# Water Research Commission
Working Group for Mineralization

SUMMARY REPORT



# STUDIES OF MINERALIZATION IN THE GREAT FISH AND SUNDAYS RIVERS



Pretoria April 1985

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# STUDIES OF MINERALIZATION IN THE GREAT FISH AND SUNDAYS RIVERS

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formerly of the
National Institute for Water Research
Council for Scientific and Industrial Research



Pretoria April 1985

# FOREWORD

Over the past twenty to thirty years the salinity of a number of South African rivers has increased so significantly as to present serious problems to various users of the waters. Along the Witwatersrand and on the coal fields of the Eastern Transvaal and parts of Northern Natal saline discharges from both point and diffuse sources, usually associated with mining and industrial activity, have been largely responsible for these increases in salinity, but mineralization (salinization) from natural non-point sources has also played a deleterious role in rivers draining certain semi-arid catchment areas. Among the latter rivers are the Berg, Breë and Olifants of the Western Cape and the Fish, Sundays, Bushmans and Kowie of the Eastern Cape Province.

The significance of the effects of non-point mineralization is illustrated by the serious damage to apricot orchards in the Golden Valley area of the Great Fish River during the sixties and the relatively recent deleterious effects of high chloride concentrations on citrus crops in the Kirkwood area of the Sundays River. These and other associated problems, such as the need, in the long term, to provide good quality drinking water to Port Elizabeth, stimulated the National Institute for Water Research, the then Department of Water Affairs, Forestry and Environmental Conservation, the Department of Agricultural Technical Services, the universities of Stellenbosch and the Orange Free State and the Cape Provincial Administration to initiate collaborative research programmes on river mineralization from natural sources (including saline irrigation return flow).

Co-ordination of the research programme during the early and middle period of the investigation was the responsibility of the Committee for Inland Waters but in 1978 their function was taken over by the Water Research Commission's Co-ordinating Research and Development Committee for Water Quality.

The catchments selected for early attention, on the basis of priority allocations by the then Department of Water Affairs, were those of the Fish, Sundays, Berg and Breë rivers. Progress with the programme was slow at first, because although an effective and comprehensive sampling and analysis routine was soon established, a dearth of measurement weirs and consequently flow data made quantification of the salt loads difficult and unreliable. However, the Department of Water Affairs gave the programme its active support and additional weirs were constructed in most of the critical locations and meaningful work proceeded. The only remaining poorly gauged catchment is that of the Breë River, where very difficult conditions prevail, but this too is receiving attention.

After the initial problems had been overcome and a high degree of effective collaboration established between the participants in the programme excellent progress, particularly with respect to the Fish and Sundays River catchments was made. This culminated in the preparation of a series of reports providing background information, the results of field surveys, masses of data that had been collected over a period of many years, but with the main fruit of the endeavour being the computer-based systems model, developed by du Plessis and Hall and aptly named FLOSAL, which can be used to simulate river flows and salinities in complex river systems such as that of the Great Fish-Sundays.

The major task that this team of scientists and engineers has accomplished is a first for South Africa and has provided a tool which the Department of Water Affairs is already using to test river system management options. The successful application of this systems model in the Fish-Sundays catchment can now be extended to other river systems and while the authors acknowledge that the Flosal Model is only a first step in the development of even more effective and widely applicable models, we pay tribute to the dedication and innovative research that have established a very high standard for others to follow in the years ahead.

G.R. Botha

Chairman - Working Group for Mineralization

# PREFACE

I am privileged to present an overview of the research and planning studies carried out by a team of scientists and engineers on salinity problems in the Great Fish and Sundays rivers (eastern Cape). The research programme, spanning 12 years, yielded a wealth of information and, through studies using mathematical models, provided valuable guidance to Government planners.

Most of the research was based at three institutions:

- The National Institute for Water Research (NIWR) of the Council for Scientific and Industrial Research (CSIR),
- the Soil and Irrigation Research Institute (SIRI) of the Department of Agriculture, and
- the University of the Orange Free State.

A committee of representatives from these institutions, researchers from other South African universities, and contributors from Government departments coordinated the programme. Since 1978, this committee -- known as the Working Group for Mineralization -- has functioned under the auspices of the Water Research Commission.

All those involved in the programme found it to be extremely rewarding. The fruit of their labour is a four-volume report series, titled *Studies of Mineralization in the Great Fish and Sundays Rivers*. The four volumes are subtitled:

| | |
|---|---|
| Volume 1: | *Early Research of a Qualitative and Semi-Quantitative Nature* |
| Volume 2: | *Modelling River Flow and Salinity* |
| Volume 3: | *User's Guide to FLOSAL* |
| Volume 4: | *Environmental Data Used in Modelling* |

Volume 3 documents a computer-based mathematical model developed for studying planning options for salinity control in river systems. Copies of all four volumes are available on request from: The Chairman, Water Research Commission, P.O. Box 824, Pretoria, 0001.

Garth C. Hall

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## 1. INTRODUCTION

This summary draws selected material from the four-volume report: *Studies of Mineralization in the Great Fish and Sundays Rivers.* References are cited in all four volumes but not in this summary report.

### Background to the Study -- the Orange River Project

Since the early 1960s, concern has grown over high salinity in the Great Fish and Sundays rivers, in the eastern Cape. Saline water is harmful when used to irrigate crops and is unsuitable for municipal supply. Salinity in these river basins is a problem that could limit their further development as part of the Orange River Project (ORP).

The ORP is the largest water project ever undertaken in South Africa. It includes: the H.F. Verwoerd and P.K. le Roux dams on the Orange River, large irrigation developments, and the 83 km Orange-Fish Tunnel.

The South African Government's Directorate of Water Affairs (DWA), having opened the Orange-Fish Tunnel in 1977, is now able to supplement Great Fish River runoff with low-salinity Orange River water, thus catering for expansion of the irrigation schemes in the Great Fish River valley. (*Figure 1* shows the major features of the Great Fish-Sundays River system.) DWA also delivers water, via a link to Lake Mentz in the Sundays River, to augment citrus irrigation in the Sundays River valley below Lake Mentz. It plans to provide, ultimately, a supply link from the Sundays River to the City of Port Elizabeth on the coast. However, it is concerned that large flows of Orange River water, far in excess of quantitative requirements, may be needed to dilute runoff sufficiently for irrigation development in both river valleys and for the supply to Port Elizabeth.

### Nature of the Problem -- Salts from Natural Sources

Waters with relatively high concentrations of dissolved solids are referred to as "saline." The dissolved solids encountered in greatest concentrations are usually sodium, chloride, calcium, bicarbonate, magnesium and sulphate ions; in the solid phase, they would form common minerals such as halite ($NaCl$), calcite ($CaCO_3$), and gypsum ($CaSO_4$).

The dissolved solids found in waters of the Great Fish and Sundays rivers are derived from natural sources. No significant contribution is due to urban pollution, mining waste, cropland fertilization, or stabilization of irrigated soil with gypsum. Nor are there are any significant isolated sources of saline water; runoff from almost all parts of these river basins has relatively high salinity. Runoff in the upper reaches of the Great Fish River has a total dissolved solids (TDS) content of as low as 100-200 mg/$l$ during short-lived runoff peaks but it has a TDS of 1 200–1 800 mg /$l$ most of the time, when groundwater discharge is the dominant form of runoff. Salinity in the middle and lower reaches of the Great Fish River is higher than in the upper reaches, partly due to seepage of saline drainage water from irrigated lands (irrigation return flow).

Salinity in the Sundays River above Lake Mentz is higher still, but in this case irrigation return flow plays a minor role; baseflow TDS associated with naturally saline groundwater typically lies in the 3 000–6 000 mg /l range. This water has a predominantly sodium-chloride composition. Chloride concentrations in Sundays River runoff, which have increased over the past 30 years, are a cause for great concern to citrus farmers in the Sundays River valley below Lake Mentz. Whereas most irrigated crops experience damage due to high salinity (irrespective of composition), citrus is particularly sensitive to high chloride concentrations in soil water.

Although our studies did not lead to estimates of how much salt originates from various sources, Dr. E.A.W. Tordiffe (whose work is described in Volume 1 of the report) identified likely geological sources in the Great Fish River basin and described soil and rock weathering processes that produce $Ca^{++}$, $Mg^{++}$, $Na^{+}$, $SO_4^{=}$ and $HCO_3^{-}$ ions in groundwater.

A literature survey, covered in Volume 2, revealed that salts in rainfall and wind-borne dry particles can account for significant quantities of salt input to a river basin. Some of the sodium and most of the chloride in Great Fish River and Sundays River runoff may have been originally deposited in rainfall. Based on model calibration results referred to in Section 5 below, chloride concentrations in rainfall over the Sundays River basin would have to average only 3 to 4 mg/$l$ to fully explain chloride loads in its runoff over the past 50 years.

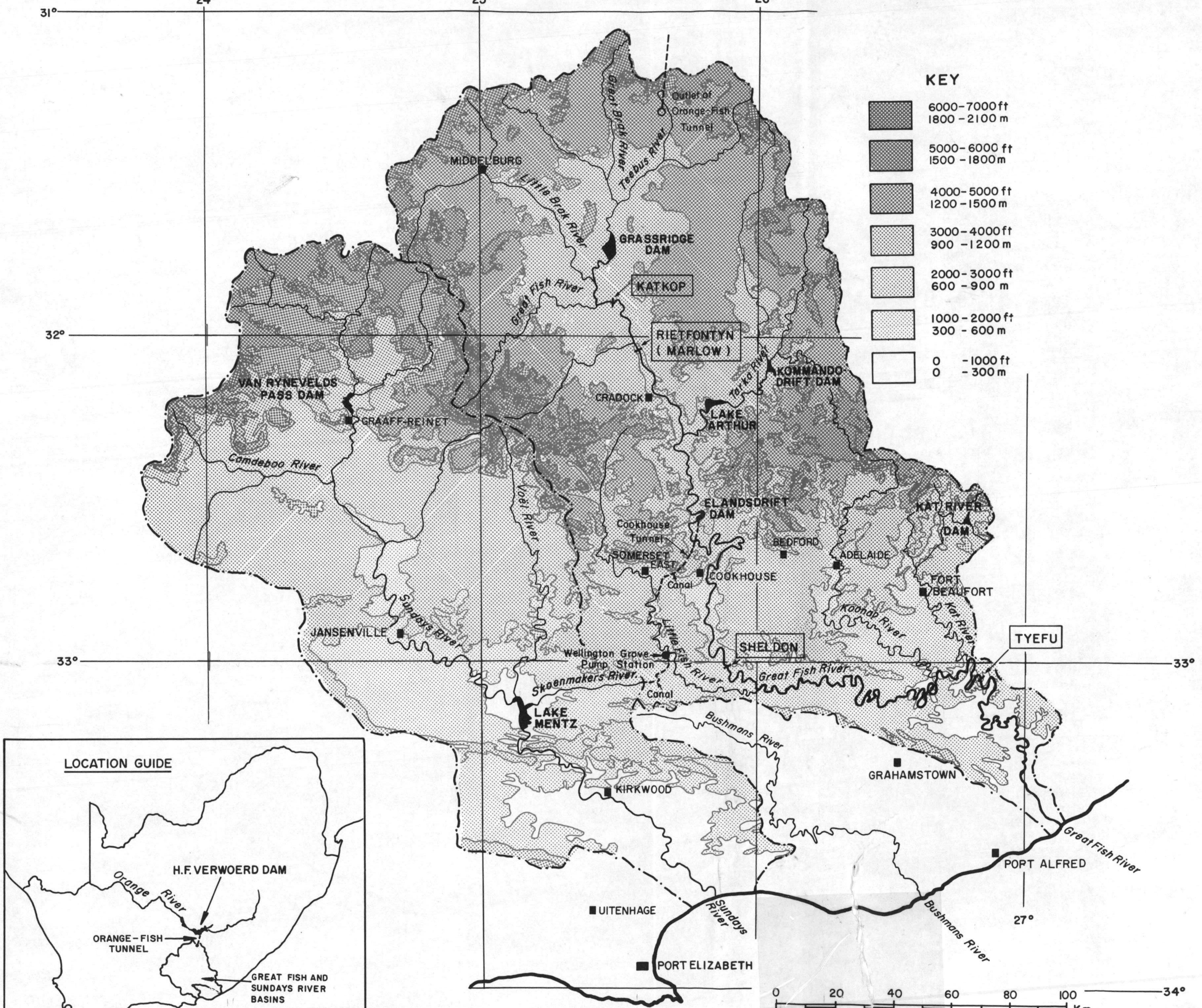


*FIGURE 1* *Major features and topography of the Great Fish-Sundays River system.*

### Adding to the Problem -- The Irrigation Cycle

Although the salt originates from diffuse natural sources, much of it passes through the irrigation cycle. Irrigators in the Great Fish River valley have, for decades, diverted water from the river to irrigate crops of lucern (alfalfa), wheat, and maize grown in the alluvial soils next to the river channel. Salt in irrigation water applied to the land becomes concentrated in the soil as water is lost due to evapotranspiration. The remaining water percolating down through the root zone to the groundwater is therefore highly saline; this water eventually reaches the river channel as seepage.

### The Research Programme in Outline

The research programme undertaken by the Working Group for Mineralization had four main thrusts:

- Field surveys to gain insight into mineralization (salinization) phenomena.
- Continuous measurement of river flow and salinity to provide necessary data for mathematical modelling.
- Developing a mathematical model to simulate river flow and salinity.
- Using the model to test various planning options available to DWA for salinity control.

The field surveys provided data on the geohydrology and on physical and chemical properties of the irrigated soils. They also provided data on salt transport during typical short-duration releases of water down the Great Fish River channel for irrigation.

## 2. GEOHYDROLOGY

Since natural groundwater discharge appears to be a significant source of saline water in both the Great Fish and Sundays rivers, the National Institute for Water Research (NIWR) and the University of the Orange Free State undertook studies to gain some insights into groundwater mineralization in these river basins.

**Tordiffe's Studies of the Great Fish River Basin**

Dr. E.A.W. Tordiffe of the Department of Geology, University of the Orange Free State, identified and mapped rock formations in the Great Fish River basin. He also recorded groundwater levels and determined ionic composition from borehole samples. His major findings are reported in Volume 1 of the report.

The Great Fish River basin is underlain mainly by sediments of the Beaufort Group of the Karoo Sequence. Groundwater moves mainly through fracture zones along intrusive dolerite dykes (of which there are a great number) and also through joints within the sedimentary rocks. Dolerite is also responsible for the formation of groundwater compartments in the basin.

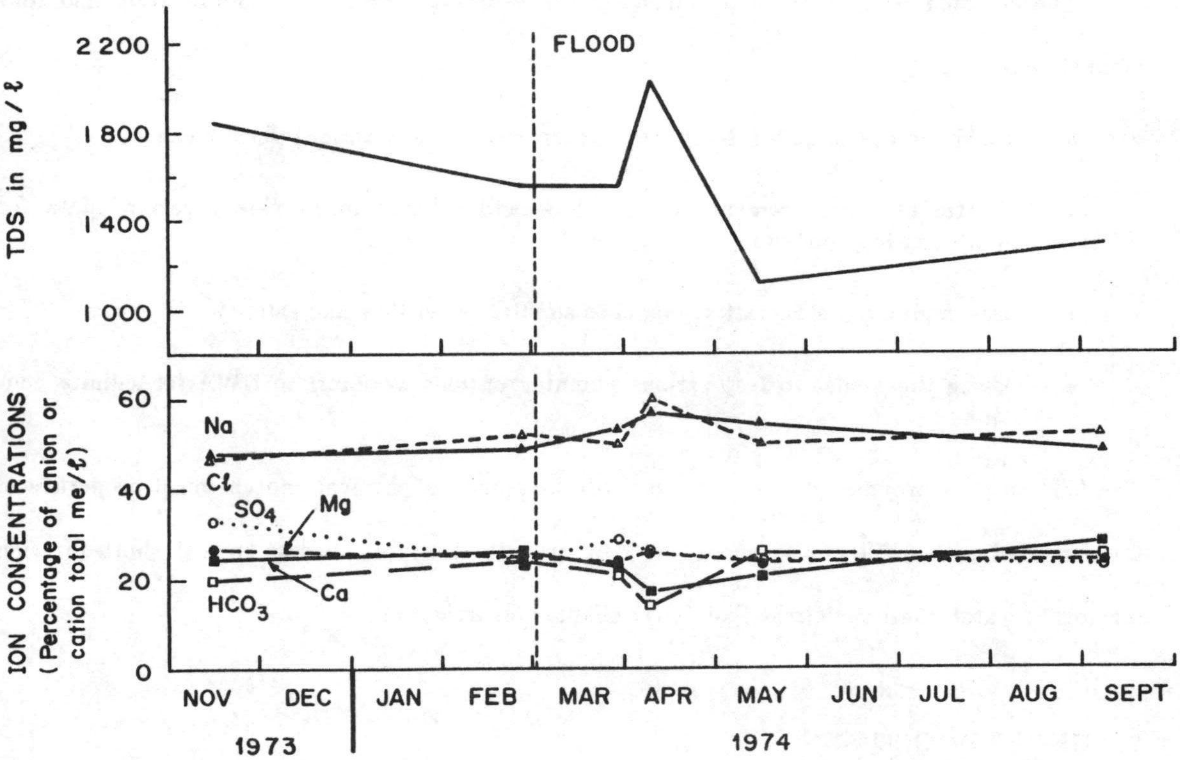


*FIGURE 2 Groundwater TDS and ionic composition observed at a farm borehole near Katkop in the upper Great Fish River basin -- before and after the exceptional rains of 1974.*

Low mean annual precipitation (350-400 mm) and high evaporation potential means that only a small percentage of the precipitation recharges groundwater storage. Only during saturating rains, which occur infrequently, are salts in the soil dissolved and transported in bulk down into the groundwater. Tordiffe observed changing ionic composition and TDS of water sampled from a single borehole over several months before and after heavy rains in 1974. His observations, shown in *Figure 2,* suggest that salt mobilization is rapid under such conditions. The 1974 rains, which marked the start of an exceptionally wet period, triggered strong, saline baseflow in the Great Fish and Sundays rivers.

Tordiffe associates the regionally varying ionic composition of groundwater in the Great Fish River basin with the different formations of the Beaufort Group and underlying Ecca Group. However, he points out that it is not only geology but also topography and climate that influence groundwater chemistry. The predominant cations -- calcium, magnesium and sodium -- are produced by the action of carbonic acid (from dissolved carbon dioxide) on soil and rock minerals. The major anions are:

- chloride, the origin of which is not well understood but Tordiffe suggests its possible entrapment in clays when connate water pressed upward during deposition of overlying strata
- sulphate, produced by oxidation of pyrite ($FeS_2$), present in many of the Beaufort formations
- bicarbonate, produced by the action of carbonic acid on soil and rock minerals.

*Figure 3,* produced by Tordiffe, shows zones of different groundwater TDS in the Great Fish River basin.

### Other Groundwater Surveys

NIWR personnel conducted several surveys of groundwater salinity in the Great Fish River basin and in the Sundays River basin above Lake Mentz. Their surveys of groundwater salinity along the Great Fish River supplement those done earlier by Tordiffe. *Figure 4* shows the salinity of Sundays River groundwater in the area surveyed by the NIWR. Volume 1 includes results from these surveys.

Dr. B. Verhagen and colleagues at the Nuclear Physics Research Unit, University of the Witwatersrand, undertook a pilot study of groundwater dynamics in the upper Great Fish River

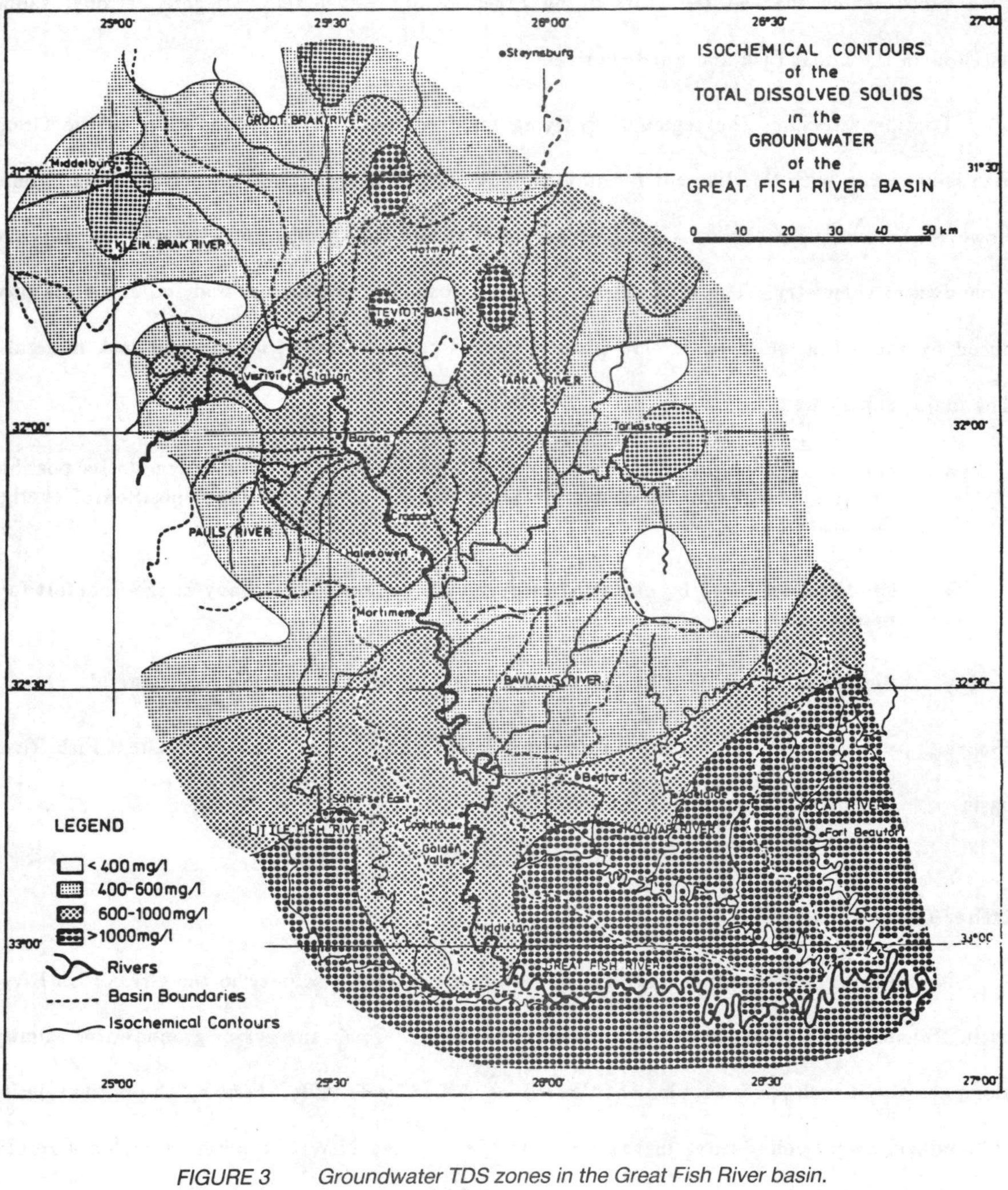


*FIGURE 3 Groundwater TDS zones in the Great Fish River basin.*

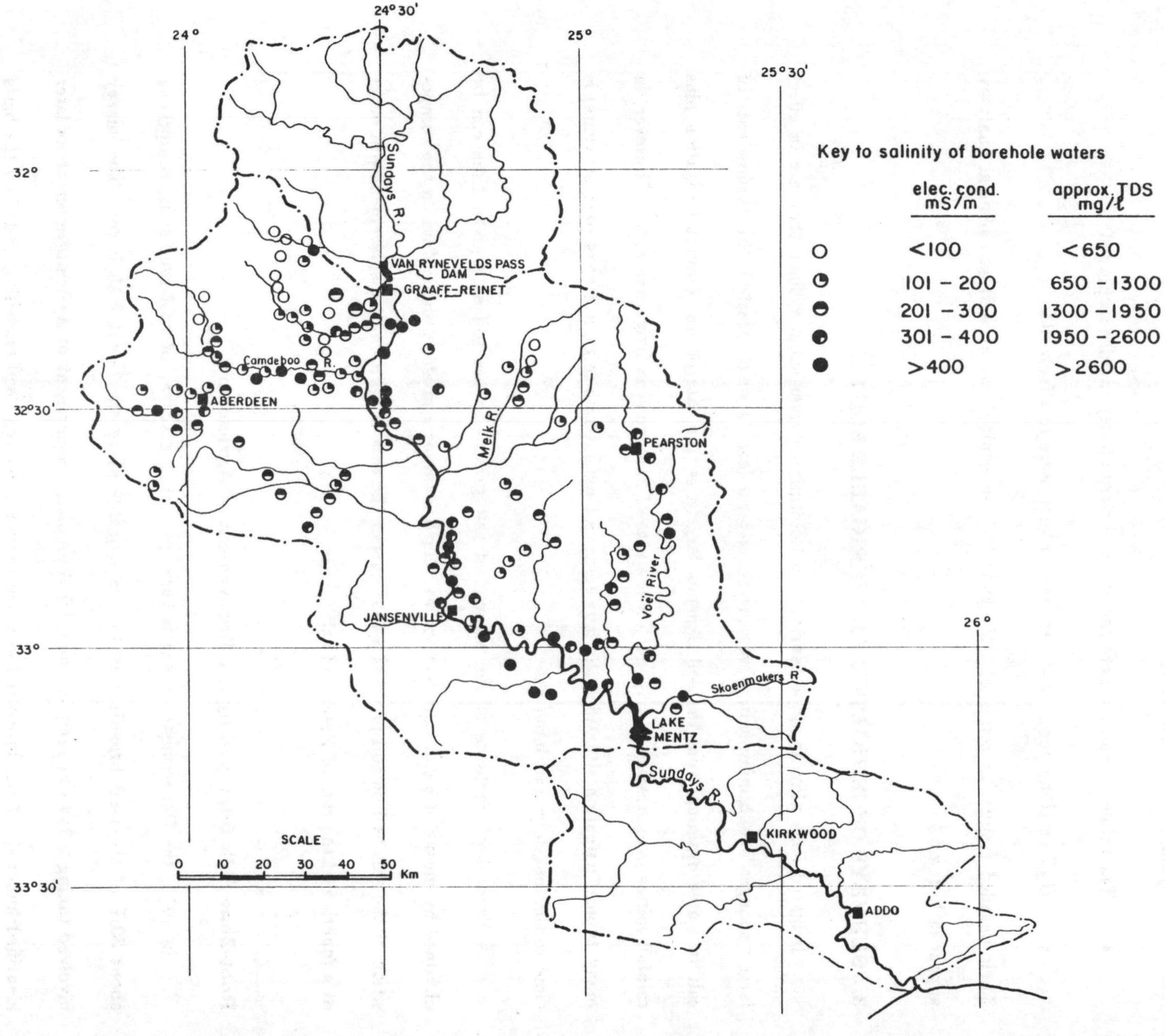


FIGURE 4 *Salinity of borehole waters in the Sundays River basin below Van Rynevelds Pass and above Lake Mentz.*

basin – with the aid of chemical and environmental isotope analysis. They concluded, on the basis of a dozen samples, that:

- The high salinity of seepage encountered along the river banks was due to leaching (partially or totally due to irrigation) which occurred relatively rapidly; these were "young," shallow-cycling waters.

- The saline borehole waters encountered were mostly rapidly recharged.

- $H_2S$-smelling borehole waters encountered were relatively old.

Their detailed results, in terms of $^3H$ and $^{14}C$ determinations as well as chemical analyses, appear in Volume 1.

## 3. SURVEYS OF IRRIGATED AND IRRIGABLE SOILS

Irrigated soils play an important role in determining river salinity since they are in effect large "sponges" containing salt. Over the short term (e.g., a single season), the outflow rate of salt in water draining from the soil depends largely on the rate of water input (irrigation plus rainfall minus evapotranspiration), not on the rate of salt input in irrigation water. However, in many typical irrigation situations the long-term salt output rate (e.g., averaged over 30 years) is close to the long-term salt input rate.

A "snapshot" measure of the amount of salt present in the soil at a given time can be obtained by means of a soil sampling survey. Such a survey can also provide data on the composition of the salt and on soil properties that govern the rate at which salt displacement will occur as a function of the rate of water and salt inputs.

### Root-Zone Soils Surveyed by the Department of Agriculture

In 1973, the Department of Agriculture conducted a survey of root-zone soils, comprising about 30% of the land broadly classified as irrigable along the Great Fish River. The survey involved taking 9 344 soil samples from 2 946 profiles. Department of Agriculture scientists later identified hundreds of soil types and grouped them into eleven "soil modelling units" on the basis of texture and structure – for use in computer simulation of irrigation drainage salinity. *Figure 5* shows the occurrence of these soil groups in different reaches of the valley. Within each soil

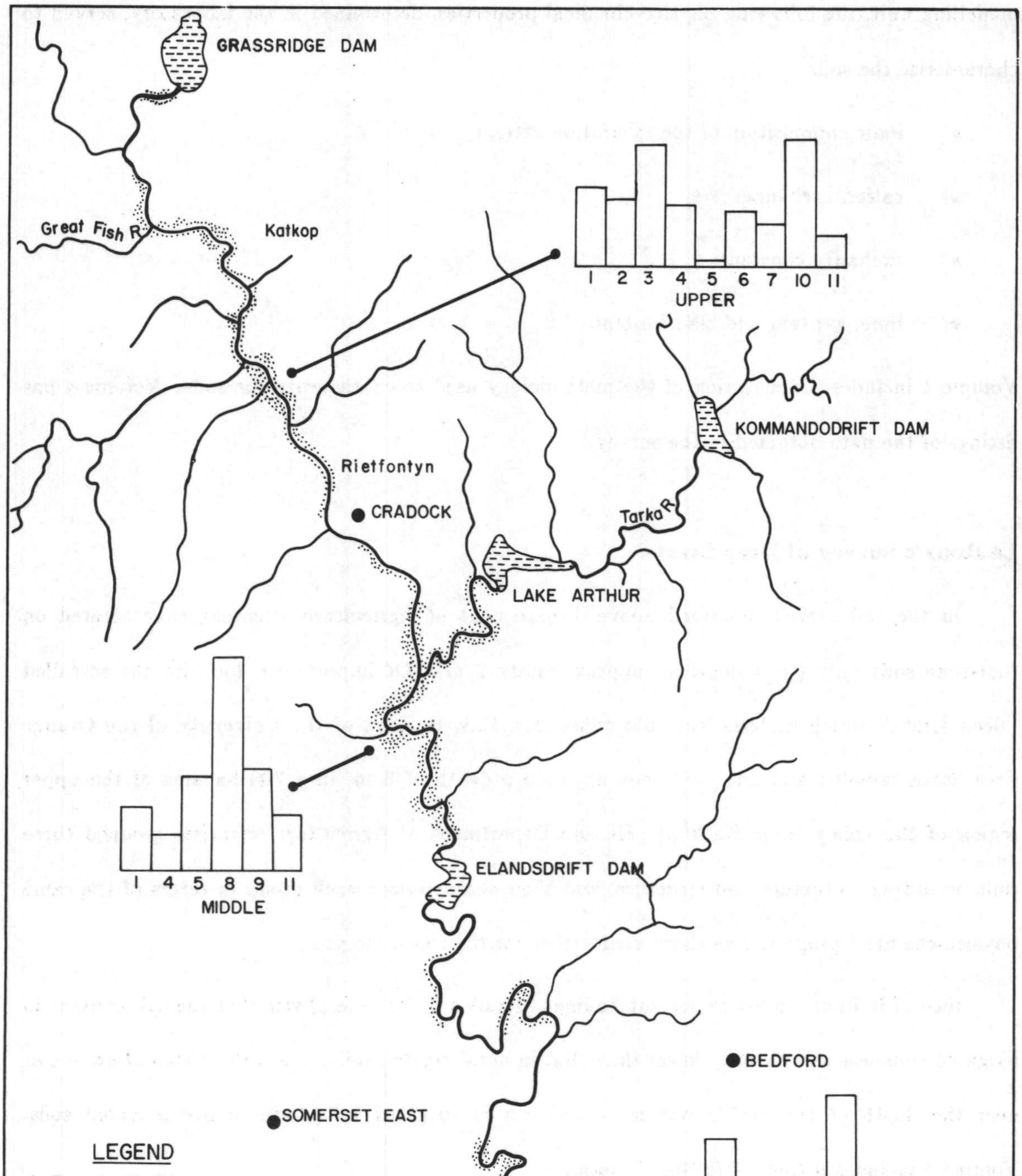


*FIGURE 5* *Relative distribution of soil modelling units in the upper, middle and lower regions of the Great Fish River Irrigation Scheme.*

modelling unit, the following physico-chemical properties, determined in the laboratory, served to characterize the soils:

- ionic composition of the saturation extract
- cation exchange
- exchange constants
- lime, gypsum and clay content.

Volume 1 includes a description of the methodology used to characterize the soils. Volume 4 has listings of the data obtained in the survey.

### Le Roux's Survey of Deep Strata

In the soil survey described above, Department of Agriculture scientists concentrated on root-zone soils only (to a depth of approximately 2 m). Of importance, too, are the so-called "deep strata" which underlie the root zone. Mr. P.A. le Roux of the University of the Orange Free State sampled and analyzed soils down to a depth of 8 m in a 700 ha area of the upper region of the valley (near Katkop). He and Department of Agriculture scientists grouped these soils according to texture and structure, and then characterized each group in terms of the same physico-chemical properties as those used earlier for the root-zone soils.

One of le Roux's most important findings (detailed in Volume 1) was that the salt content in irrigated soils was significantly lower than that in non-irrigated soils. Also, the distribution of salt over the depth of the profile was more uniform in irrigated soils than in non-irrigated soils. Volume 4 includes listings of le Roux's data..

### Viljoen's Soil Survey

Additional data on the salt content of irrigated soils along the Great Fish River is available from a pilot study conducted by Mr. P.T. Viljoen of the NIWR in 1974. The average depth of the 37 holes drilled in this survey was 6,7 m. Viljoen found that the average soluble salt content in soil above the water table was 247 t/ha. Average composition of the saturation extract as a percentage of total ions, calculated in me/$l$, was:

| | | | |
|---|---|---|---|
| $Na^+$ | 40,65 | $HCO_3^-$ | 28,61 |
| $K^+$ | 1,53 | $Cl^-$ | 11,70 |
| $Ca^{++}$ | 2,55 | $SO_4^=$ | 9,15 |
| $Mg^{++}$ | 4,47 | | |

Viljoen's detailed results are given in Volume 1.

## 4. FIELD SURVEYS OF RIVER WATER SALINITY

Water released in alternate weeks from Grassridge Dam for irrigation along the Great Fish River appears to increase rapidly in salinity as it passes down the river channel. Early surveys provided insights into how this salinity increase occurs.

### Viljoen's River Surveys

Mr. P.T. Viljoen of the NIWR, with assistance from NIWR and DWA personnel, conducted special surveys of flows and salt loads at key points along the Great Fish River. One of these surveys, in July 1972, was timed to coincide with an irrigation lead from Grassridge Dam. (Water is typically released from Grassridge Dam for irrigation in alternate weeks; one week has little or no release of water and the following week has a strong four- to five-day release.) Viljoen based his findings on water samples and flow measurements taken at half-hourly to hourly intervals. He observed that, from the time that higher flows are first registered at the downstream weirs, many hours lapse before salinity drops to steady levels. For example, at Marlow Weir -- some 69 km downstream from Grassridge -- the time lapse is approximately 30 hours (see *Figure 6*). This observation can be explained in terms of plug-flow displacement of saline water present in the river channel when the release starts. The body of low-salinity water released from Grassridge Dam pushes ahead of it the saline water present in the channel. At the same time, seepage of saline water into the river continues to mingle with the released water, thus increasing its salinity in step with its passage downstream.

Viljoen also noticed in the July 1972 survey that when higher flow was first registered at Marlow Weir, salinity rose sharply before it began to fall (see *Figure 6*). A possible explanation is that the rising water rapidly dissolved salts that had precipitated above the low-flow water level along the river bank after the previous irrigation lead. In support of this explanation, white lime ($CaCO_3$) precipitation can often be observed along the river banks.

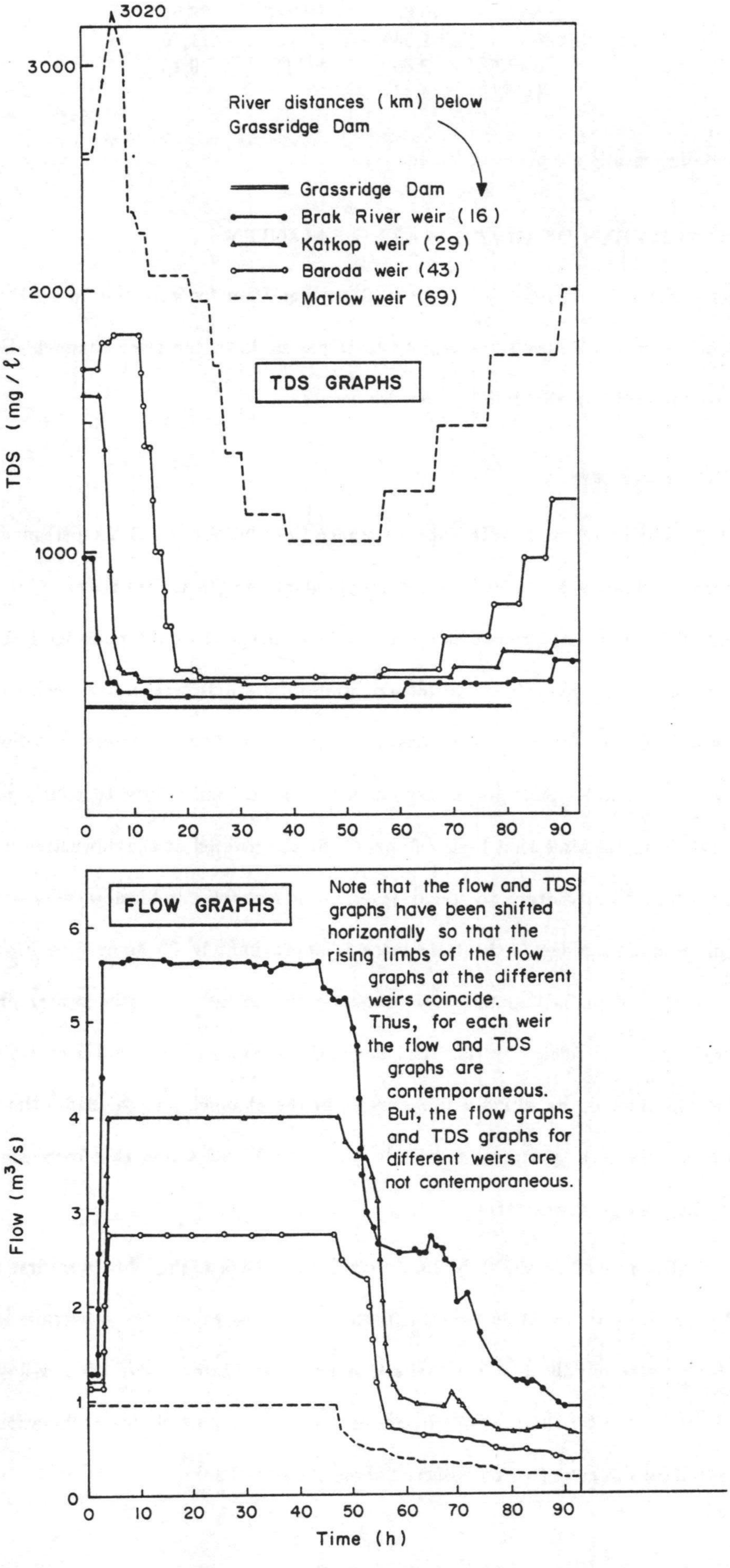


*FIGURE 6 Flows and TDS recorded at weirs below Grassridge Dam during an irrigation lead in July 1972.*

*Table 1* shows the TDS and composition of water at Grassridge Dam and at Marlow once the saline water present in the river channel at the start of the July 1972 lead had been fully displaced. Thus, the numbers in *Table 1* reflect only the influence of saline seepage flow. Note that they are also a function of the quantities of water diverted at weirs between Grassridge Dam and Marlow during the lead.

**Table 1**

**Composition of Grassridge Water and Steady-State Composition of Water at Marlow, 69 km Downstream, During the July 1972 Irrigation Lead: Concentrations in mg/l**

| | TDS* | $Na^+$ | $K^+$ | $Ca^{++}$ | $Mg^{++}$ | $HCO_3^-$ | $Cl^-$ | $SO_4^{=}$ |
|---|---|---|---|---|---|---|---|---|
| Grassridge Dam | 422 | 78 | 2 | 25 | 15 | 227 | 39 | 36 |
| Marlow | 1 039 | 215 | 4 | 45 | 49 | 366 | 230 | 130 |

* TDS estimated by adding the concentrations of the ions shown.

## 5. MATHEMATICAL MODELLING

Modelling the river system led to better understanding of the mineralization phenomena and provided a tool for evaluating planning options for salinity control.

### Description of the System Model

The computer-based system model, developed by Mr. H.M. du Plessis of the Department of Agriculture and Dr. G.C. Hall while employed by the NIWR, can simulate river flow and salinity in complex river systems such as the Great Fish-Sundays River system. *Table 2* summarizes key information on the model. Separate subroutines provide for simulation of flows and salt transport in different components of a river system.

Subroutine CATCH incorporates rainfall-runoff functions taken from the hydrological model developed by Dr. W.V. Pitman of the University of the Witwatersrand's Hydrological Research Unit. Du Plessis and Hall modified some of Pitman's hydrological functions and piggy-backed runoff-salt transport functions to them. Thus, with rainfall data as input, this subroutine generates output time series of runoff and transported salt. Du Plessis and Hall introduced the

**concept of a groundwater reservoir containing saline water which discharges only after periods of exceptionally heavy recharge (see *Figure 7*). Water levels are depleted slowly through evaporation losses over time – so that, in semi-arid and arid basins, replenishment of the reservoir is necessary before discharge can begin. This concept led to satisfactory matching of historic chloride loads in Sundays River runoff, as explained below.**

**Table 2 Features of the System Model FLOSAL**

| | |
|---|---|
| **Description in a nutshell** | **Computer-based model which simulates flow and salinity in river systems of virtually any configuration.** |
| **Type:** | **Deterministic, conceptual, physically based.** |
| **Structure:** | **Main Routine plus several subroutines, each applicable to a river system component type, e.g., impoundment. Simulation is controlled by the a sequence of subroutine calls given as input to the Main Routine and by the parameters specified in each subroutine call.**<br><br>MAIN ROUTINE<br>CATCH DAMIT ROUTE RETFLO DISCH ABSTR<br><br>**Other subroutines: MONOUT, DAYOUT, SENSIT, STORE, FETCH are used to operate on the flow and salinity time series. For example, MONOUT prints out hardcopies of monthly numbers. Flow and salinity time series can be passed from one subroutine to another in a user-prescribed way.** |
| **Time Base:** | **Two model versions, one which operates at a monthly time step and one which operates at a daily time step.** |
| **Programming Language:** | **FORTRAN IV for use on IBM 370/3033 computers.** |
| **Documentation:** | **User's Guide to FLOSAL (Volume 3 of *Studies of Mineralization in the Great Fish and Sundays Rivers*) plus a supplementary binder containing program listings, sample inputs and sample outputs.** |
| **Availability:** | **Program listings on magnetic tape, available from the Chairman of the Water Research Commission, P.O. Box 824, Pretoria, 0001.** |

**Subroutine RETFLO simulates irrigation return flow in response to water and salt inputs to irrigated land. It simulates drainage from the irrigated soil in one of two ways. The simpler way essentially assumes that water is removed from the top soil layer at a given evapotranspiration**

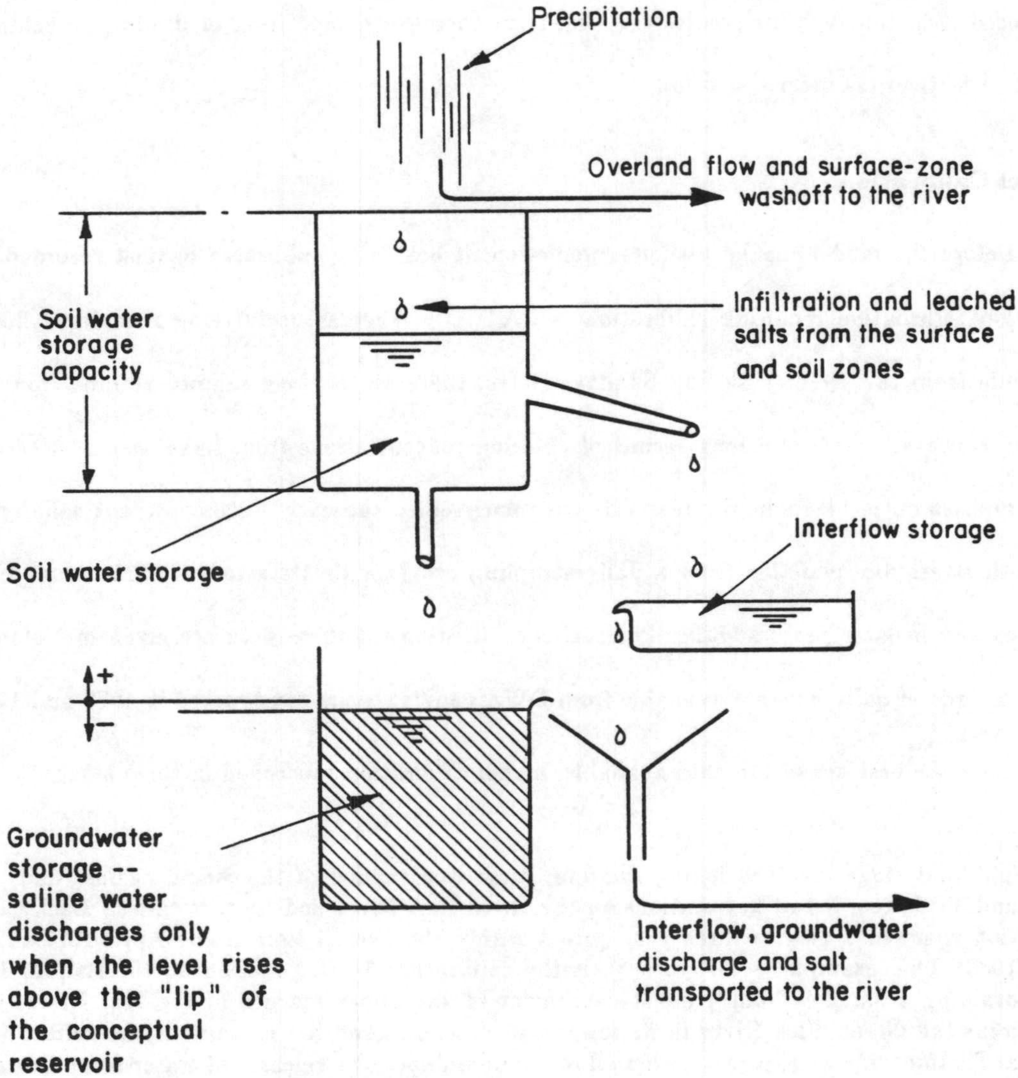


*FIGURE 7 Conceptual representation of rainfall-runoff processes in subroutine CATCH.*

rate, the remaining water and all of the salt then percolating rapidly to the saturated zone. The more rigorous way involves the use of a separate model component which represents physico-chemical processes in the soil. This model component, referred to as the Thomas model (or subroutine THOMAS), is a modified version of a model developed several years ago by researchers at the Utah Water Research Laboratory. It can also be used on its own, and in fact du Plessis and Hall used it in that way to predict the long-term chemical composition of drainage reaching the Great Fish River, as described below.

**Model Calibration**

Before the model can be used for prediction, it has to be calibrated against recorded data. (The key subroutine requiring calibration is CATCH.) Whereas useful long records of flow are available from the Great Fish and Sundays rivers, there are no long salinity records from these rivers. However, there is a long record of chloride concentrations from Lake Mentz, determined from grab samples taken in the reservoir irregularly since the early 1920s. Recent salinity data for both rivers are available from a daily sampling program that started in 1975 at one or two stations and in later years at other key stations. (Listings of these data are given in Volume 4.) Good records of daily flow are available from DWA gauging weirs constructed in 1977 and 1978.

To make best use of the data available, model calibration proceeded in three stages:

1) The first stage involved fitting the daily time-step version of the model against daily flows and TDS recorded at key stations on the Great Fish River and its tributaries. Each calibration spanned a two to three year period within the overall time frame April 1977 to April 1980. One example (see *Figure 8*), is the calibration fit at a station on the Balfour River, draining a small (76 $km^2$) moist catchment in the upper reaches of the Kat River, which joins the Great Fish River in its lowermost reaches. Another example is the calibration fit at Rietfontyn (see *Figure 9*), where flows are dominated by releases of water from Grassridge Dam. Volume 2 gives, for all the calibration fits, plotted time series (like *Figures 8* and *9*), plotted duration curves of flow and TDS, and statistics to show how well the simulated values match the recorded ones.

2) The second stage involved fitting the monthly time-step version of the model against the long record of monthly flows at Lake Mentz on the Sundays River, and against the record of chloride concentrations in water impounded in Lake Mentz. *Figure 10* shows plotted storage volumes and chloride concentrations in Lake Mentz. The simulated storage volumes were obtained by:
   - fitting simulated runoff to recorded Lake Mentz inflows, and
   - calculating a monthly water balance from the simulated inflows, recorded releases, and estimated evaporation quantities.

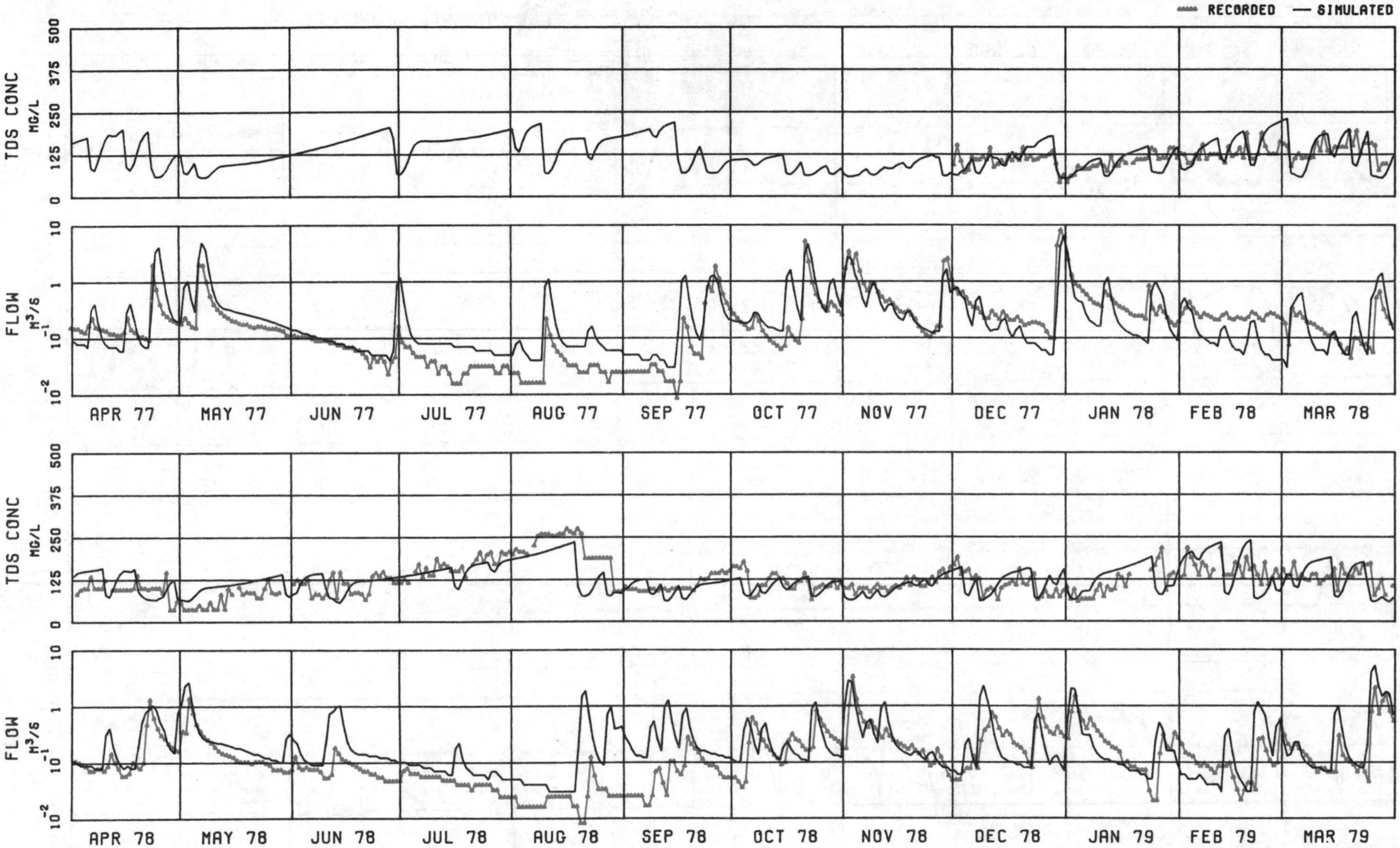


*FIGURE 8* *Plotted daily time series of simulated vs. recorded runoff and TDS in the Balfour River at Greykirk: calibration fit.*

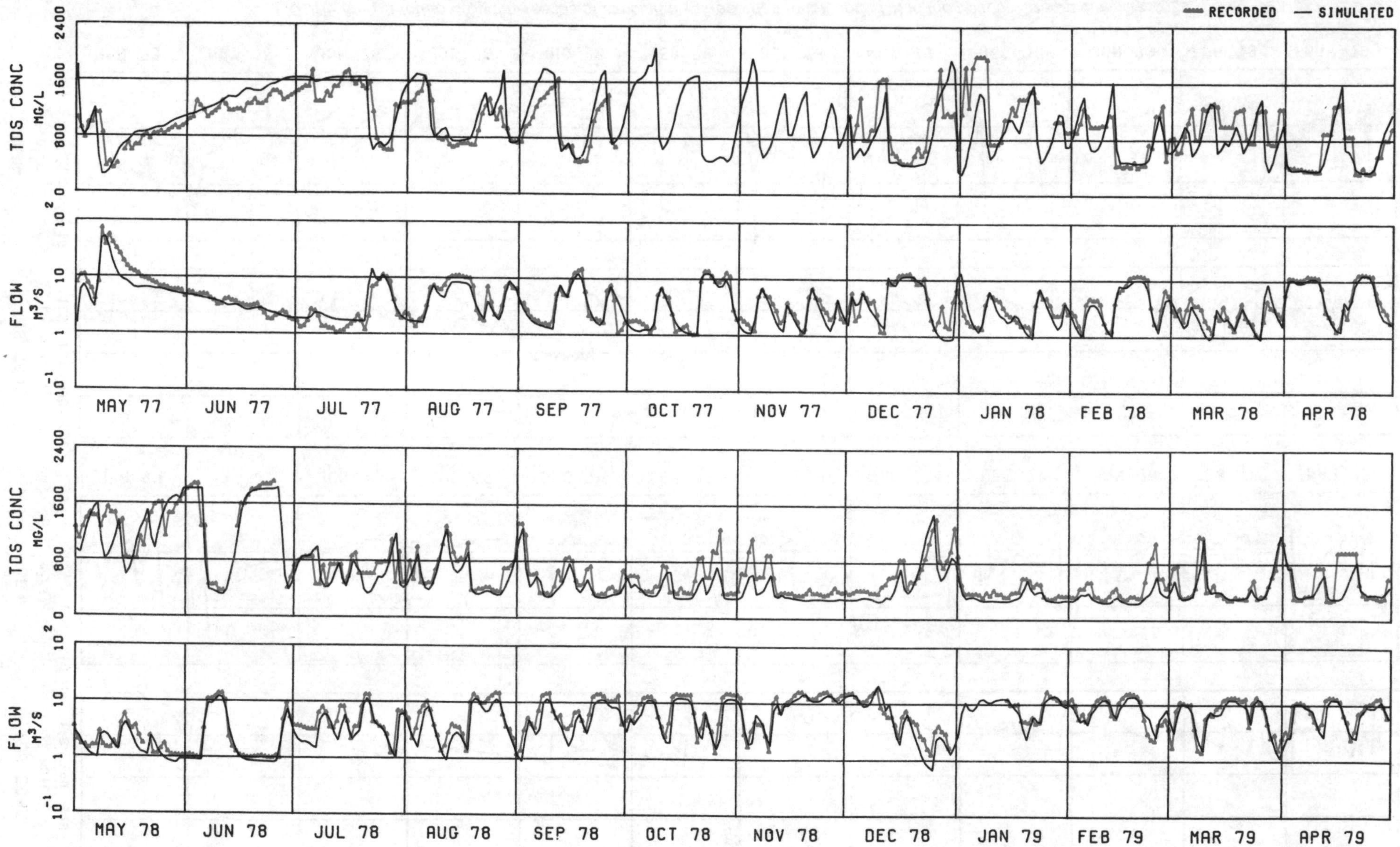


FIGURE 9 Plotted daily time series of simulted vs. recorded flow and TDS at Rietfontyn: calibration fit.

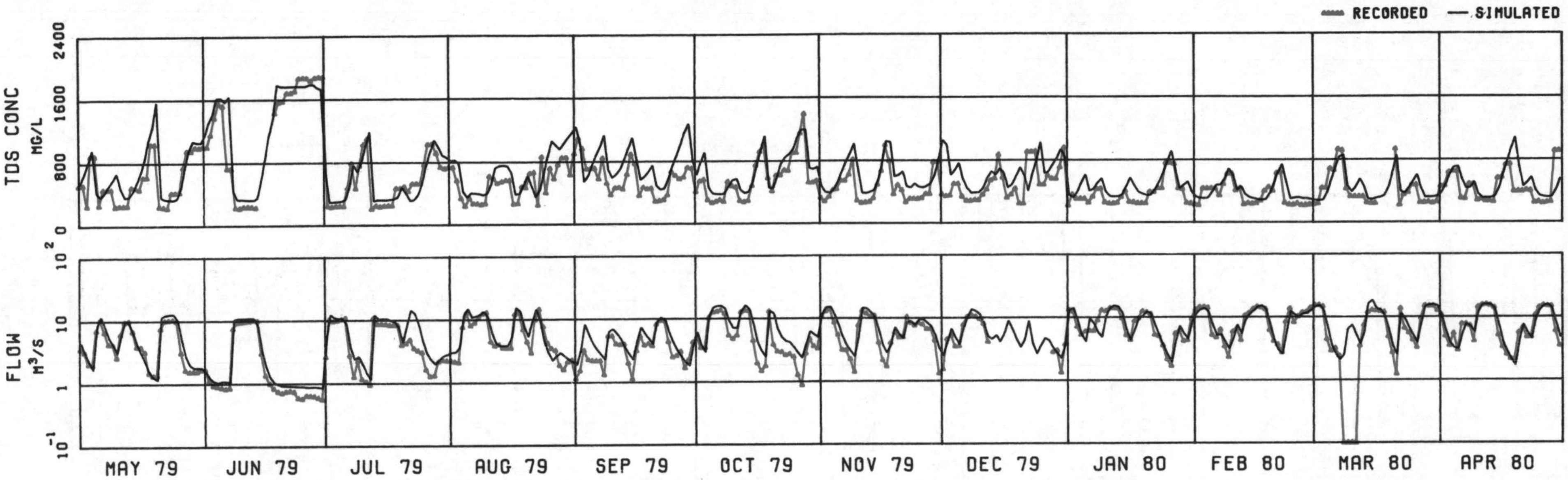


*FIGURE 9 (continued).*

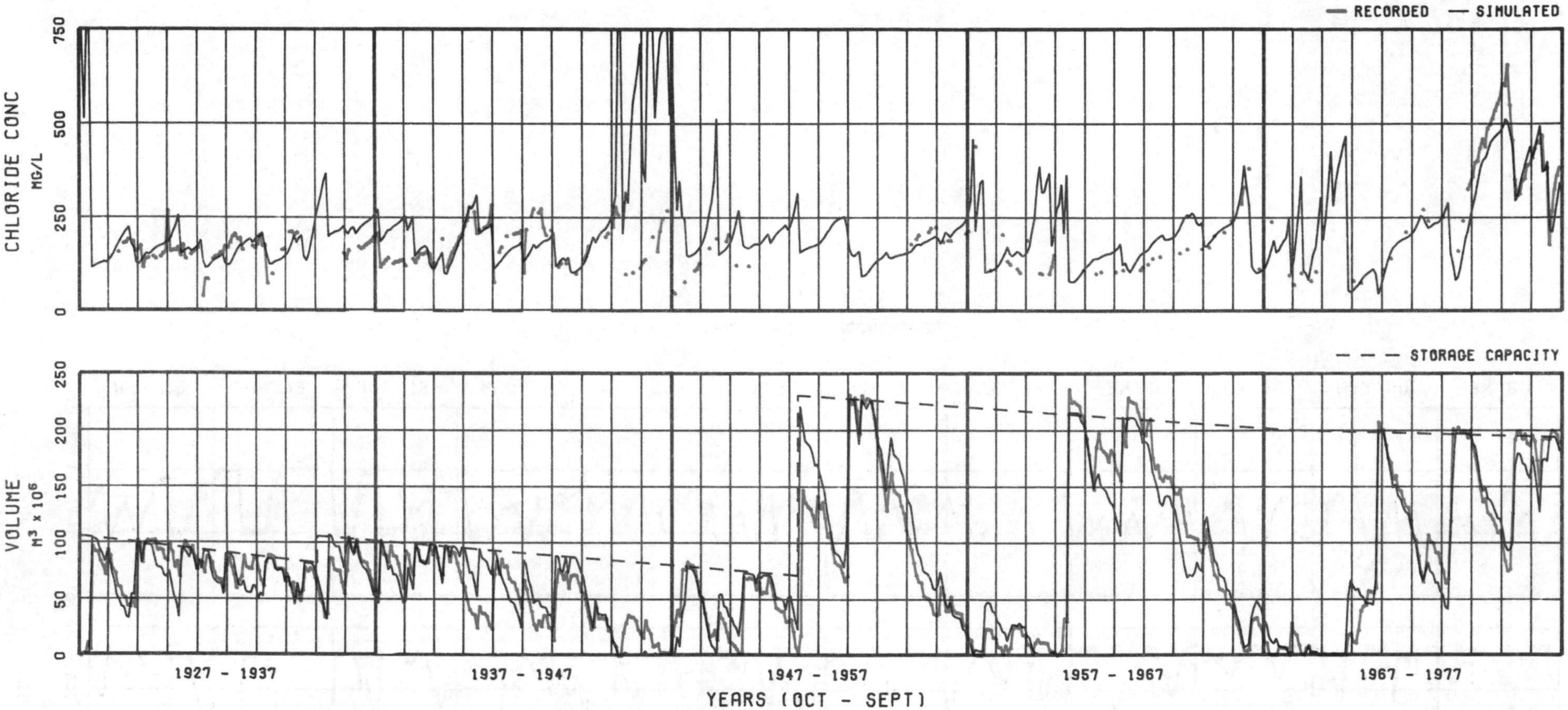


FIGURE 10 Plotted time series of simulated vs. recorded storage volumes and chloride concentrations in Lake Mentz: calibration fit for chloride transport by runoff.

Calibration against the chloride record required "visual" matching, i.e., adjusting the salinity parameter values (and fine-tuning the runoff parameter values) until the best possible fit of chloride concentrations in Lake Mentz was obtained. This stage also involved fitting the model against an estimated TDS "record" at Lake Mentz; the TDS record was estimated from the chloride record together with a chloride-TDS relationship established using recent Lake Mentz data. Matching the TDS "record" was done in the same way as the chloride match, except that the runoff parameter values were left as finalized in matching the chloride record.

3) The third stage involved fitting the monthly time-step version of the model against long records of flow at stations on the Great Fish River and its major tributaries. Records of monthly irrigation quantities were unavailable and had to be estimated from recorded releases from Grassridge Dam and other reservoirs. This stage included generating long time series of TDS values associated with the simulated flow time series, using salinity parameter values estimated from those obtained in the calibration fits in stages 1 and 2 above.

To represent irrigation return flow entering the Great Fish River, du Plessis and Hall used the option in subroutine RETFLO that allows simplified treatment of salt balances in irrigated soils; in other words, they did not call on subroutine THOMAS. Irrigation return flow in the Sundays River above Lake Mentz is not significant so they used an even simpler approximation to estimate its contribution there.

Calibration against the long records of runoff in the Great Fish and Sundays rivers revealed that runoff has declined over time. In all catchments modelled, except the relatively moist Kat River catchment, runoff since the early 1950s has declined sharply relative to rainfall. (The decline resulted from soil conservation measures implemented following the Soil Conservation Act of 1946.) Calibration at Lake Mentz revealed that, associated with the decline in runoff, there has been a decline in chloride loads -- but not in proportion to the decline in runoff. In other words, average chloride concentrations have increased. This is undoubtedly true for TDS as well. The Sundays River calibration in terms of chloride and TDS guided the choice of parameter values for TDS in the Great Fish River basin (in stage 3 above).

In the Lake Mentz calibration, the unprecedented high chloride levels accompanying the 1974-1977 wet period are matched satisfactorily (see *Figure 10*). In all years except 1974-1977, groundwater storage, as represented in the model, remained below the level at which significant discharge to the river occurs. The 1974-1977 period was the first instance since at least the early 1920s of major discharge of saline groundwater.

## 6. MODEL PREDICTIONS

Du Plessis and Hall used the calibrated model as the basis for testing various planning options put forward by DWA for the Sundays and Great Fish rivers. The objective in each case was to minimize the quantity of imported Orange River water – subject to the requirements that demands for supply are met and that specified operation rules are followed to bring down salinity to acceptable levels.

### Sundays River Planning Options

DWA has identified several options for controlling chloride levels in Lake Mentz. Two of these are: (1) bringing more Orange River water across from the Great Fish River to Lake Mentz, and (2) bypassing saline Sundays River baseflow around Lake Mentz. Du Plessis and Hall used the model to study the operational viability of these options. Their studies included a proposed operation rule whereby water in Lake Mentz can be "dumped" (i.e. discharged to the ocean) when its salinity exceeds a given threshold, thus allowing low-salinity Orange River water to be imported in its place. An important criterion specified for the studies was a 250 mg/l upper limit to chloride concentrations in water delivered below Lake Mentz.

Since future trends in Sundays River runoff and salinity are unknown, two scenarios were defined:

- Worst Scenario, having runoff conditions as they appeared to be in the 1970s, i.e. low relative to rainfall, and having higher salinity levels than those prevalent in the 1970s.
- Best Scenario, having slightly higher runoff relative to rainfall than that occurring in the 1970s and considerably lower salinity levels than those prevalent in the 1970s.

In the short term (the 1980s), imports from the Great Fish River will be physically constrained to an average sustainable flow of 3,2 $m^3/s$. The study merely comprised simulation runs with and without the dumping rule. Results indicate that unacceptably high chloride levels will occur intermittently. The dumping rule will help only marginally because DWA cannot risk dropping storage levels too low; the 3,2 $m^3/s$ import rate alone is insufficient to meet demands – so target storage levels in Lake Mentz are set high (to provide enough carry-over storage for a possible dry cycle).

For the intermediate term (the 1990s), du Plessis and Hall assumed no increase above present levels in the demands for water below Lake Mentz but tested an option in which the maximum import rate is raised to 20 $m^3/s$. They also studied a proposed 1,5 $m^3/s$ conveyance for bypassing saline baseflow around Lake Mentz. Results indicate that importing water at 20 $m^3/s$, when needed, would lower chloride levels significantly. With the 20 $m^3/s$ maximum import rate, dumping would be an effective policy since Lake Mentz can then be practically emptied without risk of running short of water. *Figure 11* shows duration curves of storage volume and chloride concentration with and without the dumping policy (and without the baseflow bypass option). Note that, even with the dumping policy, Best Scenario chloride concentrations will exceed 250 mg/$l$ 5% of the time. Results (not presented here) showed that adding the baseflow bypass option would lower chloride levels still further.

For the long term (i.e. beyond the year 2000), the assumed irrigation demand below Lake Mentz is $248{,}5 \times 10^6$ $m^3$ per year (roughly double present-day demand) and the assumed delivery to Port Elizabeth is $207{,}3 \times 10^6$ $m^3$ per year. The increased demands will require large flows of Orange River water via the Great Fish River -- resulting in lowered salinity levels in Lake Mentz. Results (not illustrated here) indicate that, even without the baseflow bypass scheme, chloride concentrations will exceed 250 mg/$l$ less than 2% of the time, which is quite acceptable. But, without the bypass scheme, TDS will exceed 500 mg/$l$, the desired maximum for municipal supply, at least 10% of the time. Even with the bypass scheme, TDS will exceed 500 mg/$l$ at least 3% of the time.

**Great Fish River Planning Options**

Du Plessis and Hall used the calibrated daily time-step version of the model to test operation rules for a proposed diversion works for irrigation at Tyefu, in the lowermost reaches of the river. Government planners specified a desirable maximum TDS level of 650 mg/$l$ for the study. The model runs revealed that a diversion works consisting merely of a weir and canal would be feasible but would require large quantities of Orange River water -- far in excess of the quantitative demands -- to dilute Great Fish River saline runoff and irrigation return flow sufficiently. For this type of scheme, the operation policy that turned out to be most effective (and it is also con-

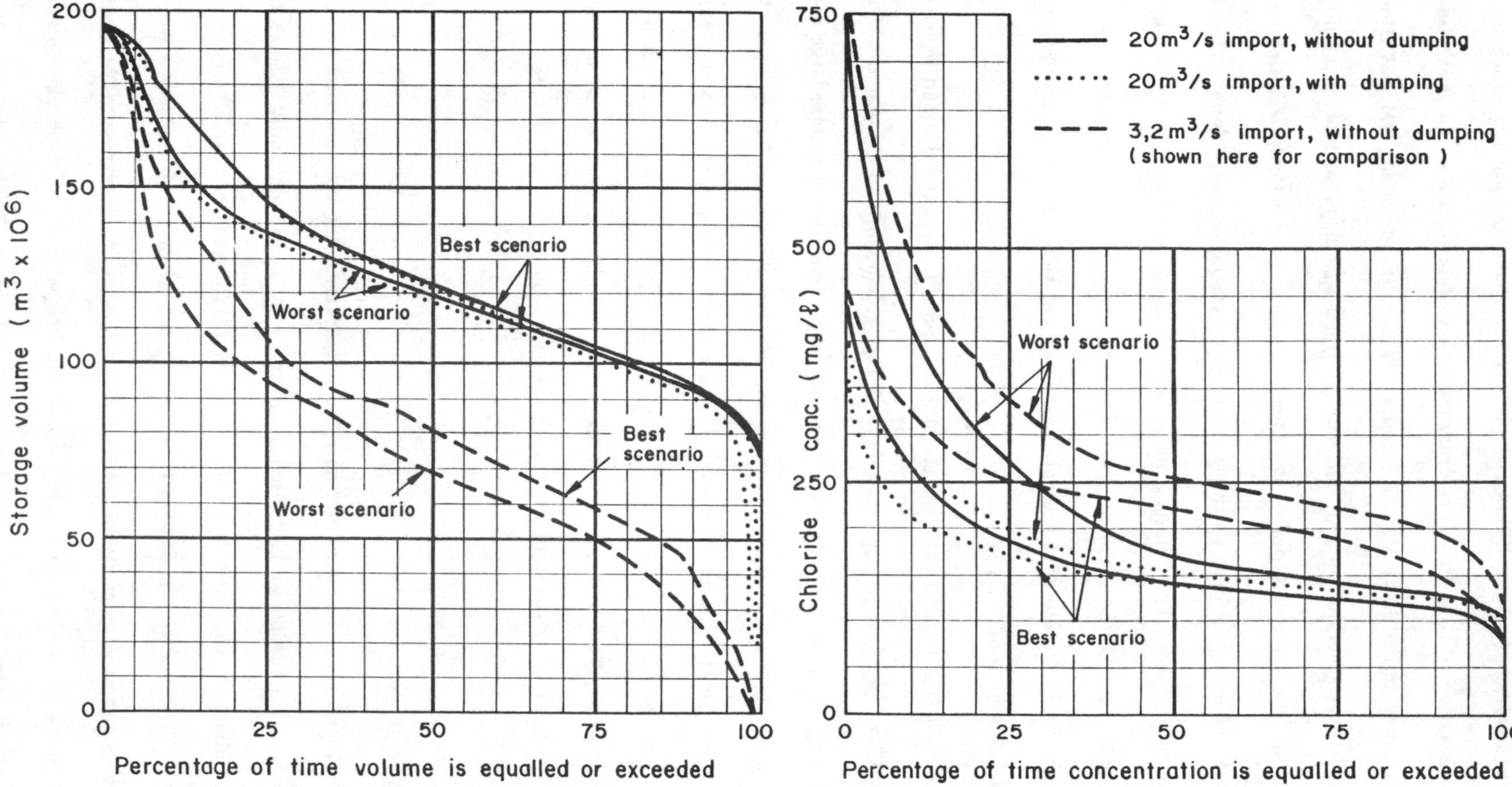


FIGURE 11 *Predicted duration curves for Lake Mentz intermediate-term options with a 20 m³/s max. import rate: Worst and Best Scenarios, without bypassing saline baseflow, with and without dumping.*

sistent with current operation for irrigation in the upper and middle reaches) involves a two-week release cycle. In the first week of each cycle a large body of water is passed down the river from Grassridge Dam and Elandsdrift Dam while in the second week no release is made.

Model runs also showed that a Tyefu diversion scheme that includes a small off-channel reservoir would be far better operationally than the one consisting only of a weir and canal. With off-channel storage, releases of Orange River water for Tyefu would be required relatively infrequently -- only when off-channel storage needs replenishment. The scheme would allow diversion to off-channel storage at a high rate (e.g., 15 $m^3/s$ ). Thus, a short-duration large release of water from Grassridge can be diverted at Tyefu with relatively little wastage; once the saline water initially present in the river channel has been displaced in plug-flow fashion, a large percentage of the water of acceptable salinity that follows can be diverted.

The off-channel storage scheme would also save water in another way -- by allowing low-salinity storm runoff to be captured. If water is diverted at maximum rate during the typically short-lived runoff peaks, subsequent releases of water from Grassridge can be deferred. The model runs were useful in quantifying these savings.

Du Plessis and Hall also used the monthly time-step version of the model to simulate performance of the alternative Tyefu diversion schemes. The monthly model allowed simulation over 55 years, rainfall input being taken from the historic record. (Using the daily model, in the manner described above, involved testing operation over only one year of typical flows and salinity.) The monthly simulation runs were based on both current and projected future demand levels. These monthly runs indicated how the different Tyefu diversion schemes would perform under a wide range of runoff and salinity conditions and under future conditions when irrigation demands will be higher.

*Table 3* compares prediction results obtained using the monthly model for schemes with and without off-channel storage at Tyefu. These results are for the assumed Most Likely Scenario of future runoff salinity and are for the near term, in which irrigation demands are assumed to increase 10% above 1980 levels. Volume 2 includes Most Likely and Worst Scenario predictions for the long term, when irrigation demands are assumed to increase 100% above 1980 levels.

**Table 3 Summarized near-term prediction results(1) for an irrigation scheme at Tyefu and a TDS goal of 650 mg/l**

| Statistic | Units | Prediction | |
|---|---|---|---|
| | | Without Off-channel Storage at Tyefu | With Off-Channel Storage(2) at Tyefu |
| Mean annual import of Orange River water | $m^3 \times 10^6$/yr | 402,4 | 281,6 |
| Irrigation demand down to Sheldon(3) | $m^3 \times 10^6$/yr | 159,5 | 159,5 |
| Mean annual diversion to Sundays River(4) | $m^3 \times 10^6$/yr | 107,1 | 107,1 |
| Tyefu irrigation demand(5) | $m^3 \times 10^6$/yr | 46,4 | 46,4 |
| Mean(6) TDS, water abstr. above Rietfontyn | mg/$l$ | 161 | 185 |
| Mean(6) TDS, water abstr. below Elandsdrift | mg/$l$ | 291 | 360 |
| Mean(6) TDS, water at Sheldon | mg/$l$ | 404 | 546 |
| Mean(6) TDS, water abstr. at Tyefu | mg/$l$ | 478 | 556 |
| Percent. time(7) Tyefu irrig. TDS > 650 mg/$l$ | – | 9,4 | 9,8 |

(1) For the near term, Great Fish River irrigation demands are assumed to increase 10% above 1980 levels. These results are for the Most Likely Scenario of runoff salinity.

(2) Off-channel storage capacity assumed to be $12 \times 10^6$ $m^3$.

(3) Includes $16,4 \times 10^6$ $m^3$ per year for irrigation along the Little Fish River.

(4) Assumes maximum use of the diversion link (including Wellington Grove pump station) to Lake Mentz.

(5) Based on the DWA projection of a 3 320 ha development on the left and right banks of the Great Fish River.

(6) Flow-weighted mean.

(7) An assumed reasonable interpretation of the Tyefu TDS goal is that 650 mg/$l$ can be exceeded up to 10% of the time.

General conclusions drawn on future salinity levels in the Great Fish River are as follows:

- As more Orange River water is brought in to meet growing irrigation demands in the Great Fish River valley, the salinity levels in supply water will fall. Passing more Orange River water down the Great Fish River for diversion to the Sundays River will lower salinity levels still further. With only a modest 10% increase in Great Fish River and Sundays River irrigation demands, the mean TDS of supply to the irrigation boards below Elandsdrift will be 360 mg/$l$; it will drop further to 258 mg/$l$ if irrigation demands in both river valleys increase by 100% and if Port Elizabeth takes 207 $\times 10^6$ $m^3$ per year.

- There are two reasons for the expected drop in TDS levels. First, the increased flux of low-salinity Orange River water through the system, particularly in the reach down to Elandsdrift, will dilute naturally saline runoff and saline irrigation return flow. Second, as supply water for irrigation becomes less saline, so also will the resultant irrigation return flow – once equilibrium conditions have been reached in the irrigated soils and saturated zone. Whereas the TDS of irrigation return flow (including natural groundwater discharge) in the reach above Rietfontyn was about 1 450 mg/$l$ at the end of 1979, its equilibrium level will be about 900 mg/$l$ for the case with 10% increase in irrigation demand and about 800 mg/$l$ for the case with 100% increase in irrigation demand. These results are based on the Most Likely Scenario of runoff and salinity.

- Equilibrium conditions in the irrigation cycle are reached only several years after any major change in irrigation water and salt inputs. For the Great Fish River, this time is about nine years if one is concerned only about TDS; if one is concerned about concentrations of individual ions, it could be much longer (see the following subsection).

- The proposed development at Tyefu, with an off-channel storage diversion scheme, is feasible in that the 650 mg/l TDS goal can be accomplished satisfactorily without excessive wastage of Orange River water. However, as irrigation development in the Great Fish River valley below Elandsdrift and in the Little Fish River valley increases in future, so will the quantity of irrigation return flow in the lower reaches of the river. Consequently, more Orange River water will be needed to achieve the 650 mg/l TDS goal. The 3 320 ha development at Tyefu will call for an average of $40 \times 10^6$ $m^3$ of Orange River water per year for a 10% increase in Great Fish River irrigation and $48 \times 10^6$ $m^3$ per year for a 100% increase in irrigation.

## Ionic Composition of Irrigation Drainage

Du Plessis and Hall used the Thomas model component to predict the change over time in ionic composition of water draining from irrigated lands in the Great Fish River valley. Inputs consisted of the monthly irrigation water quantities and the average water composition recorded over the period October 1977 through April 1980. These inputs reflect the new availability of Orange River water in the system, i.e., more water is available than in the past and its salinity is lower than in the past. The prediction runs made use of soil physical and chemical characteristics for the eleven representative soil modelling units described in Section 3 above.

*Figure 12* shows, for example, the predicted drainage composition from irrigated lands in the upper Great Fish River valley, above Rietfontyn. This prediction involved using le Roux's deep strata data (see Section 3) based on the assumption that, although from a limited area, they are representative of deep strata in that region. The effect of including the deep strata is to lengthen the predicted time to reach equilibrium in drainage water composition.

*Table 4* shows the predicted time for *root-zone* drainage to reach equilibrium in the upper and lower regions of the Great Fish River valley (as defined in *Figure 5*). Note that the predicted time to reach equilibrium in the upper region is much longer than in the lower region. This difference can be attributed to the fact that the mass throughput of salt in irrigation water is greater in the lower region than in the upper region. (Therefore, in the lower region the number of ions required to reach a new equilibrium is contained in a relatively small volume of irrigation water). Also, the salinity of irrigation water assumed for the lower region was much closer to long-term historical salinity than was the case for the upper region.

Du Plessis and Hall compared their Thomas model prediction results with results they obtained using another model -- the United States Salinity Laboratory (USSL) chemical

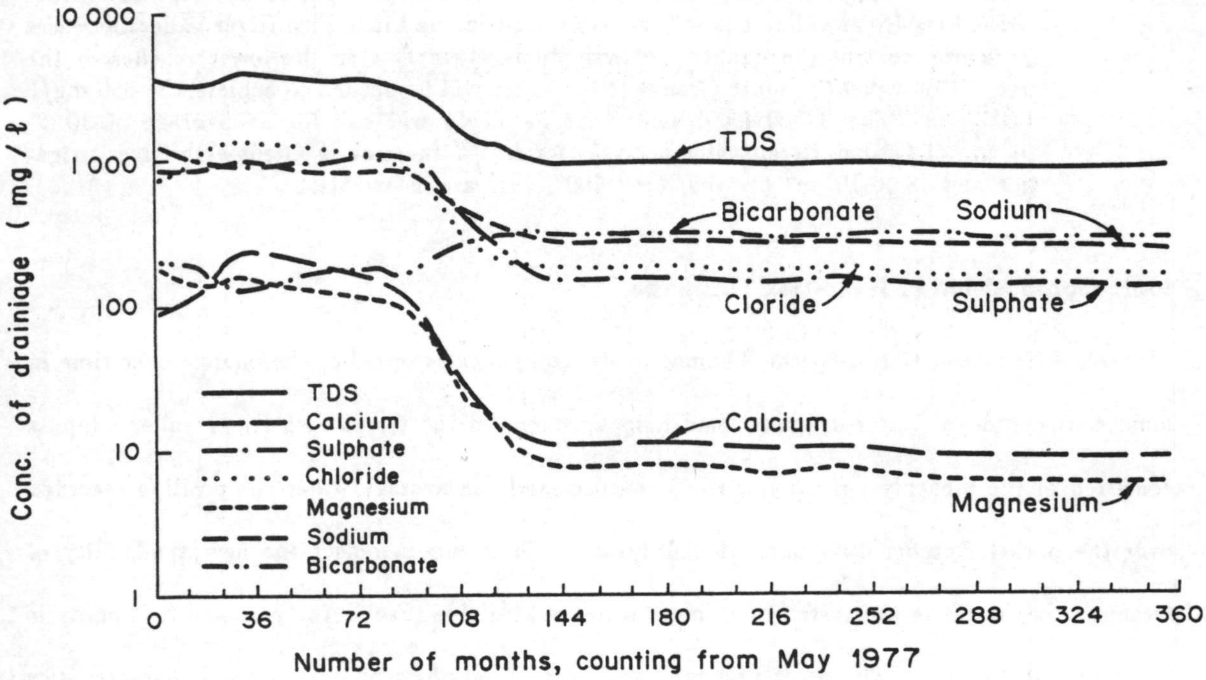


*FIGURE 12* *Predicted ionic composition of drainage from irrigated lands in the upper region of the Great Fish River Scheme, incorporating the contribution of deep strata.*

**equilibrium model. The USSL model's predicted calcium and bicarbonate concentrations were considerably higher. However, results from the two models agreed closely for all the other ions. Since the USSL model describes chemical reactions in solution more rigorously than the Thomas model, its predictions of calcium and bicarbonate are arguably better. The Thomas model appears to overstate lime($CaCO_3$) precipitation; however, Volume 2 presents a simple way of overcoming this shortcoming.**

**Ionic composition of drainage, predicted using the Thomas model, is of interest under transient conditions (i.e., following significant changes in irrigation water and salt inputs). However, under equilibrium conditions the simpler procedure incorporated in subroutine RETFLO is quite adequate. Model runs for the Great Fish River planning options described earlier (i.e., those involving alternate diversion schemes at Tyefu) made use of the simpler procedure and were based**

**Table 4 Predicted Time Required for Individual Ions to Reach Equilibrium in Root Zone Drainage Water, Upper and Lower Regions, Great Fish River**

| Soil Modelling Unit | Time (years) required to reach equilibrium * Ca | Mg | Na | $SO_4$ | Cl | $HCO_3$ | TDS |
|---|---|---|---|---|---|---|---|
| | | | Upper Region | | | | |
| 1 | 187 | 210 | 3 | 2,5 | 2,3 | 36 | 2 |
| 2 | 33 | 255 | 34 | 3,3 | 2,8 | 71 | 17 |
| 3 | 180 | 195 | 35 | 3,5 | 2,8 | 123 | 16 |
| 4 | 213 | 217 | 39 | 3,3 | 2,8 | 188 | 30 |
| 5 | 202 | 210 | 40 | 3,3 | 3,0 | 165 | 23 |
| 6 | 255 | 258 | 45 | 3,3 | 3,3 | 232 | 25 |
| 7 | 129 | 135 | 20 | 3,0 | 2,5 | 117 | 3 |
| 10 | 158 | 161 | 28 | 3,0 | 2,5 | 142 | 3 |
| 11 | 135 | 137 | 13 | 3,0 | 1,5 | 125 | 2 |
| Comb. | > 50 | > 50 | 35 | 3,3 | 2,8 | 50 | 19 |
| | | | Lower Region | | | | |
| 1 | 74 | 74 | 14 | 1,3 | 1,5 | 65 | 16 |
| 4 | 79 | 79 | 2 | 1,5 | 1,8 | 65 | 2 |
| 5 | 97 | 97 | 20 | 1,3 | 1,5 | 88 | 25 |
| 6 | 117 | 117 | 2 | 1,8 | 1,8 | 108 | 2 |
| 7 | 49 | 49 | 6 | 0,8 | 1,0 | 37 | 8 |
| 10 | 114 | 115 | 2 | 1,5 | 1,5 | 103 | 22 |
| 11 | 12 | 18 | 5 | 0,5 | 0,8 | 5 | < 1 |
| Comb. | > 50 | > 50 | 2 | 1,5 | 1,8 | 50 | 1 |

* Equilibrium taken to be when ion concentrations (in me/$l$) reach ±10% of their final constant values.

on the assumption that sufficient time had lapsed for the irrigation cycle to be in equilibrium. Thus, those predictions were static in the sense that irrigation demands and river system operation rules were unchanged from one year to the next; but they were dynamic with regard to the runoff and salinity time series used.