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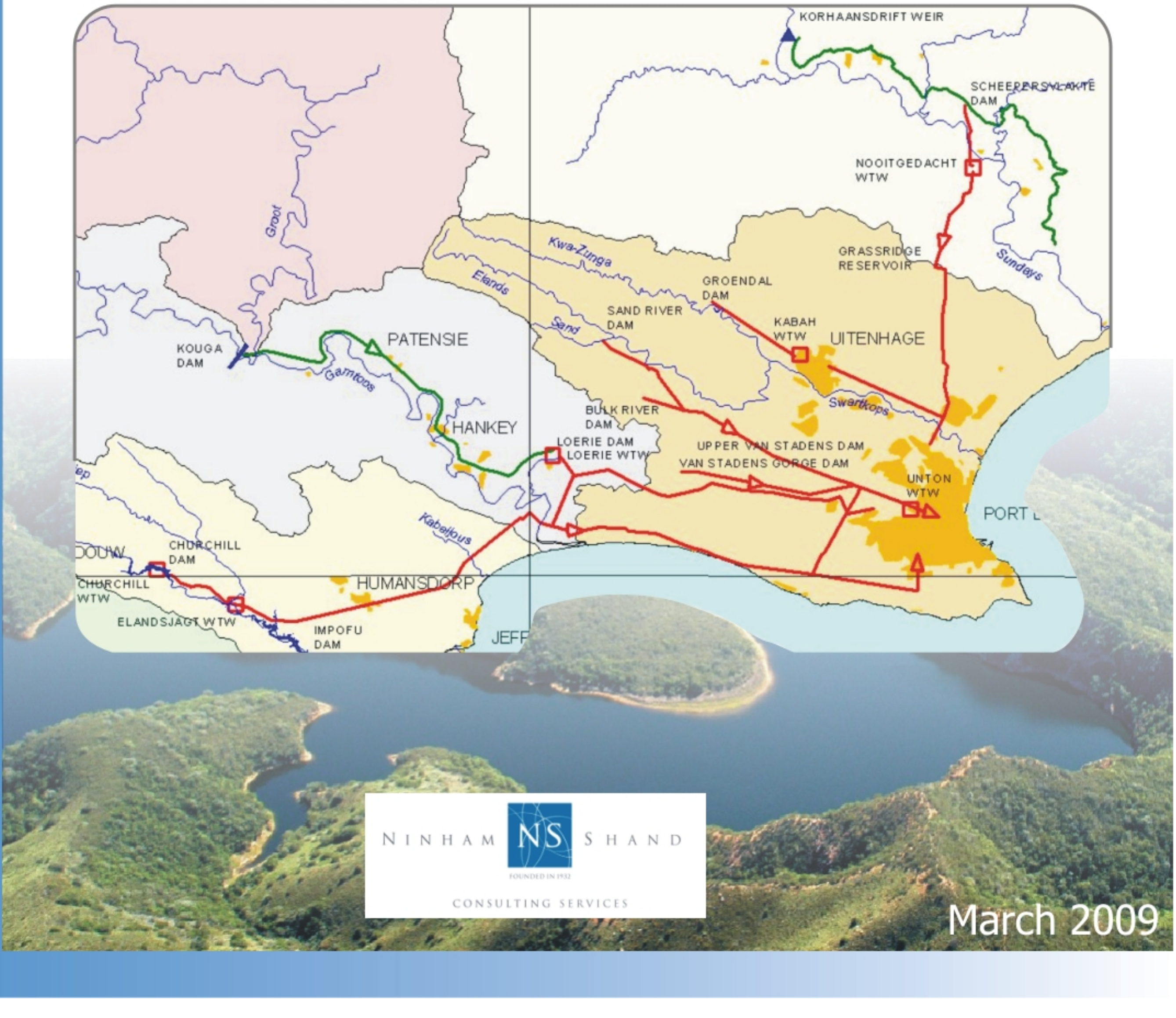
Water Reconciliation Strategy Study for the Algoa Water Supply Area

Impact of changed crops on water quality in the Great Fish River



NINHAM NS SHAND
FOUNDED IN 1932
CONSULTING SERVICES

March 2009

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Department of Water Affairs and Forestry
Directorate: National Water Resource Planning

NS Project No. 402448

Water Reconciliation Strategy Study for the Algoa Water Supply Area

IMPACT OF CHANGED CROPS ON WATER QUALITY IN THE GREAT FISH RIVER

Final

March 2009

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Department of Water Affairs and Forestry
Directorate National Water Resource Planning

Water Reconciliation Strategy Study for the Algoa Water Supply Area

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APPROVAL

Title : Impact of changed crops on water quality in the Great Fish River.

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Consultants : Ninham Shand (Pty) Ltd

Report status : Final

Date : March 2009

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EXECUTIVE SUMMARY

INTRODUCTION

This report provides an overview of the application of the ACRU*Salinity* daily hydrosalinity model to the portion of the Fish River Basin located between the confluence of the Pauls River with the Fish River and Elandsdrift Weir. The primary objective of this study was to quantify the change in irrigation return flow salinity as a result of replacing 5 000 ha of existing irrigated crops with sugar beet.

Salinisation has always been a concern in the Great Fish River (especially the lower reaches) (DWAF, 1986 and WRC, 1988). With the possible initiation of this project, a concern about further water quality deterioration has again been raised

SALINITY SCENARIOS

To achieve the primary aim of the study the ACRU*Salinity* model was configured for the Fish River Basin. Simulated daily TDS exceedance percentages were then compared with observed TDS exceedances percentages to ensure that the model was as representative of reality as possible. Four scenarios were then configured and the outputs compared to the current day situation. The scenarios tested were as follows:

Base Case Scenario

The base case scenario was specifically configured to test the model's representation of current day condition in terms of stream flow salinity. The following shortcomings in the configuration should be noted:

- Rainfall data could not be updated to 2008 level since most of the rainfall stations, intended for use as driver rainfall stations, had been closed since 1999.

- Information on abstraction volumes for the various canals supplying the irrigation boards were only available from 2000 onwards and therefore did not overlap with the period of available rainfall data.

To overcome the above shortcomings, the abstractions were assumed to occur during the period 1990 to 2000. The crop factors used for the assumed crop mix are shown in Table E1 below.

Table E1 Area weighted crop factors used for the current crop mix in the Fish River

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Crop Factor	0.61	0.6	0.45	0.45	0.5	0.5	0.5	0.5	0.48	0.39	0.44	0.56

The irrigation depths for the various irrigated areas within the irrigation boards varied on a daily basis. This daily irrigation depth, however, was calculated as follows:

$$Irrigation\_Depth = \frac{Vol_{canal\_abs} \cdot \dfrac{Area_{irrig}}{Area_{IB}}}{Area_{irrig}} .3600.24.1000$$

Where,

Vol_{canal_abs} = Volumetric flow rate of the canal abstraction (m^3/s)
$Area_{irrig}$ = pseudo sub-catchment irrigated area (m^2)
$Area_{IB}$ = Total area of the irrigation board (m^2)
Irrigation Depth = Depth of irrigation (mm/day)

Scenario1

This scenario was specifically configured to test the effect of changing all the irrigated areas to sugar beet, on the irrigation return flow salinity. All irrigated areas were changed to sugar beet using a modified Food and Agriculture Organisation (FAO) approach for estimation of monthly crop factors (Table E2). The current day depths of irrigation were, however, maintained.

Table E2 Crop factors for sugar beet based on a modified FAO approach

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Crop factor	0.62	0	0	0.29	0.29	0.3	0.46	0.68	0.9	1	1	0.98

Scenario 2

This scenario was specifically configured to test the effect of changing the crop factors of sugar beet on the irrigation return flow salinity. The change in return flow salinity was assessed relative to the base case scenario and Scenario 1. The crop factors used in this scenario were obtained from the SAPWAT program and are as listed in Table E3 below.

Table E3 Crop factors for sugar beet obtained from the SAPWAT program

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Crop factor	1.15	1.15	1.15	0.04	0	0	0	0.46	0.63	0.97	1.15	1.15

Scenario 3

This scenario was based on Scenario 2 and assumed irrigation depths required to achieve maximum sugar beet yields were applied. These irrigation depths were also obtained from the SAPWAT program and are as listed in Table E4 below.

Table E4 Monthly irrigation depths required for maximum sugar beet yield

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Irrigation depth in mm	443	348	297	8	0	0	0	88	157	288	370	434

The irrigation depths in Table E4 above have been calculated taking into account the effective monthly rainfall for the region and assuming a maximum loss of 25% in the amount of water between the points of abstraction and application.

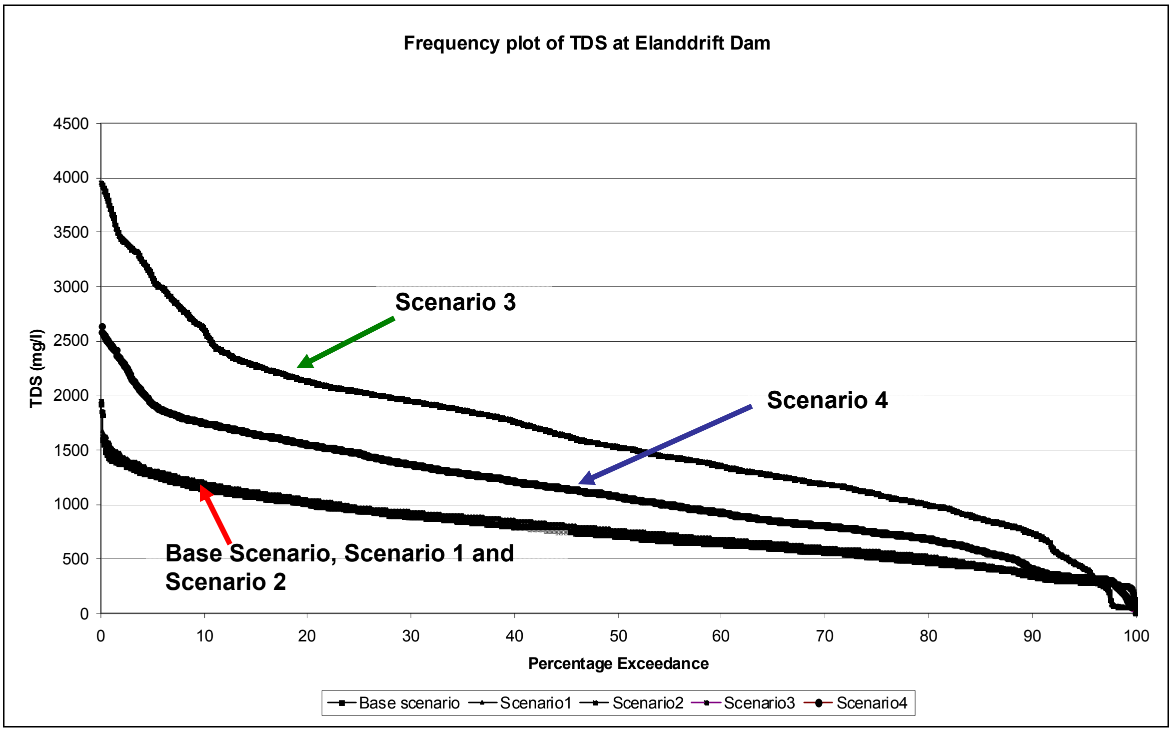
Scenario 4

This scenario was specifically configured to test the effect of replacing 5 000 ha of existing crops with sugar beet on the return flow salinity. In this scenario it was assumed that 5 000 ha of existing crops would be replaced with sugar beet and that the allowable quota (i.e. 13 500 m^3/ha/a) would be used in an attempt to maximise the yield of sugar beet. In particular, the irrigated crops in the Baroda, Marlow and Mortimer irrigation boards were replaced with sugar beet.

Calculations revealed that the daily irrigation depths in the table above would require application of approximately twice the quota available to these irrigation boards. Since no extra water would be made available for the sugar beet cultivation, it was necessary to reduce the irrigation depth by 50% to ensure that the quota was not exceeded.

RESULTS

A comparison of the exceedance percentages of the daily TDS concentrations from the various scenarios is depicted below.



The figure shows that an increased application volume, as is the case for Scenarios 3 and 4 would lead to increased mobilisation of salts to the mainstem of the Fish River. Typically, it could be expected that a TDS concentration of 1 500 mg/l would be exceeded for 20% of the time, increasing the percentage exceedance from less than 5% seen under the current conditions

The increase in TDS concentration with an increase in irrigation could be related to the selection of final salinity-related parameter values. Since the contribution of irrigation return flow salinity, in the model, is determined by the rate of dissolution and the available carrying capacity to transport these dissolved salts, it can be hypothesised that the availability of carrying capacity is probably the limiting step in the salinisation process. The added carrying capacity in the form of increased irrigation depths, removes this limitation – resulting in increased mobilisation of dissolved salts.

CONCLUSIONS

Based on the results and discussion above, the following can be concluded

- The replacement of 5 000 ha of existing crops in the Fish River Basin could result in a substantial increase in the TDS concentrations of the Fish River mainstem if the maximum allowable allocation is utilised.

- The modelling results suggest that the increased irrigation depths that will be required to achieve near maximum yields of the sugar beet will be the determining factor in the mobilisation of salts and not specifically the irrigation of the sugar beet crops. If current day irrigation depths are maintained it is likely that the TDS concentrations of the return flow would not increase significantly.

- The main objective of the sugar beet venture is to maximise yield for bio-ethanol production. In recognition of this, it is more than likely that the irrigation boards would use more of the allocation for irrigation to achieve the maximum yield.

- The annual irrigation requirement to achieve maximum yield with the current crop types are only 15% less than the requirement to achieve maximum yield with sugar beet. It is therefore unclear why the full quota for irrigation is not used since this is what would be required to achieve near maximum yields of the current crops.

- The rotational irrigation effect was not modelled because 5 000 ha sugar beet would exist at some location in the study area. It was therefore assumed that the effect of the sugar beet cultivation would only be shifted higher up or lower down on the Fish River mainstem.

RECOMMENDATIONS

Based on the discussion and conclusions, the following recommendations can be made:

- A survey of the irrigated areas and crop types of the Fish River basin should be undertaken and maintained on a GIS database to enable the use of accurate land-use data in modelling studies.

- An optimum irrigation depth, which would compromise between achievable yield of sugar beet and the extent of TDS mobilisation, should be established. This could be achieved by completing additional scenario runs in which the daily irrigation depths are reduced until acceptable TDS exceedance percentages are obtained. The monthly irrigation depth obtained from this exercise should then be tested to ascertain what the achievable yield of sugar beet would be.

- Realistic estimates of crop factors, leaf area indices, interception losses by vegetation and fraction of the effective root depth in topsoil horizon for sugar beet should be obtained. This would enable the determination of more accurate consumptive water use by the crop.

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ABBREVIATIONS

ACRU	Agricultural Catchment Research Unit
DUL	Drained upper limit
DWAF	Department of Water Affairs and Forestry
EC	Electrical Conductivity
FAO	Food and Agricultural Organisation
ha	Hectares
MAP	mean annual precipitation
mg/l	milligrams per litre
m^3/s	cubic metres per second
mS/m	millisiemens per meter
TDS	Total Dissolved Solids

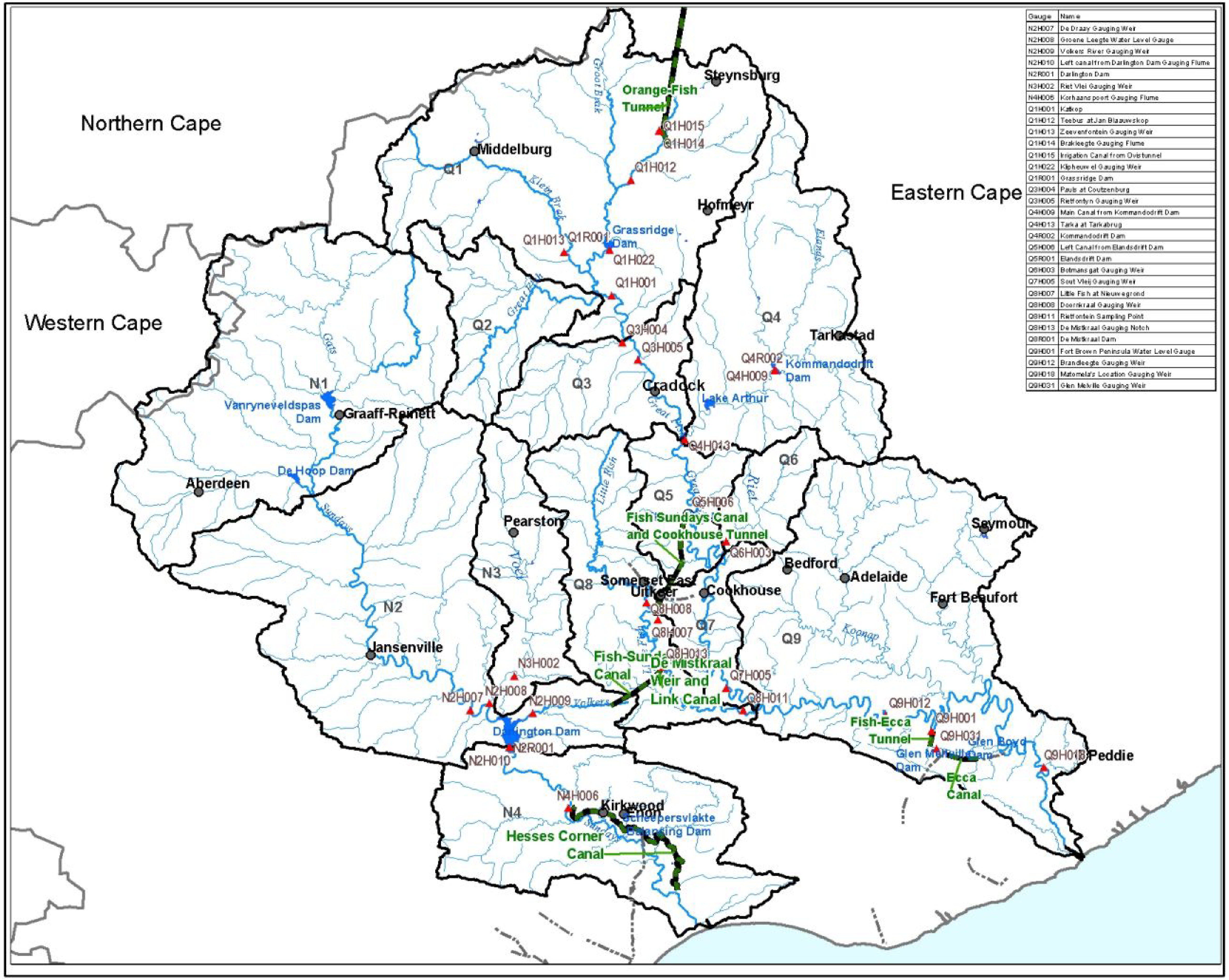
1. INTRODUCTION

This report provides an overview of the application of the ACRU*Salinity* daily hydrosalinity model to the portion of the Fish River Basin between the confluence with the Pauls River and Elandsdrift weir. The primary objective of this study was to quantify the relative change in irrigation return flow salinity as a result of replacing 5 000 ha of existing irrigated crops with sugar beet. Interim aims required in achieving the primary objective were as follows:

- Assimilation of land-use, canal abstraction and irrigation application information
- Estimation of crop factors for sugar beet
- Identification of appropriate rainfall stations in the catchment
- Configuration of the ACRU*Salinity* model for the sub-catchments of concern.

According to Mullineux (2007), Sugar Beet SA originally intended to develop an additional 5 000 ha – 15 000 ha under sugar beet cultivation in the upper Great Fish River catchment, with the intention of supplying sugar to the local and Southern African markets. In mid-2006, however, this approach changed to the cultivation of at least 4 000 ha of sugar beet on a 3-year rotational basis for use as raw material in a bio-ethanol production plant.

Salinisation has always been a concern in the Great Fish River (especially the lower reaches) (DWAF, 1986 and WRC, 1988). With the possible initiation of this project, a concern about further water quality deterioration has again been raised. **Figure 1.1** shows the Fish-Sundays catchment as well as the area relevant to the sugar beet project.



Gauge	Name
N2H007	De Draay Gauging Weir
N2H008	Groene Leegte Water Level Gauge
N2H009	Volkers River Gauging Weir
N2H010	Left canal from Darlington Dam Gauging Flume
N2R001	Darlington Dam
N3H002	Riet Vlei Gauging Weir
N4H006	Korhaans poort Gauging Flume
Q1H001	Katkop
Q1H012	Teebus at Jan Blaauwskop
Q1H013	Zeevenfontein Gauging Weir
Q1H014	Brakleegte Gauging Flume
Q1H015	Irrigation Canal from Ovistunnel
Q1H022	Klipheuwel Gauging Weir
Q1R001	Grassridge Dam
Q3H004	Pauls at Coutzenburg
Q3H005	Rietfontyn Gauging Weir
Q4H009	Main Canal from Kommandodrift Dam
Q4H013	Tarka at Tarkabrug
Q4R002	Kommandodrift Dam
Q5H006	Left Canal from Elandsdrift Dam
Q5R001	Elandsdrift Dam
Q6H003	Botmansgat Gauging Weir
Q7H005	Sout Vleij Gauging Weir
Q8H007	Little Fish at Nieuwegrond
Q8H008	Doornkraal Gauging Weir
Q8H011	Rietfontein Sampling Point
Q8H013	De Mistkraal Gauging Notch
Q8R001	De Mistkraal Dam
Q9H001	Fort Brown Peninsula Water Level Gauge
Q9H012	Brandleegte Gauging Weir
Q9H018	Matomela's Location Gauging Weir
Q9H031	Glen Melville Gauging Weir

Figure 1.1 Extent of the Fish River catchment

2. SALINITY SITUATION OF THE MIDDLE FISH RIVER BASIN

For the extent of the area considered in this study, the Pauls River (Q3H004) and the Tarka River (Q4H013) are the only gauged tributaries which confluence with the Fish River mainstem. Ungauged tributaries which join the Fish River mainstem include the Wilgebooms and Riet Rivers.

Previous studies (WRC, 1983) have shown that mineralisation (increase in TDS concentrations in the river) of the Fish River mainstem is caused by the mobilisation of salts, either by the applied irrigation water or the interaction with rainfall. In the case of the irrigation-induced mobilisation, potentially more salts could be available due to cultivation practices which increase the rate of mechanical and chemical weathering. Additional salt loads are also contributed by the tributaries but these would coincide with rainfall events in those catchments.

As is the case with many other semi-arid catchments where mineralisation is a concern (e.g. Berg and Breede), the origin of the salinity-enriched soils is not definitive; its effect (as it relates to the extent and rate of dissolution of salts) on the quality of river water, however, cannot be disputed.

The deterioration in water quality, with respect to total dissolved salts (TDS), along the Fish River mainstem is depicted in **Figure 2.1** which shows an increase in the median TDS concentration from the upper to lower reaches. This effect can, to a larger extent, be attributed to saline irrigation return flow generated along this river reach.

The effect of irrigation return flow salinity on the water quality of the Fish River mainstem between gauging station Q3H005 and Q5H006 is shown in **Figure 2.2**. The increase in the monthly median value at gauge Q5H006 is approximately 300 mg/l, except for June when the medians were almost equal and July, when the value at Q5H006 was approximately 900 mg/l higher. The increase of 300 mg/l in the median TDS concentration at Q5H006 could be attributed to the salt load contributed by the irrigation return flows between Q3H005 and Q5H006. The increase of 900 mg/l, during July, however, could be associated with reduced flow in the mainstem of the Fish River, subsequently producing reduced dilution capacity at Q5H006.

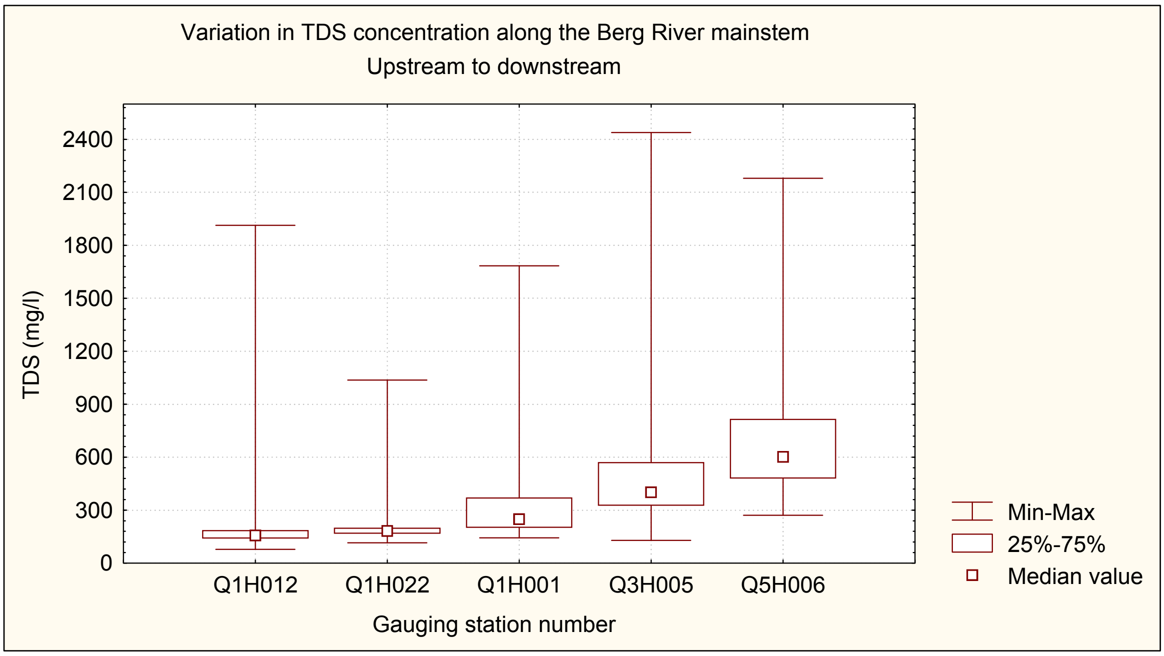


Figure 2.1 Variation of TDS along the Fish River mainstem (Month 1 = January)

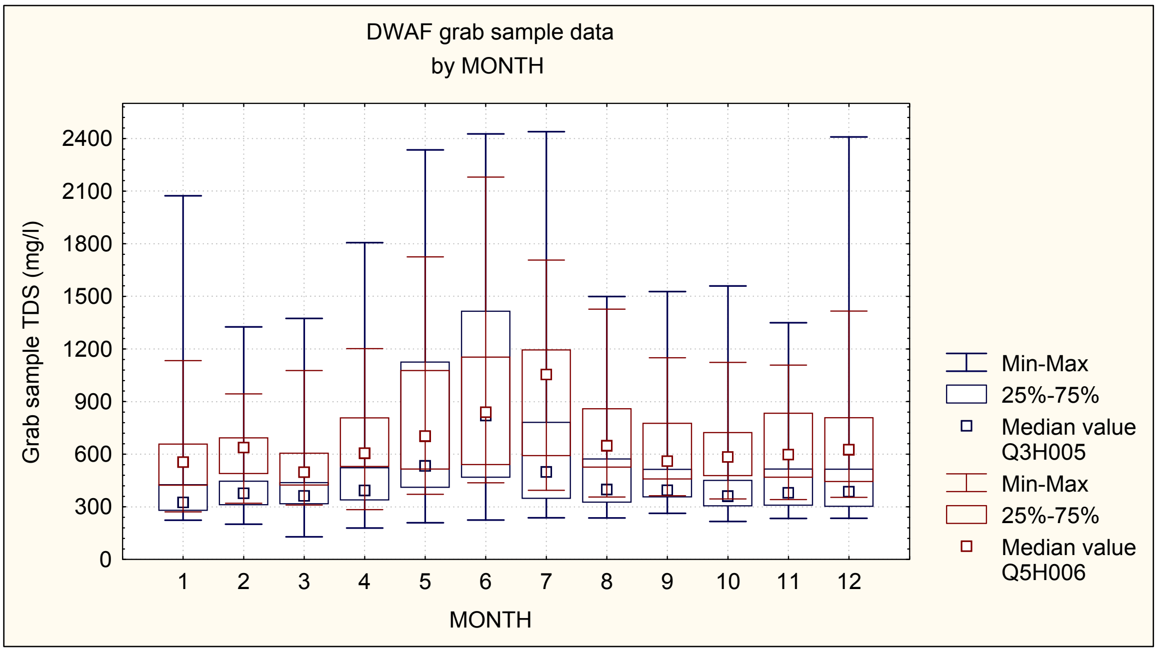


Figure 2.2 **Comparison of seasonality of observed grab sample TDS values at Q3H005 and Q5H006 (Month 1 = January)**

3. PREVIOUSLY COMPLETED SALINISATION STUDIES OF THE FISH RIVER BASIN

Several studies relating to the salinisation of the rivers comprising the Fish River Basin have been undertaken in the past. To provide a contextual background to the extent of the salinisation concerns, the major findings from these studies have been summarised below:

3.1 STUDIES OF MINERALISATION IN THE GREAT FISH AND SUNDAYS RIVERS (WRC, 1983)

***Volume I** : Early research of a qualitative and semi-quantitative nature (1983)*
A comprehensive Water Research Commission (WRC) project was undertaken in the 1970s to investigate the mineralisation processes occurring in the Fish and Sundays Rivers. The objectives of Phase 1 of the study were to:

- collect data on background water quality (in terms of TDS),
- investigate factors affecting water quality, and
- make recommendations to alleviate the problem of mineralisation.

The monitoring network for the system consisted of the collection of water quality samples, soil and geological survey data, flow data, meteorological data and land-use data. Motivation for mathematical modelling of the hydrology and mineralisation of the system was provided in the study, leading to the development of a deterministic hydrological model and theoretical soil model (FLOSAL). Empirical relationships were used to describe the groundwater mineralisation process. The above components were integrated into a systems model describing mineralisation in the catchment.

***Volume 2**: Modelling river flow and salinity (September 1984)*
The project team, using the FLOSAL model, tested several planning options for the Fish-Sundays system. The final report contained details of the model calibration using observed records, model testing and outputs from the various options tested in terms of the water quality. A set of operating rules were proposed and recommendations on the impacts of future irrigation developments were made.

3.2 REPORT ON A SITUATION STUDY OF IRRIGATION RETURN FLOW (WRC, 1985)

In the WRC study of 1985 the daily ACRU agrohydrological model was used as one of the approaches to estimate the soil moisture balance and potential irrigation return flow in the Great Fish River System. Data requirements for modelling included that of climate (rainfall and pan-evaporation); soils (field capacity, wilting point, porosity, and effective rooting depth); crop factors and irrigation efficiency (application, storage and conveyance).

Daily and monthly return flows were simulated for selected irrigation schemes along the Fish River, with the monthly results displaying somewhat erratic behaviour. Return flows for certain schemes were simulated both as a percentage of the volume of irrigation water supplied plus rainfall, and of irrigation volume alone. Irrigation application was found to be an important factor in modelling salinisation of the Great Fish River System. The model was highly sensitive to the conveyance losses, with a 5% change leading to a 10 - 20 % change in irrigation return flow.

The general outcomes of that study were found to be more realistic when compared to those of the crop water balances in the same report. The fact that ACRU accounts for the storage characteristics of the soil and the potential lag in travel time for irrigation return flow to reach the river channel, could be the reason for this. The ACRU results for the Great Fish River are shown in **Table 3.1**.

Table 3.1 Estimations of irrigation return flow using the daily soil moisture balance model ACRU (as in Schulze, 1985)

Reach	Date	Average volumes ordered (1000 m^3/month)	Irrigation return flow (% of net irrigation application)
Brak	1976-1979	575	8
Baroda	1976-1979	1200	23
Marlow	1976-1979	992	22
Mortimer	1976-1979	1108	40
Halesowen	1976-1979	283	20
Scanlan	1976-1979	1	16
H. Abramson	1976-1979	2	44
Middleton	1977-1979	2	44

3.3 A HYDRO-SALINITY MODELLING STUDY (DWA, 1986A)

This report outlined the modelling process starting with the data collection, initial calibrations using a split sample method and final recalibration with the full dataset. Different operational and development scenarios were also tested in an attempt to optimise system efficiency. The model usage was aimed at supporting the increasing irrigation development in the catchment and to maximise supply capacity to Port Elizabeth.

3.4 INTEGRATED STUDIES OF THE GENERATION OF RUNOFF AND SOLUTES (WRC, 1988)

This study was initiated to deal with the problem of salinisation in semi-arid conditions, by investigating the natural process of salt generation and the interaction with the runoff generation process. A motivating factor for this work was the need to develop process-based models (as opposed to empirical ones) to simulate the above processes. The project involved data collection, analysis and interpretation as well as the testing of new models with functionality for evaluating management options. The updated ACRU (Smithers *et al*, 1995) agro-hydrological model was used for soil moisture-budgeting and the MODANSW (Park *et al*, 1983) hydrological model was used to simulate streamflow and sediment transport. Modelling of hydrosalinity was performed to a limited degree due to insufficient input data.

3.5 FISH TO TSITSIKAMMA WATER MANAGEMENT AREA: WATER RESOURCE SITUATION ASSESSMENT (DWAF, 2001)

The study was conducted on a desk-top basis, making use of available data and covered a greater area than the Fish-Sundays river catchments. Water quality constituents of concern included surface and groundwater TDS as well as microbial concentrations. Water quality with regard to TDS was assessed based on the South African Water Quality Guidelines (DWAF, 1996b and c) for domestic and irrigation water use. Microbial water quality was assessed based on surface water quality with regard to microbial contamination and groundwater vulnerability to contamination using the DRASTIC approach, an acknowledged method for assessing aquifer vulnerability to contamination.

3.6 REAL-TIME OPERATION OF THE ORANGE-FISH-SUNDAYS WATER SUPPLY SYSTEM

In this study the MIKE11 (DHI, 2007) hydrodynamic and water quality model was configured for the Orange-Fish-Sundays Water Supply System (OFSWSS) from Grassridge Dam (Q1H022) to Korhaansdrift weir (N4H006). The model was then calibrated for hydrodynamics and TDS at gauges where acceptable water level and water quality data was available. Results from the calibration process suggested that irrigation return flow volumes as well as quality played a significant role in obtaining simulated outputs.

To quantify the volume of irrigation return flows in the various reaches of the system several approaches were tested. These included:

- Water and solute balances in the river channel;
- Monthly crop water balances, and
- Daily agrohydrological modelling using ACRU.

The monthly crop water balances eventually became the preferred approach for the study. The preferred approach could not be used to calculate the irrigation return flow quality and subsequently became a calibration parameter in the MIKE11 model. It should be noted the ACRU modelling approach was abandoned because the cost associated with the configuration of the model could not be accommodated within the available budget for the task.

The final irrigation flow concentrations as well as the return flow volumes used in the study are listed in **Table 3.2**.

Table 3.2 Irrigation return flow quality and volumes for various reaches in the Orange-Fish-Sundays Water Supply System

River Reach	Irrigation Return Flow Concentration (mg/l)	Irrigation Return Flow Volume (m^3/s) added by water quality team
Ovis Tunnel outlet to Groot Brak River Confluence **(Teebus)**	200	0
Groot Brak River confluence to Grassridge Dam **(Grootbrak1)**	200	0
Grassridge Dam to Waaikraal **(Grootbrak2)**	500	0
Grootvis River inflow **(Grootvis1)**	500	0
Waaikraal to Elandsdrift weir **(Grootvis2)**	1500	0
Elandsdrift weir to Sheldon **(Grootvis3)**	1000	0
Sheldon to Hermanuskraal **(Grootvis4)**	5000	0.5
Little Fish tributary to Demistkraal **(LittleFish1)**	2000	0
Demistkraal Dam to Grootvis River confluence **(LittleFish2)**	4000	0.5
Skoenmakers canal to Darlington Dam **(Skoenmakers)**	1500	0
Darlington Dam to Korhaansdrift **(Sundays2)**	2000	0

4. DESCRIPTION OF THE ACRU SALINITY MODELLING SYSTEM

4.1 ACRU STRUCTURE

The ACRU agrohydrological model was developed by the Department of Agricultural Engineering at the University of KwaZulu-Natal in Pietermaritzburg, South Africa. The main modelling philosophies as reported by Kienzle (1997) are as follows:

- A *physical conceptual* model - conceptual in that it conceives a catchment system in which hydrological processes are idealised and physical in that physical processes are presented explicitly.
- Not a parameter optimising model since parameter values are intended to be estimated from the physical characteristics of the catchment.
- A *multi-purpose* model that compartmentalises (see **Figure 4.1**) rainfall into various components of runoff. It can be applied in design hydrology, reservoir yield simulation, determination of irrigation demand and supply and regional water resource assessments.
- A daily time-step model which can be used to highlight the daily responses of fast responding rivers. Data to which the model is relatively insensitive (e.g. temperature and reference potential evaporation) can be entered on a monthly basis to be transformed to daily values by Fourier Analysis.
- A multi-layered model which allows for a variety of approaches for estimating the values of certain parameters, depending on the available information. The parameters include reference potential evaporation, interception losses, values of soil water retention constants, leaf area index, etc.
- It can operate in lumped or in distributed mode, depending on the size of the catchment and the complexity of land-use within the catchment.

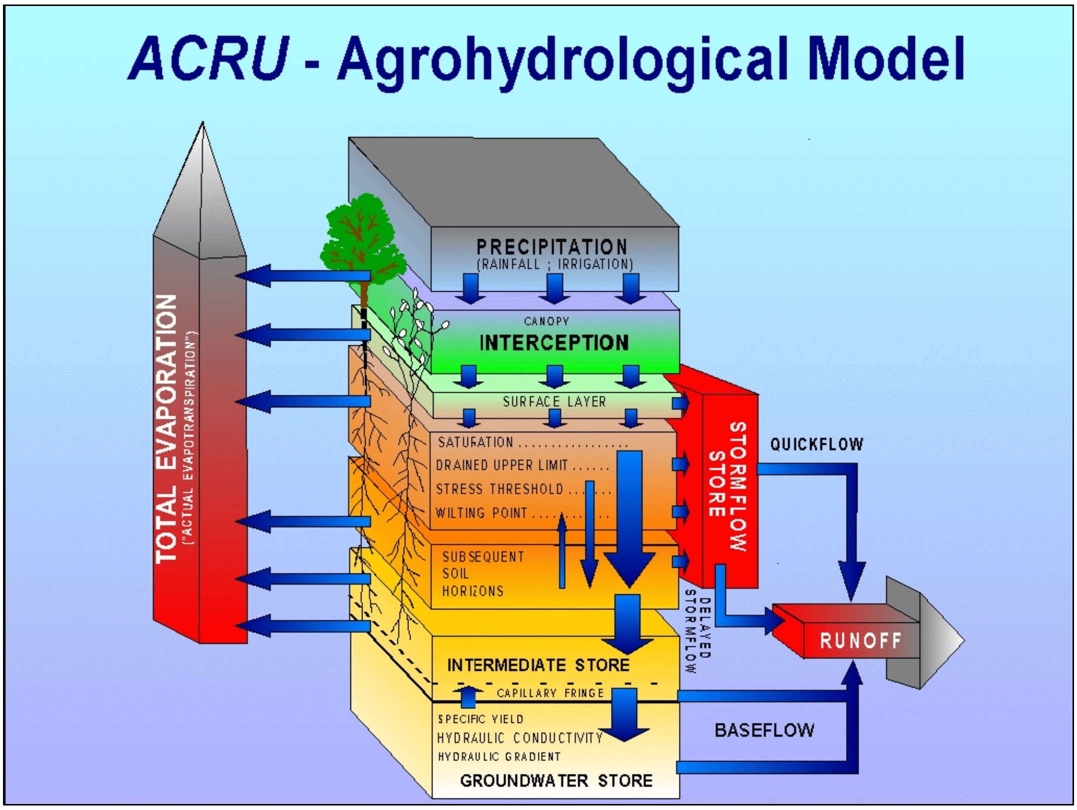


Figure 4.1 **The *ACRU* agrohydrological modelling system : general structure (after Schulze, 1995)**

The processes modelled on a daily basis using the ACRU model (as described by Kienzle *et al*., 1997) are as follows:

- Canopy interception of rainfall by vegetation,
- Net rainfall reaching the ground surface,
- Infiltration of net rainfall into the soil,
- Total evaporation (transpiration as well as soil water evaporation) from the various horizons of the soil profile,
- The redistribution of soil water in the soil profile (saturated and unsaturated), and
- Percolation of soil water into the immediate groundwater zone.

The concepts and uses of the ACRU model are depicted in **Figure 4.2**.

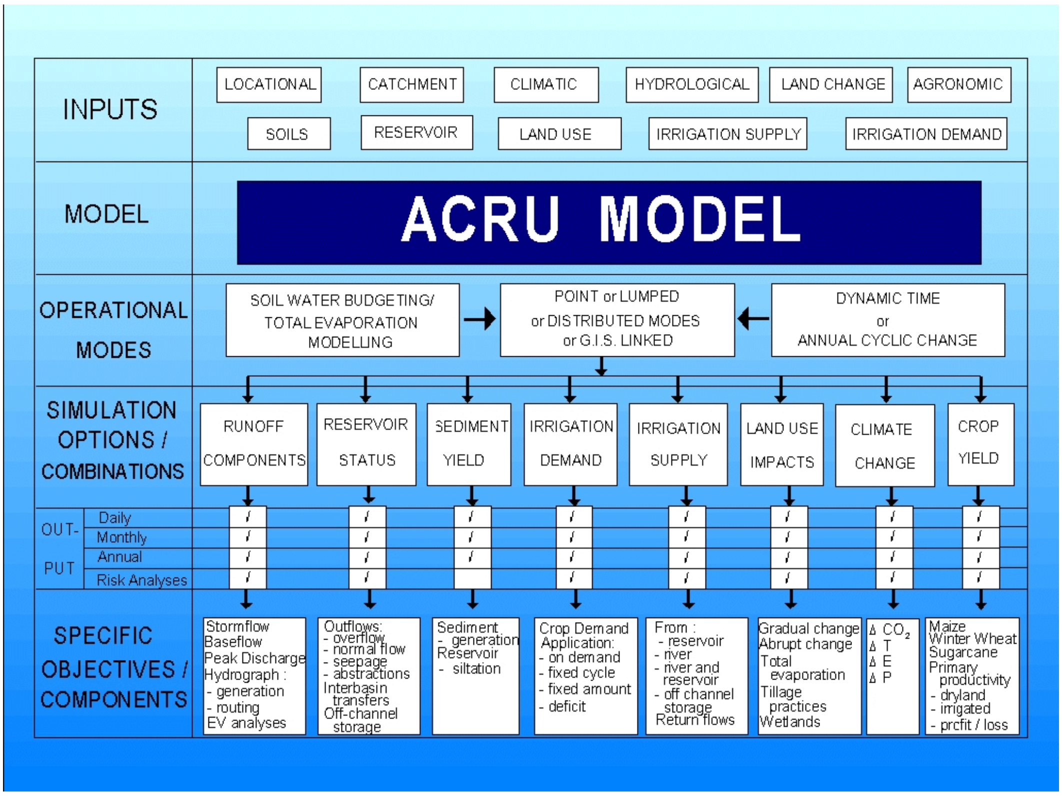


Figure 4.2 The *ACRU* agrohydrological modelling system : concepts (after Schulze 1995)

4.2 ACRU*SALINITY* CONCEPTS

The salt movement processes considered in ACRU*Salinity* are ***Initialising Salt Load***, ***Salt Input***, ***Surface Salt Movement***, ***Sub-surface Salt Movement***, ***Reservoir Salt Budget*** and ***Channel Salt Movement***. Operations of the aforementioned processes are described in the ensuing sections.

4.2.1 Initialising Salt Load

This process allows for the conversion of the user-specified inputs for initial soil concentration (in mg/l) to salt load, taking into consideration the volume of water in that soil layer.

4.2.2 Salt Input

This object contains algorithms that are responsible for salt load input from rainfall and irrigation water to the top-soil horizon of irrigated and non-irrigated lands as well as to reservoirs. Rainfall is the external salt input to non-irrigated lands and reservoirs, while irrigation water provides an additional source of salt input to irrigated lands. TDS concentration for rainfall is not always available and can therefore be specified as a constant value. Irrigation water TDS concentrations are more readily available and need to be specified on a monthly basis. The quantity of salt load added is the product of the added volume of water (rainfall and/or irrigation) and the salinity of the added water.

4.2.3 Surface Salt Movement

In response to understanding the salt mobilisation process in the Berg Catchment gained from the work of Fourie and Görgens (1977), as well as the current research by Fey *et al*. (2008), the following routines have now been included in ACRU*Salinity* for land segments with no irrigation.

- Additional surface layer of 10 mm depth,
- Dissolving a portion of the precipitated salts in the soil surface layer back into the solute state during an event, based on event contact time and soil characteristics,
- Mixing of salts in the soil surface layer with rainfall when calculating stormflow salinity, and
- Precipitation of dissolved salts in the soil layers if the salt concentration exceeds a maximum value.

These changes are detailed by Thorton-Dibb *et al*. (2005) in v1.2.5 of ACRU*Salinity.*

4.2.4 Sub-surface Salt Movement

ACRU*Salinity* is divided into vertical layers, *viz*. the top-soil and sub-soil together with a groundwater store and is based on the assumption that each layer is deep enough to store more volume of water than that percolated out of the particular layer for each day.

Teweldebrhan (2003) explained that in conceptualising the salinity module in ACRU*Salinity* careful consideration was given to the hydrological processes which led to a change in concentration of soil salinity, i.e. evaporation and transpiration. In the standard version of ACRU the water balance is active within the defined top-soil and sub-soil horizons. These horizons constitute the region of root development, soil water extraction/uptake and drainage. The soil water budgeting process (which is the main driving force for salt movement) as summarised by Teweldbrhan (2003) is modelled as follows:

- Stipulation of soil water content at total porosity, drained upper limit (DUL), and permanent wilting point for each active soil horizon,
- Re-assessment of soil water content after addition of net rainfall,
- If soil water content exceeds the DUL for the top-soil horizon, a proportion of the excess water is drained to the sub-soil horizon.

Similarly, if the soil water content of the sub-soil horizon exceeds the DUL for this horizon, a portion of the excess water drains to the groundwater store. Baseflow is then calculated as the product of the previous day's groundwater store and the user-specified baseflow recession coefficient. If drainage rates from the lower horizons are very low (low permeability rock), water can accumulate through the sub-soil and top-soil to eventually contribute to stormflow runoff, if the top-soil porosity is exceeded.

Unsaturated soil water redistribution can also be modelled. This slow movement of water will proceed from the top-soil horizon, when the soil water content is below its DUL, to the sub-soil horizon if the top-soil horizon is relatively wetter than the sub-soil horizon. Unsaturated redistribution depends on the soil water gradient, the head of water and soil texture. Upward soil water redistribution in ACRU mimics capillary movement, and takes place when the sub-soil horizon contains a higher relative soil water fraction compared to that of the top-soil (Schulze, 1995c).

Since the salt movement in ACRU*Salinity* is based on the routines in the Daily Irrigation and Salinity Analysis (DISA) (Görgens *et al*., 2001) model, it is controlled by the movement of water. More specifically, the movement of salt is dependent on the net movement of water between the layered soil profiles.

Sub-surface salt movement in ACRU*Salinity* can either be upwards or downwards. Downwards movement is dependent on the percolation of water from the top-soil horizon to the lower horizons while upward salt movement is dependent on saturated upward flow of water, i.e. when the water inflow rate to the bottom horizons is faster than the rate at which water is drained from this horizon.

Although the original ACRU model allows for the option of unsaturated water movement, the original salinity module in ACRU*Salinity* was not linked to this option and downward salt movement was only allowed to proceed once the DUL of the top-soil was exceeded. The later version (v1.2.5) (Thorton – Dibb *et al.*, 2005) of ACRU*Salinity* developed during a Water Research Commission (WRC) project (Rossouw *et al*., 2006), however, does allow for unsaturated salt movement, making surface salt accumulation possible. Algorithms for sub-surface salt movement were written assuming a multi-layered soil, even though ACRU only has two soil layers and a groundwater store, making it possible for additional layers to be added should the need arise. Even though sub-surface movement occurs in both irrigated and non-irrigated lands only the equations for the non-irrigated lands will be discussed in the ensuing sections as the two sets of equations are really identical.

Sub-surface salt movement in irrigated lands proceeds in a similar way except that a single horizon and the groundwater store are considered (this is ACRU's approach for irrigated lands). Additionally, since the irrigation months in ACRU are user-specified, the sub-surface salt movement algorithms in irrigated lands are only activated during those months.

Downward sub-surface salt movement

All salt balance calculations are only performed after all the hydrological processes have been calculated for a particular day. Salt loads in a particular horizon are only calculated after water percolation from a higher-to lower-lying soil horizon.

Upward sub-surface salt movement

In the model, upward salt movement through the soil profile and its influence on surface and sub-surface salt balance is determined by the upward salt transport algorithm. In this process, salt load moves from the bottom horizon through the overlying horizons to quickflow under a saturated condition. Hence, upward salt movement under this process occurs only if the rate of water recharge to a layer exceeds the rate of water loss from that particular layer.

In the version of ACRU*Salinity* (v1.2.5) used in this study the sub-surface salt movement is also linked to the unsaturated water movement to provide a more accurate account of salt movement.

4.2.5 Reservoir Salt Budget

Reservoir salt balances are performed on a daily basis considering all the inflow volumes and concentrations to the dam and assuming instantaneous mixing of dam contents.

4.2.6 Channel Salt Movement

Channel reach concentrations are calculated as the salt load in the channel reach divided by the volume in the channel reach for that day.

4.2.7 Salt Generation

The development of the salinity generation module (Teweldebrhan, 2003) in ACRU*Salinity* was essentially based on the "combined salt generation and mixing model" and adopts the first order approach proposed by Ferguson *et al.* (1994). In principle, this approach assumes that all the discrete steps involved in the weathering process can be captured in **Equation 1**, which indicates that the rate of change of the solute concentration is proportional to how far the current concentration (C) is from the equilibrium concentration (Ce) and equal, if a rate constant (k) is introduced.

$$\frac{\partial C}{\partial t} = k(C_e - C) \qquad \textbf{Equation 1}$$

For pre-selected high and low values of k the equation depicts higher and lower rates of "production" of solutes with a decrease in the rate as the equilibrium concentration is approached. The phenomenon is depicted in **Figure 4.3**.

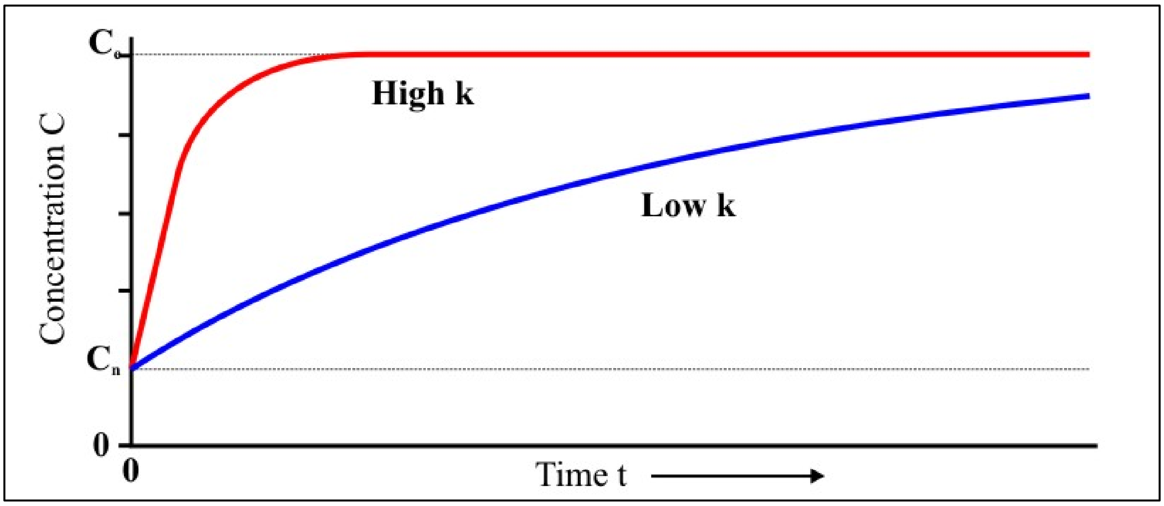


Figure 4.3 Salt generation curves (after Ferguson *et al*, 1994)

According to Ferguson *et al*. (1994) the concentration of the new water (C_n) can be estimated from TDS measurements of rainwater while the equilibrium concentration can be estimated from the river TDS measurements under low flow conditions and after a long spell of dry weather. It is further suggested that the rate constant (*k*) should be estimated from the rate of change in solute concentration (*C*) during an inter-event period after mixing has occurred. The proposed method would require a least squares, straight line regression fit of the differential form of the Nernst equation.

4.3 DETERMINATION OF SALINITY-RELATED PARAMETERS IN ACRUSALINITY FROM KINETIC THEORY

Ferguson *et al*. (1994) proposed that the rate constant (*k*) (see Equation 1) be determined from the rate of change in solute concentration after a rainfall event and after complete mixing. This approach is essentially an evaluation of kinetic data and according to Levenspiel (1972), a predefined rate equation (as is the case in the ACRU*Salinity* module of ACRU) could be subjected to the Differential or Integral methods of analysis. Both of these methods, in effect, provide mechanisms for evaluating the goodness-of-fit of the experimental data with the proposed rate equation.

4.3.1 Differential method of analysis

The steps required to implement this method are as follows (Levenspiel, 1972):

1. Define a rate equation (not necessary because it is predefined in ACRU*Salinity*).
2. From experimental data obtain a concentration-time plot.
3. Draw a smooth curve through the data and determine the slope of the curve at suitably selected concentration values. These slopes represent the rates of reaction at these concentration values.
4. Evaluate *f*(*C*) at each concentration.
5. Plot the rate of the equation $\partial C/\partial t$ versus *f*(*C*) at each concentration.

To illustrate the approach, the data set of TDS concentration after a rainfall event was considered. The best-fit curve though these data points are depicted in **Figure 4.4**.

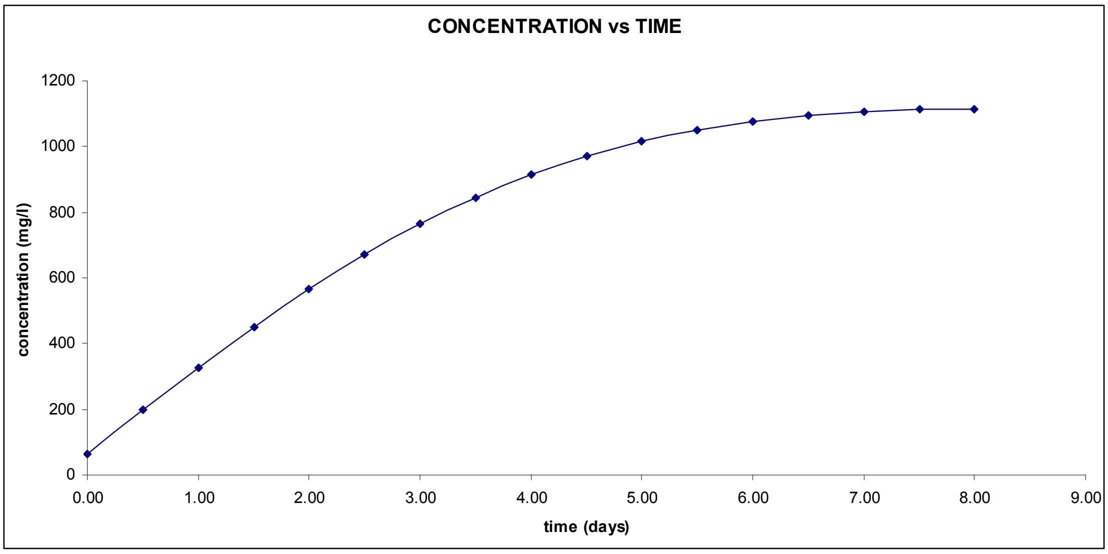


Figure 4.4 Change in streamflow TDS concentration after a rainfall event

In this particular example, the best-fit curve had a format which was amenable to analytical differentiation and as a result the slopes of the curve at various concentrations could be determined analytically. Based on the procedure outlined above, **Figure 4.5** was obtained. **Figure 4.5** shows a the best-fit straight line through the data which yielded values of 0.221 day^{-1} and 1496 mgℓ$^{-1}$ for k and C_e, respectively.

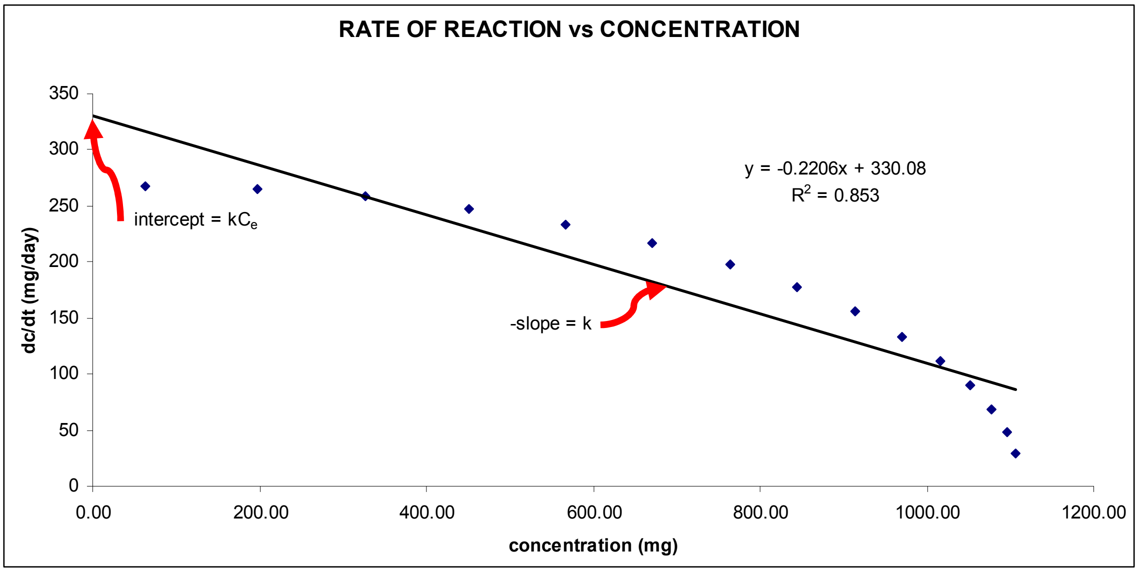


Figure 4.5 Rate of dissolution as a function of concentration

4.3.2 Integral method of analysis

Alternatively, an ***Integral Method of Analysis*** (Levenspiel, 1972) could be used. Integration of **Equation 1** for the time period (0 → t) and concentration ($C_0 \rightarrow C$) results in **Equation 4**.

$$c = c_0 + (c_e - c_0)\left[1 - \exp(-kt)\right]$$

Equation 2

where C_0 is the initial concentration at time t = 0.

In this method, the final plot is one in which $-\ln\left(\frac{Ce-C}{Ce}\right)$ vs t, from which the values of k and C_e can be determined. Using the same dataset as before, the resulting plot is shown in **Figure 4.6** which on visual inspection shows that k has a value of 0.203 day^{-1} and, after some manipulations, that C_e equals1591 mgℓ$^{-1}$.

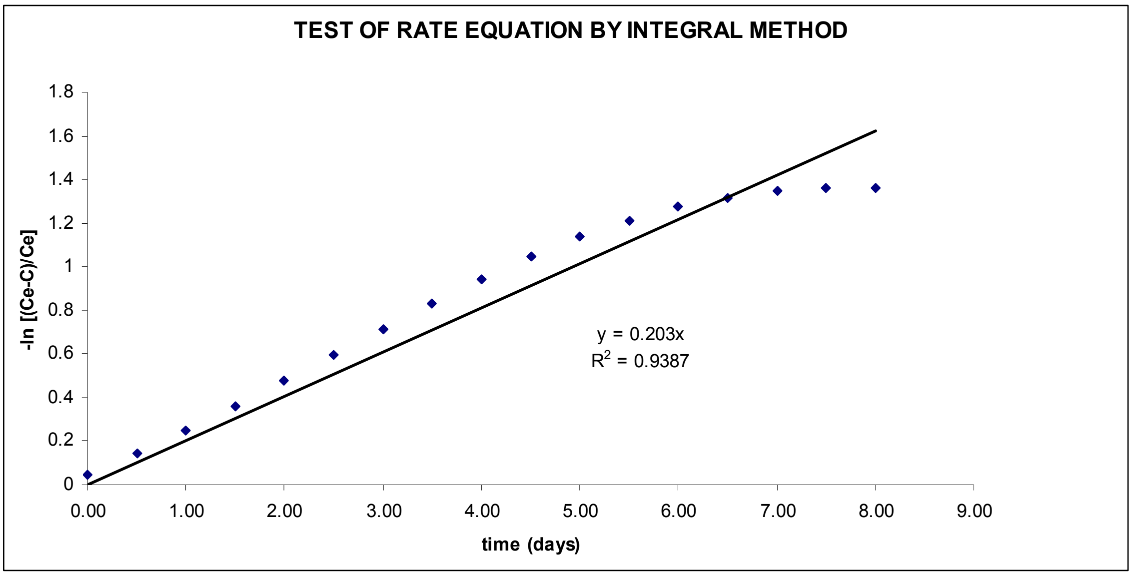


Figure 4.6 Test of rate equation by the integral method of analysis

It should be borne in mind that this treatment is normally reserved for highly controlled situations not subjected to the natural variations present in nature. However, despite the inevitable variability of natural systems, the aforementioned approaches still provide a reasonable and defendable way for providing first-order estimations of the most important parameters controlling the rate of dissolution in the ACRUSalinity model.

In this study, the aforementioned methods were used to obtain first estimates of the salinity values k and C_e, but were eventually combined with a calibration approach to produce simulated TDS concentrations that were representative of the observed. Notwithstanding this, the aforementioned approaches still provide valuable insights into the order-of-magnitudes which should be expected for these parameters. In this study the values of 0.413 day^{-1} a 1354.33 mg/l were used as starting values for k and C_e, respectively.

5. APPLICATION OF THE ACRUSALINITY MODEL FOR FLOW SIMULATIONS

5.1 DATA PREPARATION FOR THE ACRU MODEL

In general, it can be expected that a daily model, such as ACRU, has significant data requirements. In many cases the preparation of this information is the most time-consuming task in the modelling process. ACRU is also supported by a suite of pre-and post-processors that are useful in the preparation of the input information.

The major input parameters to ACRU per primary catchment includes daily rainfall, farm dam sizes and location and land-use data (e.g. vegetation type and area).

The following sections present not only the data requirements that were prepared for the modelling but also the pre-processor programs that were used in the preparation, as well as their availability to the model user.

5.1.1 Rainfall data

In this study the “driver station” approach was used to drive the runoff response of the catchment. In this approach, one station is selected to be representative of catchment rainfall. The selection of this station is based on:

- its proximity to the catchment,
- its altitude relative to the catchment's mean altitude,
- the length of the record, and
- the extent of missing data.

Missing data in the best driver station is replaced with data from the "next best" driver station. Correction factors[1] are then applied to the rainfall of each month in the driver station so that it is more representative of the daily areal catchment rainfall.

According to Schulze et al. (1995), the advantage of this method is the preservation of the statistical properties of this point rainfall and the fact that it is fairly straightforward to apply. The major disadvantage of the approach, however, is the over-simplification of the daily areal rainfall distribution, e.g. the method would presume that the temporal rainfall pattern experienced at that particular rainfall gauge was experienced throughout the catchment.

This method is recommended when:

- the aim of the study is for planning rather than operational hydrology,
- the catchment is smaller than 28 km^2 (Seed, 1992)[2],
- topography exerts little influence within the catchment.

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[1] The correction factor for each month is calculated as the ratio of the median monthly precipitation of the driver to median monthly precipitation of the catchment (Schulze, *et al*., 1995)

[2] Seed (1992) showed that the rainfall at a rain gauge may be considered representative of the area within a 3 km radius around the rain gauge.

For this study, the "Daily Rainfall Data Extraction Utility" program (Kunz, 2004) was used for prioritising the rainfall gauges that could be used for a specific sub-catchment. The prioritisation was based on the following criteria (as described in the output file of CALC_PPTCOR):

- record length of the station in years,
- MAP of the rainfall station compared to that of the sub-catchment,
- altitude of the station compared to the altitude of the centroid of the catchment,
- distance of the rainfall gauge from the centroid of the catchment,
- the number of out-of-range months, i.e. months where the correction factors are less than 0.70 or more than 1.30.

This utility also had the built-in functionality which allowed the user to match the most appropriate rainfall station (driver rainfall station) to the co-ordinates of interest, i.e. the centroid of the catchment.

A map showing the locations of “driver stations” used in this study is included in **Appendix A**. Rainfall data for most of the driver rainfall stations used in this study could not be updated to 2008 since these weather stations had been closed (SAWS, 2008).

5.1.2 Land-use information

Land-use information was obtained from the Department of Agriculture (Elsenberg office) which was available at a 2000 level of development. This land-use information is depicted on a map included in **Appendix B**.

In this study, the GIS coverage of the relevant primary sub-catchments (shown in **Appendix C**) was intersected with land-use information obtained from the Department of Agriculture to produce further sub-divisions of each primary sub-catchment., i.e. pseudo sub-catchments. For example, if primary sub-catchment 1 was made up of maize, lucerne and natural veld, it would result in three pseudo-sub-catchments after the intersection process. It should be noted that the irrigated areas were indicated only as "cultivated, permanent, commercial, irrigated" or "cultivated, temporary, commercial, irrigated" with no indication of the crop type. This information was therefore deemed unsuitable for use in its raw form.

In recognition of the actual variation in planted crop types, the spilt in irrigated areas (as provided by the Department of Agriculture) was based on a previous estimate provided by Mr Andreas Engelbrecht (CEO of the Great Fish River Water Users Association). These estimates, based on the results of an in-house survey, assumed that the following split was representative: 50% lucerne, 40% maize and 10% wheat. The aforementioned split in crop types was also assumed representative of the areas belonging to the Great Fish River Water User’s Association (GFRWUA) (Mullineux, 2008).

Land cover Information for present day crops and sugar beet

Information on the crop factors, leaf area indices, canopy interception losses and the fraction of the effective root system in the topsoil horizon for lucerne, maize and wheat was obtained from the ACRU database (i.e. User’s Manual).

However, since a constant split between the abovementioned crops was assumed, area-weighted crop factors could be calculated. These are shown in **Table 5.1**.

Table 5.1 Land cover information used

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Crop factors												
Lucerne	0.3	0.4	0.5	0.7	0.8	0.8	0.8	0.8	0.7	0.5	0.4	0.3
Maize	1.1	0.95	0.46	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.49	0.98
Wheat	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.5	0.6	0.4	0.2
Area Weighted	0.61	0.6	0.45	0.45	0.5	0.5	0.5	0.5	0.48	0.39	0.44	0.56
Leaf Area Indices												
Lucerne	3	2.5	4.05	0.65	0.4	0.4	0.4	0.5	0.65	1.2	3.6	4
Maize	3.5	5.1	1.8	0	0	0	0	0	0	0	0.2	0.7
Wheat	0	0	0	0	0	0.5	1.8	2.1	5	5.3	3.2	0
Area Weighted	2.9	3.29	2.745	0.325	0.2	0.25	0.38	0.46	0.825	1.13	2.2	2.28
Canopy interception loss												
Lucerne	1.4	1.4	1.4	1.4	1.2	1	1	1.2	1.3	1.4	1.4	1.4
Maize	1.5	1.4	1.3	1.2	0.5	0.5	0.5	0.5	0.5	0	0.5	0.9
Wheat	0.5	0.5	0.5	0.5	0	0.4	0.4	0.5	0.9	1.5	1.4	0.5
Area Weighted	1.35	1.31	1.27	1.23	0.8	0.74	0.74	0.85	0.94	0.85	1.04	1.11
Fraction of the effective root system in topsoil horizon												
Lucerne	0.8	0.8	0.8	0.9	1	1	1	1	0.9	0.9	0.8	0.8
Maize	0.74	0.78	0.91	1	1	1	1	1	1	1	0.92	0.79
Wheat	1	1	1	1	1	0.95	0.9	0.65	0.5	0.4	0.4	1
Area Weighted	0.79	0.81	0.864	0.95	1	0.99	0.99	0.96	0.9	0.89	0.81	0.82

Land cover information for sugar beet was not readily available and several approaches for estimating crop factors, in particular, were used. These are:

- Crop factors obtained from the SAPWAT (Van Heerden *et al*., 2001) program, and
- Crop factors obtained from Food and Agriculture Organisation (FAO) methods.

Crop factors obtained from SAPWAT

The monthly crop factors obtained from the SAPWAT program were based on the following selection criteria:

- In the vicinity of the Cradock weather station,
- A climatic region which is arid to semi-arid with hot summers, and
- a growing season which started in August.

According to the outputs from the SAPWAT program, the growing season for sugar beet would last for 9 months with monthly crop factors as indicated in **Table 5.2**.

Table 5.2 Crop factors for sugar beet (from SAPWAT)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Sugar beet	1.15	1.15	1.15	0.04	0	0	0	0.46	0.63	0.97	1.15	1.15

Crop factors obtained from the FAO methods

In the application of this approach it is assumed that the crop coefficient curve would be of the form shown in **Figure 5.1**.

The symbols $K_{c\ ini}$, $K_{c\ mid}$ and $K_{c\ end}$ in **Figure 5.1** represent the crop factors at the initial, middle and end of the growth season respectively. In accordance with the FAO approach, the values used for $K_{c\ ini}$, $K_{c\ mid}$ and $K_{c\ end}$ were 0.35, 1.2 and 0.7 respectively for sugar beet.

Also according to the values specified in the FAO approach, the corresponding length of the various crop development stages, i.e. Initial ($L_{ini,}$), crop development (L_{dev}), mid-season (L_{mid}) and late season (L_{late}) were 25, 30,25, 10 and 90 days respectively. Summing to these lengths indicates a growing season of only 90 days as opposed to the 10 months to 1 year claimed by Sugar Beet SA (Sugar Beet Newsletter, 2005).. To mimick the growing period of 10 months the lengths of the various crop development stages were increased to 83,100, 83 and 83 days, respectively for the modelling exercise.

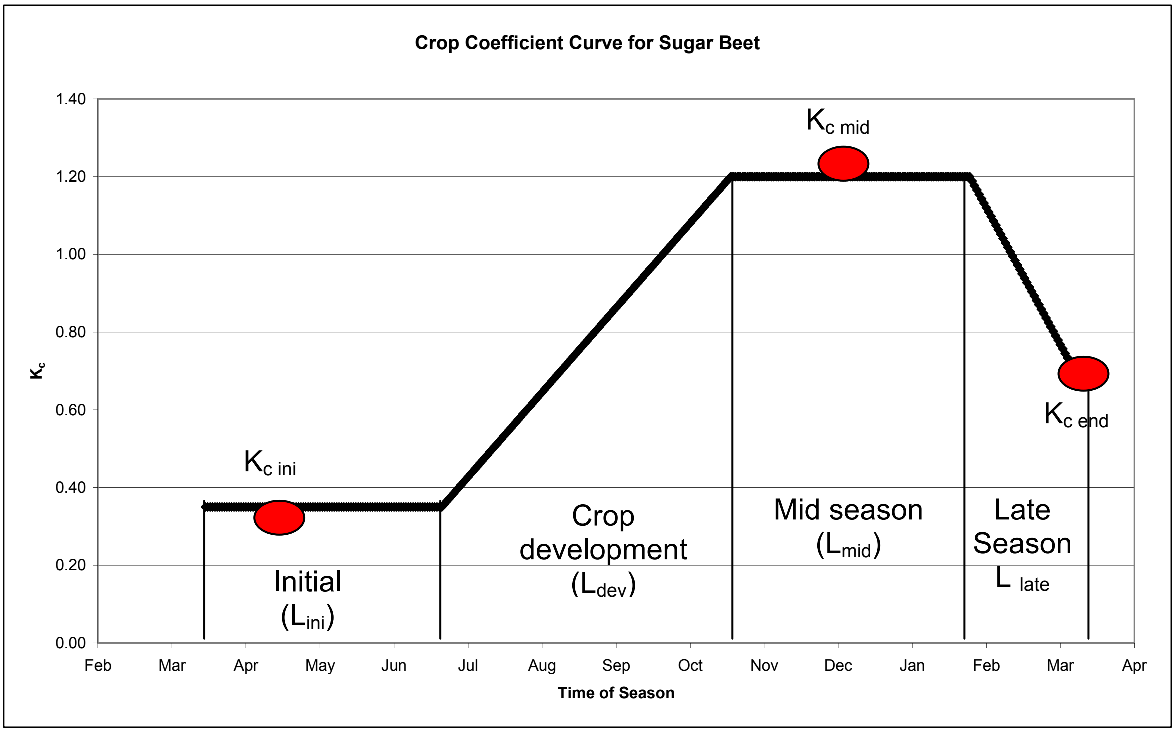


Figure 5.1 Crop coefficient curve

The crop factors obtained for sugar beet using the above approach are shown in **Table 5.3**.

Table 5.3 Crop factors for sugar beet using a modified FAO approach

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
crop factors	1.00	0.97	0.73	0.29	0.29	0.29	0.34	0.52	0.69	0.88	1.00	1.00

The calculation leaf area indices were based on the approach by Kristensen (1974) and these are shown in **Table 5.4**.

Table 5.4 Leaf area indices for sugar beet

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Leaf Area Index	3.29	2.82	1.18	0.00	0.00	0.00	0.09	0.49	1.05	1.98	3.29	3.29

Plant canopy interception losses were determined internally in the ACRU model on an event-by-event basis using the Von Hoyningen-Huene equation. The fraction of the effective root system which is located in the topsoil horizon was assumed at 0.7.

5.1.3 Farm dams

The surface areas of farm dams were obtained from the land-use coverage of the Department of Agriculture. Since no information on volumes of these farm dams were readily available, the volumes of these were based on the following equation:

$$Area = A.Capacity^{B}$$

Where,

Area = km^2 and
Capacity = Mm^3
A,B = Constants

In this study the constants A and B were assumed to be equal to 0.5.

5.1.4 Irrigation boards

No GIS coverage depicting the location of the various irrigation boards was available and as such, this information was inferred from other sources of information. The approach adopted to estimate the approximate positions of irrigated areas within an irrigation board was achieved as follows: The description of the properties which constitute the various irrigation boards were obtained (DWAF, 2007) and the farm boundary for each of these properties were then plotted. The resulting farm areas were then intersected with the primary sub-catchment boundaries and the Department of Agriculture's land-use coverage to ascertain the position of the irrigated areas relative to these primary sub-catchments and to assign the irrigated areas to an irrigation board. This process was deemed important since the depths of irrigation could be determined based on the estimated irrigated areas within the irrigation board.

The irrigated areas estimated for the various irrigation boards within the area of concern are as listed in **Table 5.5**.

Table 5.5 Estimated irrigated areas within the study area

Irrigation Board	Area under irrigation (km^2)
Baroda	21.5
Groot Vis	2.8
Marlow (includes Halesowen)	13.69
Mortimer	17.30
Scanlan	21.14
Tarka	14.6
Total	**91.03**

5.1.5 Irrigation application depths and losses

Daily canal flow rates were obtained from the DWAF website and were assigned to the supply of the various irrigation boards as indicated in **Table 5.6**. The Groot Vis area was not considered since the Tarka River inflow at Q4H013 was used as a specified inflow in the model.

Table 5.6 Canals supplying Irrigation Boards

Canal abstraction point	Irrigation Board Supplied
Supplied from outside the study area	Baroda
Q3L005	Marlow
Q5L005	Mortimer
Q3L015	Scanlan and Tarka

Irrigation depths for the irrigated areas within a particular irrigation board were determined by apportioning the daily volumetric canal abstraction according the ratio of the irrigated area within a pseudo sub-catchment to the total area of the irrigation board. This can be represented as follows:

$$\frac{Vol_{canal\_abs} \cdot \dfrac{Area_{irrig}}{Area_{IB}}}{Area_{irrig}}.3600.24$$

Where,

Vol_{canal_abs} = volumetric flow rate of the canal abstraction (m^3/s)
$Area_{irrig}$ = pseudo sub-catchment irrigated area (m^2)
$Area_{IB}$ = total area of the irrigation board (m^2)

In the above approach the volumetric flow rate abstracted at the canal is equal to the volume of water applied for irrigation in the respective irrigation boards.

Losses in water in transferring from the point of abstraction were accounted for as follows:

Conveyance losses = 15%
Farm dam losses = 10%
Irrigation losses = 10%

According to the SAPWAT program, the irrigation depths required to achieve maximum yield of a mixed crop type dominated by lucerne are as shown in **Table 5.7**.

Table 5.7 Irrigation water requirements to achieve maximum yield of a crop type dominated by lucerne (mm)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Monthly irrigation depths	297	232	191	137	83	54	70	101	159	209	241	277

5.2 DELINEATION OF THE FISH RIVER BASIN

The delineation of the sub-catchments of interest is probably one of the most important steps in the configuration of the model.

To facilitate the process of catchment delineation two terms were defined:

- ***Primary sub-catchment*** – a sub-catchment that is located within the confines of natural watersheds or within the confines of natural watersheds and the Fish River mainstem.
- ***Pseudo sub-catchment*** – a sub-catchment that consists of a particular land-use and that is not necessarily confined within natural watersheds, e.g. irrigated grapevines, dryland crops or natural vegetation.

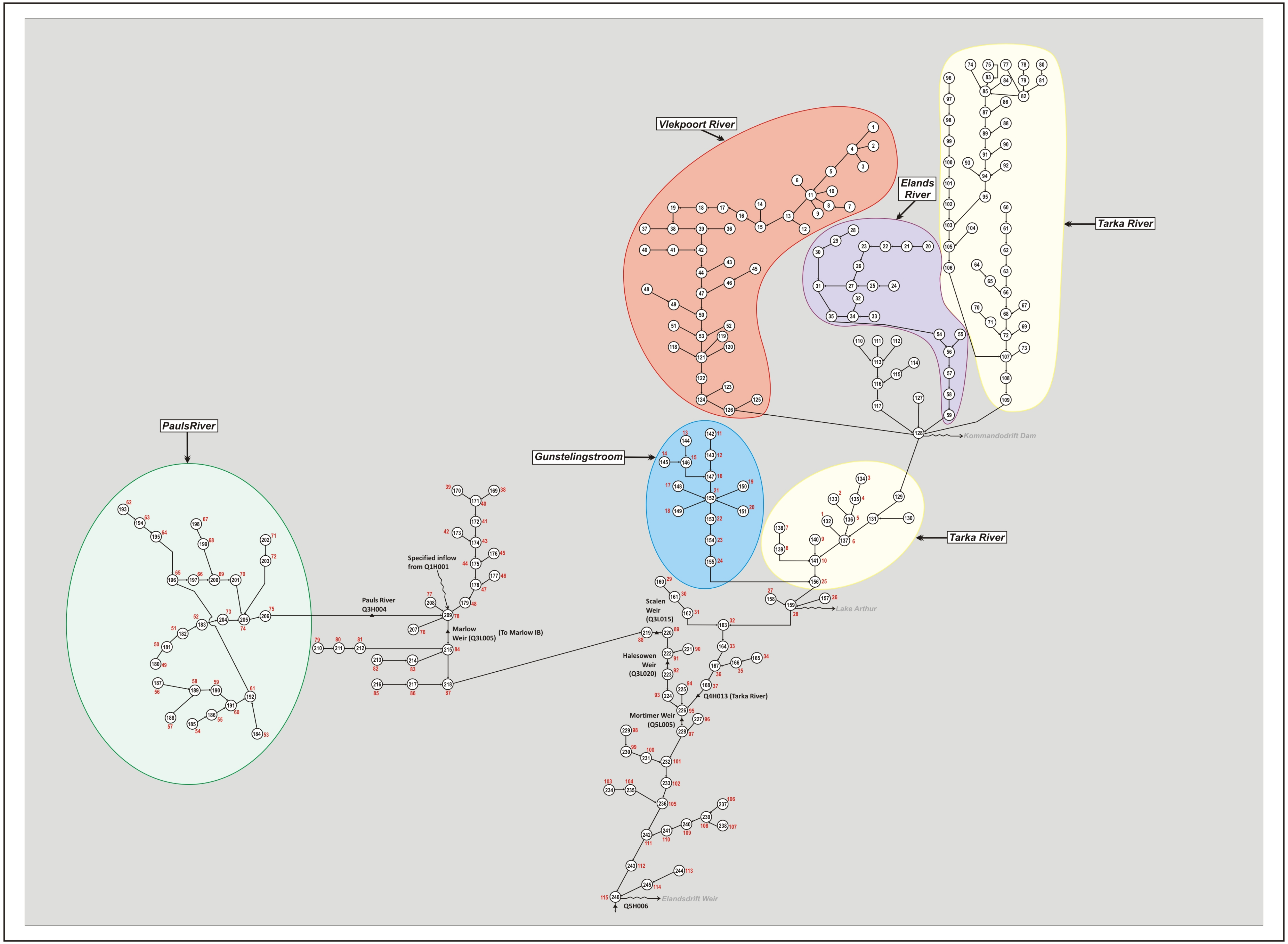
Only one rainfall file can be used per primary catchment and it was therefore important to recognise areas that had a distinctly different MAP from the rest of the catchment, at an early stage in the configuration.

Criteria used for the delineation of the sub-catchment are as follows:

- points of interest, e.g. gauging stations with acceptable observed flow records,
- discharge points of tributaries into the Fish River mainstem, and
- areas with a distinctly different MAP compared with other zones in the rest of the catchment.

Based on the guidelines provided in the ACRU user's manual (Smithers and Schulze, 1995) the primary sub-catchments were delineated to have an approximate area of 50 km^2. This process resulted in the formation of 246 primary catchments which are depicted in **Figure 5.2.** Significant gauged tributaries which confluence with the Fish River include the Pauls River (Q3H004) and the Tarka River (Q4H013). The delineation of the catchment is shown in **Appendix C**.

The delineation process was also guided by the location of flow gauging stations and canal abstraction points. The system layout for the sub-catchment is depicted in **Figure 5.2**.



I:/hydro/402448.../photos and graphics/graphics/flowdiagram.cdr

Figure 5.2 ACRU system layout for the Fish River Basin for area of interest

5.3 SALINITY SCENARIO RUNS WITH THE ACRUSALINITY MODEL

5.3.1 Salinity model run – base case

As was previously mentioned, the rainfall data could not be updated to 2008 since most of the rainfall stations, intended for use as driver rainfall stations, had been closed since 1999. Additionally, the information on abstraction volumes for the various canals supplying the irrigation boards were only available from 2000 onwards and therefore did not overlap with the period of available rainfall data. To overcome this, the abstractions were assumed to occur during the period 1990 to 2000 with all other inputs to the model remaining unchanged. The crop factors used for the assumed crop mix are shown in **Table 5.8**.

Table 5.8 Area weighted crop factors used for the current crop mix in the Fish River

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Crop factor	0.61	0.6	0.45	0.45	0.5	0.5	0.5	0.5	0.48	0.39	0.44	0.56

Since a one-to-one daily comparison of TDS concentrations was not practical, a comparison based on percentage exceedence was opted for. This approach is currently used as part of the Basin Salinity Management Strategy for controlling salinity in the Murray-Darling basin in Australia, where salinisation of the rivers has become a major threat to agricultural activities. A key feature of the strategy is the adoption of TDS concentrations as well as percentage allowable exceedence of this concentration, as indicators of the measure of success of the strategy (Rossouw *et al*., 2006).

The irrigation depths for the various irrigated areas within the irrigation boards varied on a daily basis. This daily irrigation depth, however, was calculated as follows:

$$Irrigation\_Depth = \frac{Vol_{canal\_abs} \cdot \dfrac{Area_{irrig}}{Area_{IB}}}{Area_{irrig}} .3600.24.1000$$

Where,

Vol_{canal_abs} = volumetric flowrate of the canal abstraction (m^3/s)
$Area_{irrig}$ = pseudo sub-catchment irrigated area (m^2)
$Area_{IB}$ = total area of the irrigation board (m^2)
Irrigation Depth = depth of irrigation (mm/day)

5.3.2 Scenario runs for sugar beet

Scenario 1

This scenario was specifically configured to test the effect of changing all the irrigated areas to sugar beet on the irrigation return flow salinity. The change in return flow salinity will be assessed relative to the base case scenario.

In this scenario it was assumed that all irrigation in the catchment was under sugar beet but that the irrigation water application (and irrigation depths) would be the same as those used in the *base case run*. Crop factors used for this run were based on the methods suggested by the Food and Agriculture Organisation (FAO) (FAO, 2008) but modified such that the growing season equalled 10 months, to match the expected growth season for the study area.

The crop factors used are as listed in **Table 5.9.** All other input parameters remained the same.

Table 5.9 Crop factors for sugar beet obtained from a modified FAO method

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Crop factor	0.62	0	0	0.29	0.29	0.3	0.46	0.68	0.9	1	1	0.98

Scenario 2

This scenario has specifically been configured to test the effect of changing the crop factors of sugar beet on the irrigation return flow salinity. The change in return flow salinity will be assessed relative to the base case scenario and scenario 1.

This scenario is based on scenario 1, except that the crop factors were obtained from the SAPWAT (WRC, 2001) program. These crop factors are listed in **Table 5.10**.

Table 5.10 Crop factors for sugar beet obtained from the SAPWAT program

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Crop factor	1.15	1.15	1.15	0.04	0	0	0	0.46	0.63	0.97	1.15	1.15

Scenario 3

This scenario has specifically been configured to the test the effect of increased irrigation depths on irrigation return flow salinity.

This scenario is based on Scenario 2, but assumes that the irrigation depths applied are those required for maximum sugar beet yield. These irrigation depths were also obtained from the SAPWAT program and are as listed in **Table 5.11**.

Table 5.11 Monthly irrigation depths required for maximum sugar beet yield (mm)

	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Irrigation depth in mm	443	348	297	8	0	0	0	88	157	288	370	434

The irrigation depths in **Table 5.5** have been calculated taking into account the effective monthly rainfall for the region and assuming a maximum loss of 25% in the amount of water between the points of abstraction and application.

The daily irrigation depths are as indicated in Table 5.12.

Table 5.12 Daily irrigation depths required for maximum sugar beet yield (mm)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Irrigation depth in mm	14.2	12	9.6	0.3	0	0	0	2.8	5.2	9.3	12.3	14

It should be noted that this scenario did not take the maximum allowable quota (13 500 m^3/ha/a) into account. However, the irrigation demand resulting from these irrigation depths were accounted for in the model.

Scenario 4

This scenario was specifically configured to test the effect of replacing 5 000 ha of existing crops with sugar beet on the return flow salinity.

In this scenario it was assumed that 5 000 ha of existing crops would be replaced with sugar beet and that the allowable quota (i.e. 13 500 m^3/ha/a) would be used in an attempt to maximise the yield of sugar beet. In particular, the irrigated crops in the Baroda, Marlow and Mortimer irrigation boards were replaced with sugar beet.

Calculations revealed that the daily irrigation depths in Table 5.12 would require application of approximately twice the quota available to these irrigation boards. Since no extra water would be made available for the sugar beet cultivation, it was necessary to reduce the irrigation depth by 50% to ensure that the quota was not exceeded.

The crop factors used in this run are those obtained from the SAPWAT program.

5.4 RESULTS AND DISCUSSION

The comparison between the simulated and observed exceedances for TDS concentrations at Elandsdrift weir is shown in **Figure 5.3** which shows that TDS values between 1 250 mg/l and 500 mg/l are over-estimated by the simulated values while values above 1 250 mg/l and below 500 mg/l are under-estimated by the simulated values.

Because the flow-routing option in ACRU*Salinity* was not activated, a 1:1 daily comparison of flows and TDS concentrations, based on values of statistical parameters was not possible.

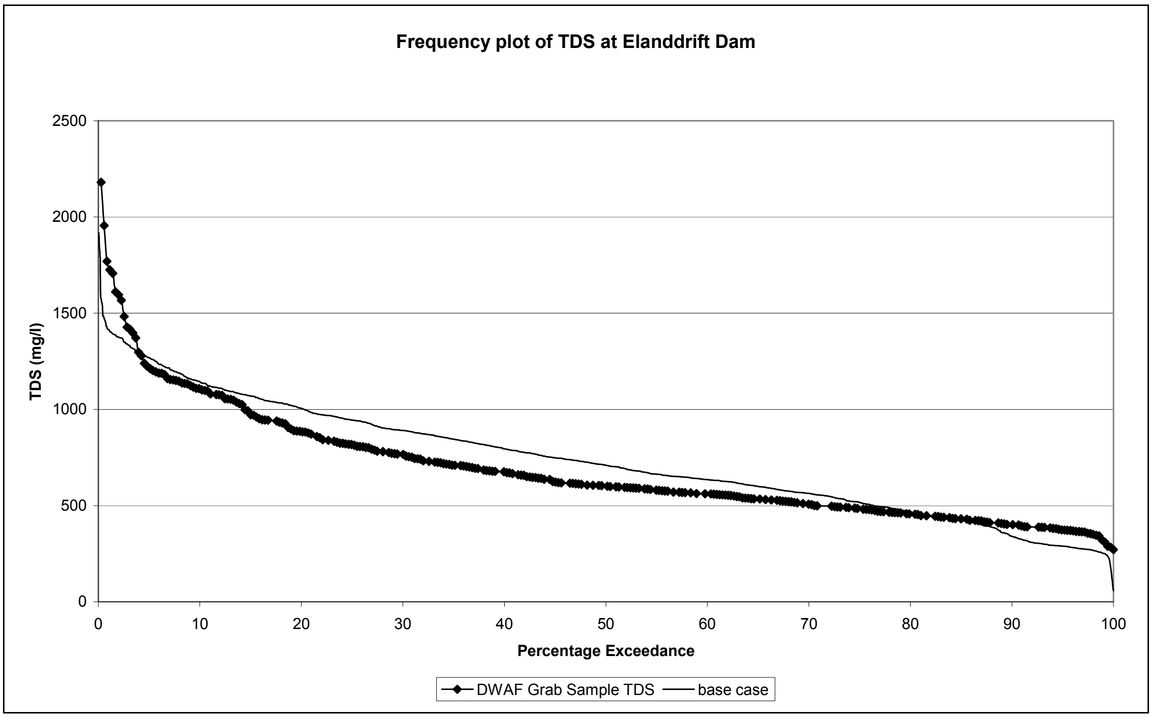


Figure 5.3 Exceedance of simulated and observed daily TDS at Elandsdrift weir

The comparison between the base case and the defined scenarios is depicted in **Figure 5.4**, which shows that an increased application volume, as is the case for Scenarios 3 and 4 would lead to increased mobilisation of salts to the mainstem of the Fish River. Typically, it could be expected that a TDS concentration of 1 500 mg/l would be exceeded for 20% of the time, increasing the percentage exceedance from less than 5%, as seen under the current conditions.

The increase in TDS concentration with an increase in irrigation could be related to the selection of final parameter values of 0.1 and 9 000 for *k* and C_e, respectively. Since the contribution of irrigation return flow salinity, in the model, is determined by the rate of dissolution and the available carrying capacity to transport these dissolved salt, it can be hypothesised that the availability of carrying capacity is probably the limiting step in the salinisation process. The added carrying capacity in the form of increased irrigation depths, removes this limitation – resulting in increased mobilisation of dissolved salts.

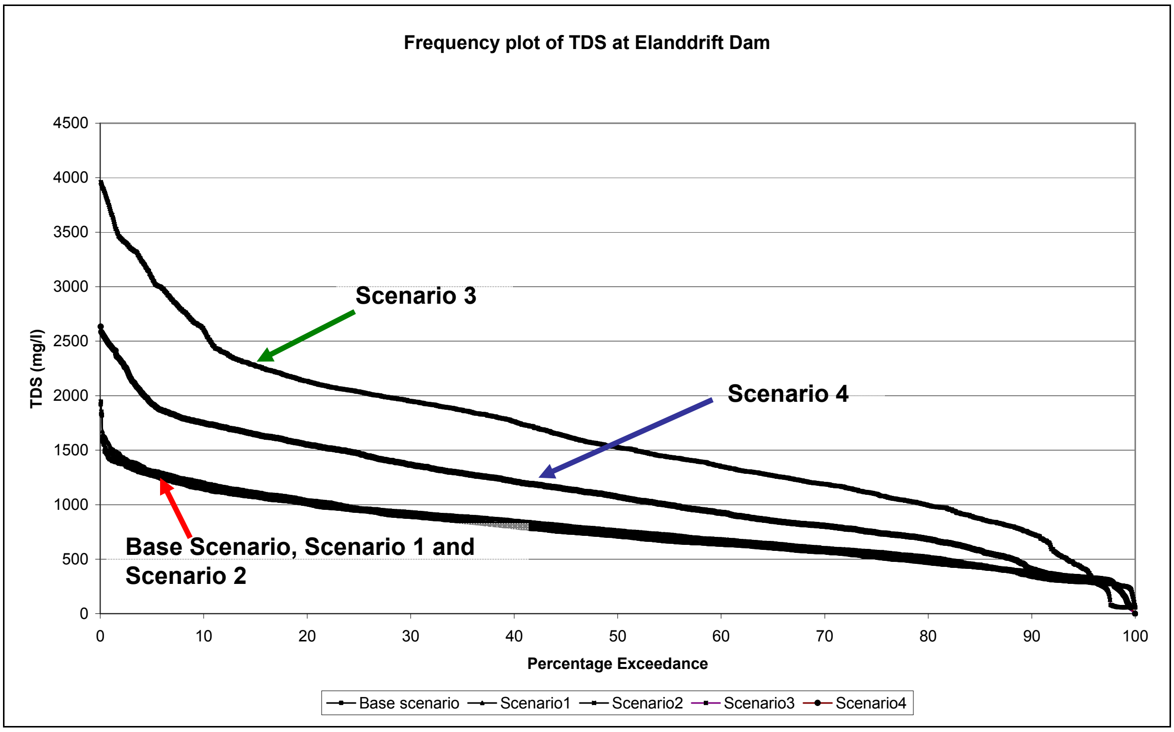


Figure 5.4 Exceedances of simulated daily TDS concentrations for the various sugar beet scenarios

6. CONCLUSIONS

Based on the results and discussion above the following can be concluded

- The replacement of 5 000 ha of existing crops in the Fish River Basin could result in a substantial increase in the TDS concentrations of the Fish River mainstem if the maximum allowable allocation is utilised.

- The modelling results suggest that the increased irrigation depths that will be required to achieve near maximum yields of the sugar beet will be the determining factor in the mobilisation of salts and not specifically the irrigation of the sugar beet crops. If current day irrigation depths are maintained it is likely that the TDS concentrations of the return flow would not increase significantly.

- The main objective of the sugar beet venture is the maximise yield for bio-ethanol production. In recognition of this it is more than likely that the irrigation boards would use more of the allocation for irrigation to achieve the maximum yield.

- The annual irrigation requirement to achieve maximum yield with the current crop types are only 15% less than the requirement to achieve maximum yield with sugar beet (this is based on the observation that currently the Irrigation Boards use less water than what is allocated to them). Outputs from the SAPWAT programme, however, suggested that more water would be required to achieve maximum yields of the current crops. Considering that the water is available, it was unclear why it is not used to maximise yields. Perhaps the decision not to achieve maximum yield was based on other factors which still have to be highlighted (e.g. loss of colour, loss of sweetness etc.). Also, if some of the fields are replanted with sugar-beet, the farmers will certainly aim for higher yields (it is assumed that bigger yield = bigger biomass = bigger profits) and this could compel them to use their full quota, resulting in more irrigation return flow.

- The rotational irrigation effect was not modelled because 5 000 ha sugar beet would exist at some location in the study area. It was therefore assumed that the effect of the sugar beet cultivation would only be shifted higher up or lower down on the Fish River mainstem.

7. RECOMMENDATION

Based on the discussion and conclusions the following recommendations can be made:

- A survey of the irrigated areas and crop types of the Fish River basin should be undertaken and maintained on a GIS database to enable the use of accurate landuse data in modelling studies.

- An optimum irrigation depth, which would compromise between achievable yield of sugar beet and the extent of TDS mobilisation, should be established. This could be achieved by completing additional scenario runs in which the daily irrigation depths are reduced until an acceptable TDS exceedance percentages are obtained. The monthly irrigation depth obtained from this exercise should then be tested to ascertain what the achievable yield of sugar beet would be.

- Realistic estimates of crop factors, leaf area indices, interception losses by vegetation and fraction of the effective root depth in topsoil horizon for sugar beet should be obtained. This would enable the determination of more accurate consumptive water use by the crop.

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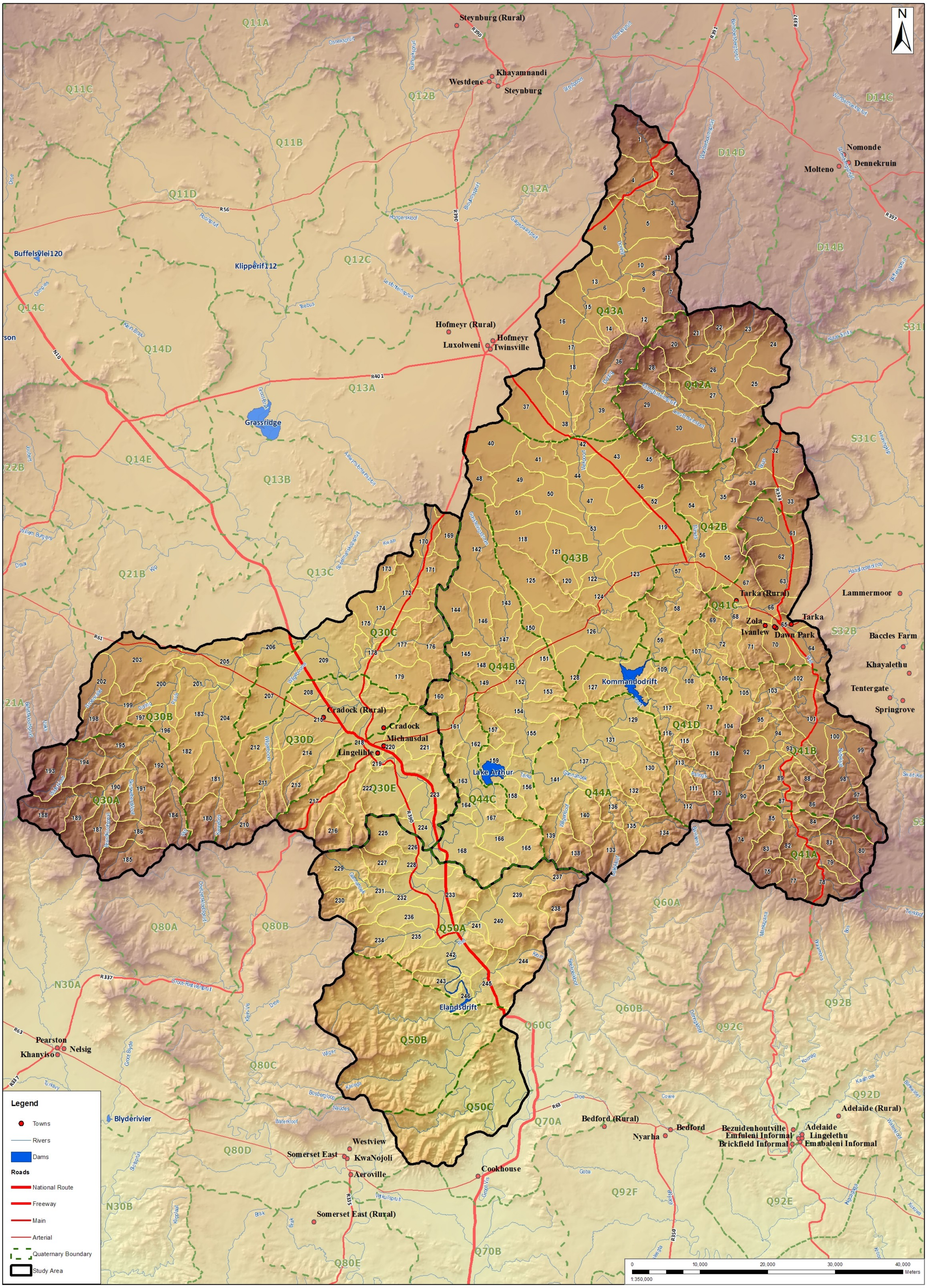
APPENDIX A

Driver Rainfall Stations



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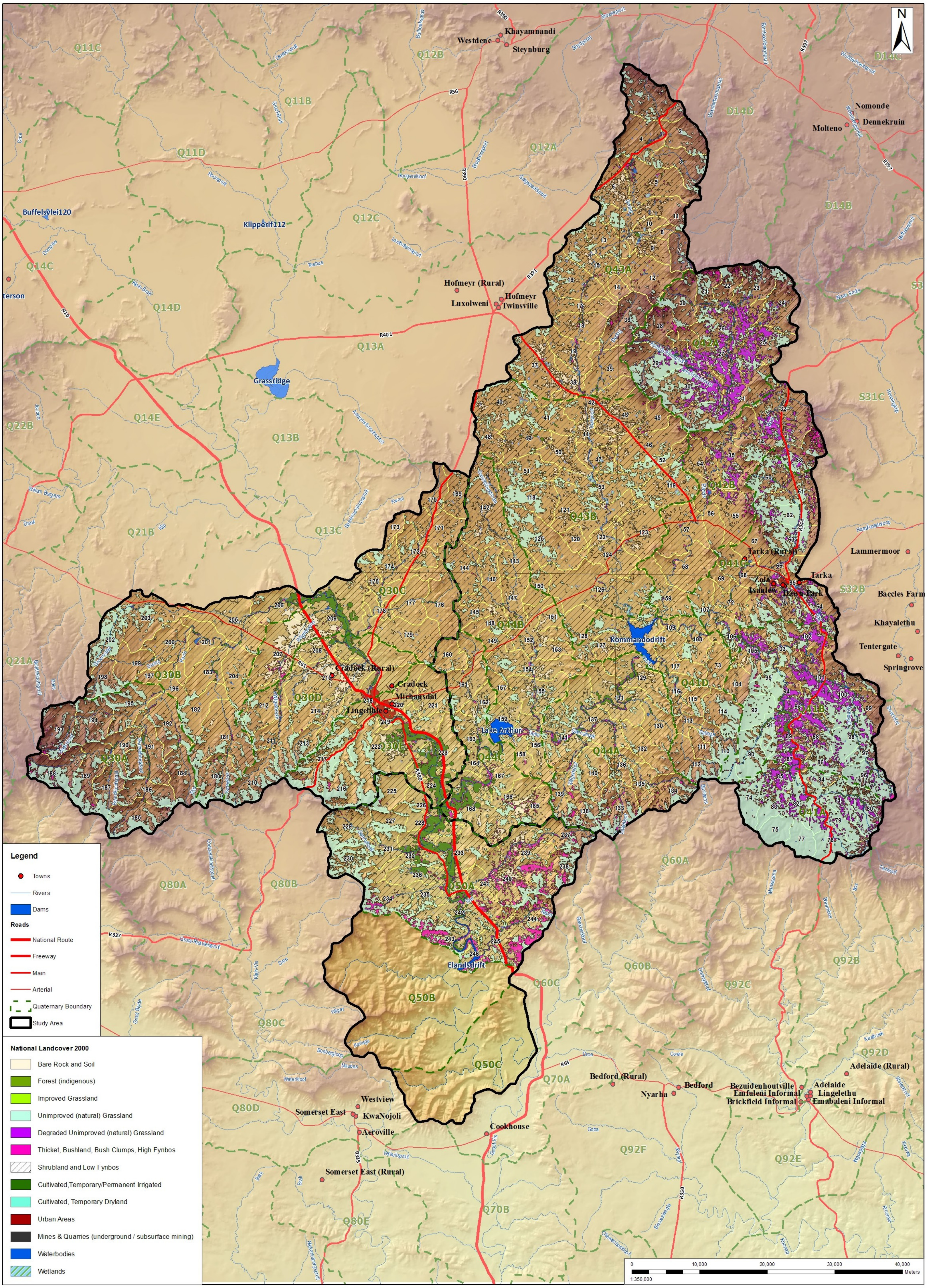
APPENDIX B

Land-use Information



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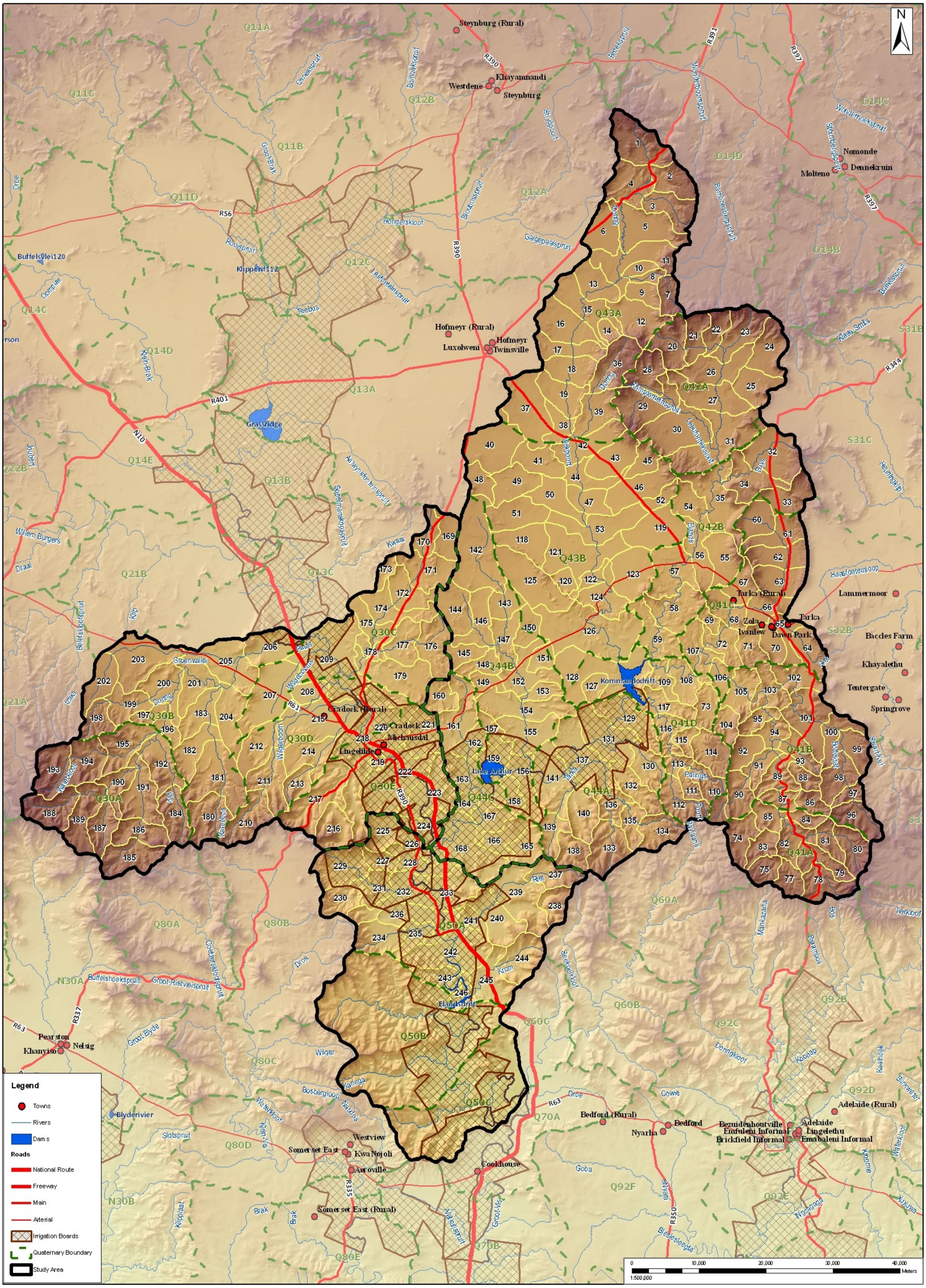
APPENDIX C

Delineation of Catchment



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Water Reconciliation Strategy Study for the Algoa Water Supply Area

Study Reports

Report Name	DWA Report Number	NS Report number
Impact of Changed Crops on Water Quality in the Great Fish River	WMA 15/ M00/00/1409/01	5004
Preliminary Reconciliation Strategy	WMA 15/M00/001409/02	5005
Inception	WMA 15/ M00/00/1409/03	5006
Reconciliation Strategy (future)	WMA 15/ M00/00/1409/04	5007