land cover types (especially cultivated areas) and possibly classes delineating areas showing vegetation stress. It was very difficult to assess the results without detailed ground truth data, because the classes need to be associated with land cover types. The lack of this data meant that the results could only be used to distinguish between broad generalised cover types, such as cultivated and uncultivated land. In spite of this limitation it was clear that these broad land cover classes could be classified with high levels of certainty. The 20 class classification was recoded to two classes, showing cultivated and uncultivated land (Fig. 5.2). It can be seen that the class containing most of the cultivated land also includes areas of shadow along sharp ridges tending in a north westerly and south easterly direction.

5.2 Vegetation Indices

To overcome the problem caused by the lack of detailed ground truth data at this stage of the research project, another approach was investigated. It was thought that a vegetation index may be more sensitive to spectral differences between cultivated areas experiencing vegetation stress and those with healthy vigorously growing crops.

The Normalized Difference Vegetation Index (NDVI) and the Transformed Normalized Difference Vegetation Index (TNDVI) were tested (Wiegand *et al.*, 1991). As expected, these indices clearly distinguished between cultivated and uncultivated areas, but also showed within field variations (Fig. 5.3). This fact was exploited by passing Standard Deviation filters (3x3) over the TNDVI image to find areas with high local spatial variability. It was argued that within field variations may be indicative of vegetation stress. This technique picked out areas of interest, but tended to highlight field boundaries (Fig. 5.4).

A method was consequently sought that would identify fields with high internal variability in their vegetation index values. The twenty-class unsupervised classified and TNDVI images were exported and converted into ESRI GRID format. The twenty class unsupervised grid was regionalized. Zonal statistics of the TNDVI values were then computed for these regions. Regions with high mean TNDVI and high zonal standard deviations were identified. These were expected to demarcate fields which included potentially salinized areas. As there were no ground truth data available the results could not be checked.

In the absence of delineated field boundaries the technique is only partially successful. To overcome this problem field boundary were traced directly from the image by on screen heads-up digitizing, using the TNDVI image as a backdrop (Fig. 5.4). This proved to be a slow and tedious process, dependent upon the visual interpretation abilities of the analyst and not sufficiently reliable to continue.

In the final step the NDVI image derived from the mosaiced Landsat images was used to obtain estimates of the total area under cultivated land along the Orange River from Augrabies to Boegoeberg dam. An unsupervised classification with ten classes was applied to the NDVI image (Fig. 5.5).

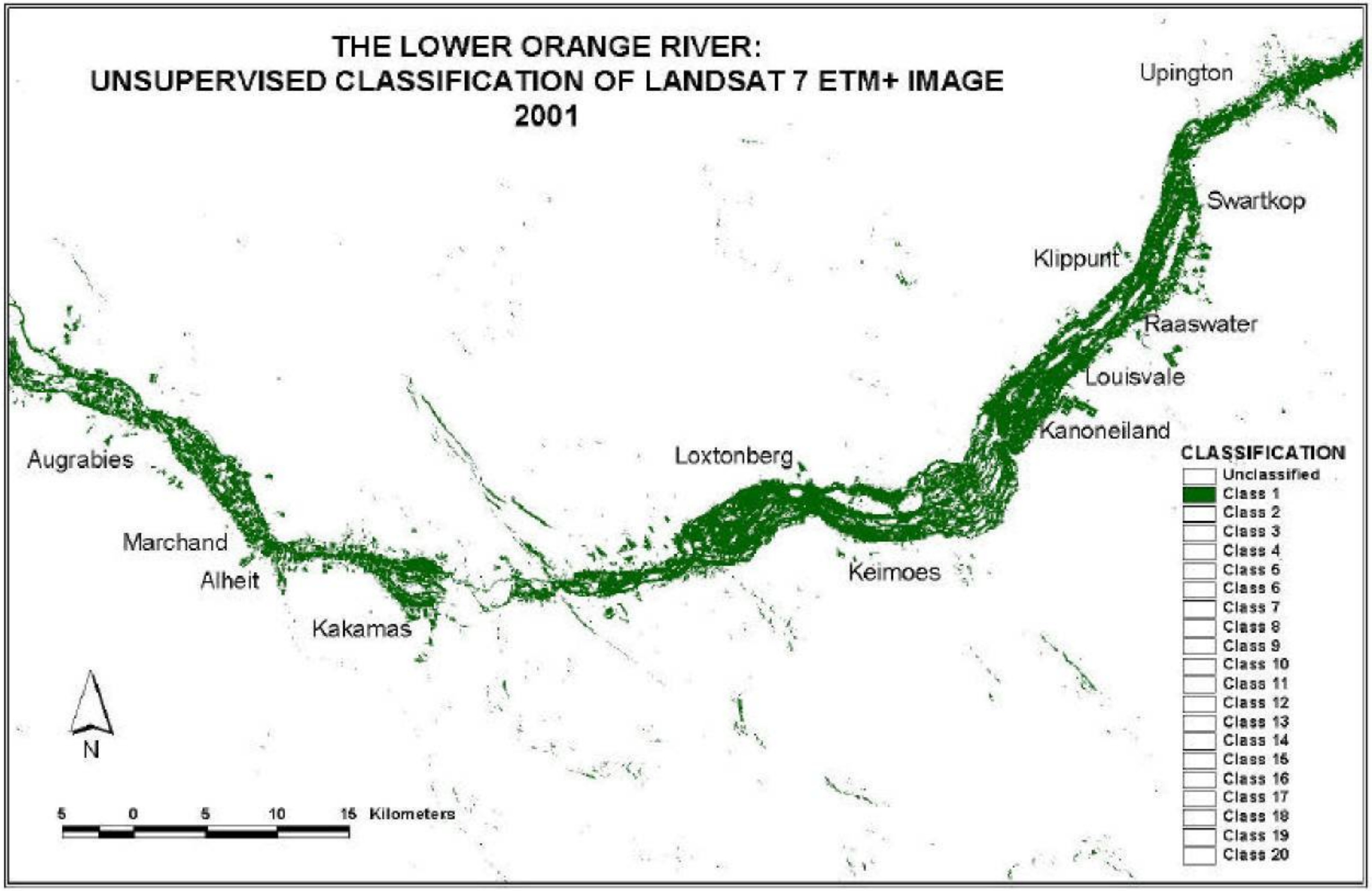

Figure 5.2. An unsupervised classification of Landsat 7 ETM+ imagery showing cultivated land along a portion of the lower Orange River in 2001.

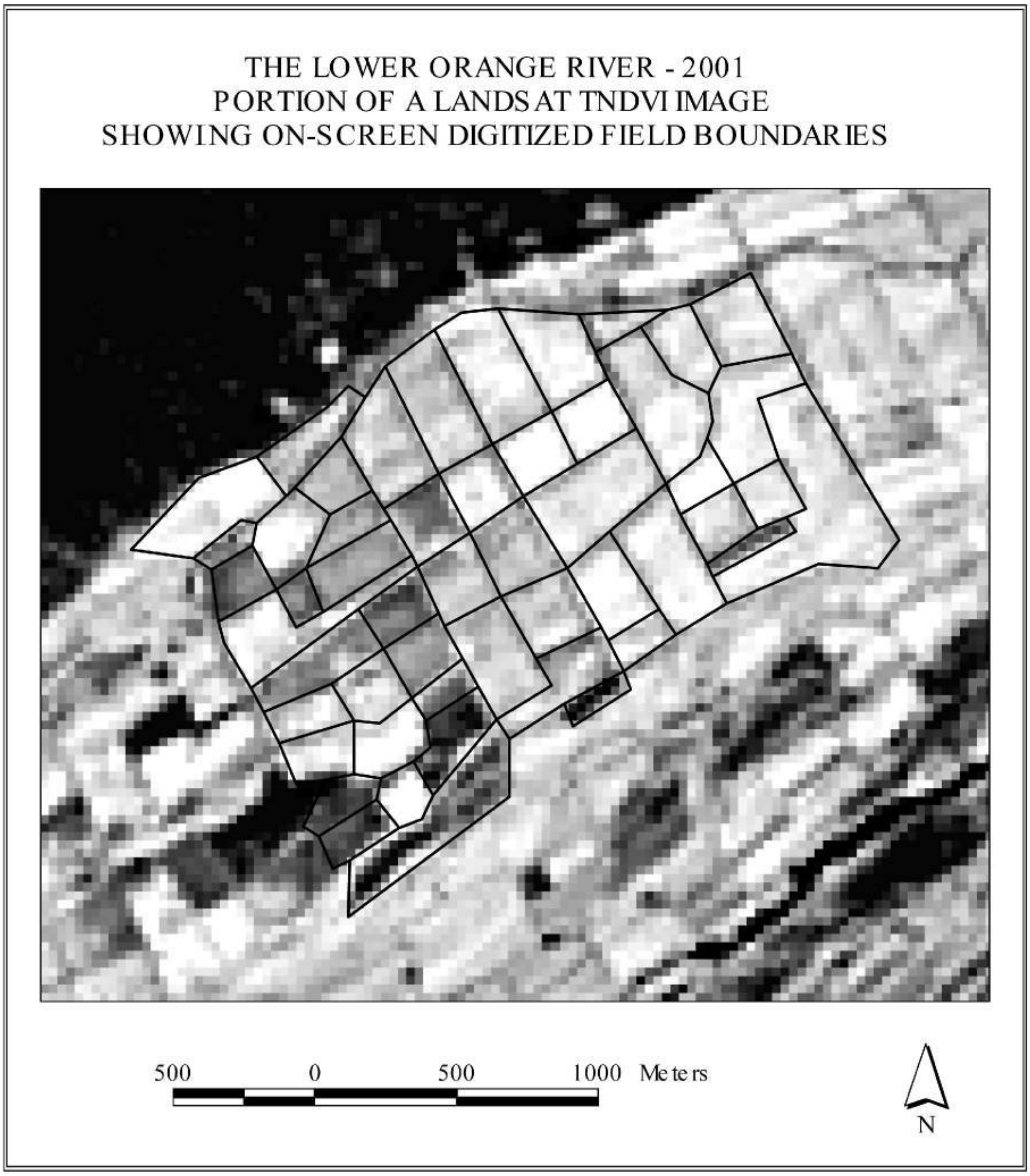

Figure 5.3. On-screen manually digitized field boundaries in a part of the lower Orange River using a Landsat Transformed Normalized Difference Vegetation Index (TNDVI) image as a backdrop.

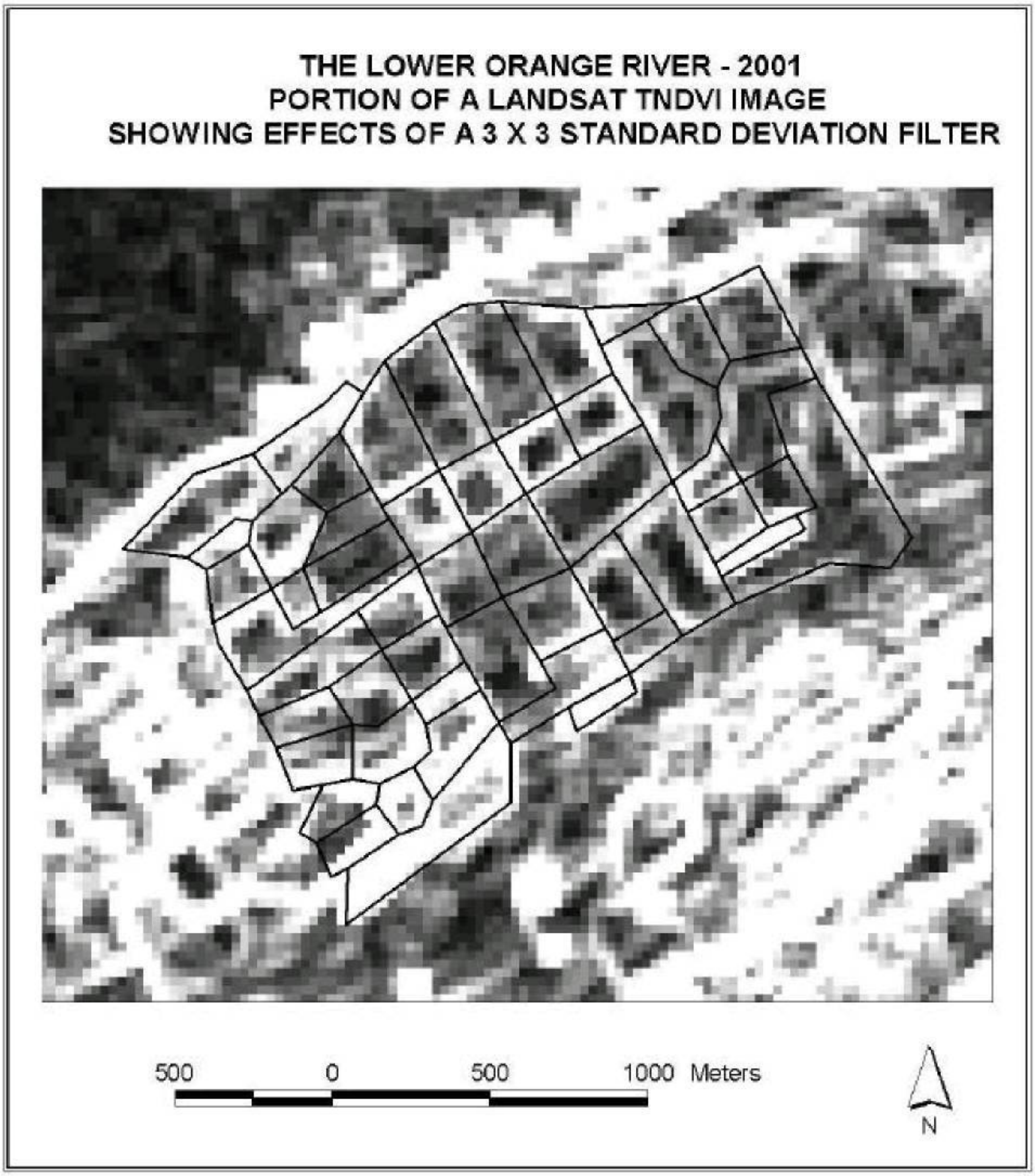

Figure 5.4. A portion of the lower Orange River showing the effects of edge enhancement of a Landsat Transformed Normalized Difference Vegetation Index TNDVI image using a Standard Deviation filter.

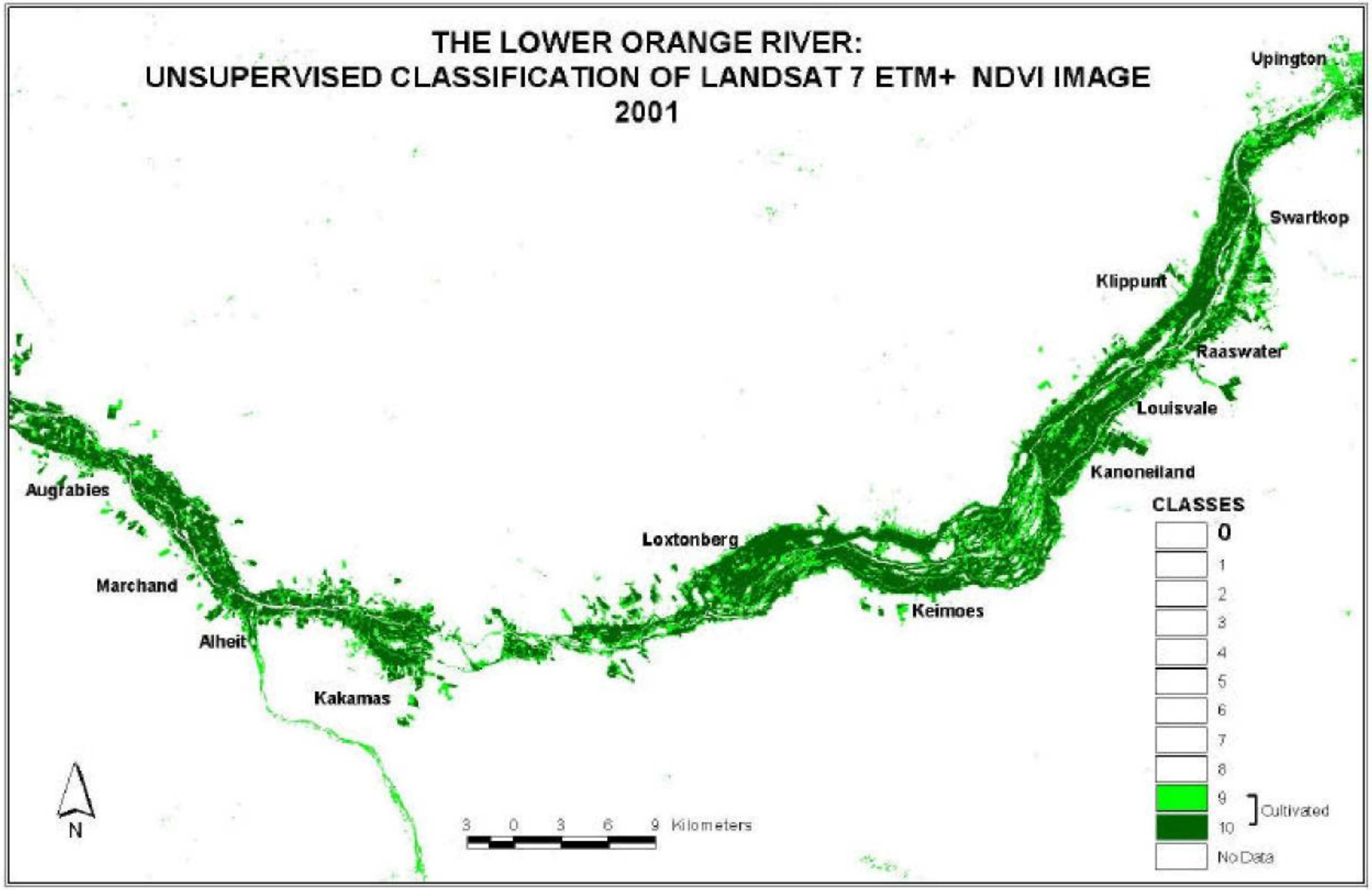

Figure 5.5. An unsupervised classification Landsat Normalized Difference Vegetation Index (NDVI) image showing cultivated land along a portion of the lower Orange River in 2001.

A comparison with the results of the unsupervised multi-spectral classification obtained previously (Fig. 5.2) indicated that the cultivated land was primarily contained within one class (Class 10) of the classified NDVI image. A second class (Class 9) also contained some of the younger newly planted vineyards adjacent to and at higher elevations than the floodplain. This classified image was vectorized and exported as an ESRI shapefile. These areas were incorporated into the final cultivated land cover dataset by manually editing the resultant shapefiles (Fig. 5.6). The area along the Orange River from Boegoeberg to Augrabies under cultivation as calculated from this coarse analysis was 39 540 ha in extent.

The insights gained from the previous experimental work indicated that the 20 metre pixel resolution of the multi-spectral Landsat 7 ETM+ imagery would not satisfy the requirements of the project. The spatial extent and localized nature of salinized areas are too small to map successfully using Landsat imagery. Also given the time and budgetary implications of manually tracing field boundaries it was decided to discontinue the originally proposed approach as this would require too many hours of labour to complete. Consequently, in order to progress a two pronged strategy was followed:

(a) The availability of higher resolution satellite imagery was investigated and;
(b) In parallel, every effort was made to obtain additional funding for an infra-red aerial photographic survey of the study area should the former not be cheaply available.

5.3 Higher resolution satellite imagery

The World Wide Web was searched for sites about the latest generation of satellites, hoping to identify a satellite system that would provide high resolution multi- or hyper-spectral imagery at an affordable price. SPOT 5, IKONOS, MODIS and ASTER appeared to provide possible solutions. However, it was found that the spatial resolution of SPOT 5 multi-spectral imagery was 10 m, which is still not high enough and also quite expensive. Whereas IKONOS multi-spectral imagery has a spatial resolution of 4 m, which may be sufficient, it was too expensive for this project. MODIS imagery has a hyper-spectral sensor with 36 channels, but the spatial resolution is only 250 m. The ASTER imagery has a scanner in the visible and near-IR spectra with a spatial resolution of 15 m. Initially it was thought that the latter data could be downloaded free of charge. Unfortunately the experimental phase of the ASTER programme had been concluded and free data provision terminated. However it was ascertained that ASTER data for the whole of the Southern African region had been obtained by a private firm GEODATEC during the experimental stage. The data were still in an archived format and could not be obtained from the firm before the end of 2002. An index of the available ASTER imagery also showed that the study area along the Orange River was only partially covered. It was therefore decided not to pursue this avenue further.

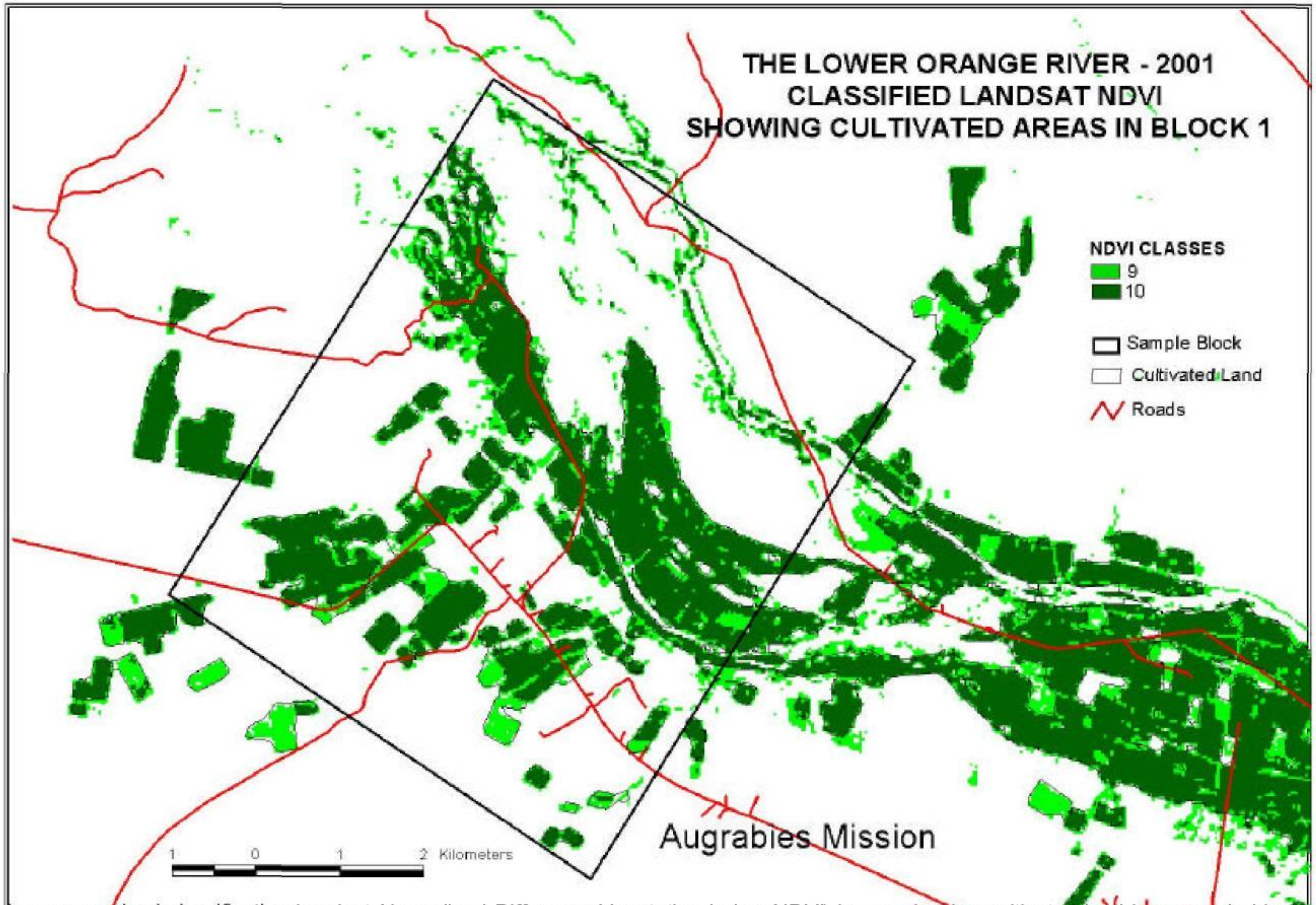

Figure 5.6. An unsupervised classification Landsat Normalized Difference Vegetation Index (NDVI) image showing cultivated land in a sample block along the lower Orange River in 2001.

6 IDENTIFICATION, CLASSIFICATION AND VERIFICATION OF POTENTIALLY SALINIZED AREAS UTILIZING AERIAL SURVEY IMAGERY

In order to overcome the limitations imposed by the coarse spatial resolution of Landsat multi-spectral imagery and to exploit the relationship between plant stress and reduced spectral reflectance in the NIR, an aerial survey using photography was considered (Blackeman 1990; Meyer *et al.*, 1996). Two companies were approached to obtain quotes on an infra-red aerial survey of the study area. Only one company responded positively. Their quote was too high for the limited budget.

Three courses of action followed:

a) Additional funding was sought from the ARC;
b) A sampling strategy to reduce the area to be photographed was considered;
c) Digital infra-red videography by the ARC was investigated.

It was hoped that the digital IR videography would be less expensive than IR photography, as the costs of IR film, its processing and scanning would be eliminated. Unfortunately, the IR videography quotes given by the ARC were even higher than that obtained for the IR photography.

The aerial surveying company was again approached to find a workable solution. The company responded by indicating that they were in the process of acquiring a digital IR camera and that the system would be operational by November 2002. The company also indicated that the cost of digital IR photography was expected to be much lower that quoted previously. They undertook to supply a new quote by the end of October 2002.

More funds had been allocated to the project by the Northern Cape Department of Agriculture, so that an aerial survey could be undertaken. An aerial survey of the area was conducted in December 2002 using a digital IR camera. Colour (RGB) photography was to be acquired simultaneously to assist in the process of identifying irrigated and salinized soils. Unfortunately, the latter could not be done due to technical difficulties with the camera mounting system and the firm decided to fly the area twice, once for capturing the IR imagery and once for the RGB imagery.

The whole study area was flown as shown by the distribution of waypoints on Figure 6.1. This resulted in about 2200 digital images totalling 110 Gb of data. The average flying height was 4450 m above mean sea level (or 3650 m above land). A Kodak H20 camera with a 50 mm focal length was used. The images were 4000 rows by 4000 columns in size with a pixel resolution of 0.09 mm. This equates to a ground area of about 5 km by 5 km per image and a pixel size of roughly 0.65 m. Both the RGB and IR images were captured at this resolution.

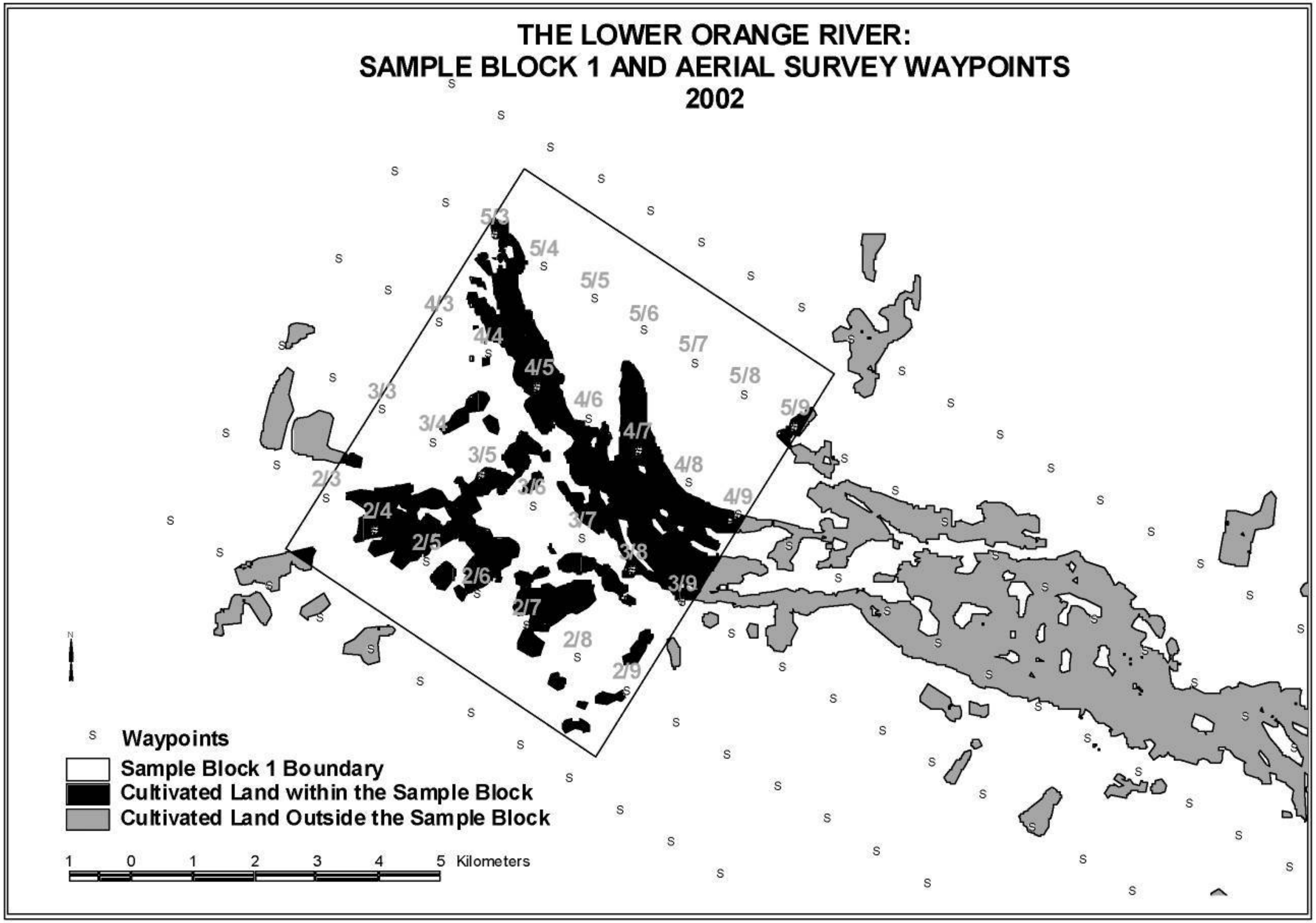

Figure 6.1. Distribution of aerial survey waypoints in a sample block in the lower Orange River in 2002.

The raw images were obtained from the company on about 200 CDs during January 2003. As the project budget did not cover the costs of image orthorectification, an agreement was reached that the company would undertake this task in exchange for the right to sell the orthorectified imagery to the farmers in the study area as well as any other parties who may have a need for the information. The first batch of orthorectified images was to be delivered during March 2003. Unfortunately the company developed internal problems which led to its demise in May 2003. After many months of delays it was decided that the project team should take the responsibility to undertake the orthorectification of the imagery internally. The project team, however, did not have access to suitable orthorectification software or the capacity to process all the images covering the full study area.

To solve the problem of gaining access to suitable software the local distributor of ERDAS Imagine Orthobase was approached for assistance and they agreed to grant a temporary licence. The volume of work to orthorectify the digital imagery was reduced by devising a spatial sampling strategy. This strategy is discussed in the following section.

6.1 Spatial sampling strategy

After much deliberation it was decided that there was not sufficient time, funding or capacity to map the full extent of the area under irrigation along the Orange River from Augrabies to Boegoeberg-dam using digital aerial imagery as initially proposed.

In order to proceed with the research and still derive scientifically valid results a sampling approach was required. The approach utilized Landsat imagery to obtain the full extent of irrigated land in the study area. These data were then supplemented by analysing the land cover from sampled areas using larger scale aerial imagery. From the sampled areas it would be possible to determine the proportional presence of areas showing plant stress. Investigation by field checking to determine the actual causes of plant stress was to be done in these areas. From these data it would be possible to estimate the total hectares affected by salinization.

The areas for aerial analysis were selected using a modified systematic sampling approach (Lounsbury & Aldrich, 1979). It was decided that 20% of the aerial images would be sampled. The sample consists of twelve subsets of 21 images each, evenly spaced at 22 km distances from the western extreme at Augrabies to Groblershoop at the eastern limit. Each subset of images covers an equal sized area of about 20 km^2. The location of the centre position of the first subset of images was selected randomly. Thereafter all the other subsets were selected at equally spaced distances along the course of the river (Fig. 6.2).

This methodology was discussed with Prof Niel le Roux at the Department of Statistics, University of Stellenbosch. He concurred with the approach and also agreed that taking equal sized subsets at regular intervals was acceptable. There was some discussion about the possibility of reducing the size of the subsets in proportion to the amount of irrigated land along the river as this diminishes upstream. As this

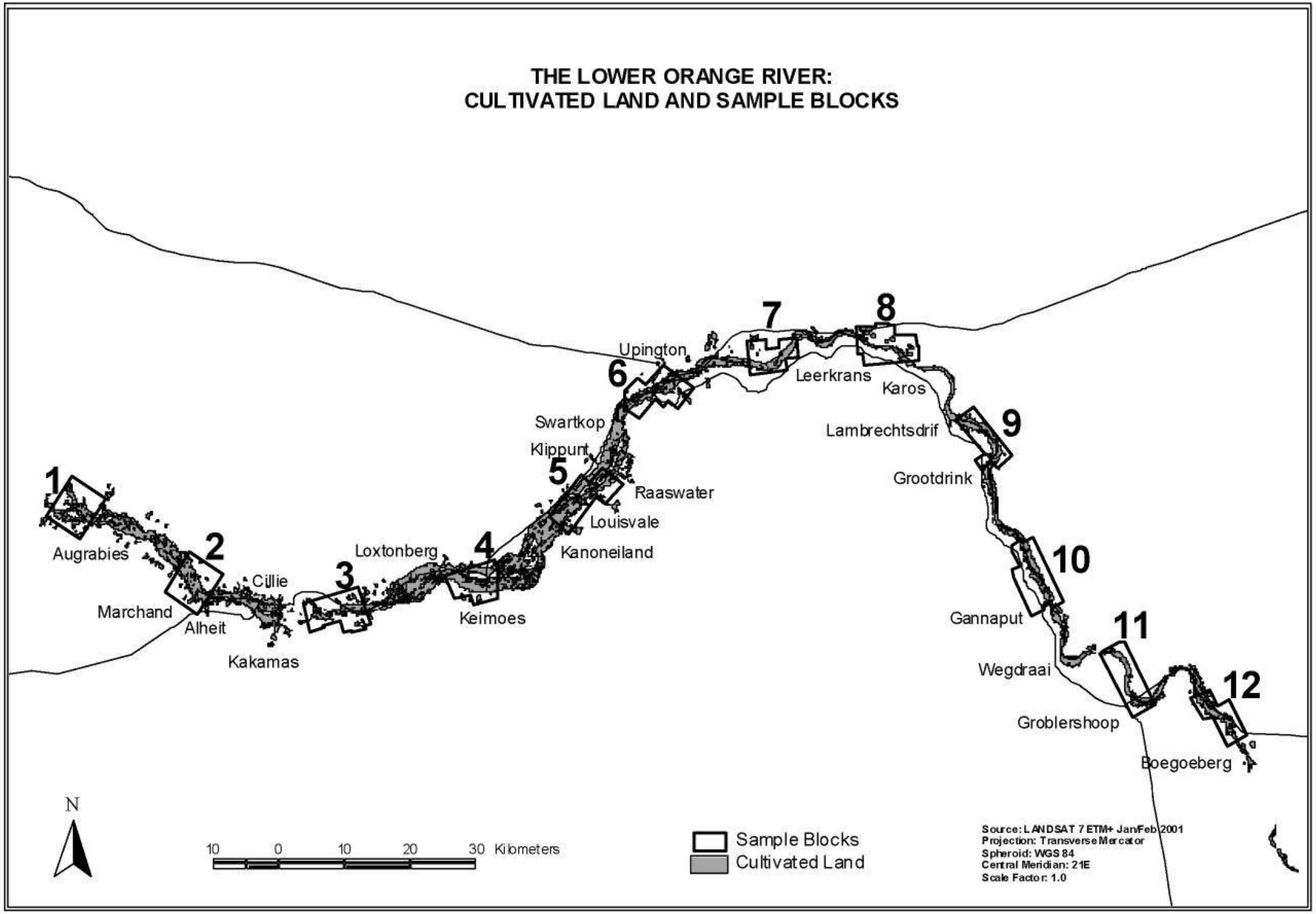

Figure 6.2. Location of sample blocks along the lower Orange River.

would have complicated the amalgamation of the data it was decided to use equal sized sampling areas because this would not materially affect the results, but expedited subsequent calculations. Prof Le Roux also recommended that a stratified approach be investigated. As the effect of irrigated land outside the alluvial flood plain was thought to have an effect on the occurrence of salinization in the flood plain this was regarded as a possible basis for stratification. An attempt was made to select subsets in pairs with one member including irrigated land outside the floodplain and the other not. This was not practical as it was not possible to find these combinations at many of the selected locations along the course of the river. Consequently the attempt was abandoned.

Another base for possible stratification was land type. The 1:250 000 scale Land Type map of the study area showed no differences in land types along the length of the river within the flood plain. So this approach was also disregarded. These factors will be considered in explaining the spatial distribution of salinized areas. There are so many other environmental variables that could reasonably be expected to contribute to the phenomenon that it is not practical to try and incorporate these into a spatial sampling strategy. Factors that come to mind are the direction of slope, presence of tributaries, local depressions, leaking canals etc.

6.2 Orthorectification of imagery

Othorectification is essential before aerial photographic imagery can be utilized for accurate mapping and measuring of areas (Yehuda & Brand, 1998). The number of digital images in each of the twelve sample areas (blocks) varied slightly depending on the local shape and size of the area involved. In total 300 RGB images were finally processed. Orthorectification of these images proved to be a major task. In order to undertake the orthorectification sufficient ground control points (GCPs) were required. This meant that 1:10000 scale black and white orthophoto maps of the study areas had to be obtained. The sampling areas are covered by 54 of these map sheets. Apart from the fact that these orthophoto maps were needed for identifying GCPs, they were also necessary to generate digital elevation models (DEMs), as these are essential for obtaining elevation values for the GCPs used in the orthorectification process. Although it is possible to generate DEMs using the orthorectification software, it is computationally intensive, so the DEMs generated from the 5 m contours on the orthophoto maps were used to save time.

Scanned orthophoto maps and contour separates were obtained from the Division of Surveys and Mapping at Mowbray, Cape Town. The scanned digital images were georeferenced using Arcview 3.2 and subsequently imported into ERDAS Imagine to locate and collect GCPs for orthorectifying the aerial images. This was a time consuming, tedious and error-prone task, as most of the scanned images were of fairly low resolution (scanned at 300dpi) and very out of date. It was extremely difficult to find enough well positioned GCPs on these images as the land cover changes in the study areas were very substantial due to the extensive expansion of new areas under irrigation into the adjacent landscape outside the flood plain of the valley.

The scanned contour separates were used to create DEMs by firstly editing the images in Photoshop Version 6.0 in order to clean the images by manually erasing all unnecessary information from these images, such as contour values within the contour lines, other text such as place names as well as lines framing the image etc. Where contour values were removed the contour lines had to be repaired by joining up the interrupted lines. Editing also required separating contour lines in steep areas by erasing strips between lines that were merged. Once these contour separates had been edited they were converted from image files to ArcInfo GRID files using the IMAGEGRID command. These GRID files were then thinned and vectorized using the ArcInfo GRIDLINE command with the appropriate parameters. Line topology was subsequently built for each of these coverages. Once this was done an extra item (HEIGHT), to contain the elevation values for the contour lines, was added to the Arc Attribute Tables (.AAT). The coverages were then processed by using the ArcEdit module to remove all unnecessary pseudo nodes in the vectorized contour lines. Once this was done elevation values for each contour line were manually added to the .AAT files by processing the coverages in Arcview. This was done by displaying the original scanned maps with the contour values as a backdrop and overlaying the vectorized lines. Lines of equal elevation were selected and the appropriate elevation values inserted into the associated .AAT.

A point file containing at least four GCPs with their associated map co-ordinate values was created for every vector coverage during the same editing session. These files were used to georeference the vectorized vector contour coverages by executing the ArcInfo TRANSFORM command for each coverage.

The final processing step to create DEMs from these contour coverages was to firstly generalize the contour lines by specifying appropriate Weed- and Tolerance parameter values and then to create Triangulated Irregular Networks (TINs) using the ARCTIN command. Generalization was necessary to prevent long thin and flat triangles that would result in tiger banding (stepped features) in the resulting TIN. TINs were checked visually for correctness and then converted into Lattices and Lattices into USGS DEMs for importing into ERDAS Imagine. This conversion from TINs to USGS DEM file formats was necessitated by the fact that the Orthobase Module would not correctly read any of the other file formats to add elevation data to the GCPs. DEM mosaics were created in ERDAS Imagine for each of the twelve sampling areas.

All the RGB and IR digital aerial images were to be orthorectified and mosaics created for the twelve sample blocks. However, after this process had commenced it was established that the Division of Surveying and Mapping at Mowbray, Cape Town, was in the process of updating the orthophoto maps along a part of the lower Orange River. This was good news as it would expedite the process tremendously if more recent digital orthophotos of higher quality could be obtained, as well as DEMs. A meeting was arranged with the staff at Surveys and Mapping and it was confirmed that they were indeed updating the orthophoto maps from aerial imagery flown in 2001. The part of the study area in question stretched from Augrabies to just east of Upington, covering eight of the twelve sample blocks (No 1 to 8). They assisted by re-scheduling their updating process in order to deliver the required digital images and DEMs within the next six weeks during October 2003.

In the meantime processing went ahead to generate DEMs for the remaining four sample blocks (No 9 to 12) and to orthorectify the imagery. Once the digital orthophotos and DEMs for the other sample blocks had been received the necessary processing was done and all RGB images orthorectified in December 2003 and January 2004.

Orthorectification of the images was hampered by the fact that a camera calibration report could not be obtained from the defunct company who had captured the imagery. Numerous phone calls and visits to their site in Somerset West were not successful. Direct approaches to the Kodak's systems engineers via the WWW also did not elicit any response to queries in this regard. Fortunately the ERDAS Imagine Orthobase module has the ability to compute these internal image orientation parameters by using the pixel sizes and focal length of the camera in a Self Calibrating Bundle Adjustment (SCBA) procedure during the triangulation process.

After Block Triangulation overall external positional accuracies in the orthorectified imagery were less than 2 m. In most cases error estimates (Root Mean Square Errors) were between 0.5 m and 1.5 m. In spite of these apparently satisfactory results it was found that adjacent overlapping orthorectified images in some cases still did not fit well spatially. Ground displacements of up to 30 m were observed. Images with gross errors were reprocessed by adding additional GCPs. However, in a few images these errors could not be resolved and due to time pressures it was decided to proceed with the rest of the image analyses.

6.3 Object-Oriented Image Classification

While the orthorectification of the images was continuing, one of the blocks was subjected to Object-Oriented Image Classification in order to test the feasibility of setting up a rule base with which land cover types and potentially salinized areas could be identified using the Definiens eCognition Version 3.0 software. If this approach proved to be successful, the rule base would be applied to the rest of the imagery. This would speed up the process of identifying and mapping land use types and potentially salinized areas and have tremendous value for future research of this nature.

As a first step it was necessary to stack the RGB and IR images of the selected sample block so that the rule base could be developed using all the spectral bands available. Although the RGB and IR images had been orthorectified it was soon apparent that these two sets of images did not fit exactly on each other. The resultant images appeared fuzzy due to spatial displacements of features in the images. Another hampering factor was the fact that the aerial images were not radiometrically calibrated. This meant that the seams where adjacent images were joined during the mosaicing process were still visible due to differences in lighting conditions and angular differences of the exposure station at the time of image acquisition. Attempts to remove these differences were only partially successful. Histogram equalization of mosaics resulted in images with very low contrasts, making visual interpretation virtually impossible. Colour balancing using manual methods, linear and other stretches as well as adaptive filters all proved futile. Various image normalization procedures within the ERDAS Imagine software, such as Topographic Normalization and Hyper-spectral Normalize also did not produce the required results. It was even considered to do atmospheric corrections by applying the S6 atmospheric correction software (Vermote *et al.*, 1997) or an Anisotropic Reflectance Normalization Model developed by Lloyd Coulter of San Diego State University which is included in the models available in ERDAS Imagine 8.6.

The S6 model was developed for satellite imagery and requires certain parameters about the sensitivity limits and range of the multi-spectral sensors, such as the LMIN and LMAX values. These were not available for the digital camera used in the aerial survey, so this avenue was abandoned. The Anisotropic Reflectance Normalization Model would have been a solution, but it only operates on single bands of images. This means that all the images would first have to be split into three separate bands before applying the normalization model. Once this had been done, the separate bands would again have to be combined into a single RGB image. This was just not feasible within the constraints of this project, given the large number of images that would have to be processed and the time it would take to process the data. According to Coulter a SUN Ultra1 workstation took 2 hours to process a single 50 Mb file!

The eCognition software has the ability to automatically segment an image into areas with spectrally homogeneous characteristics at different spatial scales. This means that feature objects can be demarcated at different spatial resolutions. Multi-level segmentation allows identification of objects by considering not only the properties of the features themselves, but also of their spatial contexts, both horizontally and vertically. Additional ancillary data can be entered into the classification process to provide a very rich contextual environment. As the approach is object-orientated and not pixel based the results are more robust and repeatable. Experimentation with the eCognition software showed that it was feasible to build a rule base with which broad land cover classes for Cultivated and Uncultivated land could be identified. Within the Cultivated class, potentially salinized areas could be delineated (Fig. 6.3). Object properties found useful for demarcating these areas were Image Brightness, Length/Width ratios and Ratio to RGB band 2.

However, when this rule base was exported to another sample block it was found that the parameter values all needed to be adjusted to fit the new set of images. The reason for this was the fact that the images were not radiometrically calibrated. Illumination differences between images and between sample blocks of images meant that the rule base was not transferable and that this approach was not feasible. It takes hours of testing different criteria and functions to determine which are most successful at identifying different object types in an image. Once the rule base has been established the resultant classification needs to be visually checked for consistency. If the rule base is not transferable to the rest of the study area no economy of scale is realizable and no gain is achieved.

It was therefore decided that the eCognition software would be used to segment the images and automatically digitize the field boundaries between different land cover types at a more generalized spatial scale (Level 2). Within these field boundaries smaller scale features at a higher resolution would be identified based on their spectral properties (Level 1). A comparison between image segmentation results using just the three RGB bands versus an image segmentation based on the three RGB as well as

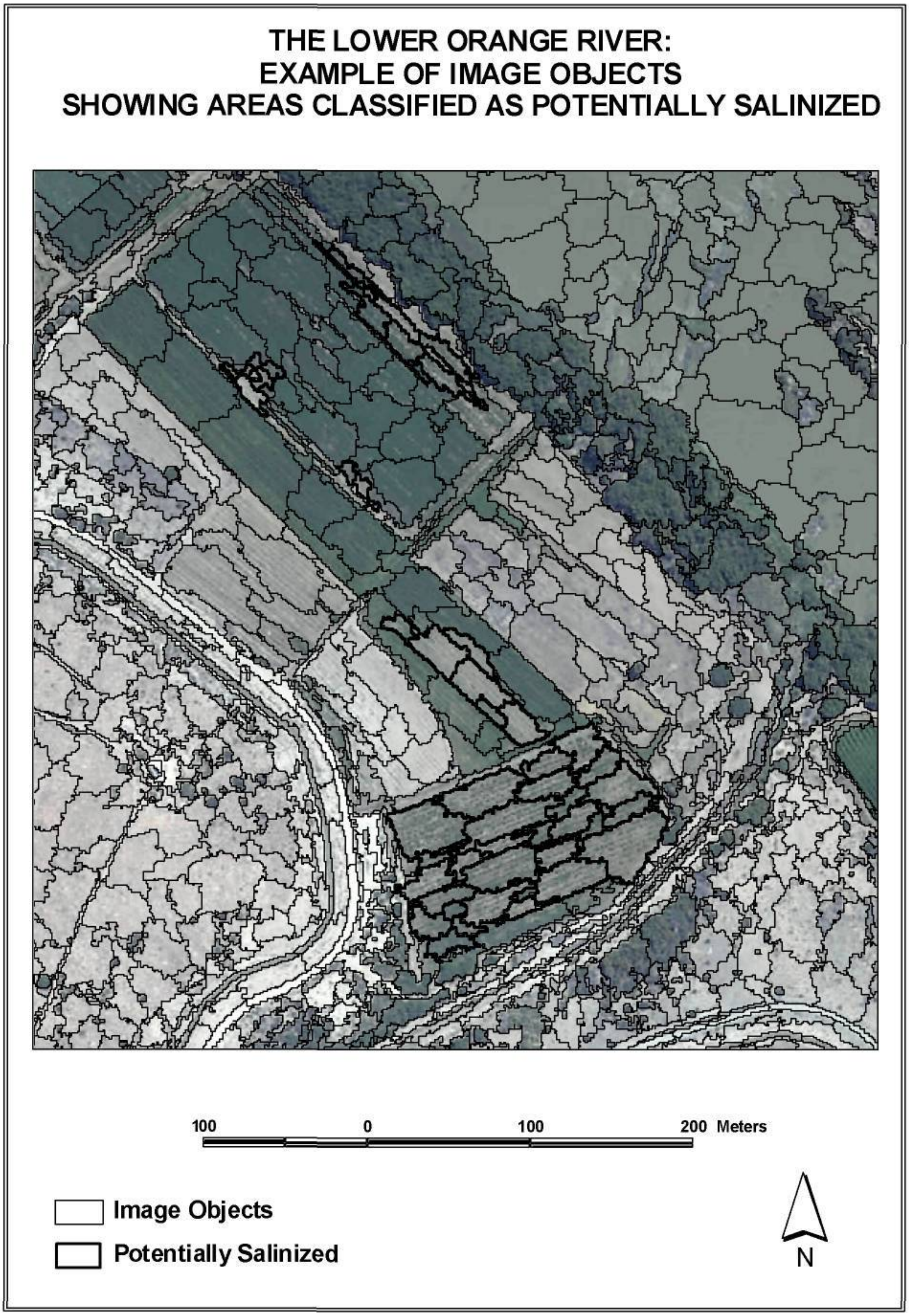

Figure 6.3. A segmented digital aerial image showing Level 1 image objects along a portion of the lower Orange River.

the IR band was done. The results were very similar. The RGB solution was crisper than the RGB+IR result. Field boundaries in the latter solution were often displaced from their true locations because of the spatial mismatch between the RGB and IR images referred to in the previous section. As the IR band did not substantially improve the results it was decided to base all further processing on the RGB images alone. Orthorectification of the remaining IR images was suspended.

Once a mosaiced sample block of images was segmented the objects at the lower spatial resolution (Level 2) were visually inspected and classified according to standard aerial interpretation queues, such as colour, pattern, size, shape, location, etc. Objects were manually assigned to two classes of land cover, namely *Vines and Orchards* and *Other Crops or Fallow* Land (Fig. 6.4). At the higher spatial resolution (Level 1) intra field features that had lower greenness values and higher brightness values were inspected visually to determine whether this was due to the absence of vegetated material or caused by smaller plants. Where intra field differences could be ascribed to impaired vegetation growth, the areas were classified as potentially salinized. These vectorized layers of information were exported from the eCognition system as Arcview shapefiles and processed further to obtain the required area statistics and to act as a sampling framework for selecting sites for taking soil samples in the field (Figs. 6.5, 6.6, 6.7 & 6.8). The soil samples are used to validate the results of the land cover and potentially salinized land classifications derived from the aerial imagery.

Area statistics obtained from the analysis of the aerial photography estimate that *Vines & Orchards* make up 68% of the cultivated land and *Other crops* the remaining 32%. The area of the cultivated land in the twelve sample blocks was 9 627 ha. In comparison, the satellite derived areas for cultivated land in the twelve sample blocks were 14 768 ha. This is an overestimation factor of 1.53 (obtained by dividing 14 786 ha by 9 627 ha). Strips of land between fields, such as roads and verges, hedges, reeds along the river bank, trees and shrubs, lawns and gardens are all included in the satellite derived area statistics due to its coarse spatial resolution. These areas are excluded from the area statistics derived from the digital aerial images. As the area statistics obtained from the aerial photography are much more accurate, it means that to get a more accurate estimate of the total area of cultivated land in the study area the figure of 39 540 ha should be reduced by a factor of 1.53 giving 25 843 ha. From this figure the area under *Vines & Orchards* can be estimated at 17 573 ha (68% of the total) and the rest of the land (8 270 ha) being devoted to *Other crops* (Table 6.1).

Table 6.1 Estimated areas of cultivated land along the lower Orange River

Cultivated Land	Satellite Image (Full Study Area)	Satellite Image (Sample Blocks)	Aerial Photography (Sample Blocks)	Estimates for Full Study Area
Vines & Orchards	-	-	6 540 (68%)	17 573 ha
Other	-	-	3 088 (32%)	8 270 ha
Total	39 540 ha	14 768 ha	9 628 ha	25 843 ha

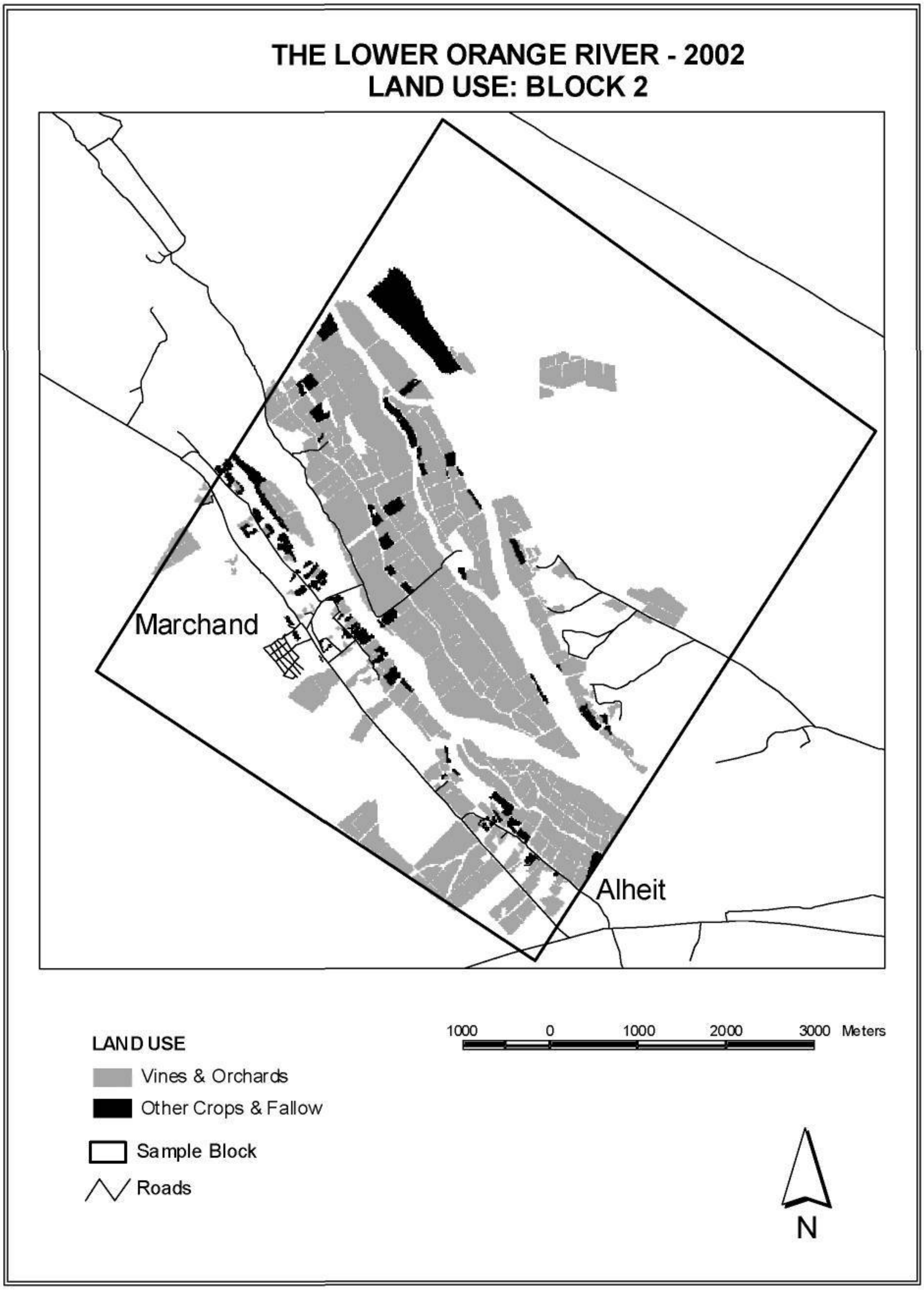

Figure 6.4. A classification of Level 2 image objects showing land use types in a sample block along the Lower Orange River.

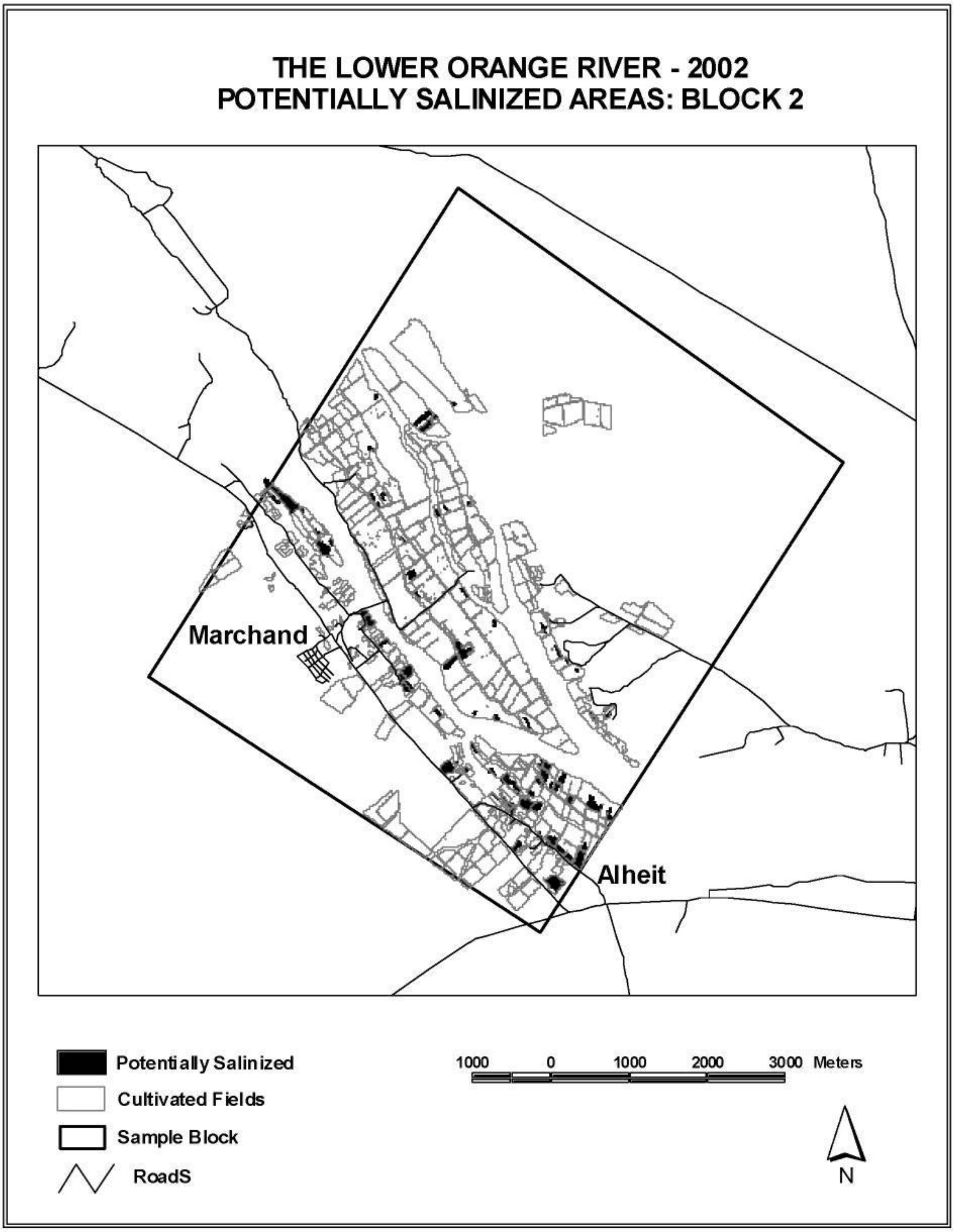

Figure 6.5. Potentially salinized areas in a sample block along the lower Orange River from a classification of image objects.

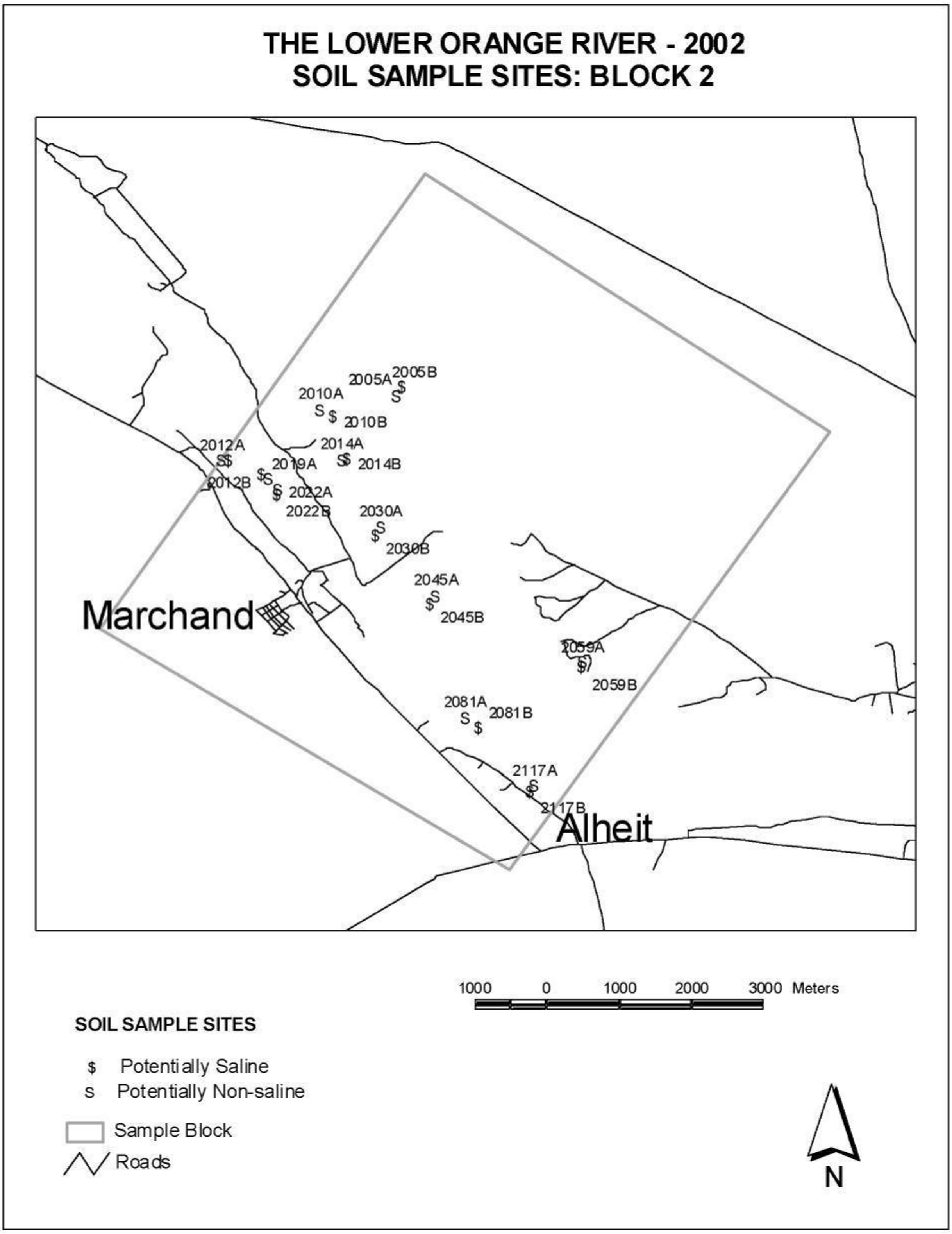

Figure 6.6. Random selected sites for sampling potentially saline and non-saline soils in a sample block in the lower Orange River.

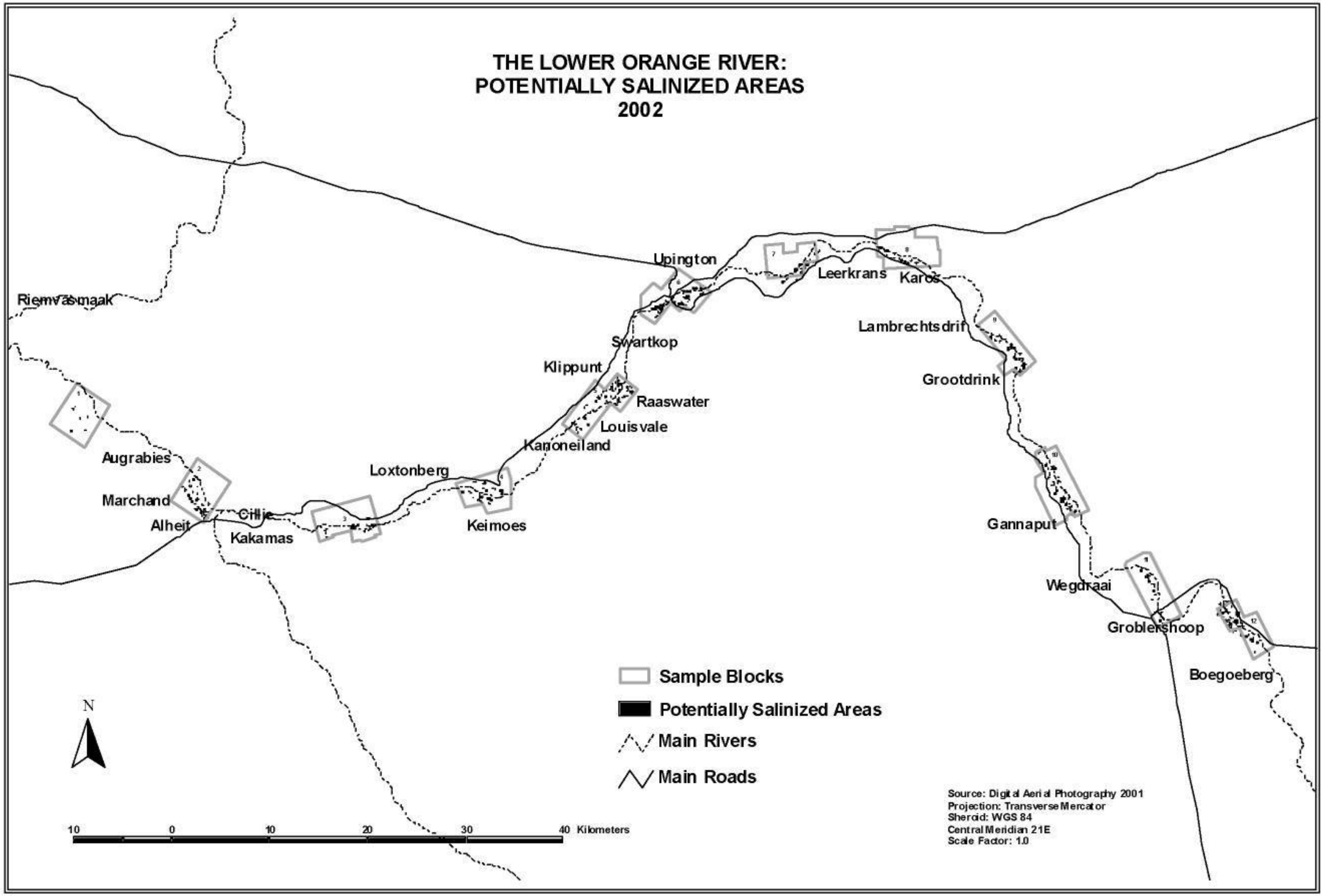

Figure 6.7. Distribution of potentially salinized areas in sample blocks along the lower Orange River in 2002.

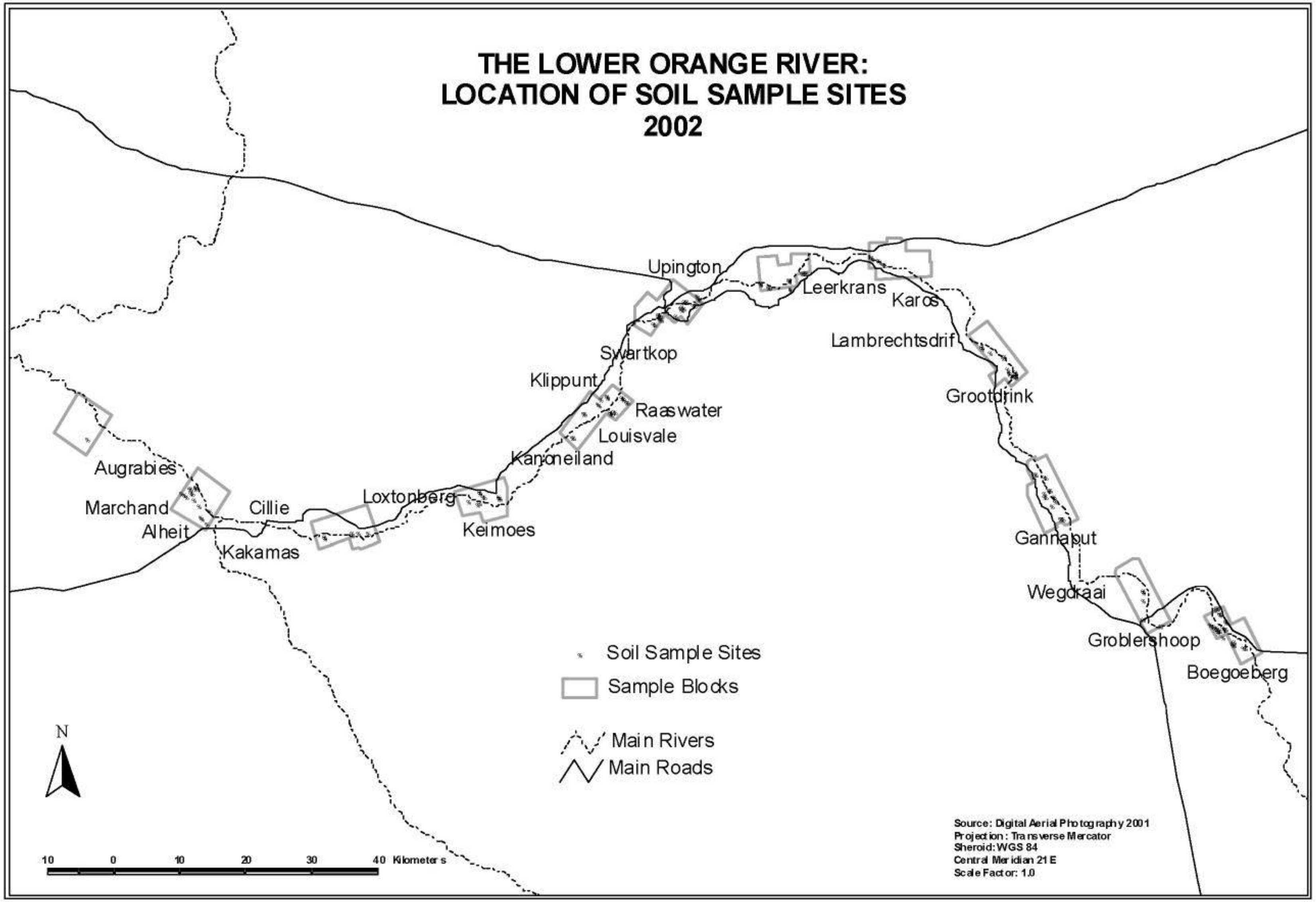

Figure 6.8. Location of soil sample sites in sample blocks along the lower Orange River.

6.4 Verification of potentially salinized areas

As the purpose of this research is to determine how serious the problem of soil salinization is in the irrigated land along the Orange River, the digital aerial photography was employed to map potentially salinized plots as described in the previous section. It was not possible to determine what caused impaired vegetation growth by interpretation of the imagery, but only that plant density was lower and that foliage coverage was less complete. Many other factors other than soil salinity could be responsible for plant stress, such as stony, sandy or water logged soils. It was therefore necessary to select a sample of the potentially salinized plots and to obtain soil samples for laboratory analysis.

It was also decided to select a control sample of soils from adjacent plots identified as non-salinized in order to test whether the aerial photo interpretation technique produced valid results or not. Considering the cost of laboratory analysis and the amount of time available to execute a field survey, it was decided that 200 soil samples would be collected (100 from potentially salinized areas and 100 from non-salinized areas). These samples were randomly and proportionally selected from the twelve sample blocks (Table 6.2 & Figs. 6.6, 6.7 & 6.8). The total number of soil samples varied from 2 to 34 per sample block (Including 100 non-salinized sites). The geographical co-ordinates of the selected sites were extracted and provided to the field team for locating the sites using a GPS. To expedite the location of these sites in the field the feld team was given a set of twelve A1 sized colour maps showing the mosaiced RGB images with a graticule and an overlay of the selected sample sites. This set of twelve maps was accompanied by similar data in TIF and Shape file formats on a Notebook computer, using ESRI's ArcExplorer software, so that the field team could zoom into any area and determine exactly where any particular soil sample point was located. The field teams were also instructed to note the land cover type of the sample sites as well as any observations on the soil conditions or factors that could assist in explaining observed patterns. These observations were captured on the database and used in an assessment of the accuracy of the aerial photographic techniques employed in identifying areas showing some form of vegetation stress.

Table 6.2 Number of soil samples per block based on area of potentially salinized land per sample block in the study area

	Potentially Salinized Land			Soil Samples	
Block	**Area (ha)**	**% Total Area**	**Number of Plots**	**Number**	**% Sites in block**
1	6.9	1.4	14	1	7.1
2	53.5	11.1	80	11	13.8
3	21.8	4.5	34	5	14.7
4	28.1	5.8	52	6	11.5
5	56.4	11.8	104	12	11.5
6	68.1	14.2	95	14	14.7
7	29.2	6.1	55	6	10.9
8	16.5	3.4	41	3	7.3
9	44.8	9.3	57	9	15.8
10	51.2	10.7	69	11	15.9
11	23.8	4.9	36	5	13.9
12	79.6	16.6	102	17	16.7
Total	**480**	**100.0**	**739**	**100**	**13.5**

Soil samples were taken to determine the total salt concentration by measuring the electrical conductivity of the saturated soil water extract (EC_e) and the soluble cations and anions. Soils were sampled at the following depths: 0 to 300 mm, 300 to 600 mm and 600 to 900 mm. Soils were dried, sieved and saturated paste extracts made (Richards, 1954). The saturation percentage, pH and EC of the saturated extract (EC_e, dS m^{-1}) were determined. The soluble cations (Na, K, Ca, Mg) in the saturated extract were determined using an inductive coupled plasma atomic emission spectrometer (Liberty 200 ICP, Varian Australia Pty Ltd, Australia), and anions (Cl, SO_4) according to Richards (1954). The soils were classed for salinity status according to the profile mean EC_e and soils were considered saline if the EC_e was equal to or exceeded 0.75 dS m^{-1}, which is the salinity threshold value beyond which a decrease in yield for grapevine is expected (Moolman *et al.*, 1999). The soils were also classed for potential water infiltration problems according to the SAR in the top 300 mm of soil and the long-term average EC of the infiltrating water for the Boegoeberg to Onseepkans river reach (Table 3.15). In this regard the classification similar to that for irrigation water was followed (Table 3.5, DWAF, 1996). The threshold values for classification of soil toxicity were based on the sensitivity of grapevine for sodium and chloride. Soils were considered to be potentially toxic for grapevine cultivation if the SAR in the saturated water extract was equal to or exceeded a value of 3 (Myburgh & Howell, unpublished final report, ARC Infruitec-Nietvoorbij, Project WW04/13), and/or when the chloride concentration exceeded 354 mg L^{-1} in the saturated water extract (Ayers & Westcot, 1985).

Soil salinity

Soil analyses (Appendix B) revealed that *ca.* 10% of the randomly selected plots were saline and that sodium could hamper infiltration rates of soils or cause toxicity effects at *ca.* 14% of plots (Table 6.3). Chloride toxicity was limited to less than 2% of sites. Any one of the four water quality problem related conditions occurred at 15% of the sites. Figure 15 shows the distribution of the saline soil samples. The size of the the saline and non-saline combination sample set was reduced to 99 (total sample number of 198), because one potentially non-saline soil sample could not be taken as the GPS co-ordinates were located in the middle of a very dense reed population. If the data in Table 6.3 are extrapolated for the whole area under cultivation in the Lower Orange River, it is found that 436 ha of soil may be salinized. This figure is calculated from the area statistics (1.69% salinized) presented in Table 6.4 as applied to the total cultivated area of 25 843 ha which was obtained from the aerial survey and satellite data presented in Table 6.1.

Table 6.4 also confirms that the photographic interpretation of potentially non-salinized areas was very accurate (99.7%). Although only 14.3 % of the potentially salinized plots were actually salinized this is ascribed to the fact that vegetation stress is caused by numerous other local conditions. The field survey confirmed that these sites were either stony, sandy or water logged. Most salinized plots were found at the lowest elevation points in the floodplain, such as where old drainage channels had been filled and subsequently cultivated. Although the number of saline sites in the sample is too small to make any definite deductions about factors that could explain the spatial patterns, it would appear as though most saline soil samples are in the lower section of the river stretching from Upington to Augrabies. This is confirmed by the map (Fig. 6.9) and the data in Table 6.3.

Table 6.3 The prevalence of plots where soil salinity, soil sodicity as related to infiltration problems and toxicity (based on sodium adsorption ratio) and chloride toxicity may cause problems for vegetative growth or yield of crops. The percentage of plots per zone and river reach are indicated (n = total number of plots sampled)

Sampled Blocks	Plots with salinity/sodicity/toxicity problems (%)				N
	Salinity	Infiltration problems	Sodium toxicity	Chloride toxicity	
1	50.0	50.0	50.0	0.0	2
2	13.6	18.2	22.7	0.0	22
3	30.0	40.0	30.0	10.0	10
4	8.3	16.7	8.3	0.0	12
5	25.0	25.0	25.0	4.2	24
6	10.7	14.3	17.9	3.6	28
7	0.0	8.3	8.3	0.0	12
8	0.0	16.7	16.7	0.0	6
9	5.6	5.6	5.6	0.0	18
10	0.0	4.6	4.6	0.0	22
11	0.0	0.0	0.0	0.0	10
12	3.1	6.3	6.3	0.0	32
Boegoeberg to Upington	2.0	6.0	6.0	0.0	100
Upington to Augrabies	17.4	21.4	21.4	3.06	98
Boegoeberg to Augrabies	9.6	13.6	13.6	1.52	198

Table 6.4 Areas and salinity classification of sampled sites. Potentially salinized areas are characterized by poor vegetative growth

Soil Salinity Class	Sample Sites		
	Actually Salinized	Actually Non-salinized	Total
Potentially Salinized	8.0 ha (14,34%)	47.8 ha (85,66%)	55.8 ha (100,0%)
Potentially Non-salinized	1.3 ha (0,26%)	493.9 ha (99,74%)	495.2 ha (100,0%)
Total Area	9.3 ha (1,69%)	541.7 ha (98,31%)	551.0 ha (100,0%)

The idea to use historical soil survey data to aid in validation of salinized areas was eventually discarded as the exact positions of the historically sampled points were unsure and therefore could not be overlayed on the potentially salinized areas identified by this study. Also, the salinity status of these soils could have changed since their previous sampling and may correlate poorly to the more recent survey of vegetation response. The availability of GPS co-ordinates for the sites where the soils for this study were sampled will enable future reference and increase possibilities for resampling to monitor changes in salinity status over time.

6.5 Conclusions

It is estimated that grapevines and orchards are cultivated on 17 573 ha of land, while other crops utilize a total of 8270 ha of land between Boegoeberg and Onseepkans. Approximately 1.7% of the total sampled area was actually salinized, which amounts to 436 ha of soil for the whole area of 25 843 ha under cultivation in the Lower Orange River. The identification of salinized areas by means of the aerial survey approach was not very successful as only 14.3 % of the potentially salinized area was actually salinized. The limited success of this method is ascribed to the fact that vegetation stress is caused by numerous other local conditions such as either stony, sandy or waterlogged soils.

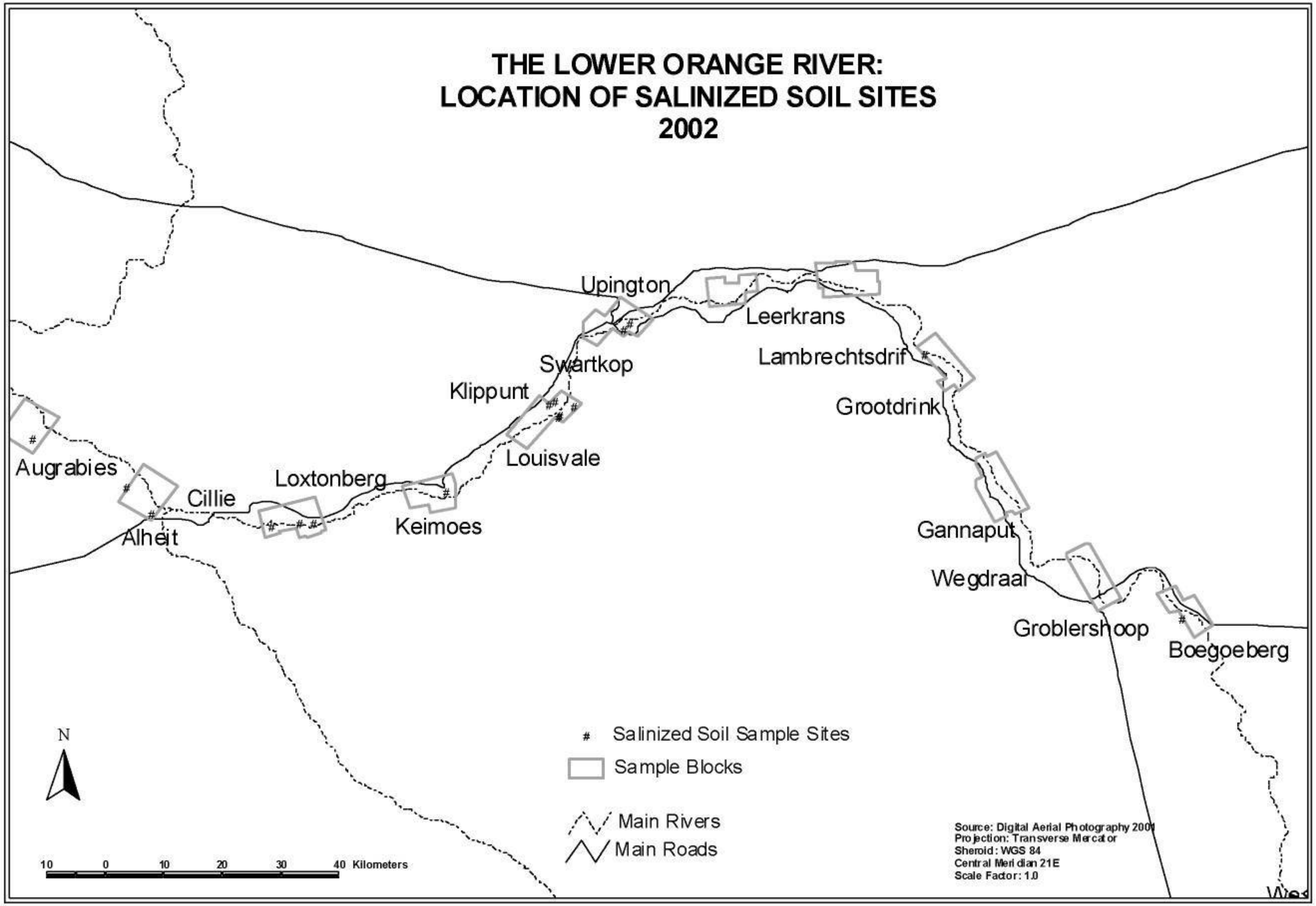

Figure 6.9. Distribution of salinized soil sites in sample blocks along the lower Orange River.

7 WATER QUALITY AND SOIL SALINITY MANAGEMENT

The surface water quality in the lower Orange River region is good (Chapter 3) and it is estimated that salinized soil covers a mere 1.7% of the cultivated land area (Chapter 6). These results may entice one to conclude that salinization is not a problem in the area. Concerns exist, however, regarding the development and expansion of local saline patches within vineyards (Chapter 4). Furthermore, recurring investigations of salinization problems in the region over a period of nearly a hundred years indicated that salinization of localized nature does occur, which is almost invariably associated with the presence of a water table (Marchand, 1909; Louw, 1936; Klinthworth, 1944; Van Garderen & Klinthworth, 1948; Murray, 1952; De Villiers, 1957; Murray, 1960; Van Woerkom & Streutker, 1963; Van Woerkom, 1965; Viljoen *et al.*, 1991; Van Veelen & Van Heerden, 1998). In this regard, the area of land in the Lower Orange River region that has been withdrawn from crop production as a result of salinization problems remains unknown.

The salt balance of a river can serve as indication of the sustainability of irrigated agriculture. The salt balance for the river reach between Boegoeberg and Onseepkans displays an oscillatory behaviour, with the soil and/or groundwater apparently retaining salt from and releasing salt to the river during flood and low flow periods, respectively (Chapter 3). From the available data, it appears as if the river, over the long term, is in equilibrium – undulating between salinization and desalinization (Fig. 3.17). As the salt efflux data set is incomplete (Fig. 3.19), however, it is not possible to determine whether the periodic retention of salt during, or following high flow periods, equals the total salt efflux during low flow periods and the immediate years thereafter. The oscillating behavioural pattern is furthermore of concern as it may be disturbed by changes in the flow regime of the river and/or the volume and quality of the irrigation return flow.

The irrigated agriculture in the Lower Orange WMA is, in addition, vulnerable as it is largely dependant on the incoming water quality from the Vaal and Upper Orange WMAs and needs relatively good quality water to sustain especially its grape industry (Moolman *et al.*, 1999; De Clercq *et al.*, 2000). In addition, the fact that almost all the water resources in the Orange River are allocated (DWAF, 2004b) leaves limited options for salinity management should the problem become serious. The latter can have international implications as Namibia is increasing its developments along the Lower Orange River stem (Becker & Luger, 2004). As the Orange River is an arid river basin and such basins are naturally prone to salinization problems (Smedema, 2000), a management strategy should be in place to prevent such problems, which may develop over several decades, and which cannot simply be rectified. Naturally, the institutional structure and necessary water, environmental and agricultural policy to drive and support the salinity management strategy should also be in place to ensure sustainable usage of scarce resources. An inquest to determine current salinity management practices, which institutional structures are responsible for management of salinity problems and what the proposed salinity management strategy for the Lower Orange River region is, is therefore appropriate. Options for management of water and soil salinization are furthermore outlined of which the most important and immediately achievable for the region is discussed in more detail.

7.1 Situation assessment

7.1.1 Management practices

A meeting with important role players in the lower Orange River region was held on 7 August 2002 at Upington to provide an opportunity to determine what management of salinization is currently being practiced. Role players that were invited to provide input for the project included DWAF; the Northern Cape Department of Agriculture and Land Reform or DALR (the then Northern Cape Department of Agriculture, Nature Conservation, Land Reform and Environmental Affairs); Northern Cape Agricultural Union; Vinpro consultants; representatives of the South African Dried fruit industry (SAD) and producers representing commercial and small scale farmers. Information on water quality and salinization management was acquired by means of a group discussion.

Management of water quality and salinization in the lower Orange River area is achieved by determining the salinity status for soils that are being developed for the first time and deciding if installation of drainage is necessary. Installation of drainage can be recommended, but cannot be enforced. With regard to soil and land management, some soils are leveled by means of laser and restrictive layers removed during soil preparation. Irrigation efficiency varies and is influenced by irrigation scheduling (controlled and uncontrolled over irrigation) and use of different irrigation systems (flood, sprinkle and drip). Water quality is monitored at selected points in the river. Surface drainage from natural streamlets and disposal of subsurface drainage water (where, how, quality) were seen as specific problem areas. A drainage management plan for the area does not exist and surface and drainage water is canalized by means of the shortest and most economical route to the river.

Priorities were allocated to specific water quality and salinization management actions for the region (Table 7.1). Implementation of management options 1, 2 and 5 (55% of votes) could result in reduction of excessive drainage, while 3, 4 and 6 (41.2% of votes) are mainly concerned with management of surface runoff - and subsurface drainage volumes and its accompanying salt load. The relevant research institutes of the Agricultural Research Council as well as extension services and consultants could be used especially to promote options 1, 3 and 4.

Table 7.1 Priorities for management of water quality and salinization in the Lower Orange River area.

No.	Management option	Priority (% of votes)
1	Improvement of irrigation efficiency	27.5
2	Adjustment of water delivery systems to supply water on demand/ adjustment of demand to delivery (on farm water storage)	15.7
3	Soil analysis, assessment of necessity for drainage, recommendation for installation of drainage	15.7
4	Proactive drainage	15.7
5	Implement incentives for improving irrigation efficiency	11.8
6	Management plan for dumping of surface and drainage water (where/how/quality)	9.8
7	Extension and research	3.8

7.1.2 Institutional structure and catchment management

Since the abovementioned meeting, the Department of Water Affairs (DWAF) documented an *"Internal Strategic Perspective"* for each WMA in order to facilitate implementation of integrated water resource management, including water quality management. These documents contain the perspectives and strategies of DWAF regarding integrated water resource management and are intended to be regularly updated to keep information and management strategies relevant. The water quantity and quality in the Lower Orange River Management Area is to a large extent determined by the water resources it receives from the Upper Orange River WMA. Due to the interdependency of the two WMAs, water resource management strategies are coordinated for the Orange River System as described in an inclusive or "overarching" Internal Strategic Perspective (DWAF, 2004a), although water resource management strategies specific to each WMA are documented separately (DWAF, 2004b; DWAF, 2004c).

The management of the Overarching Orange River System is to be performed at National level and the so-called "Central Cluster" is expected to be responsible for implementation of the overarching Internal Strategic Perspective (DWAF, 2004a). The Central Cluster is responsible for Water Services and Forestry functions in the Gauteng, Free State, Northern Cape and North West provinces and Water Resources Management in the Vaal and Orange basin and the Crocodile Marico WMA. The transformation to integrated water resource management is still in progress and the eventual aim of DWAF is to hand over certain water resource management functions to CMAs (DWAF, 2004b).

Until the CMAs are established and operational, the regional offices of DWAF will continue to manage water resources in their jurisdiction (DWAF, 2004b). Although DWAF is the primary agency responsible for water resources management, other national, provincial, and local government departments involved in non-point source management should closely interact to manage water quality (DWAF, 1999b) and in this regard co-operation between DWAF and DALR, which is responsible for land management programmes in the Lower Orange WMA, is considered to be especially important.

Irrigation boards are currently being transformed into WUAs and are expected to fulfil their roles as set out in the National Water Act and National Water Resource Strategy. The establishment of seven WUAs in the Lower Orange WMA has started, with the viability of some existing Irrigation Boards being investigated and new WUAs are to be established particularly for Resource Poor Farmers (DWAF, 2004b). This transformation process is estimated to be near completion for the Lower Orange WMA by 2007 or 2008 (B.Conradie, personal communication, 2004). The irrigation action committees are also in the process of being transformed into Coordinating Committees for Agricultural Water and will provide a forum for technical planning and efficient liaison between relevant departments (DWAF, 2004b).

7.1.3 Water quality management strategy

Water quality of the resource is protected in each WMA through water quality management plans, which each has specific Water Quality Objectives (DWAF, 2004a). Due to the interdependence of the Orange and Vaal River Systems and the associated downstream water quality impacts of their WMAs, a fully integrated water quality management plan is necessary to ensure appropriate Water Quality Objectives in all the WMAs involved. The main management objective for the Orange River System therefore is that an integrated water quality management plan be developed in coordination with such a management plan for the Vaal River system. This necessitates the development of an integrated water quality management tool for the Orange River Basin to enable realistic assessment of factors that impact on water quality (DWAF, 2004a).

The main management objective of the water quality management strategy for the Lower Orange WMA is *"to ensure a sound and reasonable balance between development impacts and the protection of the resource. Fitness for use by all users (especially downstream users), and protection of the natural ecosystems, must be used as the basis for strategy development"* (DWAF, 2004b). The Internal Strategic Perspective for the Lower Orange WMA (DWAF, 2004b) proposed seven management actions in their water quality management strategy of which five are of specific importance for this study:

- Development of a management plan to address issues related to irrigation along the main stem of the Orange River. Subjects of importance here are quantification of the return flow volumes and qualities, recharge of salt to the groundwater, interaction with surface water and the diffuse washoff loads.
- Promotion of sustainable water management at local authority level by communicating the relevant guidelines and protocols to the local authorities.
- Assembling a literature review of water quality related studies performed in the Lower Orange WMA.
- Production of a map of groundwater zones in terms of radioactivity, fluoride and nitrates utilizing all available data sources.
- Additional research regarding the behaviour of algae and sources to enable development and implementation of appropriate management options.

The other management actions, which also are the responsibility of the DWAF regional office, were related to sanitation system issues, and management of mining activities (DWAF, 2004b).

Non-point source pollution of surface waters in South Africa is largely caused by rainfall and the associated surface runoff or groundwater discharge (Pegram & Görgens, 2001). Non-point sources may be diffuse and intermittent (storm washoff and drainage from urban or agricultural areas) or concentrated (mines, feedlots, landfills and industrial sites). According to DWAF, the formulation of a catchment non-point source strategy should be a key requirement of every catchment management strategy (1999b), but the diffuse discharges from agriculture are not yet included in the Waste Discharge Charge System (DWAF, 2003). The Waste Discharge Charge System is a framework for charging for the discharge of waste into water resources. The system is currently under evaluation by DWAF for point-source pollution sources, where after the scope may be extended to include diffuse pollution sources (DWAF, 2003).

Concerns regarding the pollutive effect of diffuse discharges on surface water quality are expressed in the Lower Orange Internal Strategic Perspective and the proposed water quality management strategy includes management actions to provide information that can support non-point source management (DWAF, 2004b). A strategy specific for non-point source management for the Lower Orange WMA, however, is not clear and this may be ascribed to the Waste Discharge Charge System still being under evaluation as well as to a lack of information about the non-point source areas. The water resources protection strategy in the "overarching" Internal Strategic Perspective (DWAF, 2004a), clearly indicates a need for research to enable better understanding of catchment water balances and waste load discharges. Such research should regard the use of the guidelines for non-point source assessment by Pegram and Görgens (2001).

The fact that non-point source management should be based on management practices for land use (Pegram & Görgens, 2001) may be another reason why a strategy specific for non-point source management has not been formulated. Although care should be taken by DWAF not to exceed the mandate for water management when developing non-point source measures (DWAF, 1999b), it is impossible to effect integrated water management in an irrigated catchment without inclusion of drainage water management. Several researchers stressed the fact that drainage management is an important aspect to ensure sustainability of irrigated catchments (Rhoades & Loveday, 1990; Tanji & Hanson, 1990; Ayars & Tanji, 1999; El-Ashry & Duda, 1999; Rhoades, 1999; Van Schilfgaarde, 1999). In this regard the absence of a drainage water management strategy for the Lower Orange WMA (Section 7.1.1.) needs urgent attention. Formulation of a regional drainage water management strategy, and the policy to support it, needs to be mutually addressed by DWAF and the land management personnel of the Department of Agriculture at provincial level, and should compliment the catchment management policies and strategies proposed by DWAF for water quality management. Such a strategy for the Lower Orange WMA should be included whenever the Internal Strategic Perspective document of DWAF on Integrated Water Resource Management is updated.

7.2 Options for water quality and soil salinity control

Surface water salinization may be reduced through judicial land use planning in the basin, other measures to restrict saline effluent generation and salt mobilization and the preventing these salts to reach the river. Land use planning can affect water quality through its effect on river abstraction, the generation of saline flows and salt mobilization or aid in control of downstream salinity in several ways (Smedema, 2000). Options include adoption of alternative land use or cropping patterns to optimize water use efficiency, especially in the upper part of the basin, upstream shifting of downstream irrigation scheme intakes, retirement of irrigated land with uncontrollably high saline drainage rates or leaving land with high salinity unreclaimed (Smedema, 2000). The use of low lying unproductive land as salt sinks or so-called "dry drainage", however, is not recommended until more research results on this option for disposal of saline drainage water become available (Madramootoo, 1997). Cropping patterns may need to be adjusted according to the salinity of the irrigation water, as was the case for the lower reaches of the Vaal and Riet rivers (Armour & Viljoen, 2000), while salt-loading of the river by nonirrigated land should also be considered in the land use planning of the basin (Smedema, 2000).

Successful restriction of salt mobilization primarily depends on the planning of irrigated areas and system layouts, which should be based on the geohydrological conditions of the area (Smedema, 2000). The mapping of resident soil layers and drainage flow paths can supply the necessary information to enable effective measures to decrease irrigation-induced seepage flows. Such information is also much needed for the astute construction of interceptor drains that can prevent saline seepage flows from reaching the drainage and river systems (Smedema, 2000). Management to limit saline effluent generation and salt mobilization include measures to reduce the volume of return flow, and accountable re-use and disposal of drainage water (Tanji & Hanson, 1990; Rhoades & Loveday, 1990). Irrigation management for soil salinity control, however, necessitates frequent irrigations, adequate leaching, drainage and water table depth control (Rhoades & Loveday, 1990). Applying adequate leaching appears to be in conflict with reducing the volume of return flow. Both of these measures, however, are necessary to ensure sustainable irrigated agriculture in an arid river basin.

7.2.1 Minimization of irrigation return flow

Reduction of the volume of drainage water that needs to be disposed of is seen as the foremost action to reduce the pollutive impact of irrigation on water quality (Ayars & Tanji, 1999). In this regard, the Water conservation and water demand strategy of DWAF for the Lower Orange WMA (DWAF, 2004b) and its implementation of the water demand management recommendations forthcoming from the Orange River Development Replanning Study (Potgieter *et al.*, 1998) is most important. As largest water user in the WMA the irrigation sector is targeted for water conservation and water demand management and according to Becker and Luger (2004) and DWAF (2004b) water savings of between 20% and 47%, respectively, of the irrigation water requirement can potentially be realized through improvement of water use efficiency. Such an increase in water use efficiency will definitely decrease the volume of water and salt that leach through soils and/or percolate into groundwater. Although groundwater-surface water interaction has not previously been researched in the Northern Cape, current water quality problems in the Vaal and Orange rivers and irrigation-related waterlogging problems are indicators of such interaction (DWAF, 2004b). If such interaction exists, excessive leaching may result in saline seepages and high water tables that promote surface water and land salinization. Irrigation return flow may be reduced through effective management of water delivery and increased irrigation efficiency (Rhoades & Loveday, 1990; Tanji & Hanson, 1990; Smedema, 2000).

7.2.1.1 Management of water delivery

Leaking water supply canals that result in water seepage which promote water table formation and subsequent salinization, occur in many irrigation projects (Rhoades & Loveday, 1990). Water seepage from unlined canals, furrows and balancing dams is considerable in the Orange River area and contribute significantly to high water tables and salinization (Potgieter *et al.*, 1998). Lining of delivery and storage structures is therefore considered an important priority for water loss minimization for both water suppliers and farmers in the Orange River system. The cost of implementation may necessitate an upgrading plan that is executed over a number of years.

In order to enable farmers who extract water from canals to irrigate more efficiently, *releasing of water into the canal systems* should occur in such a way as to eliminate losses at the end of the network. According to Potgieter *et al.* (1998), tail-end losses vary from scheme to scheme and may be appreciable. For efficient control of a supply system, the water volume passing critical points, including outlets to individual farms, needs to be known (Rhoades & Loveday, 1990). This necessitates *installation of effective flow-measuring devices*, without which seepage losses are difficult to identify, and oversupply to farms may occur. The accurate measurement of water diverted to, or abstracted by, users in the Orange River system has rightly been indicated as another priority of the water demand management strategy (Potgieter *et al.*, 1998). This will necessitate evaluation of all offtakes, and upgrading where necessary. It is also suggested that abstraction by farmers becomes conditional on the installation of a satisfactory water measuring device or system. Such a system should benefit both the supplier, for monitoring purposes, and the farmer, as an aid in irrigation scheduling.

Supplying water on demand is essential to improve efficiency of on-farm irrigation scheduling (Rhoades & Loveday, 1990). However, this concept proves to be very difficult for flood irrigating farmers to implement as most of the irrigation schemes within the Orange River system are semi rigid rotation systems where the farmer does not have full control of the frequency, duration and rate of their water supply (Potgieter *et al.*, 1998). Such a delivery system does not allow farmers to improve their irrigation efficiencies and the only means for them to introduce water supply flexibility, is to construct storage dams and to increase their in-field distribution capacity. According to Potgieter *et al.* (1990), *conversion of existing schemes to demand driven or semi-demand driven systems* will be necessary to effect significant increases in water use efficiency. To achieve this, canal capacity, bulk water balancing and regulatory reservoirs as well as automation of farm outlet structures needs to be considered. It is recommended that the conversion of existing fixed schedule schemes should be investigated in terms of an economic impact assessment, which takes water saving and higher agricultural output potential into account (Potgieter *et al.*, 1998).

7.2.1.2 Improvement of irrigation efficiency

Surface return flows occur when the application rate of the irrigation system exceeds the infiltration rate of the soil, while subsurface return flows are as a result of over irrigation and nonuniform irrigation applications. Proper irrigation management can reduce over irrigation while proper irrigation system selection, design, operation and maintenance can improve the uniformity and decrease the depth of applied water (Tanji & Hanson, 1990).

Irrigation scheduling

In general, indications are that irrigation scheduling in the Orange River system is not widely practiced (Potgieter *et al.*, 1998). Irrigation scheduling is to decide when to irrigate and how much water to apply. The goal of irrigation scheduling is to supply the crop with adequate water to ensure optimum yield and desired quality while minimizing the loss of applied water – mainly to deep percolation and runoff. It depends on various soil, atmospheric, crop and irrigation system and operational factors (Potgieter *et al.*, 1998). To ensure water is applied efficiently throughout the season, the farmer should consider the combination of the above factors and devise an appropriate seasonal irrigation strategy, which could even include a component of deficit irrigation. Such an irrigation strategy should also be product specific as different irrigation strategies may apply for the production of quality wine grapes, table grapes and raisins, respectively (Williams & Matthews, 1990; Myburgh, 2003a; Myburgh, 2003b; Myburgh, 2003c).

Scheduling techniques practiced in the Orange River system vary from visual assessment of the crop to the use of technically sophisticated equipment for analyses of soil and climatic data (Potgieter *et al.*, 1998). The use of the latter information in an appropriate computerized irrigation scheduling model can improve decision making regarding when to irrigate and how much water to apply. Such irrigation scheduling models include *SAPWAT* (Crosby & Crosby, 1999; Van Heerden *et al.*, 2001) and *Vinet* (ARC, 1998; Myburgh, 1998), of which the latter has specifically been developed for irrigation management of grapevines. Until the model is calibrated, however, the occasional measurement of soil water content is considered a necessity to ensure the soil water status agrees with the modelled scenario. The modelled soil water content may differ substantially from the true soil water content due to differences in irrigation water actually used or applied in practice.

Leaching requirement

All irrigation water contains some salts which accumulate in the soil after application. Although the main aim of irrigation scheduling is to supply sufficient water for optimal crop production, additional water should be applied especially in arid regions to ensure salt accumulation does not occur to such an extent in the root zone of crops that it results in reduced yield or inferior product quality. As a high value crop, grapevine is economically most important to the river reach between Boegoeberg to Onseepkans, and more sensitive to salinity compared to the other main crops (i.e. cotton, lucerne, wheat and maize) produced in the area (Van Veelen & Van Heerden, 1998). The grape industry is of considerable importance for the socioeconomy of the region and to ensure its sustainability, the salt tolerance of grapevine will have to determine the allowable salt levels in the irrigation water and/or the appropriate leaching fraction needed. The potential effect of irrigation water salinity on grapevine and its leaching requirements is therefore specifically reported on in Appendix C.

The Department of Water Affairs and Forestry in its water requirement projections, due to lack of observed data, currently assumes return flows constitute 10% to 15% of the water volume released for irrigation (DWAF, 2004a). This could imply an assumed leaching fraction of between 0.1 and 0.15 or less. A leaching fraction of 0.1 can be expected for highly efficient irrigation practices. A leaching fraction higher than 0.2 is not recommendable as it may exacerbate water table problems in the lower Orange River area. Estimates of a salinity-yield response model (Maas & Hoffman, 1977), utilizing the salinity threshold and slope parameters for grapevine of Moolman *et al.* (1999), indicated that yield decrease of grapevine can occur if water with EC values of 0.45 and 0.60 dS m^{-1}, with a leaching fraction of 0.1 and 0.2, respectively, is applied through low frequency irrigation systems (Table C3). A yield decrease of grapevine could also occur if water with EC values of 0.60 and 0.75 dS m^{-1}, with a leaching fraction of 0.1 and 0.2, respectively, is applied through high frequency irrigation systems. According to this model and the fluctuating water quality in the river reach between Boegoeberg and Onseepkans (refer Chapter 3), yield decrease may be imminent for grapevine producers, depending on the amount of leaching that is applied.

According to the salinity-yield response model and salt tolerance parameters for grapevine of Maas & Hoffman (1977), however, a yield decrease could occur if water with an EC value of 0.85 dS m^{-1} with a leaching fraction of 0.1 is applied through low frequency irrigation systems (Table C2). No yield decrease is expected for water with an EC value of 1 dS m^{-1} if a leaching fraction of 0.1 or more is applied through high frequency irrigation systems. The large difference in the model parameters of Maas and Hoffman

(1977) and Moolman *et al.* (1999) may become important as water resources become more limited for the lower Orange River region. The validity of these results may become crucial for decision making regarding irrigation water quality and the application of leaching requirements in this region in the near future. A more conservative approach is recommended until new research results become available. Therefore, irrigation water with salinity of 0.55 dS m^{-1} is considered suitable for use during low, and 0.75 dS m^{-1} during high frequency irrigation, provided a leaching fraction of *ca.* 0.2 is maintained (Table C4).

Irrigation system efficiency (selection, design, operation, maintenance)

There is large scope to improve the efficiency of prevailing irrigation application systems in the Orange River system, as inefficiency stems mainly from irrigation systems not being appropriate for local conditions or systems not being managed to deal with specific local constraints (Potgieter *et al.*, 1998). Selection of irrigation application systems by the farmers is based on analysis of the local situation including factors such as source of water (canal or river, gravity or pumped); topography, soils; crop agronomic requirements; engineering requirements, economics/financing and social/ labour constraints. In many cases in the Orange River system it is desirable, but not economically justifiable to change from one irrigation system to another. Vineyards planted within the flood plain of the Orange River remain on basin irrigation systems where-as plantings outside the flood plain are predominantly irrigated by drip and micro-jet (Potgieter *et al.*, 1998).

Better control of the amount of water applied and its associated deep percolation will only realise if the irrigation efficiency of existing and future irrigation systems increases. This implies that the distribution uniformity will have to be improved and the depth of applied water be matched to the available soil water storage at the time of irrigation (Tanji & Hanson, 1990). Surface return flows occur when the application rate of the irrigation system exceeds the infiltration rate of the soil (Tanji & Hanson, 1990). Gravity flow irrigation systems such as furrow and border, have less control over the volume of water applied and are more significantly affected by variability in soil infiltration rate compared to pressurized systems such as sprinkler and drip irrigation (Tanji & Hanson, 1990). It follows that a larger volume of water is lost through both surface runoff and drainage from the crop root zone for the gravity flow systems.

Surface irrigation runoff (tailwater) is applied irrigation water which does not infiltrate into the soil and runs of the lower ends of irrigated fields (Tanji & Hanson, 1990). Tailwater is usually not collected in a sump or drain and is generally discharged diffusively, with potential re-use downstream. Factors that affect tailwater and sediment loading in furrow- and border- irrigated fields include soil texture, infiltration rates, length of run, slope of field and stream size. Management practices to reduce sediment loading of receiving waters include: reduction in stream size; using cutback irrigation; changing direction of irrigation to one of lower slope; changing some cultivation practices and using tailwater recovery ponds, vegetative buffer strips and/or sediment retention ponds (Carter & Bondurant, 1977 in Tanji and Hanson, 1990). Cablegation, an automated surface irrigation system, which gradually reduce furrow inflow rate, has the potential to reduce surface runoff to less than half that of a conventional system (Goel *et al.*, 1982).

Although the irrigation efficiency of surface irrigation systems is generally considered to be low (55% to 60%), application efficiencies of up to 90% are possible where the appropriate management practices are in place (Tanji & Hanson, 1990; Potgieter *et al.*, 1998). Gravity flood systems, if designed and operated properly, can achieve good water and salinity control although variation in soil properties within irrigated fields can reduce intake uniformity (Rhoades & Loveday, 1990). Distribution efficiency of such flood systems can be improved by laser-controlled precision levelling and level-basin methods of irrigation (Dedrick *et al.*, 1978).

Estimates of irrigation return flow for the Lower Orange River WMA range between 10% and 15% (DWAF, 2004b) and may in some cases be as high as 30% (Potgieter *et al.*, 1998). The widespread use of surface irrigation systems in the area and the lower efficiency of this method compared to other pressurised irrigation methods leads to the perception that flood irrigation contributes the bulk of the irrigation return flow. Unpublished research on the efficiency of flood irrigation systems in Eksteenskuil and Upington area, however, indicated that the contribution of flood irrigation on alluvial soils to irrigation return flow may be much less than that perceived (P.A. Myburgh, personal communication, 2005). Monitoring the wetting front by means of wetting front detectors in flood irrigated soils at Eksteenskuil in vineyards with both shallow (*ca.* 300 mm deep) and deeper (*ca.* 600 mm deep) root systems, disclosed that where between 75 mm to 100 mm of water was applied per fixed cycle irrigation, the wetting front passed the 300 mm depth in the shallower soils more frequently than the 600 mm depth in the deeper soils. The leaching water, however, never passed the 600 mm depth for the shallow soils or the 900 mm depth for the deeper soils. In Upington, where the irrigation was applied through furrows, the wetting front did not pass the 300 mm depth with each irrigation and never surpassed the 600 mm depth. The lack of excessive leaching was ascribed to the high soil water holding capacity (*ca.* 150 - 220 mm m^{-1}) of these alluvial soils. These results not only indicate that the flood irrigation in the Lower Orange WMA may actually be highly efficient, but also stress the importance of the knowledge of the water holding capacity and water status of soils for irrigation management.

Several methods are proposed for controlling subsurface return flow, including improving the uniformity of surface irrigation systems by using larger stream flows such that the advance time equals 25% of the minimum intake opportunity time (Walker *et al.*, 1978 in Tanji and Hanson, 1990). Although furrow irrigation is not widely practiced in the Orange River system (Potgieter *et al.*, 1998), some grape producers in the Lower Orange River region have during years with water restrictions, adopted a practice where every second work row is irrigated, and the alternate rows during the following irrigation (Myburgh, 2003c). Research by Myburgh (2003c) on Sultanina grapevines in the region in this regard indicated higher water use efficiency for both narrow bed (1.5 m) and alternate row irrigation compared to wide bed (9.6 m) irrigation on alluvial soils. Measures to increase irrigation efficiency of furrows may therefore be of use and include: use of closed conduits instead of open waterways for laterals which enable effective "on-off" control; reducing furrow lengths that improve intake distribution and minimizes tail water losses and surge irrigation that may improve uniformity of intake in fields (Rhoades & Loveday, 1990 and references therein). Surge irrigation applies water in pulses and thereby apparently decreases the soil infiltration rate and the water required for complete advance compared to that needed by conventional continuous flow methods (Tanji & Hanson, 1990). Furrow irrigation, however, may lead to salt accumulation in beds, and periodic flooding along with crop rotation is recommended for salinity control (Rhoades & Loveday, 1990).

Pressurized systems such as drip and sprinkler allow better control of the applied water compared to surface irrigation as the distribution of water is not controlled by the infiltration characteristics of the soil surface, but is a function of the hydraulics which can be established during design of the system and controlled during operation (Tanji & Hanson, 1990). Well designed trickle or drip irrigation systems are furthermore better suited for use of more saline water as they maintain high water content, move accumulating salts to the periphery of the wetted zone and allow for uniformity of application (Rhoades & Loveday, 1990). Certain types of fixed and moving sprinkler systems can also obtain good volume control and uniform distribution, but tend to produce drop impact-induced soil crusts, especially in sodic soils, which restrict seedling emergence and water entry. Runoff and erosion under sprinkler irrigation is determined by application rate and uniformity, amount applied, tillage system, crop type and rotation, soil compaction, soil type and field topography (Crowley & Loudon, 1986 in Tanji & Hanson, 1990). Measures to reduce runoff include the lowering of irrigation system application rate and improved uniformity as well as changing soil characteristics to reduce erosion.

Potgieter *et al.* (1998) recommended specific irrigation systems for use under various local conditions in the Orange River system. According to them, centre pivot irrigators in the area are in general efficient, but where peripheral precipitation rates are high and soil intake rates low, run-off may become significant, resulting in low efficiency. Low pressure pivots are also prone to high application rates that lead to significant run-off. The pressurized irrigation systems are not problem free as micro-jet irrigation, especially in orchards with compacted interrows may result in run-off, while drip irrigation in sandy soils may promote deep percolation beyond the root zone. Application problems associated with surface irrigation are inadequate flow rates, excessively long and uneven beds, soils with low water holding capacity and layered soils associated with riverine deposits. As alternative to changing less efficient irrigation systems to more efficient systems, they recommend implementation of less drastic, less costly and equally effective steps to improve irrigation efficiency such as scientific irrigation scheduling, reforming existing surface-irrigation beds, down-sizing centre pivots and selecting more appropriate sprinkler nozzles. All irrigation systems require maintenance. Leaking distribution pipes in pressurized irrigation systems seem to be a common problem in the area and producers are urged to adopt routine maintenance programs.

7.2.2 Drainage water management

Drainage of water from the soil profile is necessary to prevent excessive soil water conditions in the root zone of crops, to control salinity and to ensure trafficability of fields for execution of farming activities (Skaggs & Murugaboopathi, 1994). In many soils the natural drainage processes, i.e. groundwater flow to streams or other surface outlets, vertical seepage to underlying aquifers and lateral flow which may reappear at the surface at some other point in the landscape, are sufficient for the growth and production of crops. Poor natural drainage of some other soils may be ascribed to low surface elevation, its location being far from a drainage outlet, the receipt of seepage from upslope areas, it being in lower than the surrounding land or restricted permeability or hydraulic conductivity of the soil profile.

7.2.2.1 Drainage in the Lower Orange River

Evidence of water table and salinization problems in the Orange River system (Potgieter *et al.*, 1998; Viljoen et al., 1991) indicates that artificial drainage is a necessity for certain soils and recommendations have been made in this regard for the Lower Orange River area (Viljoen *et al.*, 1991). A survey that investigated high water table and soil salinization problems in six irrigation districts along the Lower Orange River during 1987 to 1989, indicated that 45% to 75% of the area of the individual districts has a permanent water table and that irrigation farming in some of these areas may cease if the problem is not addressed. Over-irrigation, leaking canals, stratified soils, lack of natural drainage, impermeable underlying material (dorbank or solid rock), topography and irrigation on the foothills outside the alluvium were identified as factors contributing to a permanent water table within 1.2 m of the soil surface (Viljoen *et al.*, 1991).

Waterlogging on the flood plains of the Lower Orange River is increasingly a problem due to a natural permanent water table that exists as highly permeable arable soils are situated close to the water on the flood plain of the river. Furthermore, the lowlands between the levee and the foothills act as an area of concentration for all surface run-off water and leaking canals located on levees also contribute to the existing water table (Le Roux *et al.*, 1989). As the underlying material is impermeable and deep percolation cannot take place, excess irrigation water must drain laterally to natural channels and the river (Viljoen *et al.*, 1991). Excess irrigation water of the foothills drains effectively, including laterally to the existing irrigation areas on the river alluvium (Viljoen *et al.*, 1991), exacerbating the water table and salinization problem on the flood plain. If such drainage water mobilizes significant amounts of salt, it could in combination with waterlogging render previously highly productive alluvial land unsuitable for production of crops. This could impact severely on the sustainability of some producers in the Lower Orange WMA if they mainly cultivate alluvial soils. According to Viljoen *et al.* (1991), a suitable disposal point for drainage water of the alluvial soils is difficult to provide due to the topography of the river course. The most economical solution proposed by them was to breach the levees and construct drainage structures up to 4 meters deep in saturated soil.

According to Chutter *et al.* (1996), it is estimated that approximately half (*ca.* 15 000 ha) of the flood-irrigated land between Boegoeberg Dam and Augrabies Falls is potentially affected by salinization and the reasons therefore include, amongst others, over irrigation, leaking water delivery structures and poor drainage. Between Boegoeberg and Upington, the river itself is used as main drainage facility and downstream from Upington, an effective and highly complex and costly drainage infrastructure has been developed (Chutter *et al.*, 1996). In general, surface and subsurface drainage water is routed to the river along the most economical route (N. Toerien, personal communication, 2002). Plans and specifications for drainage systems in the Lower Orange River area are completed for between 4000 ha and 5000 ha between Opwag and Onseepkans, but not all systems have been installed, which makes an estimation of the area that is actually drained difficult (N. Toerien, personal communication, 2002). Approximately 90% of drainage systems installed are cutoff drains under terraces on the floodplain soils, while the topography of the foothill soils determines the drainage system selected.

7.2.2.2 Drainage water re-use and disposal options

Re-use of drainage water for irrigation can reduce the total volume of drainage water that needs to be disposed of. On-farm strategies for irrigating with saline drainage water include 1) substitution of some of the conventional irrigation water by saline drainage water in a cyclic reuse strategy which also involves the rotation of salt-tolerant crops and salt sensitive crops (Rhoades, 1989) and 2) irrigating with diluted saline water, where low salinity water is used for crop establishment, and blending of saline water with low salinity water occurs for remaining irrigations (Tanji & Hanson, 1990). Although it is recommended that drainage waters should be kept isolated from surface water or groundwater supplies of better quality to improve flexibility for use (Rhoades, 1989), on-farm constraints may determine the best strategy (Tanji & Hanson, 1990). The first strategy may require a storage facility to accumulate sufficient water for irrigation, while the second may require a distribution system to continuously convey the water to fields being irrigated (Tanji & Hanson, 1990). There exist, furthermore, some water quality concerns about drainage water re-use with plants of increasing salt tolerance (Madramootoo *et al.*, 1997). Such concerns include that the drainage effluent in irrigated lands may be of high salt content, the drainage water can be contaminated with trace elements, toxic organic substances, industrial waste and municipal waste in open main drains. Contaminated drainage water could impair soil physical and chemical properties, lead to water related health problems and could have potential to contaminate food products.

Reuse of drainage water for irrigation eventually increases its salinity such that further reuse is impossible and other means of disposal must be found. Although natural disposal of drainage water down the river was traditionally used in almost all river basins until the downstream salinity limits were reached (Smedema, 2000), the National Water Resource Strategy dictates water resource management that will ensure sustainable use of water resources (DWAF, 2004a). Disposal by means of the river is still an option, but to ensure downstream water quality conditions are complied with, river flow and drainage return flows should be managed appropriately. Water quality may be controlled by enhancing river flow during critical low flow periods through changing reservoir operating rules, limiting upstream water diversions or by reducing saline water disposal during low-flow periods (Smedema, 2000). Alternatively, the salinity disposal can be adjusted to the dilution capacity of the receiving river (Smedema, 2000). Options other than river disposal each have their own pros and cons. Desalination of agricultural water is not considered economically feasible, which leaves discharge to evaporation ponds, natural or constructed wetlands, outfall drains to the ocean or placement in deep aquifers as alternatives (Rhoades & Loveday, 1990; Madramootoo *et al.*, 1997). The most appropriate means of disposal depends on the catchment characteristics and it should be determined for the Lower Orange WMA as part of the drainage management strategy (7.1.3).

7.3 Guidelines for water quality and soil salinity management specific for the Lower Orange River Water Management Area

Although all the aforementioned options are available for the management of water quality and soil salinity, a few selected management actions are considered to be especially important for the Lower Orange WMA to reduce the recurring soil salinization problems. As different parties are responsible for different aspects of management, the following management actions are proposed for national government, local authorities, local extension services (i.e. government/private individuals or institutions) and producers, respectively.

NATIONAL GOVERNMENT

- DWAF completes the transformation process to integrate water resource management (with its incentives for efficient water use) and establish CMAs and WMAs for the Lower Orange WMA.
- DWAF and DALR together formulate policy to enforce revision of irrigation practices or retirement of irrigated land, where appropriate, wherever severe localised soil salinization in an irrigation district is apparent.
- DWAF and DALR together formulate a drainage strategy for the lower Orange River WMA and develop the necessary policy to support it.
- DWAF incorporates the drainage strategy in their Internal Strategic Perspective for the Lower Orange WMA.
- DWAF ensures effective implementation of the water quality management strategy. Effective communication between the relevant institutions will be vital if well-planned research and successful implementation of a water quality management strategy is to take place.

LOCAL AUTHORITIES

- The Lower Orange WMA CMAs manage the lining of water delivery and storage structures of irrigation schemes to reduce irrigation return flow and localised salinization.
- The Lower Orange WMA CMAs manage maintenance of drainage systems already installed for effective water table management.
- DALR judiciously design and install cut-off drains between the irrigated foothill soils and the basin lands on a regional scale to intercept drainage water and to prevent water table formation and associated soil salinization as well as disposal of mobilized salts in the basin lands. In this regard geohydrological characteristics of the catchment or subcatchments should be taken into account.
- The Lower Orange WMA CMAs ensure that intercepted drainage water is disposed of in the river by means of a closed drainage pipe until an alternative disposal option is identified by DWAF and DALR.
- The Lower Orange WMA CMAs monitor surface and drainage water quality and flow on a consistent monthly basis and develop and regulary update a database to support timeous decision making for water quality and soil salinity management .
- In support of the abovementioned database, DALR conducts on a regular basis (*ca.* every 5 years) an aerial survey and produce orthorectified maps thereof to aid in management of the Lower Orange WMA.
- The Lower Orange WMA CMAs manage river flow carefully to ensure salt retention is not promoted and that an equilibrium salinity profile of the river results.

LOCAL EXTENSION SERVICES

- Bring the potential negative effects of applying gypsum where it is not necessary to the attention of producers and stress that gypsum application should only be used where it can be motivated.
- Promote appropriate irrigation system selection for future developments.
- Promote maintenance of existing and future irrigation systems.
- Promote scientific irrigation scheduling of existing and future developments.
- Promote increased irrigation application efficiency for all irrigation systems. Practical solutions to achieve this, specifically for furrow and flood irrigation systems, need to become more generally available to producers.
- Promote correct installation of drainage and maintenance of current and new drainage systems in alluvial as well as foothill soils.
- Formulate a co-ordinated technology transfer strategy for the lower Orange River WMA to implement the abovementioned actions.

PRODUCERS

- Apply gypsum only where it can be motivated.
- Line water delivery and storage structures on a farm scale to reduce irrigation return flow and localised salinization.
- Irrigate according to basic irrigation scheduling principles.
- Improve irrigation system efficiency (selection, design, operation, maintenance) to reduce irrigation return flows.
- Apply adequate, but not excessive leaching to ensure soil salinity levels do not affect crop production.
- Revise irrigation practices wherever severe localised soil salinization is apparent, and retire irrigated land where appropriate.
- Maintain drainage systems already installed for effective water table management.
- Install drainage on a farm scale in order to prevent undesirable lateral movement of water and to control the water table problem and its associated soil salinization problems.
- Dispose of intercepted drainage water according to the regulations of the local authority.

The implementation of some of these proposed management actions, however, may be hampered by several constraints. Although more efficient water use by the agricultural sector is an important objective, the transformation process to integrated water resource management (with its incentives for efficient water use) is still in progress as CMAs and WMAs are still being established by DWAF. It is unsure how this will affect effective implementation of their water quality management strategy. The involvement of the Vaal WMAs and Upper Orange WMA in the water demand management process and the proposed combined research approach regarding water quality is essential, but may further complicate decision making. Effective communication between the relevant institutions will be vital if wellplanned research and successful implementation of a water quality management strategy is to take place. The resources to provide, alter and maintain water delivery and storage infrastructure should be provided for by the appropriate institutions or agencies, as efficient water use and restricted leaching will not materialise if the means to achieve it are not available.

7.4 Conclusions

Several opportunities exist for improved water quality and soil salinization management in the Lower Orange WMA, which in general are based on minimization of irrigation return flow and drainage water management. Management options revolve around various aspects of improved water delivery, irrigation efficiency and reuse and disposal of drainage water. Specific management actions are proposed for national government, local authorities, local extension services and farmers, respectively. The most important management actions proposed for the region include restricted gypsum application, improvement of irrigation efficiency, application of adequate leaching, revision of irrigation practices in severely salinized areas, lining of water delivery and storage structures, maintenance of drainage systems already installed, installation of drainage in basin lands ("*hollande*") and foothill soils and well-judged installation of cut-off drains between the irrigated foothill soils and the basin lands to intercept drainage water, which is to be disposed of in the river. The absence of a drainage management strategy for the area as well as lack of appropriate policy to enforce installation of drainage or to retire irrigated land where severe salinization is apparent, undoubtedly hamper effective management of surface water and soil salinization. This needs to be addressed at national government level. Possible constraints for implementation of the management actions include the rate of the integrated water resource management transformation process by DWAF, the level of communication between relevant institutions and the availability of resources to provide, alter and maintain water delivery and storage infrastructure.

8 CONCLUSIONS

A prerequisite for sustainable and effective use of water resources through integrated water resource management is an understanding of the physical as well as socio-economic cause-and-effect relationships in a WMA and its sub-catchments. Such information is critical not only to formulate policy and an appropriate water quality management strategy for catchments, but also to allow knowledgeable decision-making at farm level. This research project attempted to identify problems for water quality management in the lower Orange River region, with specific reference to the salinity contribution of the foothills, where extensive irrigation development has occurred during the past decade.

Although the proposed study area was the Boegoeberg to Onseepkans river reach, selected water quality results for the river reach from Onseepkans to Alexander Bay were included to enhance data interpretation. The situation analysis indicated that surface water quality according to the long-term EC, SAR and cation and anion concentrations, is of good quality and is not expected to pose any serious problems regarding salinity, sodicity or toxicity. Prerequisites, however, are that a leaching fraction of at least 0.1 is applied for low frequency irrigation systems and that foliage of sensitive crops is not wetted. For low flow years the EC may be more than double the long-term value for certain months and this increase in salinity could become important if consecutive years of low flow occur and if the ameliorating effect of precipitation in summer and autumn remains negligible. An appropriate increase in leaching fraction could be applied to avoid a reduction in production or quality of crops during such scenarios.

Trends downstream from Boegoeberg to Alexander Bay indicated a significant increase in salinity and sodicity, with the EC in the Boegoeberg to Onseepkans reach increasing by *ca.* 57% and from Onseepkans to Alexander Bay by 95%, relative to that in the Orange River reach upstream from Hopetown. Trends over time indicated a general increase in the annual mean for the EC, SAR and almost all cation and anion concentrations in the water after 1992, with the EC increasing by *ca.* 0.1 dS m^{-1}. Based on the current trend and mean flow, all EC values between Boegoeberg and Onseepkans could exceed the EC Class 1 threshold of 0.4 dS m^{-1} after the next 40 years. The increase in irrigation water pH may be of concern, with the water at Vioolsdrift running the highest risk of causing problems with crop production and encrustation of irrigation equipment or clogging of drip irrigation systems. The increasing trend in pH over time seems to have levelled off, but it is uncertain how sustainable the production of crops will be should the irrigation water pH rise further at other monitoring sites. The water quality data base for the lower Orange River region was surprisingly incomplete and the importance of collecting monthly data for the interpretation of trends in salinization over the long term cannot be overemphasized. Steps should be taken immediately to ensure a reliable water quality data base for the lower Orange River region in the future.

Concerns regarding salt retention in the Boegoeberg to Onseepkans river reach appear to be valid, but should be seen in context. The longitudinal annual average river salinity profiles and salt balance for the river reach between Boegoeberg and Onseepkans for high and low flow years, respectively, indicated that the river oscillates between a salinization profile and an equilibrium, or even a mobilization profile. It is hypothesized that salt retention occurs in the Boegoeberg to Onseepkans reach during periods following extremely high or relatively high flow in the river. The salt retention in the river reach occurs due to waterlogged conditions in low lying soils, which make effective leaching of salt periodically unfeasible. The presence of high water tables promotes salinization of these soils under conditions of high evaporative demand that are typical for the lower Orange River region. During years with low water flow salts can be effluxed from the river reach as low water tables allow salts to be effectively leached from the salinized soils.

Drainage water originating from over irrigation of foothill soils may aggravate the situation during high flow years or prolong the period of waterlogging and potential for salinization. It also has potential to mobilize salts which can have devastating effects for the crops cultivated on low lying alluvial soils, and to cause deterioration in surface water quality through groundwater seepage. Return flow from irrigated fields and leaking canals between Boegoeberg and Onseepkans is estimated to constitute between 15 and 20% of the irrigation requirement per year and as such may contribute *ca.* 7% of the water if the mean annual water flow in the river is 200 x 10^6 m^3. It was, however, impossible to determine any effect of the extensive irrigation developments on foothill soils during the 1990s on the river water quality due to the myriad factors that influence the river water quality and the lack of a reliable database. A simultaneous increase in EC at Boegoeberg and Onseepkans after 1992, however, indicated that irrigation return flows from the irrigation development on the foothills, which occurred mainly beyond Boegoeberg, cannot be the main source for the salinity increase in the river reach from Boegoeberg to Onseepkans.

Laboratory research on the salt leaching potential of shallow saprolitic soils, deep Kalahari sands and calcareous terrace soils from the foothills indicated that these soils are not particularly saline in their virgin state, although some local spots of exceptionally high salinity and sodicity were also found. The sources of salt in these soils are both soluble salts as well as accelerated weathering of primary minerals such as feldspar and biotite. It is estimated that the earlier stages of vineyard development could release several times more salt than that which would be applied through irrigation water alone. Where annual application of 1000 mm of 0.3 dS m^{-1} irrigation water could result in accumulation of 2 ton of salt per hectare per metre, irrigation could release on average between 3 and 8, and even 10 additional tons per hectare per metre of soil drained within the first decade of vineyard development. For some localised spots the salt generation potential could be as low as 2 or as high as 48 tons/ha.m. Where salt release of the latter magnitude represents the majority of soils in a small primary catchment, severe consequences for crop production on the low lying alluvial soils and/or impact on river water quality could be expected if drainage water from the foothills is not intercepted and responsibly disposed of.

The EC of drainage water emanating from small catchments dominated by calcareous alluvium, weathered gneiss and Kalahari windblown sands was 1.5 dS m^{-1}, 2 to 4 dS m^{-1} and *ca.* 10 dS m^{-1}, respectively. Drainage water quality can be affected by various factors and these values are therefore not necessarily indicative of the salts generated in such catchments. It provides, however, an indication of the drainage water salinity that can be encountered in the area. The total salt contribution to the river by these waters could not be estimated as the volume of drainage water is not known.

According to the salt leaching potential scenario above, one would expect the salinity status of irrigated vineyards to decrease if salt mobilization occurred. It was therefore surprising to find the contrary, namely, that there is no indication of a drop in salinity when virgin lands are converted to irrigated vineyards, but rather some indications of a slight increase in salinity. There was also evidence of local saline patches within vineyards. To counter the development of such salinity in vineyards, sophisticated drainage should be a prerequisite for any new irrigation development on the foothills, while review of regular gypsum and fertilizer applications are strongly advocated. The prospect of localized salinization within vineyards on foothill soils is probably of more immediate concern than the issue of river water quality deteriorating through salt generation. It should, however, be kept in mind that this conclusion was based on results from a limited dataset.

The procedure used to assess the area of saline soils in the region indicated that a mere 1.7% of the sampled area was too saline for grapevine production without yield loss (i.e. soils had a saturated soil water extract EC > 0.75 dS m^{-1}). For the whole area this represents 436 ha of 25 843 ha under cultivation. The small percentage of saline soils found may be partially attributed to the fact that sampling occurred during a period of lower river flow, which is characterized by desalination. What this survey also indicated is that only *ca.* 14% of the area displaying poor growth (potentially salinized area) was actually saline. This indicates that vegetation stress on about 2000 ha in the lower Orange River area was induced by causes other than salinity, such as water deficits and localized waterlogging. Based on these results, technology transfer regarding irrigation scheduling and water table management at farm level appears to be essential.

Specific management actions are recommended to curtail water quality deterioration and development of soil salinization in the lower Orange River region, as well as to maintain optimum production of grapevines. Management actions are proposed for national government, local authorities, local extension services and farmers, respectively. The management actions focus on reduction of the amount of leached water and improved drainage management and include aspects of water delivery management, irrigation efficiency (scheduling, leaching and system efficiency), and reuse and disposal of drainage water. The most important management actions proposed for the region include improvement of irrigation efficiency, application of adequate leaching, revision of irrigation practices in severely salinized areas, lining of water delivery and storage structures, maintenance of drainage systems already installed, installation of drainage in basin lands ("*hollande*") and foothill soils and well-judged installation of cut-off drains between the irrigated foothill soils and the basin lands to intercept drainage water, which is to be disposed of in the river.

The grape industry is important to the economy of the area as vineyards constitute 68% of the cultivated area and a yield decrease due to salinity is not considered an option. Irrigation water with a maximum salinity of 0.55 dS m^{-1} is considered suitable for use during low, and 0.75 dS m^{-1} during high frequency irrigation, provided a leaching fraction of *ca.* 0.2 is maintained. The salt concentration in the river at Onseepkans reached levels equal to an EC of almost 0.7 dS m^{-1} in the irrigation water during years with low flow, which indicates that the potential exists for excessive salt accumulation during such years, especially where low frequency irrigation systems are used.

POLICY DEVELOPMENT AND FUTURE RESEARCH NEEDS

The absence of a drainage management strategy for the area, as well as lack of appropriate policy to enforce installation of drainage or to retire land where excessive salinization occurs, almost certainly hampered the management of surface water and soil salinization. The development of such policy and integration with the water quality management strategy of DWAF is therefore seen as necessary to protect water and soil resources in the Lower Orange River WMA. Possible constraints for implementation of the management actions include the rate of the integrated water resource management transformation process by DWAF, the level of communication between relevant institutions and the availability of resources to provide, alter and maintain water delivery and storage infrastructure.

To ensure sustainable use of the water resource and to support future management decisions, there is a need for ongoing collection and interpretation of information and research on specific aspects, including the following:

- For monitoring of water quality trends and salt balance calculations or systems modelling to support salinity management decision making, consistent monthly data collection, verification, processing and interpretation of surface water quality and water flow data are crucial.
- For estimation of the impact of drainage water quality on surface water quality, collection of data on drainage water quality and quantity is necessary. Such information can be included in and managed similarly to the surface water database as described above.
- For judicious installation of cut-off drains, detailed information on geo-hydrological characteristics of the catchments and sub-catchments is required.
- For estimation of the potential effect of catchment or sub-catchment characteristics on irrigation-induced ground water recharge, more research is necessary especially regarding soil water retaining properties and recharge rates.
- Recharge rate is affected by water consumption of the irrigated crop and research is needed on the minimum water requirement of all crops produced in the lower Orange River WMA. The effect of netting covers on water consumption should also be researched.
- In order to obtain a better understanding of the salinization mechanism operating in the lower Orange WMA, the contribution of salt by tributaries of the Orange River (e.g. the Sout and Hartebeest rivers) during periods of unusually high precipitation needs to be quantified.
- Effective methods of technology transfer need to be developed to ensure that producers adopt a best practices approach with respect to irrigation scheduling and salinity management.
- For an improved method to identify salinized irrigated areas from aerial survey images, an object-oriented approach should be researched.

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10 ARCHIVING OF DATA

Data that may be of interest are the aerial survey images (IR and RGB), the drainage water analyses and the soil survey data. The original compact discs of the aerial survey images are left in the custody of Prof. HL. Zietsman of the Geographic Institute at the University of Stellenbosch, and copies of these CD's (26 DVD's) are kept at both DALR and ARC Infruitec-Nietvoorbij. This arrangement will make the data available for most interested parties. The analyses data of the drainage water and soils are included in Appendices A and B of the report and are also included in the electronic copy of the report for the WRC.

11 LIST OF PUBLICATIONS AND OTHER TECHNOLOGY TRANSFER ACTIONS

Technology transfer actions for this project were limited. The GIS and aerial survey research resulted in an honours project as well as an M.Sc thesis, while one paper was delivered reporting on the water quality and soil salinity of the lower Orange River region at the recent SANCID conference.

Publications:

Mashimbye, E., 2005. Remote Sensing-based Identification and Mapping of Salinised Irrigated Land between Upington and Keimoes along the Lower Orange River. M.Sc Thesis, University of Stellenbosch, Stellenbosch, April 2005.

Stals, P.J., 2005. The Identification of Potentially Salinised Soils in the Lower Orange River using an Object Based Classification Method. Unpublished BSc Honours Project, Department of Geography and Environmental Studies University of Stellenbosch, Stellenbosch.

Paper:

Volschenk, T. & Zietsman, H.L., 2004. Situation analysis of water quality and soil salinity in the lower Orange River region. SANCID Integrated Water Resource Management conference, 16-18 November 2004, Fish River Sun.

Potential publications:

- Popular publication for *Wynboer* that gives an overview of project results.
- Popular publication on the research for the WRC magazine *The Water Wheel*.
- Scientific publication regarding water quality and soil salinity of the lower Orange River region.
- Scientific publication regarding salt generation potential and drainage water quality.
- Scientific publications of satellite imagery and aerial survey results:

Stals, P.J. Soil salinization detection by remote sensing and object orientated image analysis. MSc thesis in progress. Department of Geography and Environmental Studies, University of Stellenbosch.

H.L. Zietsman. Digital image analysis techniques for detecting vegetation stress in irrigated crops: A case study of the Lower Orange River.

Potential papers/ presentations:

- Overview of the salinity status of the Lower Orange River region for wine farmers at a SASEV meeting by T. Volschenk.
- Paper on Digital image analysis techniques for detecting vegetation stress in irrigated crops: A case study of the Lower Orange River by H.L. Zietsman.

APPENDIX A

DRAINAGE WATER QUALITY ANALYSES DATA

Table A 1 The pH, electrical conductivity (EC) and cation analysis for drainage water sampled approximately monthly from five mini-catchments in the lower Orange River area

Date	Day[1]	Mini-catchment location	pH	EC dS/m	Na mg/l	K mg/l	Ca mg/l	Mg mg/l	SAR	AdjSAR
24/06/2003	24	Carpe Diem	8.1	1.5	286.3	0.5	52.0	28.0	8.0	10.0
05/08/2003	76	Carpe Diem	8.1	1.5	273.8	0.5	45.7	23.2	8.2	9.7
09/09/2003	101	Carpe Diem	n.a.[2]	1.4	266.8	0.5	48.5	24.2	7.8	9.2
01/10/2003	123	Carpe Diem	8.2	0.9	156.7	1.1	36.1	18.9	5.3	6.2
11/11/2003	164	Carpe Diem	8.3	1.4	254.2	0.6	58.2	28.5	6.8	8.4
18/12/2003	201	Carpe Diem	7.8	1.4	212.0	1.8	52.5	28.6	5.8	7.2
16/01/2004	230	Carpe Diem	7.9	1.5	225.0	2.3	52.6	19.6	6.7	8.3
19/02/2004	264	Carpe Diem	7.9	1.5	234.6	2.4	58.2	21.4	6.7	8.4
24/06/2003	24	Chargo Trust	8.1	1.9	251.0	1.2	125.0	58.4	4.6	6.1
05/08/2003	76	Chargo Trust	7.9	1.8	219.9	1.0	100.4	49.2	4.5	5.3
09/09/2003	101	Chargo Trust	n.a	1.8	217.4	1.2	105.9	49.7	4.4	5.3
01/10/2003	123	Chargo Trust	7.7	1.5	183.5	1.0	107.6	44.1	3.8	4.9
11/11/2003	164	Chargo Trust	7.9	1.7	193.0	1.3	122.0	47.6	3.8	4.9
18/12/2003	201	Chargo Trust	7.5	1.8	188.5	0.7	116.4	46.6	3.7	4.9
16/01/2004	230	Chargo Trust	8.0	1.4	188.3	0.8	44.0	34.6	5.2	5.6
30/01/2004	244	Chargo Trust	7.6	1.7	207.8	1.0	86.4	41.1	4.6	5.7
26/02/2004	271	Chargo Trust	7.7	1.7	184.2	1.0	70.3	31.7	4.6	5.7
05/04/2004	310	Chargo Trust	7.6	2.1	251.4	4.2	178.8	52.0	4.3	6.2
24/06/2003	24	Rooiland	7.9	1.4	128.0	12.5	77.0	78.4	2.5	2.9
05/08/2003	76	Rooiland	8.0	1.5	121.9	13.8	72.7	77.2	2.4	2.7
09/09/2003	101	Rooiland	n.a	1.0	61.0	12.2	59.9	56.0	1.4	1.5
01/10/2003	123	Rooiland	8.3	0.8	50.4	10.5	62.9	50.7	1.1	1.3
11/11/2003	164	Rooiland	8.1	0.9	57.1	12.1	68.2	53.2	1.3	1.5
18/12/2003	201	Rooiland	7.6	1.0	38.3	15.7	66.1	44.3	0.9	1.1
16/01/2004	230	Rooiland	8.0	0.8	41.2	11.6	47.4	35.3	1.1	1.3
19/02/2004	264	Rooiland	7.8	0.9	50.2	11.4	32.9	30.8	1.5	1.7
24/06/2003	24	Strauss	7.5	5.1	562.0	0.8	655.0	35.3	5.8	10.5
05/08/2003	76	Strauss	7.1	3.2	378.2	3.2	283.0	42.9	5.5	7.6
09/09/2003	101	Strauss	n.a	4.3	460.3	2.8	529.3	29.6	5.3	8.1
01/10/2003	123	Strauss	7.5	3.5	455.0	3.4	346.4	48.8	6.1	9.6
11/11/2003	164	Strauss	7.5	3.8	410.8	3.5	363.7	49.7	5.4	8.3
18/12/2003	201	Strauss	7.1	3.2	354.2	4.1	337.9	48.1	4.8	7.6
16/01/2004	230	Strauss	7.4	3.1	443.5	4.3	193.0	25.2	8.0	11.4
30/01/2004	244	Strauss	7.6	2.9	493.2	4.9	147.5	34.6	9.5	11.9
26/02/2004	271	Strauss	7.5	3.0	510.3	5.3	188.7	31.6	9.0	12.7
05/04/2004	310	Strauss	7.3	4.0	530.0	8.5	313.0	50.8	7.3	11.9
24/06/2003	24	SMB	7.8	15.2	3029.0	8.4	356.0	300.1	28.6	34.5
05/08/2003	76	SMB	8.2	9.8	1833.2	5.8	204.8	149.2	23.8	27.7
09/09/2003	101	SMB	n.a	12.0	2417.0	7.9	269.3	218.0	26.5	30.2
01/10/2003	123	SMB	8.0	11.0	2203.0	6.0	257.0	171.1	26.1	32.0
11/11/2003	164	SMB	8.1	9.3	1856.6	5.6	246.1	156.8	22.8	27.6
18/12/2003	201	SMB	7.9	9.2	1684.9	6.7	273.3	188.1	19.2	23.2
16/01/2004	230	SMB	8.1	6.9	1320.1	7.1	113.1	105.9	21.4	24.0
30/01/2004	244	SMB	7.3	6.4	1300.2	6.6	155.0	109.0	19.6	23.2
26/02/2004	271	SMB	7.9	9.6	1807.2	6.2	215.4	157.2	22.8	27.5
05/04/2004	310	SMB	6.6	9.4	1643.0	7.7	287.8	205.7	18.1	22.5

1 Days from 01/06/2003

2 Data not available

Table A 2 The anion and nitrogen as ammonium and nitrate analyses for drainage water sampled approximately monthly from five mini-catchments in the lower Orange River area

Date	Day[1]	Mini-catchment location	Cl mg/l	CO_3 mg/l	HCO_3 mg/l	SO_4 mg/l	B mg/l	P mg/l	NH_4-N mg/l	NO_3-N mg/l
24/06/2003	24	Carpe Diem	61.6	0.0	725.3	207.7	0.5	0.0	0.2	2.2
05/08/2003	76	Carpe Diem	57.2	73.4	240.4	214.0	0.5	0.2	0.2	2.2
09/09/2003	101	Carpe Diem	58.5	22.8	309.9	223.0	0.5	0.0	0.0	2.6
01/10/2003	123	Carpe Diem	47.1	66.1	262.3	120.0	0.3	0.1	0.0	5.6
11/11/2003	164	Carpe Diem	72.8	55.5	361.4	179.0	0.5	0.1	0.0	11.8
18/12/2003	201	Carpe Diem	72.8	55.5	487.9	191.0	0.5	0.0	0.1	5.2
16/01/2004	230	Carpe Diem	75.5	84.6	242.5	166.0	0.5	0.1	0.2	36.8
19/02/2004	264	Carpe Diem	75.5	84.6	273.8	177.0	0.5	0.1	0.2	36.8
24/06/2003	24	Chargo Trust	219.8	0.0	592.6	260.3	0.4	0.0	0.3	3.6
05/08/2003	76	Chargo Trust	204.3	37.5	205.6	255.0	0.4	0.2	0.1	4.1
09/09/2003	101	Chargo Trust	210.7	14.7	276.8	256.0	0.3	0.0	0.2	4.0
01/10/2003	123	Chargo Trust	175.6	43.5	384.3	215.0	0.3	0.1	0.1	3.0
11/11/2003	164	Chargo Trust	214.1	48.0	346.2	226.0	0.3	0.2	0.0	2.9
18/12/2003	201	Chargo Trust	220.1	51.6	380.3	299.0	0.4	0.0	0.2	3.1
16/01/2004	230	Chargo Trust	173.2	46.1	164.3	226.0	0.4	0.1	1.4	2.4
30/01/2004	244	Chargo Trust	205.2	77.0	237.8	236.0	0.4	0.2	0.2	2.8
26/02/2004	271	Chargo Trust	209.3	84.6	256.6	207.0	0.3	0.0	0.1	2.6
05/04/2004	310	Chargo Trust	312.3	7.5	629.0	278.0	0.3	0.0	0.0	1.9
24/06/2003	24	Rooiland	87.9	0.0	610.3	115.1	0.2	0.0	0.4	14.3
05/08/2003	76	Rooiland	175.7	57.1	232.1	136.0	0.1	0.2	0.1	18.4
09/09/2003	101	Rooiland	61.9	16.9	273.5	64.0	0.1	0.1	0.0	5.9
01/10/2003	123	Rooiland	51.4	60.0	335.5	54.0	0.1	0.1	0.0	3.9
11/11/2003	164	Rooiland	59.9	41.3	305.0	66.0	0.1	0.0	0.2	5.2
18/12/2003	201	Rooiland	73.7	47.7	333.1	77.0	0.1	0.0	0.2	3.3
16/01/2004	230	Rooiland	46.0	100.0	226.9	49.0	0.1	0.0	0.1	2.3
19/02/2004	264	Rooiland	53.4	115.4	258.2	56.0	0.1	0.1	0.3	4.3
24/06/2003	24	Strauss	725.5	0.0	353.8	1431.4	1.0	0.0	0.6	6.3
05/08/2003	76	Strauss	461.8	32.6	165.9	694.0	0.6	0.2	0.2	4.7
09/09/2003	101	Strauss	572.0	0.0	202.2	1479.0	0.9	0.0	1.2	2.5
01/10/2003	123	Strauss	608.0	48.0	314.2	790.0	0.6	0.0	0.3	5.6
11/11/2003	164	Strauss	582.3	31.5	302.0	771.0	0.6	0.1	0.0	5.1
18/12/2003	201	Strauss	475.3	46.4	334.4	888.0	0.7	0.2	0.2	3.7
16/01/2004	230	Strauss	451.5	38.5	234.7	716.0	1.0	0.1	0.3	4.8
30/01/2004	244	Strauss	436.7	30.8	175.2	774.0	1.0	0.1	0.1	4.3
26/02/2004	271	Strauss	447.8	23.1	266.0	804.0	1.1	0.1	0.2	4.7
05/04/2004	310	Strauss	657.6	0.0	591.0	1007.0	1.3	0.0	0.1	5.2
24/06/2003	24	SMB	3280.0	0.0	530.7	3254.5	7.9	0.0	0.2	41.5
05/08/2003	76	SMB	1553.0	62.0	172.4	2399.0	6.0	0.0	0.3	40.8
09/09/2003	101	SMB	2700.0	16.3	202.2	2948.0	6.9	0.1	0.2	41.6
01/10/2003	123	SMB	2106.0	75.2	297.2	2406.0	6.0	0.2	0.1	39.1
11/11/2003	164	SMB	1841.0	48.0	268.4	2346.0	5.6	0.0	0.0	37.8
18/12/2003	201	SMB	1785.5	51.6	263.6	2742.0	6.6	0.2	0.2	39.0
16/01/2004	230	SMB	1256.0	76.9	156.6	1679.0	4.4	0.2	6.6	3.0
30/01/2004	244	SMB	1321.6	69.3	250.3	1593.0	4.4	0.6	0.1	38.2
26/02/2004	271	SMB	1831.0	123.1	187.8	2308.0	6.4	0.1	0.2	42.0
05/04/2004	310	SMB	2233.0	0.0	621.0	1498.0	6.8	0.7	1.3	20.4

[1] Days from 01/06/2003

APPENDIX B

SOIL CHEMICAL ANALYSES DATA

Table B1. The pH, electrical conductivity (EC_e), selected cations and anions and the SAR of the saturated soil water extract for soils from potentially saline and non-saline plots sampled for 0 to 300 mm, 300 to 600 mm and 600 to 900 mm depth increments in twelve river zones in the lower Orange River area

River Zone	Plot no.	Salinity status	Depth increment (mm)	pH	EC_e dS/m	Na mg/l	K mg/l	Ca mg/l	Mg mg/l	Cl mg/l	S mg/l	S A R
1	1016	Non_saline	0-300	6.5	2.01	274.7	62.7	225.5	107.2	211.8	300.0	3.8
1	1016	Non_saline	300-600	6.6	2.00	217.4	32.6	195.1	84.3	177.4	270.0	3.3
1	1016	Non_saline	600-900	6.7	1.08	122.9	11.2	80.8	31.2	116.8	106.0	2.9
1	1016B	Saline	0-300	6.9	0.49	28.8	7.3	34.3	13.4	60.6	19.5	1.1
1	1016B	Saline	300-600	7.2	0.42	39.9	2.5	21.7	11.0	60.8	27.0	1.7
1	1016B	Saline	600-900	7.3	0.53	76.1	2.1	31.2	13.8	60.4	42.4	2.9
2	2005	Non_saline	0-300	6.8	0.08	7.8	4.1	3.0	2.4	13.0	3.1	0.8
2	2005	Non_saline	300-600	7.1	0.14	12.1	2.3	6.2	3.2	21.6	6.6	1.0
2	2005	Non_saline	600-900	7.0	0.14	14.1	3.6	7.1	4.1	25.9	6.7	1.0
2	2010	Non_saline	0-300	7.1	0.20	16.9	15.5	11.6	6.3	17.6	6.4	1.0
2	2010	Non_saline	300-600	7.2	0.27	32.3	1.9	13.8	4.8	25.9	12.5	1.9
2	2010	Non_saline	600-900	7.3	0.60	86.1	1.7	32.1	13.6	95.2	44.1	3.2
2	2012	Saline	0-300	10.2	11.01	2119.6	17.2	35.2	9.6	112.4	306.6	81.8
2	2012	Saline	300-600	10.0	4.01	1067.0	118.6	30.2	162.5	89.2	97.1	17.0
2	2012	Saline	600-900	7.4	0.71	207.7	28.6	12.7	28.5	116.8	19.2	7.4
2	2014	Non_saline	0-300	7.3	0.31	64.8	3.1	4.6	3.5	34.6	20.6	5.5
2	2014	Non_saline	300-600	7.3	0.36	51.6	2.4	11.3	5.4	47.6	24.5	3.2
2	2014	Non_saline	600-900	7.2	0.32	46.0	1.4	9.6	4.8	47.8	22.0	3.0
2	2019	Non_saline	0-300	6.9	0.12	11.5	6.9	6.6	5.9	13.2	3.6	0.8
2	2019	Non_saline	300-600	6.9	0.09	11.6	7.6	6.4	6.5	17.4	3.8	0.4
2	2019	Non_saline	600-900	7.1	0.17	17.7	1.6	7.6	2.8	25.6	9.2	1.4
2	2022	Non_saline	0-300	6.7	0.10	10.4	4.7	4.2	3.0	21.6	3.5	0.9
2	2022	Non_saline	300-600	6.8	0.09	10.2	4.0	3.1	2.9	17.9	2.9	1.0
2	2022	Non_saline	600-900	6.7	0.09	10.5	3.4	3.8	3.5	22.3	3.9	0.9
2	2030	Non_saline	0-300	7.2	0.13	13.4	4.7	5.5	4.8	7.9	3.3	1.0
2	2030	Non_saline	300-600	7.3	0.19	25.6	4.1	8.1	5.3	25.9	9.1	1.7
2	2030	Non_saline	600-900	7.3	0.22	31.1	1.9	7.0	3.7	30.3	12.9	2.4
2	2045	Non_saline	0-300	7.4	0.24	22.4	6.9	12.2	6.6	51.9	6.4	1.3
2	2045	Non_saline	300-600	7.5	0.19	21.4	2.9	8.2	4.1	22.3	5.7	1.5

Table B1. Continued

2	2045	Non_saline	600-900	7.6	0.21	27.4	1.4	9.0	3.9	30.3	10.8	1.9
2	2059	Non_saline	0-300	7.1	0.11	9.3	3.4	6.8	3.9	17.5	2.2	0.7
2	2059	Non_saline	300-600	7.2	0.11	6.6	2.2	6.3	3.0	8.1	2.2	0.5
2	2059	Non_saline	600-900	7.0	0.26	26.2	2.3	11.9	3.8	34.7	11.0	1.7
2	2081	Non_saline	0-300	6.5	0.11	12.6	11.5	4.3	8.6	16.9	3.5	0.8
2	2081	Non_saline	300-600	6.6	0.13	13.4	8.3	4.9	6.5	24.9	4.9	0.9
2	2081	Non_saline	600-900	6.1	0.14	11.7	3.6	5.0	3.7	22.3	7.9	1.0
2	2117	Non_saline	0-300	6.9	0.35	20.3	3.0	17.6	6.4	17.3	30.5	1.1
2	2117	Non_saline	300-600	6.9	0.24	22.7	3.5	10.2	4.8	24.8	12.2	1.5
2	2117	Non_saline	600-900	7.0	0.28	32.7	2.9	10.5	4.9	22.6	15.7	2.1
2	2005B	Saline	0-300	6.9	0.06	5.6	2.3	2.5	1.8	12.8	2.1	0.7
2	2005B	Saline	300-600	6.5	0.04	5.3	2.9	2.2	2.3	13.4	1.6	0.6
2	2005B	Saline	600-900	6.6	0.10	13.1	7.0	4.4	5.2	17.3	6.2	1.0
2	2010B	Saline	0-300	7.0	0.08	7.3	2.9	5.5	2.8	14.2	1.4	0.6
2	2010B	Saline	300-600	7.2	0.08	6.7	1.4	4.7	1.8	14.5	1.7	0.7
2	2012B	Non_saline	0-300	7.5	0.33	68.2	12.5	6.9	14.3	47.6	7.6	3.4
2	2012B	Non_saline	300-600	7.5	0.66	154.0	13.6	10.9	16.0	99.5	23.7	6.9
2	2012B	Non_saline	600-900	9.6	1.49	599.4	247.5	48.7	319.3	65.8	24.6	6.9
2	2014B	Saline	0-300	7.3	0.20	22.6	3.6	10.1	4.4	22.3	4.3	1.5
2	2014B	Saline	300-600	7.1	0.33	53.1	2.6	9.5	4.9	34.6	25.3	3.5
2	2014B	Saline	600-900	7.0	0.84	127.9	1.2	29.3	15.1	121.1	78.7	4.8
2	2019B	Saline	0-300	6.9	0.07	5.5	4.3	3.2	2.5	12.4	1.3	0.6
2	2019B	Saline	300-600	7.1	0.06	5.3	2.8	2.6	1.8	8.6	0.9	0.6
2	2019B	Saline	600-900	7.1	0.06	5.8	2.6	2.4	1.7	12.8	1.5	0.7
2	2022B	Saline	0-300	6.8	0.08	6.3	2.7	3.0	1.8	8.6	1.8	0.7
2	2022B	Saline	300-600	6.6	0.06	5.6	1.7	1.9	1.3	12.9	2.4	0.8
2	2022B	Saline	600-900	6.6	0.06	6.4	2.4	1.9	1.4	13.2	1.9	0.9
2	2030B	Saline	0-300	7.2	0.11	14.8	4.2	6.0	5.3	4.5	2.1	1.1
2	2030B	Saline	300-600	8.0	0.34	83.5	6.2	7.7	8.7	21.6	15.2	4.9
2	2030B	Saline	600-900	8.9	0.73	291.7	133.3	50.3	168.1	56.2	57.4	4.4
2	2045B	Saline	0-300	7.4	0.11	10.7	8.5	9.8	7.0	12.5	3.0	0.6
2	2045B	Saline	300-600	7.5	0.18	16.5	3.2	11.9	4.5	17.4	10.1	1.0

Table B1. Continued

2	2045B	Saline	600-900		0.38	28.7	1.4	25.1	12.2	25.9	49.2	1.2
2	2059B	Saline	0-300	6.9	0.17	13.6	5.5	8.7	3.5	17.6	5.7	1.0
2	2059B	Saline	300-600	7.1	0.34	36.8	2.2	13.8	3.8	43.3	18.6	2.3
2	2059B	Saline	600-900	7.1	0.53	69.8	2.0	21.7	6.4	69.2	40.7	3.4
2	2081B	Saline	0-300	6.3	0.10	12.2	27.4	9.7	22.6	11.9	2.5	0.5
2	2081B	Saline	300-600	6.2	0.07	10.6	25.0	8.8	18.1	11.9	2.3	0.5
2	2081B	Saline	600-900	5.9	0.04	6.0	14.6	5.0	10.1	7.9	1.2	0.4
2	2117B	Saline	0-300	7.4	0.55	44.6	7.3	32.6	10.3	24.7	48.6	1.7
2	2117B	Saline	300-600	7.1	2.00	234.9	2.4	192.8	48.5	69.2	397.1	3.9
2	2117B	Saline	600-900	7.1	2.01	222.4	1.4	279.8	59.8	51.9	583.9	3.1
3	3011	Non_saline	0-300	6.3	0.14	9.9	18.5	10.0	10.9	17.4	7.1	0.5
3	3011	Non_saline	300-600	6.1	0.09	8.1	15.4	6.5	8.8	12.8	4.2	0.5
3	3011	Non_saline	600-900	5.9	0.07	5.0	6.8	3.1	3.5	12.4	3.3	0.5
3	3023	Non_saline	0-300	6.3	0.11	7.9	5.6	3.7	3.4	13.4	3.6	0.7
3	3023	Non_saline	300-600	6.6	0.14	12.4	3.4	4.6	3.6	12.9	4.0	1.1
3	3023	Non_saline	600-900	7.3	0.42	82.0	7.4	7.1	9.0	35.3	19.1	4.8
3	3027	Non_saline	0-300	6.9	0.12	12.1	6.2	4.7	4.2	12.5	2.9	1.0
3	3027	Non_saline	300-600	6.8	0.15	18.2	4.3	3.4	3.2	17.4	7.0	1.7
3	3027	Non_saline	600-900	7.0	0.24	35.5	4.6	4.0	4.9	25.6	12.9	2.8
3	3033	Non_saline	0-300	7.2	0.16	22.2	4.9	2.7	3.5	12.4	3.9	2.1
3	3033	Non_saline	300-600	6.9	0.30	27.8	3.1	8.7	5.6	34.6	16.0	1.8
3	3033	Non_saline	600-900	7.1	0.32	31.9	2.0	8.8	4.4	33.9	21.0	2.2
3	3038	Non_saline	0-300	6.0	0.10	6.0	3.6	2.8	2.5	17.3	3.9	0.6
3	3038	Non_saline	300-600	6.0	0.08	6.0	4.7	1.9	2.5	12.9	2.7	0.7
3	3038	Non_saline	600-900	6.4	0.09	8.1	8.3	2.9	4.5	17.4	2.9	0.7
3	3011B	Saline	0-300	6.4	0.15	10.9	3.0	4.2	2.5	35.3	4.7	1.0
3	3011B	Saline	300-600	6.7	0.24	17.4	1.4	7.2	4.3	43.6	7.0	1.3
3	3011B	Saline	600-900	7.0	0.18	16.2	2.6	4.9	4.9	22.6	5.5	1.2
3	3023B	Saline	0-300	7.4	1.22	241.2	3.8	14.7	9.8	181.7	74.6	12.0
3	3023B	Saline	300-600	7.6	0.77	140.0	1.8	9.6	6.4	108.2	32.9	8.6
3	3023B	Saline	600-900	7.4	0.45	55.4	1.6	12.7	7.0	51.9	24.7	3.1

Table B1. Continued

3	3027B	Saline	0-300	9.6	10.00	1579.3	17.8	18.0	8.4	2475.0	220.0	77.1
3	3027B	Saline	300-600	9.9	3.01	698.0	5.2	3.6	5.5	917.0	65.9	53.9
3	3027B	Saline	600-900	9.8	2.00	462.8	68.2	13.4	95.6	532.3	25.5	9.7
3	3033B	Saline	0-300	7.3	0.17	15.5	6.1	5.7	5.2	17.6	5.3	1.1
3	3033B	Saline	300-600	7.9	0.26	44.7	9.1	6.0	9.3	25.9	9.1	2.7
3	3033B	Saline	600-900	7.9	0.21	36.2	3.9	3.0	4.8	21.6	6.0	3.0
3	3038B	Saline	0-300	7.2	2.00	450.5	6.7	29.3	34.9	355.0	186.2	13.3
3	3038B	Saline	300-600	7.3	1.28	207.2	2.6	21.9	26.3	186.0	87.6	7.1
3	3038B	Saline	600-900	7.3	0.53	61.2	1.3	11.5	10.1	77.8	33.6	3.2
4	4005	Non_saline	0-300	7.0	0.22	19.9	4.0	6.1	5.0	34.6	5.2	1.4
4	4005	Non_saline	300-600	7.2	0.21	24.3	3.1	6.2	4.6	25.9	5.7	1.8
4	4005	Non_saline	600-900	7.4	0.44	63.1	1.9	7.4	4.9	77.9	16.9	4.4
4	4009	Non_saline	0-300	7.5	0.10	4.9	2.7	5.1	4.5	8.7	0.8	0.4
4	4016	Non_saline	0-300	6.8	0.06	4.7	3.5	2.7	1.9	13.0	0.7	0.5
4	4016	Non_saline	300-600	6.7	0.03	3.7	4.2	2.1	2.7	13.0	0.4	0.4
4	4016	Non_saline	600-900	7.1	0.07	5.5	3.0	3.1	1.9	17.4	0.5	0.6
4	4022	Non_saline	0-300	7.1	0.18	21.9	13.0	10.0	6.6	26.1	6.0	1.3
4	4022	Non_saline	300-600	7.2	0.39	42.3	6.1	15.5	6.6	52.1	24.7	2.3
4	4022	Non_saline	600-900	7.2	0.30	43.9	3.2	9.4	4.3	39.1	20.8	3.0
4	4030	Non_saline	0-300	6.7	0.16	16.3	8.6	6.4	3.7	26.1	5.2	1.3
4	4030	Non_saline	300-600	6.8	0.13	19.3	5.6	5.5	4.2	17.4	6.4	1.5
4	4030	Non_saline	600-900	6.8	0.22	37.1	5.0	5.3	4.1	39.1	13.5	2.9
4	4044	Non_saline	0-300	6.6	0.08	6.0	5.9	3.8	2.7	13.0	1.9	0.6
4	4044	Non_saline	300-600	6.4	0.09	10.1	4.4	4.1	2.8	13.0	2.4	0.9
4	4044	Non_saline	600-900	6.2	0.08	8.3	4.9	4.5	3.1	17.4	2.9	0.7
4	4005B	Saline	0-300	7.1	0.16	13.0	10.4	5.5	5.6	21.6	2.8	0.9
4	4005B	Saline	300-600	7.4	0.21	21.3	6.5	7.4	5.9	30.4	6.1	1.4
4	4005B	Saline	600-900	7.6	0.39	47.8	2.5	9.4	5.5	60.8	19.9	3.1
4	4009B	Saline	0-300	6.8	0.17	7.4	7.3	7.7	2.6	30.4	5.6	0.6
4	4009B	Saline	300-600	7.3	0.12	6.3	4.1	7.5	3.0	21.7	1.7	0.5
4	4009B	Saline	600-900	6.9	0.13	7.5	5.0	7.8	2.5	17.4	4.2	0.6

Table B1. Continued

4	4016B	Saline	0-300	6.9	0.45	40.5	13.1	22.1	7.9	69.5	16.6	1.9
4	4016B	Saline	300-600	7.2	0.39	41.5	3.4	16.6	6.1	52.1	16.0	2.2
4	4016B	Saline	600-900	7.1	0.26	37.3	4.1	10.2	4.7	34.8	10.5	2.4
4	4022B	Saline	0-300	7.3	1.70	436.5	7.7	22.1	6.8	126.0	189.0	20.8
4	4022B	Saline	300-600	7.5	2.00	603.0	6.5	21.0	7.9	173.8	262.8	28.4
4	4022B	Saline	600-900	7.9	1.73	441.3	3.9	9.0	5.1	139.0	170.6	29.1
4	4030B	Saline	0-300	6.2	0.07	5.5	4.4	2.8	2.0	21.7	1.8	0.6
4	4030B	Saline	300-600	6.5	0.08	7.2	4.7	3.1	2.1	17.4	2.3	0.8
4	4030B	Saline	600-900	6.5	0.06	7.5	5.2	2.5	2.9	17.4	1.8	0.8
4	4044B	Saline	0-300	6.5	0.06	6.3	6.0	2.9	2.5	17.4	1.4	0.7
4	4044B	Saline	300-600	6.2	0.04	3.5	3.7	1.4	1.3	8.7	0.7	0.5
4	4044B	Saline	600-900	6.0	0.03	3.4	2.7	1.3	1.3	8.7	0.4	0.5
5	5037	Non_saline	0-300	6.8	0.17	12.3	5.8	9.5	4.9	17.4	3.7	0.8
5	5037	Non_saline	300-600	6.9	0.21	20.4	3.8	12.2	5.1	26.1	7.7	1.2
5	5037	Non_saline	600-900	7.1	0.40	60.9	2.4	13.1	6.0	52.1	25.8	3.5
5	5038	Non_saline	0-300	7.1	0.14	6.9	7.2	9.5	3.3	17.4	1.6	0.5
5	5038	Non_saline	300-600	7.3	0.12	5.0	5.3	8.1	2.4	13.0	1.5	0.4
5	5042	Non_saline	0-300	6.9	0.11	6.5	4.5	7.3	2.6	13.0	2.0	0.5
5	5042	Non_saline	300-600	6.8	0.06	5.4	3.2	3.7	1.9	8.7	0.9	0.6
5	5042	Non_saline	600-900	7.5	0.11	8.1	0.9	6.6	1.5	17.4	1.8	0.7
5	5058	Non_saline	0-300	5.3	0.15	11.3	6.1	9.3	5.4	17.4	2.8	0.7
5	5058	Non_saline	300-600	5.6	0.03	4.2	2.6	1.7	1.8	8.7	0.3	0.5
5	5058	Non_saline	600-900	5.8	0.03	3.5	2.0	1.3	1.5	8.7	0.8	0.5
5	5078	Non_saline	0-300	6.7	0.09	10.1	15.0	9.1	10.4	13.0	3.1	0.5
5	5078	Non_saline	300-600	7.2	0.39	46.5	1.7	14.0	6.2	65.2	20.6	2.6
5	5078	Non_saline	600-900	7.1	0.51	83.1	1.2	14.3	8.1	78.2	36.1	4.4
5	5133	Non_saline	0-300	7.3	0.15	6.1	13.7	9.9	8.6	13.0	2.3	0.3
5	5133	Non_saline	300-600	7.1	0.13	5.7	9.3	8.7	4.5	17.4	3.4	0.4

Table B1. Continued

5	5174	Non_saline	0-300	6.7	0.21	26.3	5.7	10.1	6.4	34.8	8.4	1.6
5	5174	Non_saline	300-600	6.9	0.50	81.1	2.3	13.0	6.2	65.2	33.9	4.6
5	5174	Non_saline	600-900	7.0	0.76	169.5	6.0	11.2	8.5	86.9	65.9	9.3
5	5197	Non_saline	0-300	6.3	0.16	18.8	4.3	5.5	5.4	26.1	7.4	1.4
5	5197	Non_saline	300-600	6.8	0.43	56.0	1.8	12.5	7.0	56.5	29.9	3.1
5	5197	Non_saline	600-900	6.8	0.29	37.3	3.6	9.8	6.6	39.1	20.4	2.3
5	5209	Non_saline	0-300	6.3	0.12	11.0	6.4	6.4	5.9	21.7	3.9	0.8
5	5209	Non_saline	300-600	6.3	0.12	13.6	8.3	7.3	7.6	21.7	4.6	0.8
5	5209	Non_saline	600-900	7.1	0.15	16.2	7.0	9.9	8.1	21.7	6.1	0.9
5	5215	Non_saline	0-300	6.9	0.15	15.0	3.8	7.2	6.0	13.0	6.2	1.0
5	5215	Non_saline	300-600	7.0	0.28	37.5	5.0	10.1	7.4	34.8	16.1	2.2
5	5215	Non_saline	600-900	7.3	0.27	46.2	8.6	9.2	9.7	30.4	15.1	2.5
5	5216	Non_saline	0-300	7.0	0.69	86.9	2.1	30.4	13.1	60.8	69.3	3.3
5	5216	Non_saline	300-600	7.1	0.89	185.7	0.9	15.6	7.8	99.9	90.2	9.6
5	5216	Non_saline	600-900	7.4	1.04	236.7	1.1	12.6	6.3	117.3	99.6	13.6
5	5265	Non_saline	0-300	5.9	0.17	6.9	8.4	8.3	4.9	13.0	3.6	0.5
5	5265	Non_saline	300-600	6.0	0.05	4.1	4.6	2.8	3.4	8.7	1.6	0.4
5	5265	Non_saline	600-900	5.8	0.05	5.8	3.1	2.0	2.4	8.7	1.0	0.7
5	5037B	Saline	0-300	7.0	2.01	537.9	3.4	90.3	56.3	525.6	193.2	10.9
5	5037B	Saline	300-600	7.5	0.86	234.9	4.2	7.8	8.1	121.6	67.4	14.0
5	5037B	Saline	600-900	8.2	0.63	169.8	7.3	7.7	13.1	78.2	36.9	8.6
5	5038B	Saline	0-300	6.9	0.17	5.6	9.0	11.7	3.7	17.4	1.7	0.4
5	5042B	Saline	0-300	6.8	0.09	7.2	4.8	6.6	3.0	17.4	2.4	0.6
5	5042B	Saline	300-600	7.2	0.06	4.2	1.9	4.2	2.4	13.0	1.5	0.4
5	5042B	Saline	600-900	7.4	0.08	5.5	1.7	5.6	3.0	13.0	0.8	0.6
5	5058B	Saline	0-300	6.0	0.08	7.4	3.6	4.3	2.7	13.0	1.6	0.7
5	5058B	Saline	300-600	6.4	0.07	7.3	3.0	3.3	2.4	17.4	2.4	0.8
5	5058B	Saline	600-900	7.3	0.11	11.9	4.5	6.1	4.6	13.0	3.2	0.9
5	5078B	Saline	0-300	7.2	0.27	31.6	4.6	11.9	5.4	30.4	13.8	1.9
5	5078B	Saline	300-600	7.4	0.84	198.6	1.6	11.9	5.8	99.9	77.6	11.8
5	5078B	Saline	600-900	7.3	1.75	435.7	1.6	16.9	13.1	199.8	157.2	19.3

Table B1. Continued

5	5133B	Saline	0-300	6.6	0.95	24.1	51.8	76.2	14.9	121.6	26.9	0.7
5	5174B	Saline	0-300	8.6	0.55	325.4	379.8	121.0	496.7	73.8	9.8	2.9
5	5174B	Saline	300-600	9.5	0.87	531.0	305.5	66.0	535.2	104.3	9.3	4.7
5	5174B	Saline	600-900	9.4	1.02	513.2	220.2	59.3	396.1	108.6	23.1	5.3
5	5197B	Saline	0-300	6.7	0.14	10.5	2.9	6.2	4.3	13.0	2.4	0.8
5	5197B	Saline	300-600	7.9	0.23	56.3	25.3	15.4	29.6	17.4	5.5	1.9
5	5197B	Saline	600-900	8.1	0.29	110.6	185.0	56.9	154.9	20.9	13.9	1.7
5	5209B	Saline	0-300	7.3	8.00	1406.1	3.2	91.1	138.7	1424.8	688.0	21.7
5	5209B	Saline	300-600	7.3	2.00	553.4	1.3	26.1	45.6	417.0	207.1	15.1
5	5209B	Saline	600-900	7.1	1.85	358.8	1.4	36.8	48.5	260.6	180.8	9.1
5	5215B	Saline	0-300	6.9	0.11	8.3	8.9	5.3	4.8	13.0	3.7	0.6
5	5216B	Saline	0-300	6.8	0.18	14.1	13.2	10.0	7.7	21.7	5.9	0.8
5	5216B	Saline	300-600	6.5	0.72	64.2	4.3	42.4	18.0	104.3	67.6	2.1
5	5216B	Saline	600-900	6.5	0.75	62.4	2.7	43.2	20.1	112.9	73.4	2.0
5	5265B	Saline	0-300	6.0	0.05	3.0	3.7	2.6	2.7	8.7	1.8	0.3
5	5265B	Saline	300-600	5.9	0.03	2.0	3.1	1.4	1.7	8.7	0.5	0.3
5	5265B	Saline	600-900	5.7	0.27	2.0	1.8	0.9	1.2	4.3	0.5	0.3
6	6003	Non_saline	0-300	5.9	0.10	4.6	3.1	5.3	2.8	13.0	1.9	0.4
6	6003	Non_saline	300-600	5.8	0.11	7.9	2.5	4.2	2.5	13.0	2.8	0.8
6	6003	Non_saline	600-900	6.0	0.12	8.5	3.2	5.8	3.1	13.0	4.5	0.7
6	6013	Non_saline	0-300	5.8	0.09	3.8	6.4	3.6	2.4	8.7	1.4	0.4
6	6013	Non_saline	300-600	6.0	0.06	4.1	5.1	2.7	2.5	8.7	1.5	0.4
6	6013	Non_saline	600-900	6.0	0.12	14.4	24.2	11.2	20.6	13.0	6.8	0.6
6	6031	Non_saline	0-300	6.0	0.14	11.8	31.3	16.0	25.7	17.4	3.9	0.4
6	6031	Non_saline	300-600	6.4	0.06	8.8	17.9	10.3	18.7	13.0	2.1	0.4
6	6031	Non_saline	600-900	6.8	0.12	11.7	12.1	11.4	12.0	17.4	4.0	0.6
6	6035	Non_saline	0-300	6.7	0.17	20.6	6.6	7.9	5.9	26.1	6.3	1.4
6	6035	Non_saline	300-600	7.1	0.14	16.8	5.0	8.2	5.2	21.7	4.3	1.1
6	6035	Non_saline	600-900	7.5	0.29	29.2	1.2	16.6	4.5	43.4	11.2	1.6

Table B1. Continued

6	6058	Non_saline	0-300	6.0	0.06	4.4	4.4	3.1	1.5	13.0	2.0	0.5
6	6058	Non_saline	300-600	5.9	0.06	4.5	4.0	2.7	1.4	13.0	1.3	0.6
6	6058	Non_saline	600-900	5.8	0.06	5.0	4.2	3.8	1.8	17.4	2.4	0.5
6	6067	Non_saline	0-300	6.9	0.14	10.5	4.7	9.6	4.9	21.7	3.3	0.7
6	6067	Non_saline	300-600	7.2	0.40	80.9	7.4	11.7	7.5	47.8	32.3	4.5
6	6067	Non_saline	600-900	6.8	0.97	200.9	3.3	26.9	12.4	134.7	85.4	8.0
6	6079	Non_saline	0-300	5.0	0.12	7.4	4.2	6.8	2.6	21.7	4.5	0.6
6	6079	Non_saline	300-600	5.7	0.06	4.6	1.7	2.2	0.8	13.0	2.4	0.7
6	6079	Non_saline	600-900	5.4	0.05	4.7	5.7	3.5	2.6	13.0	1.0	0.5
6	6083	Non_saline	0-300	7.4	0.50	99.3	3.5	13.4	5.6	60.8	27.2	5.7
6	6083	Non_saline	300-600	7.3	0.22	40.0	4.0	6.8	3.4	26.1	12.7	3.1
6	6083	Non_saline	600-900	7.3	0.12	23.7	8.4	4.5	3.9	21.7	5.5	2.0
6	6133	Non_saline	0-300	7.1	3.01	789.7	9.1	233.5	52.8	212.8	602.3	12.1
6	6133	Non_saline	300-600	8.1	1.77	477.0	3.2	14.4	5.2	126.0	208.1	27.4
6	6133	Non_saline	600-900	7.5	1.30	352.4	11.2	9.6	6.6	121.6	137.0	21.5
6	6139	Non_saline	0-300	6.5	0.06	6.2	5.0	1.9	2.2	13.0	1.4	0.7
6	6139	Non_saline	300-600	6.4	0.06	5.0	4.9	2.6	2.3	8.7	1.3	0.5
6	6139	Non_saline	600-900	6.9	0.11	8.3	4.6	4.7	3.2	13.0	3.2	0.7
6	6146	Non_saline	0-300	6.2	0.05	2.3	2.8	1.5	1.2	8.7	0.4	0.3
6	6146	Non_saline	300-600	6.6	0.07	7.0	3.5	2.8	2.5	8.7	1.0	0.7
6	6146	Non_saline	600-900	6.1	0.14	17.2	10.0	6.2	6.6	21.7	6.6	1.1
6	6149	Non_saline	0-300	6.8	0.18	9.7	6.5	8.7	4.8	8.7	3.3	0.7
6	6149	Non_saline	300-600	7.0	0.11	9.0	3.8	4.5	2.5	13.0	1.3	0.8
6	6149	Non_saline	600-900	6.9	0.09	6.6	2.1	2.4	1.3	8.7	0.7	0.9
6	6180	Non_saline	0-300	6.1	0.11	4.5	10.3	5.2	4.2	13.0	2.4	0.4
6	6180	Non_saline	300-600	6.3	0.05	3.9	28.1	7.1	13.0	13.0	0.3	0.2
6	6180	Non_saline	600-900	5.8	0.03	1.4	7.5	1.8	3.1	8.7	0.4	0.2
6	6204	Non_saline	0-300	6.3	0.05	2.4	4.3	2.8	2.6	13.0	0.1	0.3
6	6204	Non_saline	300-600	5.1	0.40	36.3	2.4	13.7	5.4	112.9	15.3	2.1
6	6204	Non_saline	600-900	5.3	0.09	3.6	2.2	3.4	1.7	12.9	4.6	0.4
6	6003B	Saline	0-300	6.5	0.15	6.5	3.2	7.9	3.3	13.0	3.4	0.5
6	6003B	Saline	300-600	6.9	0.14	5.6	2.4	9.1	3.3	8.7	2.9	0.4

Table B1. Continued

6	6003B	Saline	600-900	6.8	0.12	5.0	2.1	7.1	3.5	8.7	2.7	0.4
6	6013B	Saline	0-300	5.5	0.12	5.9	4.8	5.5	3.0	13.0	2.3	0.5
6	6013B	Saline	300-600	5.8	0.05	4.6	17.3	5.7	12.4	8.7	1.2	0.2
6	6013B	Saline	600-900	5.7	0.06	5.9	34.4	9.7	23.3	13.0	1.9	0.2
6	6031B	Saline	0-300	5.7	0.06	2.7	3.3	2.5	1.8	8.7	1.0	0.3
6	6031B	Saline	300-600	5.2	0.04	2.0	2.5	1.3	1.2	8.7	0.8	0.3
6	6031B	Saline	600-900	6.2	0.03	2.4	2.5	0.7	0.7	17.4	5.3	0.5
6	6035B	Saline	0-300	6.2	0.10	10.3	30.6	12.5	13.9	17.4	2.4	0.5
6	6035B	Saline	300-600	6.1	0.07	9.0	19.3	9.4	10.0	17.4	1.4	0.5
6	6035B	Saline	600-900	6.1	0.06	8.3	18.2	8.9	10.2	13.0	2.3	0.5
6	6058B	Saline	0-300	6.3	0.04	3.6	4.8	2.1	1.6	8.7	1.3	0.5
6	6058B	Saline	300-600	6.0	0.05	3.7	4.6	2.5	1.6	17.4	2.1	0.5
6	6058B	Saline	600-900	6.0	0.07	6.1	6.7	4.4	2.9	21.7	2.3	0.6
6	6067B	Saline	0-300	5.8	0.12	8.5	5.2	7.1	3.7	17.4	3.6	0.6
6	6067B	Saline	300-600	6.6	0.07	8.8	7.0	6.1	4.5	17.4	2.7	0.7
6	6067B	Saline	600-900	6.0	0.15	15.3	5.3	9.2	4.1	34.8	9.1	1.1
6	6079B	Saline	0-300	6.7	2.00	462.3	15.1	40.1	30.9	551.7	26.1	13.3
6	6079B	Saline	300-600	7.2	0.36	66.2	6.5	8.8	5.6	78.2	12.7	4.3
6	6079B	Saline	600-900	7.2	0.39	76.0	14.3	12.9	8.4	86.9	18.7	4.1
6	6083B	Saline	0-300	6.2	0.09	6.7	4.6	4.8	1.7	13.0	4.2	0.7
6	6083B	Saline	300-600	5.9	0.04	3.5	2.1	1.6	0.8	8.7	1.4	0.6
6	6083B	Saline	600-900	6.4	0.04	3.5	2.7	2.0	1.1	8.7	2.3	0.5
6	6133B	Saline	0-300	8.4	6.01	1463.8	3.6	52.3	22.8	916.6	704.6	42.5
6	6133B	Saline	300-600	8.3	6.00	1158.2	2.7	15.5	13.7	890.5	565.7	51.7
6	6133B	Saline	600-900	8.5	3.00	733.7	1.2	5.7	4.2	438.7	264.6	56.8
6	6139B	Saline	0-300	5.9	0.07	3.9	3.9	2.4	1.7	8.7	1.2	0.5
6	6139B	Saline	300-600	6.0	0.04	3.3	4.0	1.9	2.3	8.7	0.1	0.4

Table B1. Continued

6	6139B	Saline	600-900	6.1	0.04	3.4	2.9	1.6	1.9	8.7	0.5	0.4
6	6146B	Saline	0-300	6.3	0.06	3.1	5.2	3.0	2.8	13.0	1.1	0.3
6	6146B	Saline	300-600	6.4	0.04	3.0	3.0	2.2	2.7	8.7	0.4	0.3
6	6146B	Saline	600-900	5.9	0.09	6.6	3.1	2.4	1.8	30.4	0.4	0.8
6	6149B	Saline	0-300	5.8	0.05	1.9	4.1	2.0	2.0	13.0	0.8	0.2
6	6149B	Saline	300-600	5.8	0.03	0.6	4.9	1.4	2.1	8.7	0.1	0.1
6	6149B	Saline	600-900	5.2	0.04	1.9	3.7	1.5	1.7	13.0	1.2	0.3
6	6180B	Saline	0-300	6.7	0.25	11.9	28.9	12.3	6.8	21.7	4.5	0.7
6	6180B	Saline	300-600	7.1	0.12	8.7	7.8	5.9	3.9	17.4	3.1	0.7
6	6180B	Saline	600-900	6.9	0.09	5.7	4.1	4.0	2.4	17.4	1.4	0.6
6	6204B	Saline	0-300	7.1	0.15	9.9	6.0	8.0	4.2	21.6	5.3	0.7
6	6204B	Saline	300-600	6.7	0.08	7.4	5.4	3.9	3.7	8.7	2.9	0.6
6	6204B	Saline	600-900	9.8	0.10	6.7	2.1	3.0	1.4	13.0	4.3	0.8
7	7026	Non_saline	0-300	5.9	0.19	9.7	14.0	11.3	5.1	8.9	4.1	0.6
7	7026	Non_saline	300-600	6.7	0.13	7.0	2.9	8.7	3.3	15.2	6.9	0.5
7	7026	Non_saline	600-900	7.2	0.14	6.0	0.9	9.9	2.0	10.7	6.8	0.5
7	7027	Non_saline	0-300	6.6	0.08	6.0	7.6	5.1	3.6	4.5	4.1	0.5
7	7027	Non_saline	300-600	6.5	0.12	9.3	4.9	6.6	3.3	13.4	11.0	0.7
7	7027	Non_saline	600-900	6.4	0.06	4.1	2.0	1.9	0.9	4.6	4.6	0.6
7	7074	Non_saline	0-300	6.5	0.10	5.0	2.6	5.3	2.2	13.7	1.8	0.5
7	7074	Non_saline	300-600	6.5	0.08	6.0	2.4	4.2	1.8	4.6	2.6	0.6
7	7074	Non_saline	600-900	7.0	0.06	5.4	2.7	2.9	1.7	14.2	1.5	0.6
7	7089	Non_saline	0-300	6.0	0.22	6.2	12.7	16.1	5.3	8.8	3.6	0.3
7	7089	Non_saline	300-600	6.2	0.10	6.0	4.7	5.7	2.9	8.6	2.8	0.5
7	7089	Non_saline	600-900	6.4	0.10	8.4	4.3	5.4	3.1	13.3	3.8	0.7
7	7112	Non_saline	0-300	7.2	0.16	7.2	3.4	10.6	3.9	8.7	4.1	0.5
7	7112	Non_saline	300-600	7.2	0.09	5.4	3.3	4.9	2.4	8.6	2.4	0.5
7	7113	Non_saline	0-300	7.5	0.14	4.3	2.8	10.3	2.3	8.7	2.8	0.3
7	7026 b	Saline	0-300	8.8	0.63	209.1	32.8	36.3	38.8	18.7	23.2	5.7
7	7026 b	Saline	300-600	8.8	0.41	113.2	6.4	27.5	19.2	17.8	6.2	4.1

Table B1. Continued

7	7026 b	Saline	600-900	8.8	0.52	178.6	17.7	92.2	61.0	21.4	10.2	3.5
7	7027 B	Saline	0-300	5.6	0.03	2.0	6.1	1.2	1.3	4.7	0.6	0.3
7	7027 B	Saline	300-600	5.7	0.04	2.7	4.0	1.5	1.0	4.9	1.1	0.4
7	7027 B	Saline	600-900	6.0	0.04	3.2	3.1	1.7	1.2	8.9	1.6	0.5
7	7074 B	Saline	0-300	6.5	0.04	2.7	2.2	2.1	1.3	4.6	1.2	0.4
7	7074 B	Saline	300-600	6.4	0.04	3.1	3.3	2.7	2.0	4.7	0.8	0.3
7	7074 B	Saline	600-900	7.2	0.08	5.8	3.5	5.2	2.7	4.7	1.8	0.5
7	7089 B	Saline	0-300	6.3	0.12	6.2	8.3	7.2	4.0	7.9	3.9	0.5
7	7089 B	Saline	300-600	5.5	0.10	5.1	4.6	4.6	1.9	17.8	2.6	0.5
7	7089 B	Saline	600-900	6.2	0.08	5.1	5.0	4.5	2.4	8.9	3.8	0.5
7	7112 B	Saline	0-300	6.9	0.13	7.2	4.7	8.9	3.7	8.5	3.8	0.5
7	7112 B	Saline	300-600	7.0	0.08	7.2	2.9	4.8	2.3	8.4	1.6	0.7
7	7113 B	Saline	0-300	7.2	0.15	4.0	6.3	14.4	3.7	6.5	2.3	0.2
8	8001	Non_saline	0-300	7.2	0.32	50.5	6.1	8.6	5.2	18.2	8.6	3.4
8	8001	Non_saline	300-600	7.9	0.30	62.2	5.4	4.8	4.0	22.3	13.9	5.1
8	8001	Non_saline	600-900	7.6	0.22	43.3	3.2	2.8	2.7	18.3	8.8	4.4
8	8012	Non_saline	0-300	4.8	0.21	5.2	4.7	13.1	5.2	9.3	1.8	0.3
8	8012	Non_saline	300-600	5.0	0.05	3.0	2.6	2.4	1.6	18.4	1.2	0.4
8	8012	Non_saline	600-900	4.8	0.11	5.1	1.9	5.9	2.3	13.6	2.1	0.5
8	8025	Non_saline	0-300	6.5	0.09	7.1	5.5	5.4	4.0	13.7	3.4	0.6
8	8025	Non_saline	300-600	6.6	0.11	10.2	3.8	4.9	3.2	13.1	3.9	0.9
8	8025	Non_saline	600-900	6.6	0.07	5.8	4.0	4.3	3.3	13.4	2.5	0.5
8	8001 B	Saline	0-300	6.8	0.10	3.0	6.0	5.1	2.0	8.9	2.5	0.3
8	8001 B	Saline	300-600	7.1	0.12	4.9	3.6	7.0	2.8	8.6	2.2	0.4
8	8001 B	Saline	600-900	7.3	0.13	6.7	2.6	7.5	3.0	7.9	3.6	0.5
8	8012 B	Saline	0-300	5.7	0.25	6.2	7.4	16.9	6.0	13.9	3.7	0.3
8	8012 B	Saline	300-600	6.4	0.17	9.1	2.0	8.7	3.6	9.5	4.1	0.7
8	8012 B	Saline	600-900	6.8	0.14	7.8	2.0	7.4	3.0	9.2	3.4	0.6
8	8025 B	Saline	0-300	7.0	0.20	9.7	1.7	13.6	3.8	9.2	4.1	0.6
8	8025 B	Saline	300-600	6.8	0.06	4.9	4.7	4.7	3.0	9.1	1.9	0.4

Table B1. Continued

8	8025 B	Saline	600-900	7.3	0.09	5.7	5.3	7.8	4.6	9.7	1.4	0.4
9	9011	Non_saline	0-300	7.3	0.29	12.3	1.8	20.5	5.9	8.9	4.6	0.6
9	9011	Non_saline	300-600	7.6	0.21	13.1	1.6	11.4	5.9	8.7	3.9	0.8
9	9011	Non_saline	600-900	7.7	0.18	28.2	5.0	3.0	5.7	8.7	7.5	2.2
9	9013	Non_saline	0-300	6.7	0.15	9.4	7.7	6.9	3.9	13.4	10.4	0.7
9	9013	Non_saline	300-600	6.3	0.08	5.0	4.0	3.6	1.9	5.2	6.2	0.5
9	9013	Non_saline	600-900	6.1	0.06	3.9	4.1	2.6	2.4	9.3	2.2	0.4
9	9038	Non_saline	0-300	6.6	0.06	4.5	5.0	3.7	2.9	8.9	1.5	0.4
9	9038	Non_saline	300-600	7.2	0.08	5.3	1.1	3.7	1.9	14.1	2.0	0.6
9	9038	Non_saline	600-900	7.8	0.11	5.3	0.9	8.4	2.1	8.9	2.2	0.4
9	9075	Non_saline	0-300	6.7	0.05	3.2	4.5	2.4	1.9	7.6	1.7	0.4
9	9075	Non_saline	300-600	6.7	0.04	2.5	2.9	1.2	1.0	8.7	1.2	0.4
9	9075	Non_saline	600-900	6.6	0.05	3.1	3.6	2.0	1.4	8.4	2.1	0.4
9	9118	Non_saline	0-300	6.6	0.15	6.6	7.3	6.7	4.1	13.4	3.5	0.5
9	9118	Non_saline	300-600	6.6	0.42	12.0	7.5	24.1	9.9	75.8	22.1	0.5
9	9118	Non_saline	600-900	5.3	0.20	4.7	4.4	9.1	3.5	40.1	10.3	0.3
9	9128	Non_saline	0-300	7.1	0.18	9.5	8.6	11.4	4.1	27.3	7.5	0.6
9	9128	Non_saline	300-600	7.3	0.12	8.4	6.5	8.1	4.9	9.3	3.9	0.6
9	9128	Non_saline	600-900	7.3	0.17	12.3	4.1	9.0	4.3	22.3	5.2	0.8
9	9132	Non_saline	0-300	6.7	0.06	3.7	4.7	3.1	2.6	9.3	1.8	0.4
9	9132	Non_saline	300-600	6.7	0.04	3.1	1.9	1.8	1.4	4.6	1.8	0.4
9	9132	Non_saline	600-900	6.5	0.04	3.1	2.0	1.9	1.6	9.6	2.1	0.4
9	9140	Non_saline	0-300	6.5	0.08	4.5	5.7	4.5	4.2	9.3	1.7	0.4
9	9140	Non_saline	300-600	6.3	0.06	4.1	3.3	3.4	3.4	9.1	1.8	0.4
9	9140	Non_saline	600-900	6.4	0.04	3.2	2.3	2.1	2.4	9.4	1.3	0.4
9	9147	Non_saline	0-300	6.5	0.27	5.8	11.7	14.8	5.1	18.3	4.0	0.3
9	9147	Non_saline	300-600	6.5	0.06	3.2	2.8	2.9	1.9	9.3	1.4	0.4
9	9147	Non_saline	600-900	6.4	0.05	3.1	2.2	2.2	1.6	9.1	1.2	0.4
9	9011 B	Saline	0-300	7.6	2.42	588.7	1.9	22.8	9.6	142.7	254.4	26.1
9	9011 B	Saline	300-600	8.3	2.04	532.4	1.8	6.6	3.8	191.7	177.2	41.1

Table B1. Continued

9	9011 B	Saline	600-900	7.5	0.91	219.8	1.9	3.2	3.0	102.5	82.2	21.3
9	9013 B	Saline	0-300	6.8	0.08	7.8	4.7	4.2	3.1	9.1	2.9	0.7
9	9013 B	Saline	300-600	6.7	0.06	5.3	3.1	2.3	1.9	14.4	2.3	0.6
9	9013 B	Saline	600-900	6.6	0.06	5.1	2.6	2.2	2.0	18.3	2.1	0.6
9	9038 B	Saline	0-300	7.2	0.12	8.0	4.3	7.0	3.7	8.3	4.1	0.6
9	9038 B	Saline	300-600	7.3	0.07	5.3	2.8	4.0	2.3	7.9	2.7	0.5
9	9075 B	Saline	0-300	6.7	0.07	3.7	4.5	3.7	3.1	17.1	1.9	0.3
9	9075 B	Saline	300-600	6.8	0.05	2.5	2.9	1.7	1.7	9.3	1.2	0.3
9	9075 B	Saline	600-900	6.6	0.06	3.1	2.8	2.2	1.4	17.6	2.0	0.4
9	9118 B	Saline	0-300	6.2	0.18	10.9	4.0	8.6	3.6	17.8	4.5	0.8
9	9118 B	Saline	300-600	6.9	0.14	10.7	1.6	4.9	2.1	26.8	3.9	1.0
9	9118 B	Saline	600-900	7.5	0.10	3.6	1.3	6.1	1.7	8.9	1.6	0.3
9	9128 B	Saline	0-300	7.3	0.04	3.9	3.1	2.5	2.8	4.6	1.4	0.4
9	9128 B	Saline	300-600	6.9	0.05	3.7	1.5	2.0	1.5	8.4	1.9	0.5
9	9128 B	Saline	600-900	6.8	0.05	4.4	2.2	2.6	2.4	13.4	2.1	0.5
9	9132 B	Saline	0-300	6.5	0.14	6.5	1.9	6.3	2.4	18.1	2.9	0.6
9	9132 B	Saline	300-600	7.0	0.17	13.8	2.4	6.0	3.3	13.6	4.7	1.1
9	9132 B	Saline	600-900	6.7	0.14	10.6	1.8	5.0	2.5	18.3	4.9	1.0
9	9140 B	Saline	0-300	6.8	0.07	3.3	3.6	3.8	2.4	9.1	1.5	0.3
9	9140 B	Saline	300-600	6.6	0.06	3.5	1.9	2.8	1.3	9.2	1.3	0.4
9	9140 B	Saline	600-900	6.4	0.05	3.2	1.4	2.2	1.4	9.4	1.0	0.4
9	9147 B	Saline	0-300	7.3	0.13	8.6	1.6	7.0	2.4	9.4	2.6	0.7
9	9147 B	Saline	300-600	7.2	0.13	8.6	3.2	7.9	4.2	9.2	3.4	0.6
9	9147 B	Saline	600-900	6.5	0.06	4.3	3.3	2.3	2.6	4.4	1.4	0.5
10	10031	Non_saline	0-300	7.1	0.30	8.6	6.6	17.3	4.8	8.9	4.9	0.5
10	10031	Non_saline	300-600	7.2	0.21	8.6	3.5	14.3	3.6	14.3	5.1	0.5
10	10058	Non_saline	0-300	6.6	0.09	11.2	3.8	4.8	4.9	8.6	2.6	0.9
10	10058	Non_saline	300-600	6.5	0.13	7.5	1.7	5.2	2.2	18.3	7.9	0.7
10	10058	Non_saline	600-900	6.2	0.10	5.7	1.6	4.1	1.8	13.6	5.3	0.6
10	10130	Non_saline	0-300	6.6	0.13	5.1	6.7	7.0	3.5	13.6	6.2	0.4

Table B1. Continued

10	10130	Non_saline	300-600	6.7	0.10	5.7	1.8	4.2	2.2	13.2	3.0	0.6
10	10130	Non_saline	600-900	6.5	0.09	5.4	2.0	3.8	2.4	13.1	2.9	0.5
10	10154	Non_saline	0-300	7.2	0.15	8.7	1.8	8.2	3.6	9.3	2.2	0.6
10	10154	Non_saline	300-600	7.3	0.14	7.5	0.8	11.6	2.5	4.6	2.0	0.5
10	10154	Non_saline	600-900	7.3	0.15	6.6	0.3	9.6	1.7	9.8	2.7	0.5
10	10160	Non_saline	0-300	6.5	0.05	3.1	2.4	3.1	2.5	9.2	1.2	0.3
10	10160	Non_saline	300-600	6.7	0.10	4.8	1.6	6.8	2.7	9.1	0.9	0.4
10	10166	Non_saline	0-300	6.8	0.08	4.6	4.3	4.5	3.5	8.8	0.8	0.4
10	10166	Non_saline	300-600	6.6	0.04	3.5	2.0	2.1	1.8	8.7	1.2	0.4
10	10166	Non_saline	600-900	6.4	0.05	3.3	2.2	2.1	2.1	8.6	1.5	0.4
10	10181	Non_saline	0-300	6.6	0.11	6.0	6.5	6.8	4.7	8.7	3.1	0.4
10	10181	Non_saline	300-600	6.5	0.08	6.1	3.6	3.9	3.2	30.6	1.9	0.6
10	10181	Non_saline	600-900	6.3	0.07	6.4	3.2	2.4	2.4	9.6	3.0	0.7
10	10194	Non_saline	0-300	7.3	0.17	5.3	4.9	11.0	4.9	4.5	2.6	0.3
10	10298	Non_saline	0-300	6.8	0.34	9.1	1.5	21.6	6.3	21.9	5.9	0.4
10	10300	Non_saline	0-300	6.7	0.12	7.4	10.5	8.9	6.0	26.2	5.2	0.5
10	10307	Non_saline	0-300	5.8	0.17	9.2	3.0	8.4	4.2	13.5	3.4	0.6
10	10307	Non_saline	300-600	6.2	0.06	3.7	3.6	3.5	2.9	8.9	2.5	0.4
10	10031 B	Saline	0-300	6.6	0.10	6.8	1.9	5.6	3.2	8.9	5.5	0.6
10	10031 B	Saline	300-600	6.9	0.18	9.9	7.9	9.3	4.2	8.7	8.7	0.7
10	10031 B	Saline	600-900	6.7	0.13	18.3	3.1	4.7	4.2	23.3	5.2	1.5
10	10058 B	Saline	0-300	6.5	0.07	3.9	2.0	3.2	2.0	8.8	1.6	0.4
10	10058 B	Saline	300-600	6.2	0.07	4.6	1.6	2.9	1.9	13.4	1.9	0.5
10	10058 B	Saline	600-900	6.0	0.04	3.2	1.2	1.3	1.1	4.6	1.0	0.5
10	10130 B	Saline	0-300	6.4	0.08	4.9	2.5	3.8	2.5	7.9	1.8	0.5
10	10130 B	Saline	300-600	6.2	0.03	3.0	1.0	1.1	0.9	7.8	1.3	0.5
10	10130 B	Saline	600-900	6.1	0.05	3.5	1.0	1.2	0.8	9.1	1.0	0.6
10	10154 B	Saline	0-300	7.1	0.16	4.9	5.7	11.2	3.3	4.3	2.5	0.3
10	10154 B	Saline	300-600	7.3	0.16	5.1	2.3	10.9	3.0	9.7	6.1	0.4
10	10154 B	Saline	600-900	7.2	0.14	4.6	2.6	12.4	2.8	9.3	2.6	0.3

Table B1. Continued

10	10160 B	Saline	0-300	7.3	0.21	7.6	1.5	13.7	3.7	8.9	1.8	0.5
10	10166B	Saline	0-300	6.3	0.05	3.9	2.4	2.4	2.1	4.5	1.5	0.4
10	10166B	Saline	300-600	6.4	0.05	4.1	2.9	3.0	3.7	8.9	1.7	0.4
10	10181 B	Saline	0-300	6.7	0.11	6.4	4.6	7.2	4.8	9.4	2.3	0.5
10	10181 B	Saline	300-600	7.0	0.09	6.4	2.5	4.9	2.7	9.5	2.3	0.6
10	10181 B	Saline	600-900	7.1	0.12	9.2	3.1	4.8	4.4	18.2	3.6	0.7
10	10194 B	Saline	0-300	7.1	0.26	7.8	15.6	15.7	5.1	17.9	14.7	0.4
10	10298 B	Saline	0-300	6.5	0.28	6.4	7.9	19.3	5.6	13.1	5.4	0.3
10	10300 B	Saline	0-300	6.7	0.21	9.6	9.1	10.6	5.3	9.5	6.0	0.6
10	10307 B	Saline	0-300	7.5	0.33	29.4	1.7	12.4	5.8	13.6	5.8	1.7
10	10307 B	Saline	300-600	7.6	0.45	94.0	9.0	9.1	8.8	35.4	16.4	5.3
11	11012	Non_saline	0-300	6.9	0.10	6.7	10.4	9.2	7.3	9.2	4.0	0.4
11	11012	Non_saline	300-600	6.0	0.36	17.0	1.2	34.1	9.7	48.1	10.1	0.7
11	11012	Non_saline	600-900	6.5	0.27	14.5	1.1	17.9	4.8	39.3	7.1	0.8
11	11015	Non_saline	0-300	6.9	0.11	4.7	13.8	10.3	8.3	13.6	2.5	0.3
11	11015	Non_saline	300-600	6.8	0.10	5.6	7.5	7.3	5.0	13.2	2.9	0.4
11	11015	Non_saline	600-900	6.6	0.06	1.9	7.2	4.6	2.4	13.1	2.3	0.2
11	11017	Non_saline	0-300	6.5	0.10	4.9	6.1	6.7	4.8	9.8	3.5	0.4
11	11017	Non_saline	300-600	6.5	0.06	2.5	7.5	5.2	5.4	13.6	2.1	0.2
11	11017	Non_saline	600-900	6.3	0.05	1.5	3.9	3.5	2.6	13.2	1.8	0.2
11	11032	Non_saline	0-300	6.3	0.14	2.4	6.9	8.4	4.3	17.6	3.8	0.2
11	11032	Non_saline	300-600	6.7	0.09	2.4	4.3	5.5	2.9	13.1	2.6	0.2
11	11032	Non_saline	600-900	6.8	0.07	1.6	3.9	3.0	2.4	17.8	2.2	0.2
11	11049	Non_saline	0-300	6.3	0.20	5.6	4.7	12.8	4.6	17.6	3.2	0.3
11	11049	Non_saline	300-600	5.9	0.17	6.7	2.7	10.7	2.9	17.4	4.8	0.5
11	11049	Non_saline	600-900	6.2	0.17	9.7	2.7	9.7	3.0	13.5	10.5	0.7
11	11012 B	Saline	0-300	6.3	0.03	0.5	3.1	1.6	1.3	4.5	0.9	0.1
11	11012 B	Saline	300-600	6.6	0.05	1.1	5.8	4.0	4.1	9.8	1.6	0.1
11	11012 B	Saline	600-900	6.4	0.11	3.0	2.8	6.3	2.4	13.5	2.0	0.3
11	11015 B	Saline	0-300	6.7	0.08	2.4	9.5	6.3	4.6	9.7	2.2	0.2

Table B1. Continued

11	11015 B	Saline	300-600	6.9	0.11	6.4	4.4	6.1	3.2	13.5	5.4	0.5
11	11015 B	Saline	600-900	6.8	0.08	3.7	3.2	3.6	2.3	13.1	3.3	0.4
11	11017 B	Saline	0-300	6.1	0.12	3.2	3.4	6.2	2.4	17.5	2.2	0.3
11	11017 B	Saline	300-600	6.5	0.07	0.6	2.4	2.3	1.5	13.5	1.2	0.1
11	11017 B	Saline	600-900	6.6	0.04	3.4	3.4	1.8	1.7	13.4	1.1	0.4
11	11032 B	Saline	0-300	6.4	0.14	3.1	9.0	10.2	4.8	13.4	6.0	0.2
11	11032 B	Saline	300-600	6.5	0.12	2.6	4.5	8.8	3.2	17.1	4.5	0.2
11	11032 B	Saline	600-900	6.6	0.08	3.2	6.1	6.0	4.3	8.9	5.0	0.2
11	11049 B	Saline	0-300	6.4	0.14	3.0	4.2	8.9	2.9	8.7	2.3	0.2
11	11049 B	Saline	300-600	6.5	0.17	6.9	5.4	10.9	4.7	17.6	4.6	0.4
11	11049 B	Saline	600-900	6.9	0.13	3.9	2.1	8.4	2.2	13.6	4.1	0.3
12	12019	Non_saline	0-300	7.0	0.08	2.6	2.4	5.0	2.0	13.2	2.5	0.3
12	12019	Non_saline	300-600	6.9	0.12	6.0	1.3	6.6	2.1	17.6	2.6	0.5
12	12027	Non_saline	0-300	7.0	0.11	2.9	5.4	6.3	2.0	17.6	1.6	0.3
12	12027	Non_saline	300-600	6.9	0.06	6.9	3.3	2.2	2.1	17.4	1.6	0.8
12	12027	Non_saline	600-900	7.2	0.08	7.3	11.0	3.5	1.5	17.1	1.3	0.8
12	12057	Non_saline	0-300	7.7	0.11	6.1	5.0	13.0	3.0	8.7	0.9	0.4
12	12057	Non_saline	300-600	7.8	0.10	4.8	2.9	11.5	2.0	17.5	1.1	0.3
12	12057	Non_saline	600-900	7.7	0.11	6.0	5.4	10.3	1.6	13.3	1.8	0.5
12	12164	Non_saline	0-300	6.8	0.04	3.0	4.1	3.8	1.5	4.6	0.9	0.3
12	12164	Non_saline	300-600	6.4	0.03	3.0	2.9	2.0	1.4	13.4	0.7	0.4
12	12164	Non_saline	600-900	6.8	0.03	3.7	4.0	2.2	2.7	13.2	0.8	0.4
12	12178	Non_saline	0-300	6.7	0.11	13.6	6.8	7.8	3.6	13.3	2.9	1.0
12	12178	Non_saline	300-600	6.8	0.12	17.1	8.2	8.6	5.1	21.9	4.2	1.1
12	12178	Non_saline	600-900	7.0	0.08	13.0	5.3	4.4	2.8	17.6	4.7	1.2
12	12179	Non_saline	0-300	7.0	0.11	11.6	9.7	11.3	4.9	8.7	2.4	0.7
12	12179	Non_saline	300-600	6.8	0.13	15.5	6.5	12.9	5.0	17.6	4.5	0.9
12	12179	Non_saline	600-900	6.4	0.05	6.5	3.5	3.9	2.8	13.4	1.9	0.6
12	12204	Non_saline	300-600	7.5	0.27	72.7	11.8	18.0	12.3	17.8	6.7	3.2
12	12204	Non_saline	600-900	7.8	0.44	111.5	3.6	13.1	4.8	48.1	29.1	6.7

Table B1. Continued

12	12205	Non_saline	0-300	6.6	0.10	6.5	16.1	9.6	3.5	4.4	2.5	0.5
12	12205	Non_saline	300-600	6.8	0.09	8.2	16.5	6.9	2.5	4.3	2.2	0.7
12	12205	Non_saline	600-900	6.7	0.06	8.4	6.1	4.8	1.9	13.6	2.9	0.8
12	12209	Non_saline	0-300	7.0	0.26	13.0	10.3	24.3	6.4	17.4	4.1	0.6
12	12216	Non_saline	0-300	6.1	0.15	7.5	6.5	13.3	3.8	21.9	5.3	0.5
12	12216	Non_saline	300-600	7.1	0.09	7.3	4.8	8.8	3.6	17.5	0.9	0.5
12	12216	Non_saline	600-900	6.9	0.04	6.7	3.5	4.6	3.1	13.6	0.6	0.6
12	12229	Non_saline	0-300	6.9	0.11	11.3	8.9	11.6	5.0	17.6	2.1	0.7
12	12229	Non_saline	300-600	6.9	0.10	13.7	11.6	13.5	7.9	17.4	4.0	0.7
12	12229	Non_saline	600-900	7.0	0.24	33.2	3.5	19.1	5.3	35.3	19.8	1.7
12	12281	Non_saline	0-300	6.4	0.09	5.1	13.0	5.8	4.2	13.3	2.2	0.4
12	12281	Non_saline	300-600	6.4	0.07	3.4	11.7	3.1	2.6	22.3	0.9	0.3
12	12281	Non_saline	600-900	6.5	0.04	2.6	4.3	1.7	1.6	13.6	1.2	0.3
12	12297	Non_saline	0-300	6.3	0.16	7.9	5.9	9.3	3.9	8.7	4.9	0.5
12	12297	Non_saline	300-600	6.5	0.10	8.0	4.7	11.0	3.6	26.3	3.9	0.5
12	12297	Non_saline	600-900	6.6	0.17	14.8	1.0	5.9	3.0	39.3	9.6	1.2
12	12305	Non_saline	0-300	6.8	0.10	6.2	2.5	6.3	3.0	13.5	4.6	0.5
12	12305	Non_saline	300-600	6.9	0.19	11.0	2.4	12.5	3.3	22.3	10.1	0.7
12	12305	Non_saline	600-900	7.0	0.34	16.7	0.9	27.0	6.8	39.3	24.7	0.7
12	12316	Non_saline	0-300	6.5	0.08	6.0	4.0	5.2	3.1	17.8	2.1	0.5
12	12316	Non_saline	300-600	6.2	0.04	3.3	3.4	2.1	1.6	13.5	1.2	0.4
12	12316	Non_saline	600-900	6.9	0.04	2.9	0.8	1.5	1.3	13.2	0.9	0.4
12	12318	Non_saline	0-300	5.9	0.15	7.8	4.2	9.2	3.8	21.9	3.8	0.5
12	12318	Non_saline	300-600	6.2	0.03	2.5	1.8	1.4	1.5	13.1	0.7	0.3
12	12318	Non_saline	600-900	6.4	0.02	1.9	0.5	0.9	1.1	8.7	0.8	0.3
12	12019 B	Saline	0-300	7.3	0.23	9.9	1.2	17.0	3.9	26.3	9.3	0.6
12	12019 B	Saline	300-600	7.5	0.16	3.3	0.0	10.8	2.3	26.4	4.1	0.2
12	12019 B	Saline	600-900	7.6	0.10	0.3	0.3	5.3	1.1	8.7	2.6	0.0
12	12027 B	Saline	0-300	6.7	0.08	4.4	7.2	4.6	2.1	13.1	1.2	0.4
12	12027 B	Saline	300-600	6.7	0.05	4.0	7.0	2.8	2.9	8.7	1.5	0.4

Table B1. Continued

12	12027 B	Saline	600-900	7.0	0.04	3.0	5.1	2.4	1.4	8.8	1.1	0.4
12	12040 B	Saline	0-300	7.6	1.48	380.0	9.7	13.6	8.8	192.0	138.2	19.8
12	12040 B	Saline	300-600	7.3	0.36	62.5	7.5	12.8	4.3	56.8	25.7	3.9
12	12040 B	Saline	600-900	7.1	0.23	40.2	1.8	9.9	3.4	26.2	20.7	2.8
12	12057 B	Saline	0-300	7.3	0.07	4.8	4.5	7.7	2.0	13.4	0.6	0.4
12	12057 B	Saline	300-600	7.8	0.12	6.1	3.7	19.4	2.2	4.4	1.0	0.4
12	12057 B	Saline	600-900	7.6	0.11	7.3	4.3	14.9	1.5	13.5	2.7	0.5
12	12164 B	Saline	0-300	6.7	0.04	3.3	3.6	2.8	2.4	13.1	1.0	0.3
12	12164 B	Saline	300-600	7.1	0.09	3.5	3.9	3.8	2.1	17.8	0.6	0.4
12	12164 B	Saline	600-900	7.5	0.08	4.8	6.0	6.2	1.4	13.4	0.7	0.4
12	12178 B	Saline	0-300	7.3	0.13	11.0	6.1	14.0	5.7	8.7	2.4	0.6
12	12178 B	Saline	300-600	6.9	0.08	10.5	4.2	6.8	4.4	13.4	1.6	0.8
12	12178 B	Saline	600-900	7.6	0.13	16.2	1.8	10.6	2.3	17.6	2.1	1.2
12	12179 B	Saline	0-300	7.3	0.27	11.9	38.7	26.9	5.4	26.3	3.6	0.5
12	12179 B	Saline	0-300	7.7	0.12	9.8	3.8	13.9	1.8	13.4	2.9	0.7
12	12179 B	Saline	300-600	7.7	0.15	10.4	4.2	17.8	3.0	13.6	1.7	0.6
12	12204 B	Saline	0-300	7.1	0.41	32.4	2.9	39.1	12.5	52.4	14.3	1.2
12	12204 B	Saline	300-600	6.1	0.44	40.5	2.0	43.7	12.5	65.6	33.1	1.4
12	12204 B	Saline	600-900	6.5	0.37	44.6	4.9	33.8	8.6	69.9	23.9	1.8
12	12205 B	Saline	0-300	6.9	0.08	4.3	9.7	4.9	2.7	17.9	1.0	0.4
12	12205 B	Saline	300-600	6.7	0.04	3.6	6.1	3.0	1.9	4.6	1.0	0.4
12	12205 B	Saline	600-900	6.8	0.06	6.2	10.5	4.4	2.6	8.8	1.4	0.6
12	12209 B	Saline	0-300	7.1	0.25	10.4	23.7	21.0	4.8	26.3	7.6	0.5
12	12209 B	Saline	300-600	7.3	0.11	6.5	9.9	10.9	2.7	13.5	2.7	0.5
12	12216 B	Saline	0-300	6.7	0.10	7.3	8.5	9.1	4.2	8.8	1.4	0.5
12	12216 B	Saline	300-600	6.7	0.05	6.3	6.4	5.0	3.6	13.8	1.6	0.5
12	12216 B	Saline	600-900	6.8	0.17	5.3	16.4	4.0	3.0	26.5	0.7	0.5
12	12229 B	Saline	0-300	6.2	0.10	7.2	4.3	5.5	5.0	8.8	2.7	0.5
12	12229 B	Saline	300-600	6.5	0.06	6.7	5.5	5.0	5.7	17.6	2.3	0.5
12	12229 B	Saline	600-900	6.3	0.12	12.8	17.9	8.2	7.9	21.9	5.3	0.8

Table B1. Continued

12	12281 B	Saline	0-300	6.5	0.09	6.5	3.4	4.6	2.7	17.8	2.2	0.6
12	12281 B	Saline	300-600	6.6	0.05	4.7	2.1	2.5	2.1	13.6	1.3	0.5
12	12281 B	Saline	600-900	6.7	0.05	4.3	3.2	2.0	1.7	17.9	1.1	0.5
12	12297 B	Saline	0-300	6.3	0.08	4.8	5.3	4.0	2.4	8.7	3.2	0.5
12	12297 B	Saline	300-600	6.0	0.06	4.4	2.1	2.6	1.7	8.7	1.3	0.5
12	12297 B	Saline	600-900	5.9	0.08	6.4	7.5	3.0	1.7	8.4	2.2	0.7
12	12305 B	Saline	0-300	6.6	0.42	48.0	0.8	23.8	7.2	22.3	54.1	2.2
12	12305 B	Saline	300-600	7.1	0.97	204.6	0.6	27.1	13.1	61.2	124.9	8.1
12	12305 B	Saline	600-900	7.3	1.71	363.6	0.6	62.7	30.3	113.6	240.2	9.4
12	12316 B	Saline	0-300	6.1	0.20	12.1	2.6	13.9	4.7	30.6	4.6	0.7
12	12316 B	Saline	300-600	6.3	0.08	8.2	2.6	4.4	2.7	17.8	5.1	0.8
12	12316 B	Saline	600-900	6.2	0.04	3.9	2.3	2.2	1.5	13.2	1.6	0.5
12	12318 B	Saline	0-300	6.2	0.21	7.6	9.0	11.9	4.5	13.4	4.0	0.5
12	12318 B	Saline	300-600	6.2	0.14	7.3	15.9	7.7	4.0	17.5	3.8	0.5
12	12318 B	Saline	600-900	6.3	0.06	4.6	4.8	3.0	2.5	13.1	2.5	0.5

APPENDIX C

THE POTENTIAL EFFECT OF SALINITY ON GRAPEVINE PRODUCTION

Soil salinization is the most prevalent and widespread problem limiting crop production in irrigated agriculture (Shalevet, 1994). Sustained and profitable production of crops on salt-affected soils, however, is possible if appropriate on-farm management decisions are made. In order to be successful, producers require an understanding of how plants respond to salinity, the relative tolerances of different crops and their sensitivity at different stages of growth, and how different soil and environmental conditions affect salt-stressed plants (Francois & Maas, 1994). Grapevine is a high-value crop, and due to its perennial nature a long-term investment for producers. It is therefore important to establish the effect of prolonged exposure to salinity on the growth, production and longevity vines.

In general, growth inhibition and yield reduction on saline substrates may be the result of osmotic inhibition of water absorption, oxidative stress and specific ion effects on key physiological processes (Orcutt & Nilsen, 2000). Soil salinity results in a decreased osmotic potential of the soil water that reduces plant available water (Dudley, L.M., 1994) that could cause osmotic adjustment, turgor reduction and decreased cell wall elasticity (Orcutt & Nilsen, 2000), thereby depressing growth. Water deficit could furthermore reduce stomatal conductivity by means of hydraulic signals and/or endogeneous phytohormone signals from the roots to shoots (Schulze, 1986; Munns, 1993; Poljakoff-Mayber & Lerner, 1995; Jones, 1998) and consequently decrease production of assimilates by photosynthesis. In addition to effects on leaf expansion, water deficits can reduce the number of growing points and thus leaves produced (Jones & Tardieu, 1998).

The average root zone salinity, measured by electrical conductivity of the saturated extract of the soil (EC_e), has been used to define salt tolerance of different agricultural crops (Maas & Hoffman, 1977). Grapevine responses to salinity and to specific ion concentrations in Breede River valley (Moolman et al., 1999) were more sensitive than the internationally reported value of Maas and Hoffman (1977) and showed that yields decreased progressively above an EC_e of 0.75 dS m^{-1}. The rate of decrease was three times faster than that previously reported by Maas & Hoffman (1977). More recent research, using a boundary line approach to quantify the response of grapevine to salinity in the Breede River valley (Myburgh & Howell, unpublished final report, project WW04/13, ARC Infruitec-Nietvoorbij), found similar results to that reported by Maas & Hoffman (1977), the salinity threshold being 1.5 dS m^{-1} and the rate of yield decrease, *ca.* 10% per dS m^{-1}.

In this section the salinity in the soil solution (EC_e), resulting from irrigation with water of salinity typically found in the Boegoeberg to Onseepkans river reach and beyond, was estimated for low and high frequency irrigation systems. Subsequently, the potential effect of the EC_e on grapevine yield as well as the leaching requirement to prevent yield decrease of grapevine for low and high frequency irrigation systems were determined.

Methodology

The relative concentration or electrical conductivity of soil water (saturated extract basis) at steady state, compared to that of irrigation water, can be estimated by means of a concentration factor (Fc) for different leaching fractions (Rhoades & Loveday, 1990). The Fc values to estimate EC_e from EC of the irrigation water for low frequency irrigation systems such as flood or furrow irrigation that allow considerable drying between applications are 2.79; 1.88; 1.29; 1.03; 0.87 and 0.77 for leaching fraction values of 0.05; 0.10; 0.20; 0.30; 0.40 and 0.50, respectively. For high frequency irrigation systems where the increase in matric potential between irrigations is insignificant, the Fc values are 1.79; 1.35; 1.03; 0.87; 0.77 and 0.7 for leaching fractions of 0.05; 0.10; 0.20; 0.30; 0.40 and 0.50, respectively.

The relative yield response for grapevine to soil salinity according to Maas and Hoffman (1977) can be calculated as $RY= 100 - s(x - c_t)$ in which x is the depth-weighted seasonal average rootzone salinity (EC_e expressed in dS m^{-1}) during the growing season, c_t = the threshold, the maximum EC_e without yield reduction as compared to yield under non-saline conditions; and s = the slope, the percentage yield decrease per unit salinity increase. For grapevine the salinity threshold has a value of 1.5 dS m^{-1} and the yield decrease is 9.5% per dS m^{-1} salinity increase (Maas and Hoffman, 1977). According to Moolman *et al.* (1999) a value of 0.75 dS m^{-1} can be used as salinity threshold with a slope of 30% yield decrease per dS m^{-1} salinity increase.

According to Rhoades and Loveday (1999) the leaching requirement for salinity control for low frequency and high frequency irrigation systems can be estimated as follows:

$$LR = 0.3086/ (Fc')^{1.702} \text{ for low frequency irrigation} \quad (1)$$

$$LR = 0.1794/ (Fc')^{3.0417} \text{ for high frequency irrigation} \quad (2)$$

Where Fc' = (Salinity threshold for crop, EC_e)/(EC of irrigation water)

Results and discussion

The long-term EC of the water in the Boegoeberg to Onseepkans river reach was 0.29 dS m^{-1} (Table 3.15) and the EC varied between high and low flow years (Fig. 3.3), as well as within seasons reaching almost 0.7 dS m^{-1} at Onseepkans at times (Fig.3.11). The concentration of the EC in the soil water was therefore estimated for a range of EC values which is considered to occur from time to time in the Boegoeberg to Onseepkans river reach, as well as for values exceeding the EC in the river reach, up to a maximum of 1 dS m^{-1} (Table C1). Leaching fractions of between 0.2 and 0.3 are probably realistic values of that applied in the lower Orange River area as return flows can be as high as 30% of the water applied to the land (Rossouw, 1997). The maximum EC_e reached for irrigation water with an EC of 1 dS m^{-1} with a leaching fraction of 0.2 and 0.3 was 1.29 and 1.03, respectively, for the low frequency irrigation, and 1.03 and 0.87, respectively, for the high frequency irrigation scenario (Table C1).

According to the yield response model of Maas & Hoffman (1977) a yield decrease of grapevine could occur if water with EC values of 0.6 dS m^{-1} and 0.85 dS m^{-1}, with a leaching fraction of 0.05 and 0.1, respectively, is applied through low frequency irrigation systems (Table C2). Likewise, a yield decrease of grapevine could occur if water with an EC value of 0.9 dS m^{-1}, with a leaching fraction of 0.05 is applied through high frequency irrigation systems. No yield decrease is expected for water with an EC value of 1 dS m^{-1} if a leaching fraction of more than 0.1 is applied. A leaching fraction higher than 0.2 is not recommendable as it may exacerbate water table problems in the lower Orange River area.

The results from the model when using the salt tolerance parameters of Moolman *et al.* (1999) were much more conservative compared to that of Maas and Hoffman (1977) (Tables C2 & C3). Yield decrease of grapevine can occur if water with EC values of 0.30, 0.45, 0.60, 0.75, 0.90 and 1.00 dS m^{-1}, with a leaching fraction of 0.05; 0.1; 0.2; 0.3; 0.4 and 0.5, respectively, is applied through low frequency irrigation systems. A yield decrease of grapevine could also occur if water with EC values of 0.45, 0.60, 0.75, 0.90 and 1.0 dS m^{-1}, with a leaching fraction of 0.05 and 0.1; 0.2; 0.3 and 0.4, respectively, is applied through high frequency irrigation systems. According to these results and the fluctuating water quality in the river reach between Boegoeberg and Onseepkans (refer Chapter 3), yield decrease may be imminent for grapevine producers, depending on the amount of leaching that is applied.

According to the model, utilizing the salinity threshold and slope of yield decrease of Maas & Hoffman (1977), a leaching fraction of 0.2 will not need to be exceeded to prevent yield-reducing soil salinization for grapevine, even if a water quality of 1 dS m^{-1} is used for low as well as high frequency irrigation (Table C4). If the salinity threshold and slope of yield decrease of Moolman *et al.* (1999) is accepted, however, a maximum EC of 0.55 dS m^{-1} for low, and 0.75 dS m^{-1} for high frequency irrigation is acceptable if a leaching fraction of less than 0.2 is to be maintained. The large difference in the results of these two salinity-yield response models may become important as water resources becomes more limited for the lower Orange River region. Although recent research in the Breede River valley on the effect of soil salinity levels on grapevine yield (Myburgh & Howell, unpublished final report, project WW04/13, ARC Infruitec-Nietvoorbij) agreed with the salinity threshold EC_e values found by Maas and Hoffman (1977), the more conservative model of Moolman *et al.* (1999) is recommended until more research results become available. The results of De Clercq *et al.* (2001) suggest that even the model of Moolman *et al.* (1999) may be insufficiently conservative to accommodate the long-term deterioration in grapevine performance under saline irrigation. Research on the effect of soil salinity levels on grapevine yield in the lower Orange River area has commenced at ARC Infruitec-Nietvoorbij and results of that project may indicate the appropriate model to use.

Conclusions

There are large differences in the salinity-yield response model results using the dfferent sets of salinity threshold and slope values available for grapevine. The validity of these results may become crucial for decision making regarding irrigation water quality and the application of leaching requirements in the lower Orange River region in the near future. A more conservative approach is recommended until new research results become available. Therefore irrigation water with salinity of 0.55 dS m^{-1} is considered suitable for use during low, and 0.75 dS m^{-1} during high frequency irrigation, provided a leaching fraction of *ca.* 0.2 is maintained.

Table C1 Estimated concentration of salinity in the soil water extract (EC_e) for irrigation water differing in salinity (EC) and various leaching fractions as applied by low and high frequency irrigation systems

EC of irrigation water (dS m^{-1})	EC_e (dS m^{-1})											
	Low frequency irrigation						High frequency irrigation					
	Leaching fraction											
	0.05	0.1	0.2	0.3	0.4	0.5	0.05	0.1	0.2	0.3	0.4	0.5
0.20	0.56	0.38	0.26	0.21	0.17	0.15	0.36	0.27	0.21	0.17	0.15	0.14
0.25	0.70	0.47	0.32	0.26	0.22	0.19	0.45	0.34	0.26	0.22	0.19	0.18
0.30	0.84	0.56	0.39	0.31	0.26	0.23	0.54	0.41	0.31	0.26	0.23	0.21
0.35	0.98	0.66	0.45	0.36	0.30	0.27	0.63	0.47	0.36	0.30	0.27	0.25
0.40	1.12	0.75	0.52	0.41	0.35	0.31	0.72	0.54	0.41	0.35	0.31	0.28
0.45	1.26	0.85	0.58	0.46	0.39	0.35	0.81	0.61	0.46	0.39	0.35	0.32
0.50	1.40	0.94	0.65	0.52	0.44	0.39	0.90	0.68	0.52	0.44	0.39	0.35
0.55	1.53	1.03	0.71	0.57	0.48	0.42	0.98	0.74	0.57	0.48	0.42	0.39
0.60	1.67	1.13	0.77	0.62	0.52	0.46	1.07	0.81	0.62	0.52	0.46	0.42
0.65	1.81	1.22	0.84	0.67	0.57	0.50	1.16	0.88	0.67	0.57	0.50	0.46
0.70	1.95	1.32	0.90	0.72	0.61	0.54	1.25	0.95	0.72	0.61	0.54	0.49
0.75	2.09	1.41	0.97	0.77	0.65	0.58	1.34	1.01	0.77	0.65	0.58	0.53
0.80	2.23	1.50	1.03	0.82	0.70	0.62	1.43	1.08	0.82	0.70	0.62	0.56
0.85	2.37	1.60	1.10	0.88	0.74	0.65	1.52	1.15	0.88	0.74	0.65	0.60
0.90	2.51	1.69	1.16	0.93	0.78	0.69	1.61	1.22	0.93	0.78	0.69	0.63
0.95	2.65	1.79	1.23	0.98	0.83	0.73	1.70	1.28	0.98	0.83	0.73	0.67
1.00	2.79	1.88	1.29	1.03	0.87	0.77	1.79	1.35	1.03	0.87	0.77	0.70

Table C2 Relative yield potential of grapevine according to salinity in the irrigation water (EC) and a soil salinity (EC_e) threshold of 1.5 dS m^{-1}

EC of irrigation water (dS m^{-1})	EC_e (dS m^{-1})											
	Low frequency irrigation						High frequency irrigation					
	Leaching fraction											
	0.05	0.1	0.2	0.3	0.4	0.5	0.05	0.1	0.2	0.3	0.4	0.5
0.20	100	100	100	100	100	100	100	100	100	100	100	100
0.25	100	100	100	100	100	100	100	100	100	100	100	100
0.30	100	100	100	100	100	100	100	100	100	100	100	100
0.35	100	100	100	100	100	100	100	100	100	100	100	100
0.40	100	100	100	100	100	100	100	100	100	100	100	100
0.45	100	100	100	100	100	100	100	100	100	100	100	100
0.50	100	100	100	100	100	100	100	100	100	100	100	100
0.55	100	100	100	100	100	100	100	100	100	100	100	100
0.60	98	100	100	100	100	100	100	100	100	100	100	100
0.65	97	100	100	100	100	100	100	100	100	100	100	100
0.70	96	100	100	100	100	100	100	100	100	100	100	100
0.75	94	100	100	100	100	100	100	100	100	100	100	100
0.80	93	100	100	100	100	100	100	100	100	100	100	100
0.85	92	99	100	100	100	100	100	100	100	100	100	100
0.90	90	98	100	100	100	100	99	100	100	100	100	100
0.95	89	97	100	100	100	100	98	100	100	100	100	100
1.00	88	96	100	100	100	100	97	100	100	100	100	100

Table C3 Relative yield potential of grapevine according to salinity in the irrigation water (EC) and a soil salinity (EC_e) threshold of 0.75 dS m^{-1}

EC of irrigation water (dS m^{-1})	Relative yield (%)											
	Low frequency irrigation						High frequency irrigation					
	Leaching fraction											
	0.05	0.1	0.2	0.3	0.4	0.5	0.05	0.1	0.2	0.3	0.4	0.5
0.20	100	100	100	100	100	100	100	100	100	100	100	100
0.25	100	100	100	100	100	100	100	100	100	100	100	100
0.30	97	100	100	100	100	100	100	100	100	100	100	100
0.35	93	100	100	100	100	100	100	100	100	100	100	100
0.40	89	100	100	100	100	100	100	100	100	100	100	100
0.45	85	97	100	100	100	100	98	100	100	100	100	100
0.50	81	94	100	100	100	100	96	100	100	100	100	100
0.55	76	91	100	100	100	100	93	100	100	100	100	100
0.60	72	89	99	100	100	100	90	98	100	100	100	100
0.65	68	86	97	100	100	100	88	96	100	100	100	100
0.70	64	83	95	100	100	100	85	94	100	100	100	100
0.75	60	80	93	99	100	100	82	92	99	100	100	100
0.80	56	77	92	98	100	100	80	90	98	100	100	100
0.85	51	75	90	96	100	100	77	88	96	100	100	100
0.90	47	72	88	95	99	100	74	86	95	99	100	100
0.95	43	69	86	93	98	100	71	84	93	98	100	100
1.00	39	66	84	92	96	99	69	82	92	96	99	100

Table C4 Leaching requirements to prevent grapevine yield-reducing salt accumulation in the soil profile for irrigation water of varying salinity (EC) for low (LFI) and high frequency (HFI) irrigation systems respectively. Leaching fractions were estimated for salinity threshold values (EC_e) of 1.5 dS m^{-1} and 0.7 dS m^{-1}, respectively

EC of irrigation water (dS m^{-1})	Leaching requirement			
	EC_e: 1.5 dS m^{-1}		EC_e: 0.75 dS m^{-1}	
	LFI	HFI	LFI	HFI
0.20	0.01	0.00	0.03	0.00
0.25	0.01	0.00	0.05	0.01
0.30	0.02	0.00	0.06	0.01
0.35	0.03	0.00	0.08	0.02
0.40	0.03	0.00	0.11	0.03
0.45	0.04	0.00	0.13	0.04
0.50	0.05	0.01	0.15	0.05
0.55	0.06	0.01	0.18	0.07
0.60	0.06	0.01	0.21	0.09
0.65	0.07	0.01	0.24	0.12
0.70	0.08	0.02	0.27	0.15
0.75	0.09	0.02	0.31	0.18
0.80	0.11	0.03	0.34	0.22
0.85	0.12	0.03	0.38	0.26
0.90	0.13	0.04	0.42	0.31
0.95	0.14	0.04	0.46	0.37
1.00	0.15	0.05	0.50	0.43