PRE-FEASIBILITY STUDY INTO MEASURES TO IMPROVE THE MANAGEMENT OF THE LOWER ORANGE RIVER

HYDROLOGY, WATER QUALITY AND SYSTEM ANALYSIS: VOLUME B – HYDROLOGY

Part 2

Review of RSA Hydrology

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EXECUTIVE SUMMARY

The main aim of this review is to increase the transparency of South African studies for the benefit of the Namibian Team and at the same time to ensure that they are well acquainted with the hydrology of the river basin in South Africa and Lesotho.

This review is based on three key linked information sources:

- ***Hydrological reports as obtained from the "Vaal River System Analysis Update", "Orange River Development Project Replanning" (ORRS) and the "Orange River System Analysis" studies.***
- ***The systems analysis set-ups, which facilitated understanding of priorities and transfers.***
- ***The stream flow datasets for all of the sub-catchments as derived in the studies carried out to compile the systems analysis update.***

The hydrological studies and systems analyses carried out in South Africa covering the entire Orange River Basin within South Africa and Lesotho have been reviewed. The general impression is that the work has been carried out thoroughly as far as the data will allow. There is no reason to disagree with the hydrological files being used as input for the systems analysis. However, as is generally the case with hydrological and associated data, given the human and financial resources, it would of course be possible and worthwhile to improve the accuracy of the data.

As stated on several occasions in the literature reviewed, the Vaal and Orange River Basins are the most important water resource systems in South Africa. They support more than 50% of the country's GDP. It is logical; therefore, that money spent on improving the accuracy of our knowledge of the system is well-spent and can be easily justified. Hence, the current study, and the major investments being made by the Governments of South Africa and Namibia. However, in view of the fact that some of the hydrological studies studied in this review are already more than a decade old, it would seem worthwhile to utilise any new data that have been collected since their completion and to update these studies. This includes the incremental catchment upstream of Vanderkloof Dam and downstream of the Lesotho Border, as well as the Lower Orange with the exception of the Fish River in Namibia.

The need to update hydrological data and the analysis thereof should not be limited to runoff data, but should also include improved collection of water demand data. The effort put over to analysis of water demand information in the studies reviewed reflects a strong awareness of the importance of water demand data. Any basin-wide efforts to update hydrology and water demand should not be undertaken lightly and will probably require a multi-disciplinary approach involving several Ministries. Consideration should be given to using a GIS-driven approach, which can be easily updated on a regular basis.

In the interest of transparency and common understanding at a technical level, it is recommended that key Orange River Basin river stations in South Africa (and Namibia) be identified for common monitoring. Joint monitoring would include water level monitoring (real-time telemetry), flow measurements for station calibration, and conversion of water levels into discharge. It would seem logical to extend this transparency to include all gauging stations and also to cover water demand data.

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LIST OF ABBREVIATIONS

DSL	:	Dead Storage Level
DWA	:	Department of Water Affairs (Namibia)
DWAF	:	Department of Water Affairs and Forestry (RSA)
GDP	:	Gross Domestic Product
Ha	:	Hectare
HDYP09	:	Mathematical Model for Generation of River flows from meteorological data in South Africa
LHDA	:	Lesotho Highlands Development Authority
LHWP	:	Lesotho Highlands Water Project
MAE	:	Mean annual evaporation
MAP	:	Mean annual precipitation
MAR	:	Mean annual runoff
Million m^3	:	Million cubic meter
ORP	:	Orange River Project
ORRS	:	Orange River Development Replanning Study
RSA	:	Republic of South Africa
St deviation	:	Standard deviation
VRSAU	:	Vaal River System Analysis Update Study
WRSM90	:	Water Resources Simulation Model

1. INTRODUCTION

The Orange River Basin is large, covering more than half of the land area of South Africa and the entire land area of Lesotho. Understanding the hydrology is complicated by a relatively small (considering the variability of rainfall) number of stream gauges, numerous inter-basin transfers, a large number of storage structures and high levels of demand. Given the importance of the water resources of the Orange River to South Africa, which is close to a water deficit situation, it is not surprising that numerous studies have been carried out on the hydrology of the components of the system.

In recent years, the significance of these studies has increased because of the increasing interest in the resources of the river from South Africa's neighbours, in particular Lesotho, Namibia and Swaziland. Lesotho has a water resources surplus and has reached agreement with South Africa to store and transfer water from impoundments within its territory in order to increase the yield of the system where it is needed in South Africa. Development in Namibia within the basin has increased sharply within recent years and, especially with respect to high value irrigated crops, which depend on water abstracted from the Orange River. Namibia therefore has an interest in the way in which the water resources of the system are managed further upstream in South Africa. Swaziland, while not situated within the basin is nevertheless affected by transfers from the headwaters of the Komati and Usutu Rivers. Transfers from the Usutu and Komati Basins are used to support the Vaal system, as well as Power Stations in the Upper Olifants, of which the latter also receives support from Grootdraai Dam in the Upper Vaal. Although the Komati and Usutu Rivers are not directly linked to the Orange River, the fact that they are used to augment the Vaal System will result in some effect on the Orange River. These two rivers rise in South Africa and flow eastwards through Swaziland to Moçambique and the Indian Ocean. Their water resources are critical to the sugar industry in Swaziland. The Orange River mouth at Alexander Bay/Oranjemund also has importance internationally, having been declared a RAMSAR site.

This increased international interest has resulted in a need for transparency with respect to studies on the water resources of the Orange and associated systems. There are now water allocation agreements in place between Lesotho and South

Africa, and more recently (August 2002) between South Africa and Swaziland.

The main aim of this review is to increase the transparency of South African studies for the benefit of the Namibian team and at the same time to ensure that they are well acquainted with the hydrology of the river basin in South Africa and Lesotho. This review is based on three key linked information sources:

- Hydrological reports as obtained from the “Vaal River System Analysis Update”, “Orange River Development Project Replanning” and the “Orange River System Analysis” studies.
- The systems analysis set-ups, which facilitated understanding of priorities and transfers.
- The stream-flow datasets for all of the sub-catchments as derived in the studies carried out to compile the systems analysis update.

The basic approach followed in the hydrological studies is generally the same and can be summarised as follows:

- Assembly of key “observed” data. These data are essentially:
  - the observed rainfall data for the largest possible coverage of rainfall stations;
  - the observed data for the stream flow stations for each sub-catchment. These gauges are a combination of purpose-built gauging stations and dams;
  - evaporation data; and
  - demand data including irrigation, urban, industrial and mining, domestic, forestation demands, and also seepage loss and environmental requirements.

- Pre-calibration data manipulation:
  - For the rainfall data, the quality of the data at each rain gauge is checked by consideration of the record length, amount of missing data and finally using mass plots. Gauges with unacceptably short records (normally 40 years), but this may be reduced for catchments where data are lacking. Gauges with a high percentage (normally > 8%) of unreliable record are similarly rejected. Where possible, gaps in records are “patched” using a

multiple linear regression on other gauges in the sub-catchment.

- For the stream flow data, the data for all available river gauges are considered. Those with records that are too short, water stage/discharge ratings that are unreliable, or too much missing data, are rejected. Some mass balance analyses are carried out to examine the accuracy of some of the records.
- Water demand data are examined and taken back in time. For example for irrigation data, it is necessary (see later) to estimate demand as it has grown through the period of analysis (i.e., since 1920). Similarly for other demands. This is important, because rainfall/runoff modelling is based on the principle of modelling rainfall against "naturalised runoff", that is runoff unaffected by development. This is necessary, because since (it is assumed that) rainfall is unaffected by human development, it would not be possible to model it against a non-stationary time series such as observed runoff. Once modelling has been completed and an extended runoff record produced, this extended runoff can be adjusted to take into account the realities of current/future levels of demand during the systems analysis. In view of the high level of water demand within the Basin, accurate determination of water demand is critical if accurate model calibration is to be achieved.

- Model Calibration:
  - Prior to runoff simulation and record extension, Model Calibration has to be carried out. In the South African studies, a model known as the WRSM90 runoff model, has generally been used. This is an upgraded version of the Pitman (or HDYP09) model. In simplified terms, this model aims to calculate runoff based on catchment rainfall weighted according to a number of catchment parameters. Without going into detail, the principle is that these catchment parameters approximate the physical characteristics of the catchment that may have an influence on runoff. During the calibration process, the values of these parameters are modified until the best possible fit can be achieved, while at the same time respecting the physical realities of the catchment.

- Patching and Record Extension:
  - Following calibration, the model is used to patch missing periods in the observed records and to extend the record back in time, in the case of these hydrological studies to the 1920s.
  - The process is carried out for all the sub-catchments.

- System Analysis:
  - The resultant incremental runoff records are used as input to the systems analysis for the main sub-catchment area for which the hydrology is being updated.
  - The systems analysis combines the hydrology of all the sub-catchments and takes into account all the different types of water demand, including non-consumptive uses and inter-basin transfers. The systems analysis is carried out according a set of operating rules, which define priorities for different users. These "users" include the environment and natural losses such as seepage and evaporation. Operating rules can be varied until yields are optimised as desired.

2. REVIEW OF HYDROLOGICAL REPORTS AND DATA

2.1 Reports Consulted

The following reports were supplied and reviewed:

Bailey, A. K. (1999). **Vaal River System Analysis Update; Hydrology of the Vaal Barrage Catchment**. Pretoria, Department of Water Affairs and Forestry.

Basson, M. S. (1997). **Overview of Water Resources availability and utilisation in South Africa**. Pretoria.

BKS and Ninham Shand (1998). **Potential Dam Developments and Hydro Power Options - Orange River Development Replanning Study**. Pretoria, Department of Water Affairs and Forestry.

Loxton Venn & Associates and Agrimodel (1998). **Evaluation of Irrigation Water Use Volume 3 : Possible New Irrigation Developments - Orange River Development Replanning Study**. Pretoria, Department of Water Affairs and Forestry.

Loxton Venn & Associates and Agrimodel (1998). **Evaluation of Irrigation Water Use Volume 2 : Existing Irrigated Agriculture - Orange River Development Replanning Study**. Pretoria, Department of Water Affairs and Forestry.

Loxton Venn & Associates and Agrimodel (1998). **Evaluation of Irrigation Water Use Volume 1 : Present Water Demand - Orange River Development Replanning Study**. Pretoria, Department of Water Affairs and Forestry.

Maré, H. G. and O. J. Viljoen (1999). **Irrigation and Farm Dam Information for the Vaal River System**. Pretoria, Department of Water Affairs and Forestry.

McKenzie, R. S., N. W. Schäfer, ***et al***. (1992). **Upper Orange River : Hydrology**. Pretoria, Department of Water Affairs.

McKenzie, R. S. (1998). **Vaal River System Analysis Update; Lesotho Highlands Hydrology**. Pretoria, Department of Water Affairs and Forestry.

McKenzie, R. S. and H. G. Maré (1998). **Hydrology and Systems Analysis - Orange River Basin - Orange River Development Replanning Study**. Pretoria, Department of Water Affairs and Forestry.

McKenzie, R. S. and F. G. B. d. Jager (1999). **Vaal River System Analysis Update; Hydrology of the Upper Vaal Catchment**. Pretoria, Department of Water Affairs and Forestry.

McKenzie, R. S., H. G. Maré, ***et al***. (1999). **Vaal River System Analysis Update; Hydrology of the Usutu River Catchment upstream of Swaziland**. Pretoria, Department of Water Affairs and Forestry.

Pitman, W. V. (1999). **Vaal River System Analysis Update; Hydrology of the Tugela Catchment and Hydrology of Zaaihoek Dam**. Pretoria, Department of Water Affairs and Forestry.

Pitman, W. V., C. E. Herold, ***et al***. (1999). **Vaal River System Analysis Update; Hydrology of the Middle Vaal Catchment**. Pretoria, Department of Water Affairs and Forestry.

Rossouw, J. D. (1997). **Water Demands of the Orange River Basin - Orange River Development Project Replanning Study**. Pretoria, Department of Water Affairs and Forestry.

Stassen, R., G. Hemme, ***et al***. (1997). **Hydrology and Systems Analysis - Eastern Cape Rivers - Orange River Development Replanning Study**. Pretoria, Department of Water Affairs and Forestry.

Tukker, M. J. (1999). **Vaal River System Analysis Update; Hydrology of the Lower Vaal Catchment**. Pretoria, Department of Water Affairs and Forestry

2.2 System Analysis and Data

In addition, the layouts of the systems analyses for the sub-systems listed below were reviewed. The layouts included the assigned penalty values so that it was possible to have an understanding of the operating rules.

- Combined Caledon, Lesotho Highlands Water Project, Upper Orange, Riet/Modder and Lower Vaal sub-systems.
- Namibia and Lower Orange sub-systems.
- Usutu, Komati, Upper Olifants, Zaaihoek, Upper Thukela, Thukela South, Upper Olifants and Upper Vaal sub-systems.
- Upper Vaal and Vaal barrage sub-systems.
- Middle Vaal sub-system.
- Lower Vaal and Riet/Modder sub-systems.

2.3 Runoff Data

The runoff files (*.inc) adopted for all the incremental catchments were provided and examined in order to get a feeling for monthly and annual variation and magnitude of flow. **Table 2.1** summarises the files, which were provided.

Table 2.1: Runoff Records Derived from Hydrological Studies for use in Systems Analysis

ALIW.INC	kat9.inc	rietf9.inc
allem9.inc	KATJE.INC	riets9.inc
auch9.inc	klerk9.inc	ROOD.INC
barbers.inc	klipb9.inc	rustf9.inc
barr9.inc	klipd9.inc	sand9.inc
bloem9.inc	klipr9.inc	spits9.inc
bosk9.inc	KNEL.INC	sterk9.inc
C3h013.inc	kop9.inc	suik9.inc
C5r5.inc	krom9.inc	tier9.inc
c9h007.inc	Krug10.inc	tso9.inc
dehoop9.inc	LORAN.INC	twee9.inc
dela9.inc	mal9.inc	uswentzd.inc
dswentzd.inc	mas9.inc	vaal9.inc
erf9.inc	mat9.inc	VERW.INC
FISH94.SPL	Mock.inc	vharts9.inc
fran9.inc	moh9.inc	WATER.INC
grootd9.inc	neser9.inc	WELBB.INC
HFDU.INC	nto9.inc	VIOOL.INC
HLOTS.INC	oran9.inc	BOEG.INC
kalkf9.inc	PKDU.INC	HARTB.INC

3. OVERVIEW OF ORANGE RIVER CATCHMENT

The Orange River rises as two main river systems, the Orange River and its associated tributaries, and the Vaal River and its associated tributaries. To the south, the Orange River rises as two main tributaries, the Caledon and the Senqu Rivers in the Drakensburg and Maluti Mountains in Lesotho and South Africa. To the north, the Vaal River rises in the Highveld in Mpumalanga and Northern Provinces of South Africa. The large majority of runoff is generated in these areas. The Vaal and the Orange (on crossing the border from Lesotho into South Africa the name changes from Senqu to Orange) Rivers make their confluence near the town of Douglas, more than a thousand kilometres upstream of the longitude 20 degrees where the Orange River becomes the border between Namibia and South Africa. Downstream of Douglas, the Orange River is joined by the Ongers/Brak River and the Hartbees River from the south and the Molopo and Fish Rivers from the north. The Molopo River has not been known to contribute surface runoff to the Orange River.

4. SUB-CATCHMENT HYDROLOGY

4.1 Overview

In representing and modelling the Orange River System, the approach adopted by South African Consultants and the Ministry has been to model the system as a whole, but to describe the hydrology and water demand on a sub-catchment basis. In some cases, these sub-catchments have grouped together as a large number of smaller sub-catchments. As is normal practice, the choice of sub-catchments has been made according to a combination of considerations including the location of gauging stations/dams and location of various demand centres.

The main source areas are covered by the Lesotho sub-catchment system; the Caledon River catchment and the Upper Vaal catchment (see **Figures 4.1 and 4.2**). However, this is complicated by the fact that part of Lesotho sub-catchment is also implicated in the Upper Vaal catchment since it is towards the Upper Vaal that water transfers are made. In addition, the Upper Vaal receives water transferred from other rivers outside of the Orange River Basin. These are also included in the analysis of the Vaal River System. The remainder of the Vaal River is divided into the Middle and Lower Vaal sub-catchment groupings. Upstream of the confluence of the Vaal River, the eleven Orange River sub-catchments are often defined by dams such as the Boskraai, Gariep, Welbedacht, Vanderkloof and Kalkfontein Dams. Downstream of the Vaal/Orange River, there are five large sub-catchments, those of the Ongers/Brak, Hartbees, Molopo, Fish and “River Mouth” catchments.

The hydrology of these sub-catchments as developed and described by or for the South African Department of Water Affairs (DWAF) has been reviewed and the findings, conclusions and recommendations are summarised on a sub-catchment (grouping) by sub-catchment (grouping) basis in **Sections 4.2.1 to 4.3.3.**

4.2 Vaal River Sub-catchments

4.2.1 Upper Vaal Sub-system

a) General Description

The Upper Vaal catchment forms part of the Vaal catchment, which is regarded as the most important water resources system in South Africa, supplying water to more than 40% of the population and supporting more than 50% of the country's gross domestic product (GDP). The Upper Vaal includes four major impoundments, the Vaal Dam (capacity of 2 603 million m³), Grootdraai Dam (356 million m³), Sterkfontein Dam (2 616 million m³) and Saulspoort Dam (17 million m³). The catchment has been divided up into five sub-catchments, Sterkfontein, Delangsdrift, Grootdraai, Wilge and Vaal Dam (incremental) sub-catchments. Reference should be made to **Figure 4-1**. The Grootdraai and Sterkfontein sub-catchment runoffs are supplemented by inter-basin transfers from the Usutu/Komati and Tugela catchments, respectively. The Vaal Dam also receives inflows from the Senqu River in Lesotho.

The Upper Vaal catchment covers an area of 38 638 km² with little in the way of urban development. There are thousands of small farm dams in the catchment.

b) Literature Consulted

The first major system analysis study on the Vaal River carried out in 1985 has not been reviewed in any detail, since this has been superseded by studies in 1993 and especially a study carried out between 1995 and 1997. The last-mentioned of these studies known as "Vaal River System Analysis Update Study (VRSAU)" has been reviewed in detail. The stated purpose of this study was:

> "……to revise and update the hydrological and water quality databases used in the earlier studies and to re-assess the water quantity and quality capabilities of the whole Vaal River System using the most up-to-date information and techniques."

c) Water Use

The VRSAU Study goes into considerable depth in its evaluation of water use and water demand. This is important, since only an accurate assessment of current and past water demand will allow an accurate "naturalisation" (see **Section 1**, Introduction).

Vaal Dam supplies Rand Water, South Africa's largest potable water supplier (all municipal and industrial users in Gauteng), various urban users, Grootvlei Power Station and some irrigation. Sterkfontein Dam stores water, transferred from the Tugela River System. Grootdraai Dam supplies water to various power stations and industrial users, including Sasol. It receives transfers from the Usutu catchment (Maputo River Basin).

The VRSAU included a detailed analysis of the small dams in the catchment using conventional mapping and satellite imagery. It was shown that the total capacity of all farm dams was significant. It was estimated in the study that the quantity of small (dam) storage in the basin had increased from 11.84 Mm^3 in 1920 to 166.49 Mm^3 by 1995.

The report states that there were some difficulties in accurately determining the current area under **irrigation**. The consultants made use of previous studies, Department of Water Affairs' (DWA) records and other methods to arrive at a figure of 12 200 Ha under irrigation with the majority in the Frankfort and Vaal Dam catchments. It was estimated that the area under irrigation had grown from 2 250 Ha in 1920, but that in nineties irrigation within the catchment had remained "almost constant". The report shows that considerable care was taken to model irrigation demand as accurately as possible. Cognisance was taken of different crops and monthly variations in application rates. Return flows of 10% were assumed.

Urban and industrial abstraction levels are measured by DWAF and amounted to almost 33 million m^3 from the Vaal Dam catchment in 1994.

Afforestation areas are limited. The estimated total area was only 13.4 km^2 in 1994.

d) Transfers

Since 1974, water has been pumped from the upper reaches of the Tugela River over the Drakensburg to Drieklloof Dam, a small dam adjoining Sterkfontein Dam, for hydropower generation and also for transfer to the Vaal Dam Basin. The study reports that it is not possible to accurately calculate the amount of water transferred into the Vaal Dam catchment due to the complexity of the transfer system and some unknown factors. A maximum transfer of 700 Mm^3/annum has been designed for, but this is rarely possible to achieve. Historical records of annual releases are misleading since during the first 8 years of the dams life no water was released as the dam was filling. The average amount of water transferred from the Tugela Basin to Sterkfontein Dam between 1974 and 1995 was 283 million m^3. Over the last 13 years, since Sterkfontein Dam has filled, an average of 183 million m^3 has been released (after consideration of transmission losses). Water is also transferred from the Zaaihoek Dam on the Buffalo River System, a tributary of the Tugela River for power supply, local urban water supply and can flow into the Vaal River upstream of Grootdraai Dam. The scheme started operating in 1991 and annual transfers ranged from 8 million m^3 up to 73 million m^3.

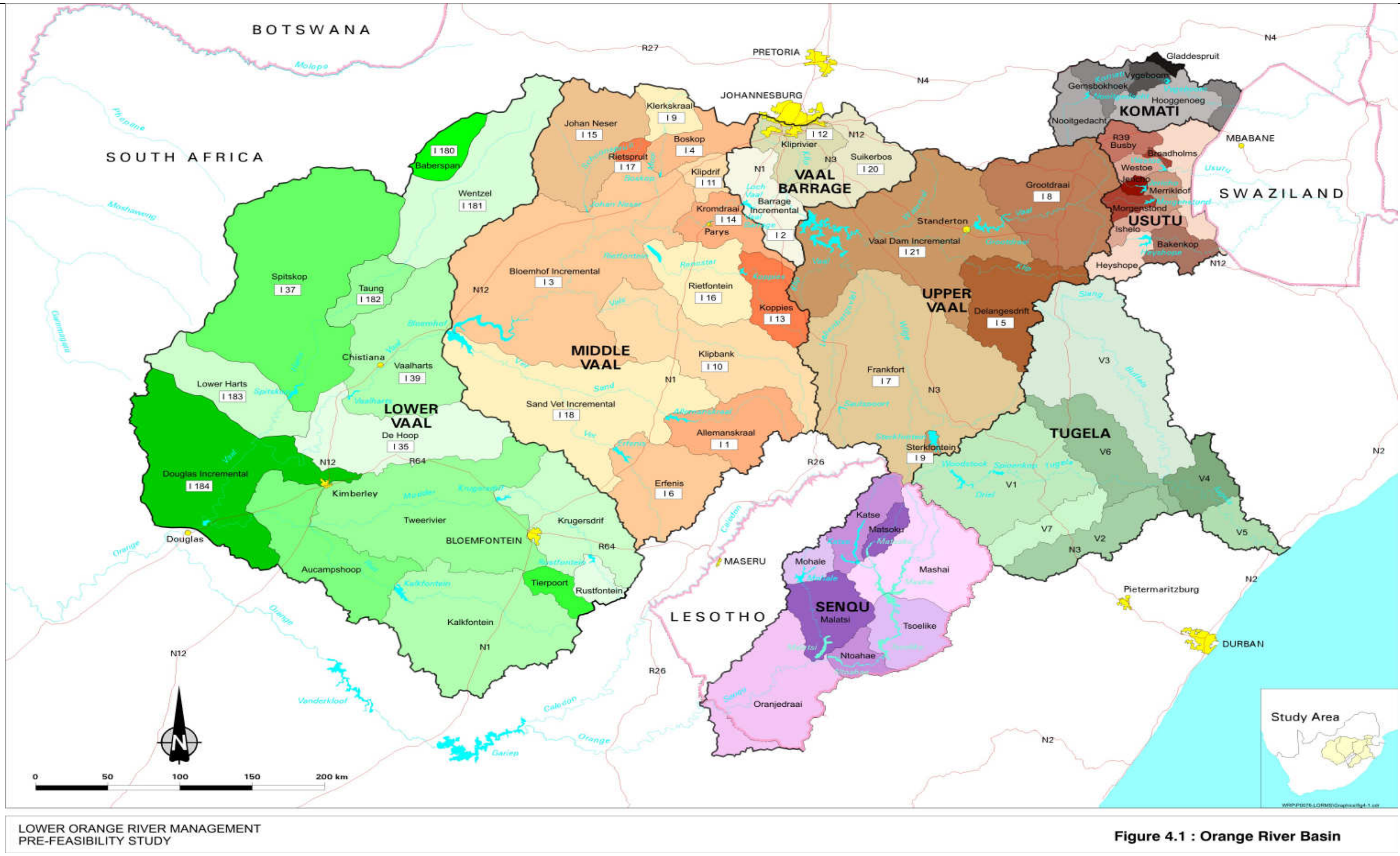

Figure 4-1: Orange River Basin

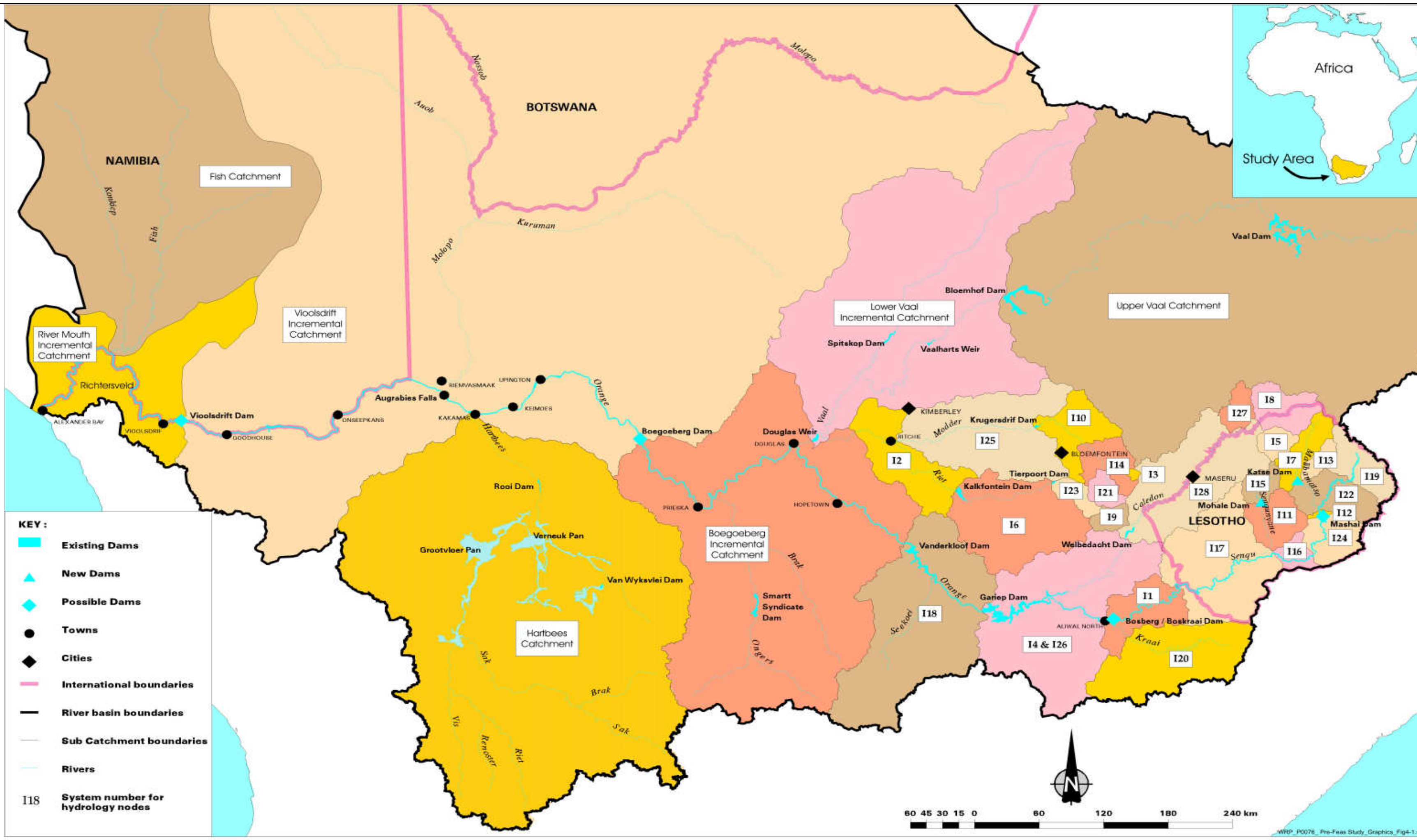

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Figure 4.2 : Orange River Basin

Figure 4-2: Orange River Basin

Water is transferred from Heyshope Dam in the Usutu River via a number of conveyances to the Grootdraai Dam on the Vaal River. Annual transfers between 1985 and 1994 varied from zero to 113 million m³.

e) Observed Records

In line with the generalised procedure as explained in the introduction, the observed rainfall records for as many stations as possible were examined for each of the five sub-catchments. The rainfall data for the Upper Vaal were found to be of a generally good quality and it was possible to apply exacting selection criteria. Nearly 20 gauges with records going back to 1920 or before were found. Sufficient evaporation data were also available.

Table 4.1: Runoff Gauges Used in 1995-1997 Upper Vaal Study

Gauge (River)	Gauge No.	Catchment Area (km²)	Date Opened	MAR	Comments
Standerton (Vaal)	C1H001	8 193	1920	453.70	MAR for 1920-1994 period. Only minor patching of the record was required. Record was completed with Grootdraai inflow after 1978
Delangesdrift	C1H002	4 152	1920	247.10	MAR for 1920-1994 period. Station unreliable at high flows (drowning). Very little need for patching.
Engelbrechtdrift (Vaal)	C2H003	38 564	1923	1 917.91	Only minor patching required. Years 1920-23 had to be simulated. Inflow record for Vaal Dam taken into account after 1936.
Frankfort	C6H001	15 673	1920	760.38	Extensive patching using C8H022 was required although recorded data was reliable.
Vaal Dam	C1R001	38 505	1936	1 858.25	No Patching required during period of record
Grootdraai Dam	C1R002	7 924	1978		Allowance had to be made for U/S abstractions during drought in 1983
Sterkfontein Dam (Wilge)	C8R003	58	1974		Station used only for naturalisation of Frankfort gauge.

There are 19 stream flow gauges in the catchment (including dams operating as gauging stations). Some of these have data extending back to the early 1900's, but much of the data is considered unreliable. After a critical analysis, the consultants retained only seven stations. Six stations were rejected due to unsuitably small catchment areas or poor data. Five stations were rejected due to the short records, having only been opened between 1971 and 1985. Clearly, in a revised analysis there would be considerable new data available. The report

provides a useful in-depth review of the available data. Using standard techniques (comparisons with other stations nearby, upstream or downstream etc.), the streamflow records were verified. Short periods of missing data for periods covered in the 1986 assessment were not re-patched. The utilised gauges are summarised in **Table 4.1**.

f) Rainfall/Runoff Modelling, Runoff Naturalisation

As is normal practice in South Africa, the well-tested WRSM90 runoff model was used for calibrating the observed record against weighted rainfall. The results are described in detail in the report and show high levels of correlation.

In order to achieve the required naturalised flow record, account had to be taken of the water use data described earlier in the report. This includes inter-basin transfers, which have to be subtracted from the observed flows. The report takes each one of the observed records and explains in sufficient depth how the naturalised records were calculated.

g) Synthesized Record

The details of the combined observed and synthesized records are summarised in **Table 4.2** as extracted from the report.

Table 4.2: Summary of Results for Upper Vaal Hydrological Analysis

Incremental Sub-catchment	Catchment Area (km^2)	Observed Incremental Runoff or Inflow (10^6m^3)	Natural Incremental MAR (10^6m^3)
Grootdraai	7 995	453.7	457.7
Delangesdrift	4 158	247.1	249.5
Frankfort incr.	15 498	696.2	733.3
Vaal incr.	10 792	493.2	518.7
Sterkfontein	195	97.3	18.1(3)
Total for Catchment	**38 638**	**1987.5**	**1977.3**

It is interesting to note that the natural incremental runoff is less than the observed. This is because of the fact that the observed runoff includes transfers from outside of the catchment.

g) Conclusions

The Upper Vaal Hydrological analysis makes use of long and generally reliable runoff records. It was found that the mean annual runoff (MAR) at Vaal Dam had not changed significantly (3%) since the less rigorous 1985 analysis. The report is very clear on the importance of correctly estimating water use/demand data since this has a significant effect on the accuracy of the record naturalisation process. Irrigation demands, which are the largest are stated as having been constant for a few years prior to 1994. While it may not be warranted to re-evaluate the hydrology, using the new data collected since 1994 (which may allow some new stations to be included in the analysis) for year or two, it is considered worthwhile to check on water demand figures, especially the irrigation demands, over the last decade.

4.2.2 Middle Vaal Sub-system

a) General Description

The Middle Vaal sub-catchment includes ten major impoundments, the most important being the Bloemhof Dam (capacity of 1 269.2 Mm^3) at the outlet of the Middle Vaal catchment. Other large impoundments are the Erfenis Dam (207.7 Mm^3), Allemanskraal Dam (174.7 Mm^3) and Koppies Dam (41.2 Mm^3). In the VRSAU Study: The catchment was divided up into 12 sub-catchments, Erfenis, Allemanskraal, Sand Vet incremental, Klipbank, Koppies, Rietfontein, Kromdraai, Klipdrif, Boskop, Klerkskraal, Johan Neser, Rietspruit and Bloemhof incremental sub-catchments. Reference should be made to **Figure 4. 1**.

The Middle Vaal catchment covers an area of just over 60 000km^2 with little in the way of relief other than the hills in the upper area of the Vals River. There are some large urban developments and mines together with extensive irrigation.

b) Literature Consulted

The 1997 VRSAU Report on the Middle Vaal was the main source for this review.

c) Water Use

As was the case with the Upper Vaal the study was particularly careful in its treatment of water demands particularly important in the Middle Vaal sub-catchment.

The VRSAU included a detailed analysis of the small dams in the catchment, on a sub-catchment by sub-catchment basis, using conventional mapping and satellite imagery. It was shown that the total capacity of all farm dams was significant at over 224 Mm^3. Older maps and the Dam Register were used to estimate historical growth in total dam capacity since 1920.

Major Irrigation schemes are sometimes part of government water schemes in which case the demand is usually monitored, or under the control of Irrigation Boards. There are also several private irrigation schemes. The report states that the Middle Vaal catchment has not been subject to any detailed irrigation investigation. Estimates were largely based on the 1988 Census of Agriculture. A number of approaches were used to derive the estimate of 23 300 ha under irrigation for 1994. The study showed that irrigation area had grown by approximately 1,78% per annum since 1920 (6 520 ha). In view of the impact of irrigation, the report goes into some detail on irrigation water usage, investigating the different water sources used, cropping patterns and seasonal demands. It was estimated that 130.6 Mm^3/annum are used for irrigation in the Middle Vaal catchment.

There was a major increase in urbanisation and urban water demand in the decade up to 1994, resulting also in significant return flows of effluent. The study clearly looked in great detail at urban and industrial abstractions and return flows and this is reported in considerable detail.

Afforestation is minimal in the Middle Vaal catchment and was not taken into account in the analysis.

Transmission losses are significant and difficult to estimate using standard approaches. A special approach was developed in the VRSAU Study. It showed that transmission losses in the Vaal River between Vaal Dam and Bloemhof are approximately 74 million m³/a.

d) Transfers

There are no transfers into the Middle Vaal Catchment.

e) Observed Records

In line with the generalised procedure as explained in the Introduction, the observed rainfall records for as many stations as possible were examined for each of the fifteen sub-catchments. The rainfall data for the Middle Vaal were found to be of a generally good quality and it was possible for the consultants to apply exacting selection criteria. The data for 140 gauges were selected for further analysis.

The report provides details on the records of all 140 gauges. 66 Gauges had records going back to 1920 or before which allows some confidence in the rainfall/runoff modelling of early years.

Table 4.3: Runoff Gauges Used in 1995-1997 Lower Vaal Study

Gauge (Catchment)	Gauge No.	Catchment Area (km²)	Date Opened	MAR (Mm³)	Comments
Witrand (Catchment)	C2H001	3 595	1903	-	Oldest record available. Various problems affect accuracy but record useable.
Schoemansdrift (Vaal River)	C2h018	49 120	1938	43	Record considered reasonable, water hyacinth can affect accuracy
Klipplaatdrift (Vaal River)	C2H061	79 903	1971	-	Some probably with accuracy at low flows and for high flows
Hoogekraal (Mooi River)	C2H085	5 485	1986	-	Reasonable accuracy but flows easily submerged
Boskop Dam (Mooi River)	C2R001	3 287	1957	72	
Johan Neser Dam (Schoonspruit)	C2R002	5 635	1922	87	Record ceases in 1951. Quality of record unknown
Klerkskraal Dam (Mooi River)	C2R003	1 335	1969	-	Low flow spillage cannot be measured accurately
Floorsdrift (Vet River)	C4H002	17 599	1950	413	Station closed after sub-mergence by Bloemhof Dam. Inaccurate at higher flows
Nooitgedacht (Vet River)	C4H004	16 533	1968	-	Not accurate for low flows. Okay for medium and perhaps high flows. Replaced C4H002
Allemanskraal Dam (Sand River)	C4R001	3 665	1959	-	High spillage flows are not accurately measured
Erfenis (Vet River)	C4H010	4 750	1959	-	Accurate crump weir
Roodewal (Vals River)	C6H001	5 674	1912	-	Low and medium flows reasonable, high flows could be overestimated
Mooifontein (Vals River)	C6H003	7 765	1966	155	Not suitable for low flows. Acceptable for medium flows, but not reliable for high flows
Dankbaar (Heuninghspruit)	C7H003	914	1947	-	Several problems affect the accuracy of this gauge. Record considered unreliable.
Arriesrust (Renoster River)	C7H006	5 758	1977	120	Low flows not accurate. Primarily a flood warning station
Koppies Dam (Renoster River)	C7R001	2 147	1920	59	Record accurate with no apparent anomalies
Bloemhof Dam (Vaal River)	C9R002	107 911	1968	1085	No rating for outflow measurement weir

There are 60 stream flow gauges in the catchment (including dams operating as gauging stations), although many of these have specialised purposes or have catchments too small to be of interest to the study. 19 gauging stations, of which seven were reservoir gauges were chosen for the calibration process. With the exception of the Schoonspruit River, coverage was considered to be adequate. Three gauges had records starting before 1920, two between 1921 and 1940, and the rest after 1960. Details on the records are provided in **Table 4.3**. Gaps in the records were patched using various techniques. Details on how the patching was carried out are presented in the report.

f) Rainfall/Runoff Modelling, Runoff Naturalisation

As is normal practice in South Africa, the well-tested WRSM90 runoff model was used for calibrating the observed record against weighted rainfall for 17 stations. Based on this calibration, it was possible to produce synthesized runoff records dating back to 1920. The results are described in detail in the report and show high levels of correlation

In order to achieve the naturalised flow records required for the calibration, account had to be taken of the water use data described earlier in the report. This includes inter-basin transfers, which have to be subtracted from the observed flows. The report takes each one of the sub-catchments and explains in sufficient depth how the water demands were calculated.

The naturalised stream-flows are discussed in some depth in the report. The approach adopted to produce the naturalised stream-flow for the entire record period was to take the observed record and to add all the calculated water demands (and subtract transfers received). This naturalised observed record is then extended using the synthesized record, which is any case already naturalised. The alternative approach, sometimes adopted since it usually leads to "better" correlations, of using just the synthesized record and none of the observed record was not adopted. Both approaches can be argued as being more correct, but this review concurs with the approach adopted in VRSAU.

Comparisons were made with previous studies and it was found that the overall MAR of the Middle Vaal was only one per cent different from the previous study.

However, there were significant differences for some of the sub-catchments. These differences are satisfactorily explained in the report.

g) Synthesized Record

The details of the combined observed and synthesized records are summarised in **Table 4.4** extracted from the report.

Table 4.4: Summary of results for Middle Vaal Hydrological Analysis

Sub-catchment	MAR (10^6m^3)
Mooi	134
Renoster	120
Schoonspruit	93
Vals	155
Sand-Vet	422
Other tributaries	161
TOTAL	**1085**

h) Conclusions

The Middle Vaal Hydrological analysis makes use of a mixture of long and shorter runoff records with records of varying reliability. The VRSAU represents an in depth effort to use all the available data to arrive at the best possible calibration for all thirteen of the sub-systems. It is stated in the report that simulated flows are over-estimated by a few per cent. It was found that the overall MAR at Bloemhof Dam had not changed significantly (1%) since the less rigorous 1985 analysis.

It was stated in the conclusions of the report that the natural MAR of the Middle Vaal catchment is 1085 Mm^3/annum based on the period October 1920 to September 1995. Annual flow volumes were stated to have varied from as little as 110Mm^3 in 1932 and 1991) up to nearly 3 000Mm^3 in 1932 and 1991.

4.2.3 Vaal Barrage Catchment Sub-system

The Vaal Barrage sub-catchment is an area of 8 561km^2 upstream of the Vaal Barrage on the Vaal River. The catchment covers all flows entering the Vaal River

between the Vaal Dam and the Vaal Barage. Almost all of the catchment lies to the north of the Vaal River and includes the catchments of the Klip and Suikerbos Rivers. The catchment only contributes 273 million m³/a but has been treated in considerable detail in its own section of the VRSAU report. The report states that analysis of the catchment was complicated by the highly urbanised and regulated nature of the catchment, the inaccuracy of several gauges, the presence of large wetland areas, and high transmission losses. In addition, sewers blocked during the 1985 political unrest complicated the analysis.

The VRSAU report has been studied carefully, but it is not considered necessary to go into the same level of detail as was done for the upper and Middle Vaal catchments. The Vaal Barage Dam has a capacity of 48million m³ and small dams are calculated to have a total volume of 44 million m³. Irrigation in the catchment has not been studied in any detail and major estimates had to be made. It was estimated that irrigated hectarages increased from 14 Ha to 98 Ha in 1995.

Data on abstraction and return flows were in many cases impossible to obtain, and in the end, an approach was developed to estimate abstraction and effluent. Abstractions are significant. Rand Water alone operates eight abstraction canals/pipelines from either the Vaal River or the Vaal Dam. T otal abstraction was calculated at 401 million m³ in 1994. However, return flows are estimated at 285 million m³ for the same year. The report makes a detailed evaluation of **urbanised** areas in each of the sub-catchment since this will play an important role in the calibration process. The catchment includes a significant portion of the Johannesburg area (see **Figure 4-1**). The total urbanised area was taken to be 648 km². This figure was divided up into three levels of urban development corresponding to the degree of imperviousness of the surface. Wetland and transmission losses also received special treatment in the report. Wetland areas were estimated at 62 km².

The study reports that an adequate number of rainfall gauges (45) were available covering the entire catchment. The catchment was divided up into 8 sub-catchments for the purpose of model calibration. There are 12 gauging stations in the catchment and all were used for the purpose of model calibration. The report provides details on the status and accuracy of all the river gauges. Approximately half of them were considered to have "reasonable" records. The report goes into

considerable detail on as to how the data problems at many of the stations were solved.

Calibration of the Barrage catchment was difficult for reasons already mentioned, and a number of supplementary analyses were performed as part of the process. In most cases, the synthesised flows compared well with the sub-catchment observed flows once water demands had been taken into account. For some stations, there were significant differences. For the Vaal River at the Barrage, it was found that the Barrage overestimates flow albeit by only three per cent when results were used in conjunction with flows from the Middle Vaal and observations at Vaal Dam.

The report summarises the problems encountered in the hydrological analysis. These included having to use some records, which were too short, some records which were not very reliable (gauges on the Klip River and others). The report recommended that a new gauging weir be constructed on the Blesbokspruit, as well as a high flow station on the Suikerbosrand River. A need for a current meter gauging programme was also highlighted. It is not known whether any of these recommendations have been implemented.

4.2.4 Lower Vaal Catchment

The Lower Vaal includes several impoundments with the purpose of augmenting and stabilising water supply for irrigation. In total there are ten major dams in the Lower Vaal, the smallest being the Wentzel Dam (capacity of 6 million m^{33}) on the Harts River and the largest being the Kalfontein Dam (319 million m^3) on the Modder River. There are several other dams on the Modder and Riet Rivers, most with the purpose of supporting irrigation. The total capacity of large dams in the Lower Vaal amounts to 683 million m^3 and of farm dams to 152 million m^3.

The Lower Vaal catchment covers an area of over 88 000 km^2 and includes three distinct river systems, the Harts River to the north, the Vaal River, and the Riet and Modder Rivers to the south. The Harts River catchment is 31 000 km^2. Runoff potential is limited but nevertheless, it is a significant supplier or water for urban and especially irrigation consumption. Of the Lower Vaal incremental catchment, it is stated in the VRSAU that only 35% contributes directly to runoff in the river network. The rest drains into pans and enclosed river basins. The combined catchment areas of the Modder and Riet Rivers are 35 000 km^2. There has been extensive

dam development in the catchment.

There are a number of in-basin and inter-basin transfers. These include:

- transfers from the Caledon River to the Modder in order to supplement supplies to Thaba Nchu and Bloemfontein.
- transfers from the Vanderkoof Dam on the Orange River via the Sarel Hayward/Orange-Riet Canal to the Riet River scheme.
- transfers from the Vaal River at Riverton for water supply to Kimberley.
- short distance transfers from the Orange River for the Douglas Irrigation Scheme.

a) Literature Consulted

The 1997 VRSAU Report on the Lower Vaal was the main source for this review.

b) Water Use

The VRSAU study goes into considerable depth in its evaluation of water use and water demand in particular of irrigation.

The largest irrigation scheme is the Vaalharts Scheme (34 000 ha) situated between the Vaal and Harts Rivers. In the Modder/Riet System, there are another five Government or Irrigation Board Schemes. The report states that there is also significant diffuse and runoff river irrigation. The total hectarage under irrigation is estimated at just over 25 000 ha. In calculating the water consumption of irrigation, cognisance was taken of known application rates, cropping patterns and scheduling.

The Lower Vaal catchment is sparsely populated and urban or industrial abstraction and resultant return flows are limited to the towns of Kimberley, Bloemfontein, Botshabelo and Thaba Nchu. In addition, the Vaal-Gamagara scheme supplying water to a number of small towns, farms and some mines.

c) Transfers

While much of Bloemfontein's water is supplied from the Modder River, water is also assured via a water transfer from the Caledon sub-catchment on the Orange River. Water is also transferred into the Lower Riet River from the

Vanderkloof Dam on the Orange River. The Douglas Irrigation Scheme just upstream of the Vaal/Orange confluence also uses water transferred from the Orange River.

d) Observed Records

Approximately 98% of the rainfall records were longer than 30 years and 60% of the stations were still open. Stations were checked during the VRSAU Study for reliability, stationarity and consistency and found to be satisfactory.

17 Runoff gauging stations were considered for use in the calibration process as shown in **Table 4.5**.

Seven of these were not utilised because of poor quality data or because their catchments were considered too small. Of the selected stations, two had records going back to the 1920s. The report provides a useful in-depth review of the available data. Using standard techniques (comparisons with other stations nearby, upstream or downstream, etc.), the streamflow records were verified. Short periods of missing data for periods covered in the 1986 assessment were not re-patched.

Table 4.5: Runoff Gauges Used in 1995-1997 Upper Vaal Study

Gauge (River)	Gauge No.	Catchment Area (km²)	Date Opened	Comments
Taung (Harts)	C3H003	10990	1927	Not ideal for low flows. Some discrepancies in early record.
Espagsdrift (Harts)	C3H007	24097	1948	Not suitable for calibration due to over-estimation of high flows. Low flows used to calibrate irrigation return flows.
Schweizer Reneke (Harts)	C3R001	2919	1935	Spills from dam not gauged
Spitskop (Harts)	C3R002	26914	1975	
Shannon Valley (Renoster)	C5H007	348	1948	Record required extensive patching
Riviera (Riet)	C5H008	593	1931	Small catchment with no significant demands, hence combined with Kalkfontein
Kromdraai Rietwater (Riet)	C5H012	2372	1953	Included with Kalkfontein
Stoomhoek (Modder)	C5H015	6009	1948	Doubts over accuracy of low flows
Aucampshoop (Riet)	C5H016	33351	1952	Not completely reliable and extensive patching required

Gauge (River)	Gauge No.	Catchment Area (km²)	Date Opened	Comments
Tweerivier (Modder)	C5H018	17315	1959	Well-situated to monitor effects of Modder GWS
Tierpoort (Kaffer)	C5R001	922	1937	Reliable record requiring limited patching
Kalkfontein (Riet)	C5R002	10268	1937	Data appears reliable
Rustfontein (Modder)	C5R003	940	1954	Record was considered to be reliable
Krugersdrift (Modder)	C5R004	6315	1974	Record considered reliable
De Hoop 65 (Vaal)	C9H009	121052	1968	Record considered reliable
Vaalharts (Vaal)	C9R001	115055	1971	Record considered reliable

There are a surprisingly large number (25) of evaporation stations in the Lower Vaal catchment. It is unlikely that better estimates of evaporation could be obtained.

e) Rainfall/Runoff Modelling, Runoff Naturalisation

As is normal practice in South Africa, the well-tested Pitman Model runoff model was used for calibrating the observed record against weighted rainfall for each of the gauging stations. The process is described in sufficient detail. The usual statistics of the concurrent and observed records are presented in the report. The results are described in detail in the report for each of the stations used in the calibration process. A summary of the results has been extracted from the report and is presented in **Table 4-6**.

Table 4.6: Summary of Results from Modelling of Lower Vaal Catchment

Gauge Number	Station Name	Effective Incremental Area (km^2)	MAP (mm)	MAE (mm)	Naturalised MAR million m^3/a	Unit Runoff mm/a
C3H003	Taung	7975	530	1916	59.0	7.4
C3R002	Spitskop	9249	438	2039	77.5	8.4
C5H016	Aucampshoop	1847	350	2050	6.4	3.5
C5H018	Tweerivier	2236	422	1871	14.4	6.4
C5R001	Tierpoort	922	491	1640	23.8	25.8
C5R002	Kalkfontein	8781	412	1746	215.9	24.6
C5R003	Rustfontein	937	543	1600	30.7	32.7
C5R004	Krugersdrift	5391	508	1639	114.4	21.2
C9H009	De Hoop	3201	406	1963	12.9	4.0
C9R001	Vaalharts	2509	444	1946	11.2	4.5
-	Lower Vaal	6096	361	2210	31.5	5.2
TOTAL		**49144**			**597.7**	**143.7**

f) Conclusions

The VRSAU Report for the Lower Vaal makes a number of recommendations on the need for new river gauges and measures to improve the quality of data recorded. These include measures with respect to the need to monitor irrigation abstractions, transfers and return flows need to be monitored accurately in the Vaalharts area. Measures were also recommended to improve monitoring in the Upper Harts River, and a new gauging site was proposed for the Vaal River downstream of the Vaal and Harts River confluence and the Vaal Gamagara abstraction point. A number of recommendations to improve monitoring in the Modder/Riet catchments are also made.

Perhaps most importantly were concerns raised regarding the need to better know how much water is being used in the catchment, especially with respect to irrigation consumption. It was therefore recommended that the aerial photography and mapping of the region be updated in order to determine the extent of irrigated area. It was also recommended that a database of all current and historical irrigation information and contact names should be compiled.

More accurate and standardised estimates of effective catchment areas need to be agreed upon.

A point of caution was also raised, particularly relevant to the Lower Vaal catchment with respect to sub-catchments where flows and irrigation are primarily supported by compensation releases from an upstream reservoir rather than from runoff generated on the incremental catchment. It was stated that care must exercised during calibration and naturalisation of the catchment, and that the water demands (irrigation or other) must be supplied by the actual compensation flows rather than the catchment runoff and river flows, since failure to model the abstraction of demands in this way would result in extreme over-estimation of natural runoff when the irrigation demands are added back to the catchment runoff during the naturalisation process.

The WR90 Regional Parameters appear to give a slightly conservative estimate of natural runoff in the catchments along the Vaal River and Lower Modder and Riet catchments.

4.3 Orange River Sub-catchments

4.3.1 Senqu River Sub-system

a) General Description

The Senqu River rises in the Maluti and Drakensburg Mountains in Lesotho. Within the catchment, these mountains rise to 3 482 m. On crossing the border into South Africa, the river becomes the Orange River and makes its confluence with the Caledon River at the Gariep Dam about 220 km downstream of the border. In South African water resources studies, it is often included under the heading of the Vaal River rather than the Orange due to the fact that water transfers are made from the Senqu River across the catchment divide to the Vaal Dam. The Senqu River is therefore an essential part of the so-called "Vaal Integrated System". The Senqu River is therefore an important water resource for South Africa for two reasons, firstly as one of the two main rivers feeding the Vanderkloof Dam, and secondly as a source of water for the industrial heartland of Gauteng. Transfers to the Vaal Dam take place as part of the Lesotho Highlands Scheme, Phase 1 of which has been implemented through the

construction of the Katse Dam and associated storage and transfer works.

In order to have been able to construct this scheme, South Africa has an agreement with the Kingdom of Lesotho, which makes provision for the payment of royalties.

b) Literature Consulted

Unlike the Vaal River Hydrology, as well as that of other parts of the Orange River, the Lesotho River Hydrology is based on relatively "new data". The first comprehensive studies of the Senqu River date back to the Lesotho Highlands Feasibility Study, carried out in the mid 1980s. An "interim" hydrology was produced for design purposes. Further studies were carried out by BKS, South Africa in 1993 and by the UK Institute of Hydrology in 1994. Finally, a study carried out jointly by BKS and the LHDA (Lesotho Highlands Development Authority) was completed in December 1998. The resultant report of this study has been the main reference document for this review.

c) Water Use

Before the construction of the Lesotho Highlands Water project (LHWP), use of water in the Senqu River was limited to water supply for small settlements. With the construction of the Katse Dam on the Malibamatso River, a 45 km transfer tunnel to Muela Power Station and the Muela Dam, which collects tailrace waters for transfer to the Vaal Dam, the situation has changed completely. From the Muela Dam water is transferred via another set of tunnels from whence the water flows into the upper reaches of the Ash River, a tributary of the Liebenbergsvlei River, which joins the Wilge River just before Vaal Dam.

It is anticipated that on average 490 million m^3/a will be transferred out of the Senqu River to the Vaal River Basin as part of Phase1A of the LHWP. This will increase when Phase 1B, the construction of a 145m high dam at Mohale on the Sequnyane River and a transfer tunnel to the Katse Reservoir, have been completed. Completion is scheduled for 2003.

d) Observed Records

The study looked at more than 120 relevant rainfall records. Of these only records, which could be patched and with a record of at least 15 years, were

utilised. It would appear that every effort was made to fully utilise the available data, even retaining parts of a record if considered acceptable and rejecting the parts considered to be unreliable. This was necessary, however, because the quality of rainfall data in the Senqu catchment was generally considerably lower than in the sub-catchments already discussed.

Most of the streamflow stations in Lesotho were set up in the middle 1960s so there are no long records. It is reported that there were 13 stations, which could be used in the analysis plus the Oranjedraai Station situated just downstream of the Lesotho/South African border. Difficult access to stations for servicing and siltation problems are two of the reasons for numerous gaps in many of the records. In general, the quality of the records is described as "fair". Three crump weirs have been installed in recent years to improve the reliability of runoff data. It is clear that a lot of effort had to go into carefully examining the observed data and especially the water stage/discharge curves for all the stations in the catchment. The stations at Marakabei and Paray were considered to be the most complete and were therefore selected as the key reference stations. Gaps in the records of several other stations were corrected by reference to these stations. The report discusses in detail each one of the gauging stations and their associated records, the gaps and how they were patched. Another key reference station was the Oranjedraai Station, which is almost complete for the full 1960 to 1994 period.

e) Rainfall/Runoff Modelling, Runoff Naturalisation

Rainfall/runoff modelling was carried out using a modified form of the Pitman Model. Features of the version used allowed input of a number of rainfall records covering the period of interest to ensure that gaps were covered, as well as relatively short runoff records.

Table 4.7 derived from the report summarises the some of the results obtained during the modelling. It would appear from the results that the main aim was to model the MARs of each station as accurately as possible, since the observed and synthesized MARs match up quite well. A comparison of the observed and synthesized record statistics show significant differences in the standard deviations and relatively low correlations. However, it is also clear from the low number of rain gauges (between 3 and 5 for each incremental catchment)

available that it would not be possible to obtain better results.

f) Synthesized Record

Having generated the synthesized runoff records, these records were then used as inflows to the various reservoir sites agreed between the Governments of South Africa and Lesotho. In view of the fact that the reservoir sites were not the same as the gauging stations sites, the inflow records were calculated by summing the upstream incremental gauging site record with a part of the downstream incremental gauging site record.

Table 4.7: Results of Rainfall/Runoff Modelling for Selected Stations

Parameter	Seaka	Mokhotlong	Paray	Marakabei	Bokong	Orangedraai
Catchment MAP (mm)	796	908	763	944	930	781
Catchment Area (km²)	10041	1660	1028	1087	403	4806
Observed MAR (Mm³/a)	1390	280.1	181.8	359.5	100.1	813.3
Synthesized MAR (Mm³/a)	1388	280.0	180.3	348.6	100.3	812.8
Observed St. Deviation	853	208.6	117.1	181.3	50.8	560.3
Sythesized St. Deviation	820	208.0	94.2	134.2	40.0	438.9
Correlation Coefficient	0.64	0.63	0.71	0.79	0.78	0.65
No. of Rainfall Records Used	4	4	5	3	3	4

Details of how the calculations were carried out are fully described in the report. Reservoir inflow sequences are provided for the 1920 to 1995 period and hence, are consistent with the VRSAU Studies. **Figure 4-3** shows the positions of the dam sites considered in the study. **Table 4.8** summarises the calculated mean annual inflows.

Table 4.8: Calculated Mean Annual Runoffs at Considered Dam Sites

	Katse	Mohale	Mashai	Tsoelike	Malatsi	Ntoahae
MAR (Mm³/anum)	554	312	1447	1795	611	1943

g) Conclusions

Due to the sensitive nature of the hydrology of the Senqu River (amount of royalties payable to Lesotho), considerable effort has been put in to ensure the best possible result under difficult (short and incomplete records) conditions.

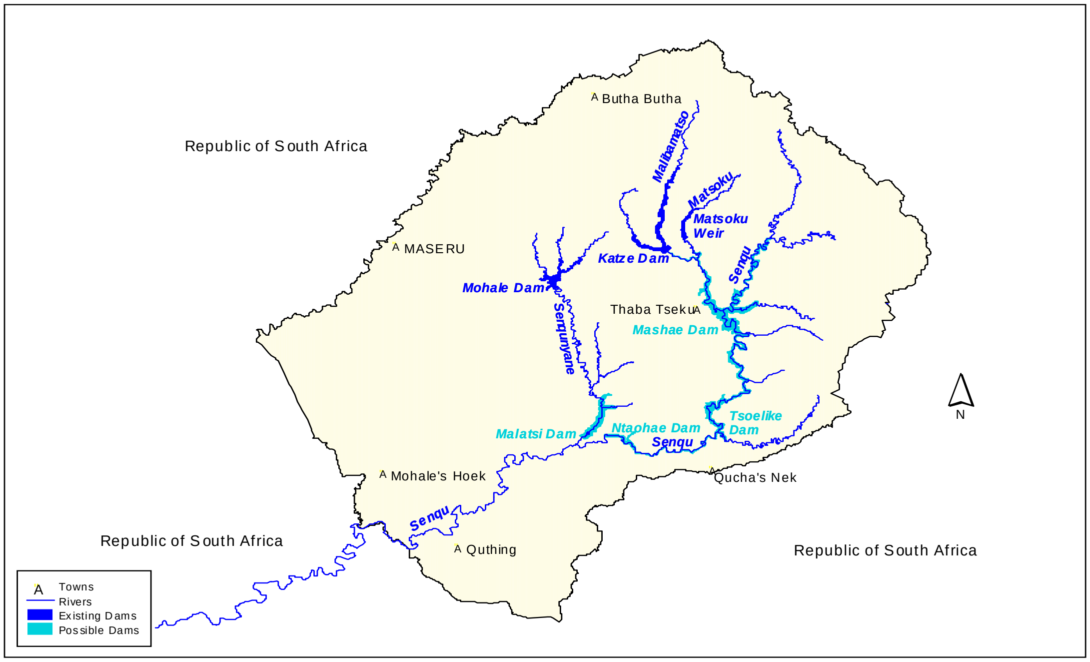

Figure 4-3: Positions of Dam Sites Considered in LHWP Systems Analysis

4.3.2 Caledon River and Upper Orange Incremental Catchment: Hydrology

a) General Description

In the nomenclature used in the South African systems analysis the Upper Orange River Incremental, catchment covers the area upstream of the Vanderkloof Dam up to Welbedacht Dam on the Caledon River and up to Oranjedraai on the Orange (Senqu in Lesotho) River. The Senqu River in Lesotho has already been discussed in the previous paragraph as far as the Oranjedraai gauging station just downstream of the Lesotho/South African border. Before making its confluence with the Caledon River, the Orange is joined by the Kraai River from the Drakensburg Mountains to the southeast. Upstream of the Wellbedacht Dam the Caledon River catchment covers an area of 15 245km², much of it in the mountains of Lesotho.

Rainfall drops off very sharply as the Orange River leaves the mountains and is down to 300mm/a at the Gariep Dam.

b) Literature Consulted

While the hydrology of the Orange/Senqu River upstream of the Orangedraai gauge was updated as part of the Lesotho Highlands Study (see paragraph) in 1999, the hydrology of the Caledon River and incremental catchments of the Vanderkloof and Gariep Dams is relatively old, dating back to a report completed in November 1992. This document, entitled “Upper Orange River : Hydrology” was the main reference document for this section of the review.

c) Water use

Water demand for Irrigation in the Upper Orange catchment was estimated at 384 million m³/a in 1990, although it would appear that this is not always met since the average water supplied was only 281 million m³/a. According to the study, total water use in the Upper Orange catchment was estimated at 1 920 million m³/a of which 885 million m³/a was estimated to be evaporation from the major storage reservoirs and farm dams. Of the remainder; it was estimated that 740 million m³/a are transferred to the Vaal catchment. Knellpoort and Welbedacht on the Caledon River are mainly used to transfer water to the Modder system to support Bloemfontein, Bothabello and other smaller urban areas with water. Welbedacht has, however, silted up to a large extent and Knelpoort Dam was built as an off-channel storage dam due to the severe silt problems. There are, however, compensation releases from Welbedacht Dam to supply irrigation downstream of the dam (irrigation that existed before the dam was built). The Welbedacht Dam is not used to support Gariep Dam at all.

d) Runoff

The incremental MAR values as calculated in the 1992 study are presented in **Table 4-9**. The natural runoff generated for this study covered the period 1920 to 1987.

Table 4.9: Incremental MAR for the Upper Orange River

River Gauge	River	Catchment Area (km²)		MAP (mm)	Incremental MAR (Mm³/annum)	Incremental Unit Runoff (mm)
		Total	Incremental			
Aliwal North	Orange	37 075	3 635	591	229	63
Roodewaal	Kraai	8 688	8 688	657	676	78
Oranjedraai	Orange	24 725	24 725	793	4 192	170
Welbedacht Dam	Caledon	15 245	15 245	755	1 217	80
Gariep Dam	Orange	70 749	18 435	456	397	22
Vanderkloof Dam	Orange	89 842	17 843	314	147	8

e) Conclusions

The report pointed out that reconciling the hydrology had been complicated by inaccurate measurement by the turbine meters at Vanderkloof Dam, and uncertainties over the accuracy of the elevation/capacity equation for the same dam. The study also recommended that combined mass balance calculations for Gariep and Vanderkloof Dams should be carried out annually.

4.3.3 Lower Orange River

a) Description

Downstream of the Vanderkloof Dam there are five incremental catchments, most of which do not make major contributions. In the South African studies, these are referred to as the Boegoeberg Incremental catchment, the Hartbees catchment, the Vioolsdrift incremental catchment, the Fish River catchment (Namibia) and the River Mouth incremental catchment.

b) Literature Consulted

A large number of reports were compiled as part of the Orange River Replanning Study (ORRS). All of these (over 30) reports were made available in electronic form for this review. Certain key reports were selected. These included the Hydrology and Systems Analysis: Orange River Basin", and the "Evaluation of Irrigation Water Use", and "Water Demands of the Orange River Basin – ORRS". While the main purpose of the first-mentioned of these studies was to carry out a large number of systems analyses in order to look at maximising yield and efficiency of the available water resources, including the inclusion of various potential reservoirs, the report also provides an overview of the hydrology.

b) Water Use

The main user of water in the Lower Orange River (and indeed of all the catchment), is the Orange River Project, which was first proposed in 1962 to irrigate thousands of hectares especially in the Eastern Cape, Northern Cape and Free State areas. This project depends on flows from the Vanderkloof and Gariep Dams. It is reported that the main functions of the Orange River Project (ORP) are to provide water for irrigation and urban users along the river, to provide irrigation water to the Great Fish and Sundays Rivers in the Eastern Cape and to the Riet River catchment. In addition, Orange River water is used to solve water quality problems in the Vaal River at Douglas, and is used to generate peak power for the Eskom Network at the Gariep and Vanderkloof Dams. The ORP also supplies water to cities and small towns such as Upington, Prieska, Port Elizabeth, Grahamstown, Alexander Bay and Port Nolloth.

In the systems analysis described, land use and associated water demand has been divided up into five areas, being:

- Area 1: Upstream of Gariep Dam (i.e., not part of ORP).
- Area 2: Area upstream of the Orange/Vaal confluence up to and including Gariep Dam.
- Area 3: Riet/Modder catchments.
- Area 4: Area downstream of Orange/Vaal confluence to 20º longitude (Namibian/RSA border).
- Area 5: From 20º longitude to River mouth.

The demands are described in the report and are summarised in **Table 4.10**.

Table 4.10: Summary of ORP Demands (excluding transfers to Riet/Modder catchments)

Water Use \ Area	Area 2 (Directly from Gariep and Vanderkloof)	Area 2 (Gariep to OrangeVaal confluence	Area 4	Area 5	Total
Irrigation	882[1]	228	469	81	1 660
Urban	16	(incl. below)	(incl. below)	(incl. below)	16
Urban/ Industrial/ Stock	(incl. above)	5	13	27	45
River Requirement (Losses)	-	64	455	441	960
Canal Losses	-	9	26	-	35
Environmental Demand	-	-	-	306	306
Totals	899	306	963	855	3022

[1] 627Mm³ by Orange/Fish Tunnel; 255Mm³ by Vanderkloof canal

[2] Lesotho Highlands Water Project transfers are not included

Clearly the updating of these demands will be an important aspect of the current study in view of significant water use developments over the last decade.

In the report studied, it would appear that all the demands are described in sufficient detail and clarity to allow relatively straightforward updating for new systems analyses incorporating more up to date runoff data. The same is true of canal and rivers losses.

4.3.4 Lower Orange River and System Analysis

a) General

The hydrology used in the Lower Orange clearly relates to the hydrology of the Upper Orange and Vaal. Hence, in view of the fact that the ORRS pre-dated some of the more recent hydrological re-assessment, some of the records used are not the most recent. For example, the runoff record used for the Riet/Modder system was the one updated in 1991, rather than the one used in the 1997 study. However, in checking the runoff data files for the total Orange River catchment as it now stands, it was found that most of the records have been updated to September 1995. The only exception is the incremental area upstream of Vanderkloof Dam and downstream of the Lesotho border.

It is estimated that approximately 900 Mm³/annum originates from the Lower Orange catchment of which more than half comes from the Fish River. It is stated in the study that the hydrology of the Lower Orange was treated in a simplified manner. The Lower Orange Hydrology covers the period 1920 to 1989. A table presented in the report provides a very useful overview of the runoff contributions from the different parts of the catchment as assumed for the 1991 study. It is not presented in full here, but a summary is provided showing the sum of the incremental MARs for each of the major systems as already discussed in this review.

Table 4.11: Summary of Incremental Streamflow Data

Catchments included (see Figure 4.1 and 4.2)	Sub-system	Total Incremental Catchment Area (km²)	Total Incremental MAR (1920 – 1983)	Unit Runoff (mm)
I7, I11, I12, I13, I15, I16, I17, I19, I22, I24	Lesotho Highlands	24 752	4 014.53	162.2
I5, I8, I9, I27, I28	Caledon	15 245	1 197.98	78.58
I1, I4, I18, I20, I26	Upper Orange	48 595	1 389.125	28.586
I2, I3, I6, I10, I14, I21, I23, I25	Modder-Riet	23 277	366.21	15.77
-	Remainder of Vaal	166 235	3 521.65	21.181
-	Fish River (Namibia)	76 000	483.90	6.36
-	Remainder of Orange River*	136 909 (319 870)	219.35	1.6
TOTAL		**491 103 (685 372)**	**11 192.74**	**22.79**

b) Scenarios

One of the aims of the systems analysis was to look at combinations of new developments in the Orange River catchment to see how yield can be most usefully augmented. These scenarios have been studied as part of this review, but are too numerous to be described here. However, in order to illustrate the principle, the "base scenario" is summarised and the sort of scenario variations that were considered are briefly mentioned.

The base scenario was as follows:

- Phase 1 of LHWP at 2005-development levels.
- Compensation releases from Katse and Mohale dams of 0.5 m³/s and

0.3m³/s, respectively.

- Environmental demand at river mouth set at 100 Mm³/annum.
- Orange to Fish transfer set at 627 Mm³/annum.
- Orange/Riet transfer set at limit of 275 Mm³/annum (demand driven).
- Orange/Douglas transfer set at limit of 88 Mm³/annum (demand driven).
- Compensation flow from Gariep Dam set at 16 m³/s.
- 2005 development level spills from the Vaal Basin.
- Hydro-electric power generated in accordance with downstream system demands only.
- Dead storage level (DSL) set at 1 231.63 m for Gariep Dam and 1 147.78 m for Vanderkloof Dam.
- Total live storage at Gariep and Vanderkloof Dams = 6 883 Mm.
- Instream flow requirements taken as equal to downstream demand.
- Transfer from LHWP to Vaal basin taken as 28.6 m³/s.
- Novo transfer from Caledon to Modder in place.
- All domestic/industrial demands at 2005 levels.
- Inclusion of all possible diffuse developments in the Caledon (Lesotho and RSA).
- 2045 sedimentation levels at dams.

The results of around 50 alternative scenarios (including minor variations or sub-scenarios) were modelled in order to find out which set of operating rules was the most appropriate. These operating rules represented a combination of operating rules for existing infrastructure and operating rules for planned potential infrastructure . It should be noted that systems analyses had to take into account not just consumptive needs, but also hydropower-related scenarios.

A number of scenarios related to the inclusion of the Vioolsdrift Dam. These included for example, raising of Gariep Dam combined with a 1500 Mm³ dam at Vioolsdrift and increased transfers from the Orange River to the Vaal, or the raising of Gariep, Bosberg, Boskraai Dams combined with a large dam at Vioolsdrift.

Conclusions are too numerous and inter-dependant to go into here. The study provides a useful basis for the current study.

5. CONCLUSIONS AND RECOMMENDATIONS

Hydrological studies and systems analyses carried out in South Africa covering the entire Orange River Basin within South Africa and Lesotho have been reviewed. The general impression is that the work has been carried out thoroughly as far as the data will allow. There is no reason to disagree with the hydrological files being used as input for the systems analysis. However, as is generally the case with hydrological and associated data, given the human and financial resources, it would of course be possible and worthwhile to improve the accuracy of the data.

As stated on several occasions in the literature reviewed, the Vaal and Orange River Basins are the most important water resource systems in South Africa. They support more than 50% of the country's GDP. It is logical, therefore, that money spent on improving the accuracy of our knowledge of the system is well-spent and easily justified. Hence the current study, and the major investments being made by the Governments of South Africa and Namibia. However, in view of the fact that some of the hydrological studies studied in this review are already more than a decade old, it would seem worthwhile to utilise the new data that have been collected since their completion and to update these studies. This includes the incremental catchment upstream of Vanderkloof Dam and downstream of the Lesotho Border, as well as the Lower Orange with the exception of the Fish River in Namibia.

The need to update hydrological data and the analysis thereof should not be limited to runoff data but should also include improved collection of water demand data. The effort put over to analysis of water demand information in the studies reviewed reflects a strong awareness of the importance of water demand data. Any basin-wide efforts to update hydrology and water demand should not be undertaken lightly and will probably require a multi-disciplinary approach involving several Ministries. Consideration should be given to using a GIS-driven approach, which can be easily updated on a regular basis.

In the interest of transparency and common understanding at a technical level it is recommended that key Orange River Basin river stations in South Africa (and Namibia) be identified for common monitoring. Joint monitoring would include water level monitoring (real-time telemetry), flow measurements for station calibration, and conversion of water levels into discharge. It would seem logical to extend this transparency to include all gauging stations and also to cover water demand data.

PRE-FEASIBILITY STUDY INTO MEASURES TO IMPROVE THE MANAGEMENT OF THE LOWER ORANGE RIVER

HYDROLOGY, WATER QUALITY AND SYSTEM ANALYSIS: VOLUME B – HYDROLOGY

Part 2

Review of RSA Hydrology

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EXECUTIVE SUMMARY

The main aim of this review is to increase the transparency of South African studies for the benefit of the Namibian Team and at the same time to ensure that they are well acquainted with the hydrology of the river basin in South Africa and Lesotho.

This review is based on three key linked information sources:

- ***Hydrological reports as obtained from the "Vaal River System Analysis Update", "Orange River Development Project Replanning" (ORRS) and the "Orange River System Analysis" studies.***
- ***The systems analysis set-ups, which facilitated understanding of priorities and transfers.***
- ***The stream flow datasets for all of the sub-catchments as derived in the studies carried out to compile the systems analysis update.***

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LIST OF ABBREVIATIONS

DSL	:	Dead Storage Level
DWA	:	Department of Water Affairs (Namibia)
DWAF	:	Department of Water Affairs and Forestry (RSA)
GDP	:	Gross Domestic Product
Ha	:	Hectare
HDYP09	:	Mathematical Model for Generation of River flows from meteorological data in South Africa
LHDA	:	Lesotho Highlands Development Authority
LHWP	:	Lesotho Highlands Water Project
MAE	:	Mean annual evaporation
MAP	:	Mean annual precipitation
MAR	:	Mean annual runoff
Million m^3	:	Million cubic meter
ORP	:	Orange River Project
ORRS	:	Orange River Development Replanning Study
RSA	:	Republic of South Africa
St deviation	:	Standard deviation
VRSAU	:	Vaal River System Analysis Update Study
WRSM90	:	Water Resources Simulation Model

1. INTRODUCTION

The Orange River Basin is large, covering more than half of the land area of South Africa and the entire land area of Lesotho. Understanding the hydrology is complicated by a relatively small (considering the variability of rainfall) number of stream gauges, numerous inter-basin transfers, a large number of storage structures and high levels of demand. Given the importance of the water resources of the Orange River to South Africa, which is close to a water deficit situation, it is not surprising that numerous studies have been carried out on the hydrology of the components of the system.

In recent years, the significance of these studies has increased because of the increasing interest in the resources of the river from South Africa's neighbours, in particular Lesotho, Namibia and Swaziland. Lesotho has a water resources surplus and has reached agreement with South Africa to store and transfer water from impoundments within its territory in order to increase the yield of the system where it is needed in South Africa. Development in Namibia within the basin has increased sharply within recent years and, especially with respect to high value irrigated crops, which depend on water abstracted from the Orange River. Namibia therefore has an interest in the way in which the water resources of the system are managed further upstream in South Africa. Swaziland, while not situated within the basin is nevertheless affected by transfers from the headwaters of the Komati and Usutu Rivers. Transfers from the Usutu and Komati Basins are used to support the Vaal system, as well as Power Stations in the Upper Olifants, of which the latter also receives support from Grootdraai Dam in the Upper Vaal. Although the Komati and Usutu Rivers are not directly linked to the Orange River, the fact that they are used to augment the Vaal System will result in some effect on the Orange River. These two rivers rise in South Africa and flow eastwards through Swaziland to Moçambique and the Indian Ocean. Their water resources are critical to the sugar industry in Swaziland. The Orange River mouth at Alexander Bay/Oranjemund also has importance internationally, having been declared a RAMSAR site.

This increased international interest has resulted in a need for transparency with respect to studies on the water resources of the Orange and associated systems. There are now water allocation agreements in place between Lesotho and South

Africa, and more recently (August 2002) between South Africa and Swaziland.

The main aim of this review is to increase the transparency of South African studies for the benefit of the Namibian team and at the same time to ensure that they are well acquainted with the hydrology of the river basin in South Africa and Lesotho. This review is based on three key linked information sources:

- Hydrological reports as obtained from the "Vaal River System Analysis Update", "Orange River Development Project Replanning" and the "Orange River System Analysis" studies.
- The systems analysis set-ups, which facilitated understanding of priorities and transfers.
- The stream-flow datasets for all of the sub-catchments as derived in the studies carried out to compile the systems analysis update.

The basic approach followed in the hydrological studies is generally the same and can be summarised as follows:

- Assembly of key "observed" data. These data are essentially:
  - the observed rainfall data for the largest possible coverage of rainfall stations;
  - the observed data for the stream flow stations for each sub-catchment. These gauges are a combination of purpose-built gauging stations and dams;
  - evaporation data; and
  - demand data including irrigation, urban, industrial and mining, domestic, forestation demands, and also seepage loss and environmental requirements.

- Pre-calibration data manipulation:
  - For the rainfall data, the quality of the data at each rain gauge is checked by consideration of the record length, amount of missing data and finally using mass plots. Gauges with unacceptably short records (normally 40 years), but this may be reduced for catchments where data are lacking. Gauges with a high percentage (normally > 8%) of unreliable record are similarly rejected. Where possible, gaps in records are "patched" using a

multiple linear regression on other gauges in the sub-catchment.

- For the stream flow data, the data for all available river gauges are considered. Those with records that are too short, water stage/discharge ratings that are unreliable, or too much missing data, are rejected. Some mass balance analyses are carried out to examine the accuracy of some of the records.
- Water demand data are examined and taken back in time. For example for irrigation data, it is necessary (see later) to estimate demand as it has grown through the period of analysis (i.e., since 1920). Similarly for other demands. This is important, because rainfall/runoff modelling is based on the principle of modelling rainfall against "naturalised runoff", that is runoff unaffected by development. This is necessary, because since (it is assumed that) rainfall is unaffected by human development, it would not be possible to model it against a non-stationary time series such as observed runoff. Once modelling has been completed and an extended runoff record produced, this extended runoff can be adjusted to take into account the realities of current/future levels of demand during the systems analysis. In view of the high level of water demand within the Basin, accurate determination of water demand is critical if accurate model calibration is to be achieved.

- Model Calibration:
  - Prior to runoff simulation and record extension, Model Calibration has to be carried out. In the South African studies, a model known as the WRSM90 runoff model, has generally been used. This is an upgraded version of the Pitman (or HDYP09) model. In simplified terms, this model aims to calculate runoff based on catchment rainfall weighted according to a number of catchment parameters. Without going into detail, the principle is that these catchment parameters approximate the physical characteristics of the catchment that may have an influence on runoff. During the calibration process, the values of these parameters are modified until the best possible fit can be achieved, while at the same time respecting the physical realities of the catchment.

- Patching and Record Extension:
  - Following calibration, the model is used to patch missing periods in the observed records and to extend the record back in time, in the case of these hydrological studies to the 1920s.
  - The process is carried out for all the sub-catchments.

- System Analysis:
  - The resultant incremental runoff records are used as input to the systems analysis for the main sub-catchment area for which the hydrology is being updated.
  - The systems analysis combines the hydrology of all the sub-catchments and takes into account all the different types of water demand, including non-consumptive uses and inter-basin transfers. The systems analysis is carried out according a set of operating rules, which define priorities for different users. These "users" include the environment and natural losses such as seepage and evaporation. Operating rules can be varied until yields are optimised as desired.

2. REVIEW OF HYDROLOGICAL REPORTS AND DATA

2.1 Reports Consulted

The following reports were supplied and reviewed:

Bailey, A. K. (1999). **Vaal River System Analysis Update; Hydrology of the Vaal Barrage Catchment**. Pretoria, Department of Water Affairs and Forestry.

Basson, M. S. (1997). **Overview of Water Resources availability and utilisation in South Africa**. Pretoria.

BKS and Ninham Shand (1998). **Potential Dam Developments and Hydro Power Options - Orange River Development Replanning Study**. Pretoria, Department of Water Affairs and Forestry.

Loxton Venn & Associates and Agrimodel (1998). **Evaluation of Irrigation Water Use Volume 3 : Possible New Irrigation Developments - Orange River Development Replanning Study**. Pretoria, Department of Water Affairs and Forestry.

Loxton Venn & Associates and Agrimodel (1998). **Evaluation of Irrigation Water Use Volume 2 : Existing Irrigated Agriculture - Orange River Development Replanning Study**. Pretoria, Department of Water Affairs and Forestry.

Loxton Venn & Associates and Agrimodel (1998). **Evaluation of Irrigation Water Use Volume 1 : Present Water Demand - Orange River Development Replanning Study**. Pretoria, Department of Water Affairs and Forestry.

Maré, H. G. and O. J. Viljoen (1999). **Irrigation and Farm Dam Information for the Vaal River System**. Pretoria, Department of Water Affairs and Forestry.

McKenzie, R. S., N. W. Schäfer, ***et al***. (1992). **Upper Orange River : Hydrology**. Pretoria, Department of Water Affairs.

McKenzie, R. S. (1998). **Vaal River System Analysis Update; Lesotho Highlands Hydrology**. Pretoria, Department of Water Affairs and Forestry.

McKenzie, R. S. and H. G. Maré (1998). **Hydrology and Systems Analysis - Orange River Basin - Orange River Development Replanning Study**. Pretoria, Department of Water Affairs and Forestry.

McKenzie, R. S. and F. G. B. d. Jager (1999). **Vaal River System Analysis Update; Hydrology of the Upper Vaal Catchment**. Pretoria, Department of Water Affairs and Forestry.

McKenzie, R. S., H. G. Maré, ***et al***. (1999). **Vaal River System Analysis Update; Hydrology of the Usutu River Catchment upstream of Swaziland**. Pretoria, Department of Water Affairs and Forestry.

Pitman, W. V. (1999). **Vaal River System Analysis Update; Hydrology of the Tugela Catchment and Hydrology of Zaaihoek Dam**. Pretoria, Department of Water Affairs and Forestry.

Pitman, W. V., C. E. Herold, ***et al***. (1999). **Vaal River System Analysis Update; Hydrology of the Middle Vaal Catchment**. Pretoria, Department of Water Affairs and Forestry.

Rossouw, J. D. (1997). **Water Demands of the Orange River Basin - Orange River Development Project Replanning Study**. Pretoria, Department of Water Affairs and Forestry.

Stassen, R., G. Hemme, ***et al***. (1997). **Hydrology and Systems Analysis - Eastern Cape Rivers - Orange River Development Replanning Study**. Pretoria, Department of Water Affairs and Forestry.

Tukker, M. J. (1999). **Vaal River System Analysis Update; Hydrology of the Lower Vaal Catchment**. Pretoria, Department of Water Affairs and Forestry

2.2 System Analysis and Data

In addition, the layouts of the systems analyses for the sub-systems listed below were reviewed. The layouts included the assigned penalty values so that it was possible to have an understanding of the operating rules.

- Combined Caledon, Lesotho Highlands Water Project, Upper Orange, Riet/Modder and Lower Vaal sub-systems.
- Namibia and Lower Orange sub-systems.
- Usutu, Komati, Upper Olifants, Zaaihoek, Upper Thukela, Thukela South, Upper Olifants and Upper Vaal sub-systems.
- Upper Vaal and Vaal barrage sub-systems.
- Middle Vaal sub-system.
- Lower Vaal and Riet/Modder sub-systems.

2.3 Runoff Data

The runoff files (*.inc) adopted for all the incremental catchments were provided and examined in order to get a feeling for monthly and annual variation and magnitude of flow. **Table 2.1** summarises the files, which were provided.

Table 2.1: Runoff Records Derived from Hydrological Studies for use in Systems Analysis

ALIW.INC	kat9.inc	rietf9.inc
allem9.inc	KATJE.INC	riets9.inc
auch9.inc	klerk9.inc	ROOD.INC
barbers.inc	klipb9.inc	rustf9.inc
barr9.inc	klipd9.inc	sand9.inc
bloem9.inc	klipr9.inc	spits9.inc
bosk9.inc	KNEL.INC	sterk9.inc
C3h013.inc	kop9.inc	suik9.inc
C5r5.inc	krom9.inc	tier9.inc
c9h007.inc	Krug10.inc	tso9.inc
dehoop9.inc	LORAN.INC	twee9.inc
dela9.inc	mal9.inc	uswentzd.inc
dswentzd.inc	mas9.inc	vaal9.inc
erf9.inc	mat9.inc	VERW.INC
FISH94.SPL	Mock.inc	vharts9.inc
fran9.inc	moh9.inc	WATER.INC
grootd9.inc	neser9.inc	WELBB.INC
HFDU.INC	nto9.inc	VIOOL.INC
HLOTS.INC	oran9.inc	BOEG.INC
kalkf9.inc	PKDU.INC	HARTB.INC

3. OVERVIEW OF ORANGE RIVER CATCHMENT

The Orange River rises as two main river systems, the Orange River and its associated tributaries, and the Vaal River and its associated tributaries. To the south, the Orange River rises as two main tributaries, the Caledon and the Senqu Rivers in the Drakensburg and Maluti Mountains in Lesotho and South Africa. To the north, the Vaal River rises in the Highveld in Mpumalanga and Northern Provinces of South Africa. The large majority of runoff is generated in these areas. The Vaal and the Orange (on crossing the border from Lesotho into South Africa the name changes from Senqu to Orange) Rivers make their confluence near the town of Douglas, more than a thousand kilometres upstream of the longitude 20 degrees where the Orange River becomes the border between Namibia and South Africa. Downstream of Douglas, the Orange River is joined by the Ongers/Brak River and the Hartbees River from the south and the Molopo and Fish Rivers from the north. The Molopo River has not been known to contribute surface runoff to the Orange River.

4. SUB-CATCHMENT HYDROLOGY

4.1 Overview

In representing and modelling the Orange River System, the approach adopted by South African Consultants and the Ministry has been to model the system as a whole, but to describe the hydrology and water demand on a sub-catchment basis. In some cases, these sub-catchments have grouped together as a large number of smaller sub-catchments. As is normal practice, the choice of sub-catchments has been made according to a combination of considerations including the location of gauging stations/dams and location of various demand centres.

The main source areas are covered by the Lesotho sub-catchment system; the Caledon River catchment and the Upper Vaal catchment (see **Figures 4.1 and 4.2**). However, this is complicated by the fact that part of Lesotho sub-catchment is also implicated in the Upper Vaal catchment since it is towards the Upper Vaal that water transfers are made. In addition, the Upper Vaal receives water transferred from other rivers outside of the Orange River Basin. These are also included in the analysis of the Vaal River System. The remainder of the Vaal River is divided into the Middle and Lower Vaal sub-catchment groupings. Upstream of the confluence of the Vaal River, the eleven Orange River sub-catchments are often defined by dams such as the Boskraai, Gariep, Welbedacht, Vanderkloof and Kalkfontein Dams. Downstream of the Vaal/Orange River, there are five large sub-catchments, those of the Ongers/Brak, Hartbees, Molopo, Fish and “River Mouth” catchments.

The hydrology of these sub-catchments as developed and described by or for the South African Department of Water Affairs (DWAF) has been reviewed and the findings, conclusions and recommendations are summarised on a sub-catchment (grouping) by sub-catchment (grouping) basis in **Sections 4.2.1 to 4.3.3.**

4.2 Vaal River Sub-catchments

4.2.1 Upper Vaal Sub-system

a) General Description

The Upper Vaal catchment forms part of the Vaal catchment, which is regarded as the most important water resources system in South Africa, supplying water to more than 40% of the population and supporting more than 50% of the country's gross domestic product (GDP). The Upper Vaal includes four major impoundments, the Vaal Dam (capacity of 2 603 million m^3), Grootdraai Dam (356 million m^3), Sterkfontein Dam (2 616 million m^3) and Saulspoort Dam (17 million m^3). The catchment has been divided up into five sub-catchments, Sterkfontein, Delangsdrift, Grootdraai, Wilge and Vaal Dam (incremental) sub-catchments. Reference should be made to **Figure 4-1**. The Grootdraai and Sterkfontein sub-catchment runoffs are supplemented by inter-basin transfers from the Usutu/Komati and Tugela catchments, respectively. The Vaal Dam also receives inflows from the Senqu River in Lesotho.

The Upper Vaal catchment covers an area of 38 638 km^2 with little in the way of urban development. There are thousands of small farm dams in the catchment.

b) Literature Consulted

The first major system analysis study on the Vaal River carried out in 1985 has not been reviewed in any detail, since this has been superseded by studies in 1993 and especially a study carried out between 1995 and 1997. The last-mentioned of these studies known as "Vaal River System Analysis Update Study (VRSAU)" has been reviewed in detail. The stated purpose of this study was:

> "……to revise and update the hydrological and water quality databases used in the earlier studies and to re-assess the water quantity and quality capabilities of the whole Vaal River System using the most up-to-date information and techniques."

c) Water Use

The VRSAU Study goes into considerable depth in its evaluation of water use and water demand. This is important, since only an accurate assessment of current and past water demand will allow an accurate "naturalisation" (see **Section 1**, Introduction).

Vaal Dam supplies Rand Water, South Africa's largest potable water supplier (all municipal and industrial users in Gauteng), various urban users, Grootvlei Power Station and some irrigation. Sterkfontein Dam stores water, transferred from the Tugela River System. Grootdraai Dam supplies water to various power stations and industrial users, including Sasol. It receives transfers from the Usutu catchment (Maputo River Basin).

The VRSAU included a detailed analysis of the small dams in the catchment using conventional mapping and satellite imagery. It was shown that the total capacity of all farm dams was significant. It was estimated in the study that the quantity of small (dam) storage in the basin had increased from 11.84 Mm^3 in 1920 to 166.49 Mm^3 by 1995.

The report states that there were some difficulties in accurately determining the current area under **irrigation**. The consultants made use of previous studies, Department of Water Affairs' (DWA) records and other methods to arrive at a figure of 12 200 Ha under irrigation with the majority in the Frankfort and Vaal Dam catchments. It was estimated that the area under irrigation had grown from 2 250 Ha in 1920, but that in nineties irrigation within the catchment had remained "almost constant". The report shows that considerable care was taken to model irrigation demand as accurately as possible. Cognisance was taken of different crops and monthly variations in application rates. Return flows of 10% were assumed.

Urban and industrial abstraction levels are measured by DWAF and amounted to almost 33 million m^3 from the Vaal Dam catchment in 1994.

Afforestation areas are limited. The estimated total area was only 13.4 km^2 in 1994.

d) Transfers

Since 1974, water has been pumped from the upper reaches of the Tugela River over the Drakensburg to Drieklloof Dam, a small dam adjoining Sterkfontein Dam, for hydropower generation and also for transfer to the Vaal Dam Basin. The study reports that it is not possible to accurately calculate the amount of water transferred into the Vaal Dam catchment due to the complexity of the transfer system and some unknown factors. A maximum transfer of 700 Mm^3/annum has been designed for, but this is rarely possible to achieve. Historical records of annual releases are misleading since during the first 8 years of the dams life no water was released as the dam was filling. The average amount of water transferred from the Tugela Basin to Sterkfontein Dam between 1974 and 1995 was 283 million m^3. Over the last 13 years, since Sterkfontein Dam has filled, an average of 183 million m^3 has been released (after consideration of transmission losses). Water is also transferred from the Zaaihoek Dam on the Buffalo River System, a tributary of the Tugela River for power supply, local urban water supply and can flow into the Vaal River upstream of Grootdraai Dam. The scheme started operating in 1991 and annual transfers ranged from 8 million m^3 up to 73 million m^3.

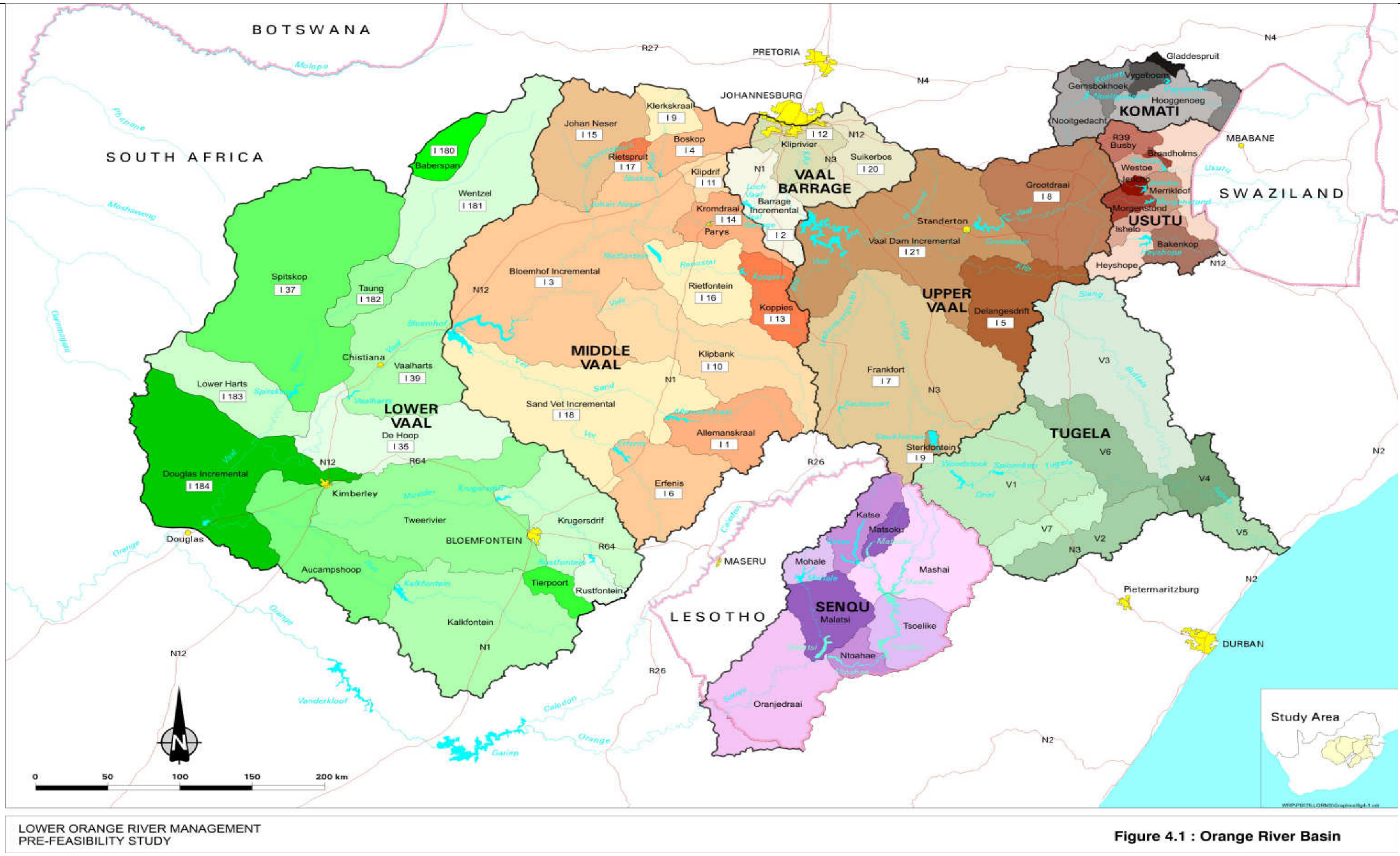

Figure 4-1: Orange River Basin

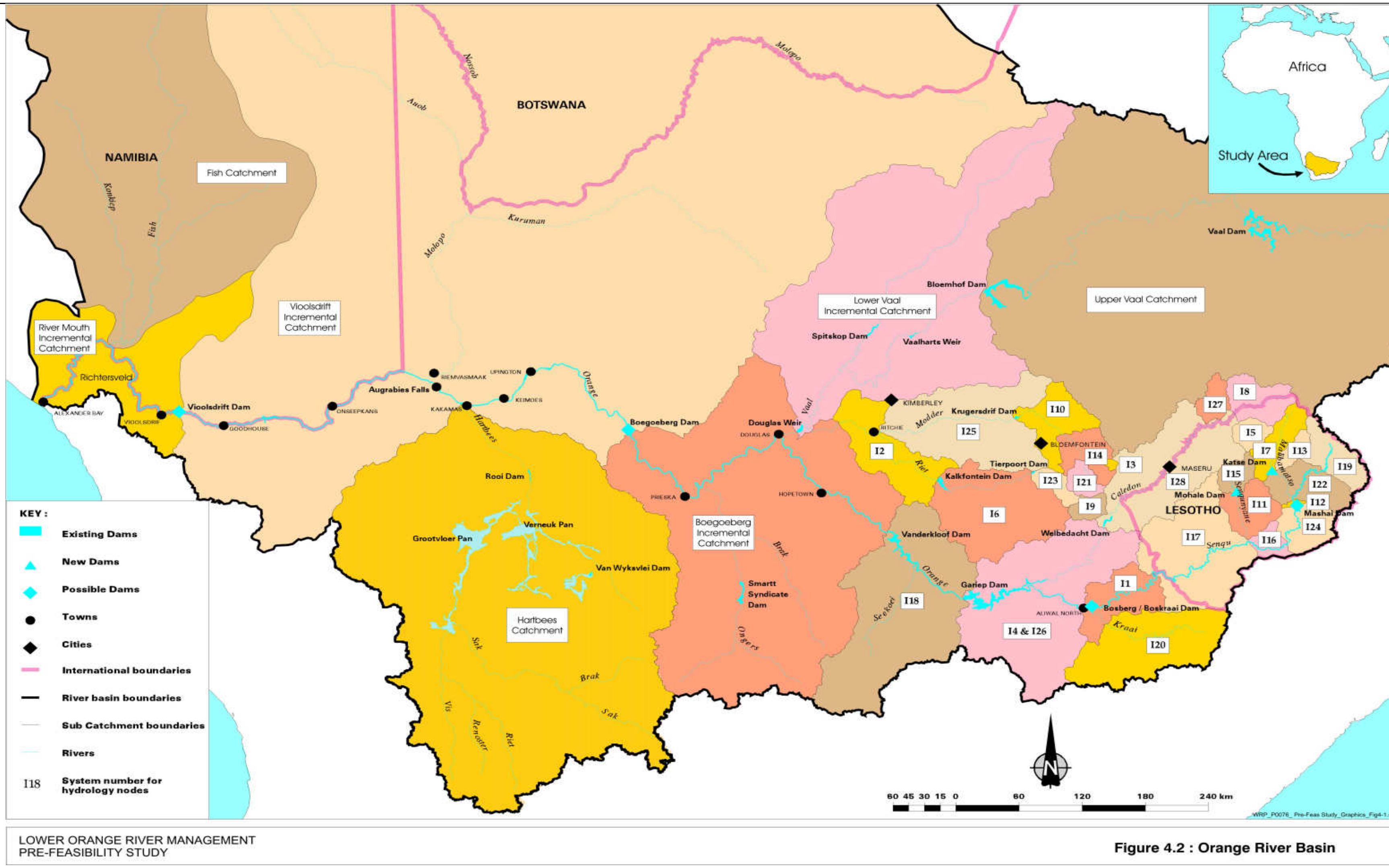

Figure 4-2: Orange River Basin

Water is transferred from Heyshope Dam in the Usutu River via a number of conveyances to the Grootdraai Dam on the Vaal River. Annual transfers between 1985 and 1994 varied from zero to 113 million m³.

e) Observed Records

In line with the generalised procedure as explained in the introduction, the observed rainfall records for as many stations as possible were examined for each of the five sub-catchments. The rainfall data for the Upper Vaal were found to be of a generally good quality and it was possible to apply exacting selection criteria. Nearly 20 gauges with records going back to 1920 or before were found. Sufficient evaporation data were also available.

Table 4.1: Runoff Gauges Used in 1995-1997 Upper Vaal Study

Gauge (River)	Gauge No.	Catchment Area (km²)	Date Opened	MAR	Comments
Standerton (Vaal)	C1H001	8 193	1920	453.70	MAR for 1920-1994 period. Only minor patching of the record was required. Record was completed with Grootdraai inflow after 1978
Delangesdrift	C1H002	4 152	1920	247.10	MAR for 1920-1994 period. Station unreliable at high flows (drowning). Very little need for patching.
Engelbrechtdrift (Vaal)	C2H003	38 564	1923	1 917.91	Only minor patching required. Years 1920-23 had to be simulated. Inflow record for Vaal Dam taken into account after 1936.
Frankfort	C6H001	15 673	1920	760.38	Extensive patching using C8H022 was required although recorded data was reliable.
Vaal Dam	C1R001	38 505	1936	1 858.25	No Patching required during period of record
Grootdraai Dam	C1R002	7 924	1978		Allowance had to be made for U/S abstractions during drought in 1983
Sterkfontein Dam (Wilge)	C8R003	58	1974		Station used only for naturalisation of Frankfort gauge.

There are 19 stream flow gauges in the catchment (including dams operating as gauging stations). Some of these have data extending back to the early 1900's, but much of the data is considered unreliable. After a critical analysis, the consultants retained only seven stations. Six stations were rejected due to unsuitably small catchment areas or poor data. Five stations were rejected due to the short records, having only been opened between 1971 and 1985. Clearly, in a revised analysis there would be considerable new data available. The report

provides a useful in-depth review of the available data. Using standard techniques (comparisons with other stations nearby, upstream or downstream etc.), the streamflow records were verified. Short periods of missing data for periods covered in the 1986 assessment were not re-patched. The utilised gauges are summarised in **Table 4.1**.

f) Rainfall/Runoff Modelling, Runoff Naturalisation

As is normal practice in South Africa, the well-tested WRSM90 runoff model was used for calibrating the observed record against weighted rainfall. The results are described in detail in the report and show high levels of correlation.

In order to achieve the required naturalised flow record, account had to be taken of the water use data described earlier in the report. This includes inter-basin transfers, which have to be subtracted from the observed flows. The report takes each one of the observed records and explains in sufficient depth how the naturalised records were calculated.

g) Synthesized Record

The details of the combined observed and synthesized records are summarised in **Table 4.2** as extracted from the report.

Table 4.2: Summary of Results for Upper Vaal Hydrological Analysis

Incremental Sub-catchment	Catchment Area (km^2)	Observed Incremental Runoff or Inflow (10^6m^3)	Natural Incremental MAR (10^6m^3)
Grootdraai	7 995	453.7	457.7
Delangesdrift	4 158	247.1	249.5
Frankfort incr.	15 498	696.2	733.3
Vaal incr.	10 792	493.2	518.7
Sterkfontein	195	97.3	18.1[(3)]
Total for Catchment	**38 638**	**1987.5**	**1977.3**

It is interesting to note that the natural incremental runoff is less than the observed. This is because of the fact that the observed runoff includes transfers from outside of the catchment.

g) Conclusions

The Upper Vaal Hydrological analysis makes use of long and generally reliable runoff records. It was found that the mean annual runoff (MAR) at Vaal Dam had not changed significantly (3%) since the less rigorous 1985 analysis. The report is very clear on the importance of correctly estimating water use/demand data since this has a significant effect on the accuracy of the record naturalisation process. Irrigation demands, which are the largest are stated as having been constant for a few years prior to 1994. While it may not be warranted to re-evaluate the hydrology, using the new data collected since 1994 (which may allow some new stations to be included in the analysis) for year or two, it is considered worthwhile to check on water demand figures, especially the irrigation demands, over the last decade.

4.2.2 Middle Vaal Sub-system

a) General Description

The Middle Vaal sub-catchment includes ten major impoundments, the most important being the Bloemhof Dam (capacity of 1 269.2 Mm^3) at the outlet of the Middle Vaal catchment. Other large impoundments are the Erfenis Dam (207.7 Mm^3), Allemanskraal Dam (174.7 Mm^3) and Koppies Dam (41.2 Mm^3). In the VRSAU Study: The catchment was divided up into 12 sub-catchments, Erfenis, Allemanskraal, Sand Vet incremental, Klipbank, Koppies, Rietfontein, Kromdraai, Klipdrif, Boskop, Klerkskraal, Johan Neser, Rietspruit and Bloemhof incremental sub-catchments. Reference should be made to **Figure 4. 1**.

The Middle Vaal catchment covers an area of just over 60 000km^2 with little in the way of relief other than the hills in the upper area of the Vals River. There are some large urban developments and mines together with extensive irrigation.

b) Literature Consulted

The 1997 VRSAU Report on the Middle Vaal was the main source for this review.

c) Water Use

As was the case with the Upper Vaal the study was particularly careful in its treatment of water demands particularly important in the Middle Vaal sub-catchment.

The VRSAU included a detailed analysis of the small dams in the catchment, on a sub-catchment by sub-catchment basis, using conventional mapping and satellite imagery. It was shown that the total capacity of all farm dams was significant at over 224 Mm^3. Older maps and the Dam Register were used to estimate historical growth in total dam capacity since 1920.

Major Irrigation schemes are sometimes part of government water schemes in which case the demand is usually monitored, or under the control of Irrigation Boards. There are also several private irrigation schemes. The report states that the Middle Vaal catchment has not been subject to any detailed irrigation investigation. Estimates were largely based on the 1988 Census of Agriculture. A number of approaches were used to derive the estimate of 23 300 ha under irrigation for 1994. The study showed that irrigation area had grown by approximately 1,78% per annum since 1920 (6 520 ha). In view of the impact of irrigation, the report goes into some detail on irrigation water usage, investigating the different water sources used, cropping patterns and seasonal demands. It was estimated that 130.6 Mm^3/annum are used for irrigation in the Middle Vaal catchment.

There was a major increase in urbanisation and urban water demand in the decade up to 1994, resulting also in significant return flows of effluent. The study clearly looked in great detail at urban and industrial abstractions and return flows and this is reported in considerable detail.

Afforestation is minimal in the Middle Vaal catchment and was not taken into account in the analysis.

Transmission losses are significant and difficult to estimate using standard approaches. A special approach was developed in the VRSAU Study. It showed that transmission losses in the Vaal River between Vaal Dam and Bloemhof are approximately 74 million m³/a.

d) Transfers

There are no transfers into the Middle Vaal Catchment.

e) Observed Records

In line with the generalised procedure as explained in the Introduction, the observed rainfall records for as many stations as possible were examined for each of the fifteen sub-catchments. The rainfall data for the Middle Vaal were found to be of a generally good quality and it was possible for the consultants to apply exacting selection criteria. The data for 140 gauges were selected for further analysis.

The report provides details on the records of all 140 gauges. 66 Gauges had records going back to 1920 or before which allows some confidence in the rainfall/runoff modelling of early years.

Table 4.3: Runoff Gauges Used in 1995-1997 Lower Vaal Study

Gauge (Catchment)	Gauge No.	Catchment Area (km²)	Date Opened	MAR (Mm³)	Comments
Witrand (Catchment)	C2H001	3 595	1903	-	Oldest record available. Various problems affect accuracy but record useable.
Schoemansdrift (Vaal River)	C2h018	49 120	1938	43	Record considered reasonable, water hyacinth can affect accuracy
Klipplaatdrift (Vaal River)	C2H061	79 903	1971	-	Some probably with accuracy at low flows and for high flows
Hoogekraal (Mooi River)	C2H085	5 485	1986	-	Reasonable accuracy but flows easily submerged
Boskop Dam (Mooi River)	C2R001	3 287	1957	72	
Johan Neser Dam (Schoonspruit)	C2R002	5 635	1922	87	Record ceases in 1951. Quality of record unknown
Klerkskraal Dam (Mooi River)	C2R003	1 335	1969	-	Low flow spillage cannot be measured accurately
Floorsdrift (Vet River)	C4H002	17 599	1950	413	Station closed after sub-mergence by Bloemhof Dam. Inaccurate at higher flows
Nooitgedacht (Vet River)	C4H004	16 533	1968	-	Not accurate for low flows. Okay for medium and perhaps high flows. Replaced C4H002
Allemanskraal Dam (Sand River)	C4R001	3 665	1959	-	High spillage flows are not accurately measured
Erfenis (Vet River)	C4H010	4 750	1959	-	Accurate crump weir
Roodewal (Vals River)	C6H001	5 674	1912	-	Low and medium flows reasonable, high flows could be overestimated
Mooifontein (Vals River)	C6H003	7 765	1966	155	Not suitable for low flows. Acceptable for medium flows, but not reliable for high flows
Dankbaar (Heuninghspruit)	C7H003	914	1947	-	Several problems affect the accuracy of this gauge. Record considered unreliable.
Arriesrust (Renoster River)	C7H006	5 758	1977	120	Low flows not accurate. Primarily a flood warning station
Koppies Dam (Renoster River)	C7R001	2 147	1920	59	Record accurate with no apparent anomalies
Bloemhof Dam (Vaal River)	C9R002	107 911	1968	1085	No rating for outflow measurement weir

There are 60 stream flow gauges in the catchment (including dams operating as gauging stations), although many of these have specialised purposes or have catchments too small to be of interest to the study. 19 gauging stations, of which seven were reservoir gauges were chosen for the calibration process. With the exception of the Schoonspruit River, coverage was considered to be adequate. Three gauges had records starting before 1920, two between 1921 and 1940, and the rest after 1960. Details on the records are provided in **Table 4.3**. Gaps in the records were patched using various techniques. Details on how the patching was carried out are presented in the report.

f) Rainfall/Runoff Modelling, Runoff Naturalisation

As is normal practice in South Africa, the well-tested WRSM90 runoff model was used for calibrating the observed record against weighted rainfall for 17 stations. Based on this calibration, it was possible to produce synthesized runoff records dating back to 1920. The results are described in detail in the report and show high levels of correlation

In order to achieve the naturalised flow records required for the calibration, account had to be taken of the water use data described earlier in the report. This includes inter-basin transfers, which have to be subtracted from the observed flows. The report takes each one of the sub-catchments and explains in sufficient depth how the water demands were calculated.

The naturalised stream-flows are discussed in some depth in the report. The approach adopted to produce the naturalised stream-flow for the entire record period was to take the observed record and to add all the calculated water demands (and subtract transfers received). This naturalised observed record is then extended using the synthesized record, which is any case already naturalised. The alternative approach, sometimes adopted since it usually leads to "better" correlations, of using just the synthesized record and none of the observed record was not adopted. Both approaches can be argued as being more correct, but this review concurs with the approach adopted in VRSAU.

Comparisons were made with previous studies and it was found that the overall MAR of the Middle Vaal was only one per cent different from the previous study.

However, there were significant differences for some of the sub-catchments. These differences are satisfactorily explained in the report.

g) Synthesized Record

The details of the combined observed and synthesized records are summarised in **Table 4.4** extracted from the report.

Table 4.4: Summary of results for Middle Vaal Hydrological Analysis

Sub-catchment	MAR (10^6m^3)
Mooi	134
Renoster	120
Schoonspruit	93
Vals	155
Sand-Vet	422
Other tributaries	161
TOTAL	**1085**

h) Conclusions

The Middle Vaal Hydrological analysis makes use of a mixture of long and shorter runoff records with records of varying reliability. The VRSAU represents an in depth effort to use all the available data to arrive at the best possible calibration for all thirteen of the sub-systems. It is stated in the report that simulated flows are over-estimated by a few per cent. It was found that the overall MAR at Bloemhof Dam had not changed significantly (1%) since the less rigorous 1985 analysis.

It was stated in the conclusions of the report that the natural MAR of the Middle Vaal catchment is 1085 Mm³/annum based on the period October 1920 to September 1995. Annual flow volumes were stated to have varied from as little as 110Mm³ in 1932 and 1991) up to nearly 3 000Mm³ in 1932 and 1991.

4.2.3 Vaal Barrage Catchment Sub-system

The Vaal Barrage sub-catchment is an area of 8 561km² upstream of the Vaal Barrage on the Vaal River. The catchment covers all flows entering the Vaal River

between the Vaal Dam and the Vaal Barage. Almost all of the catchment lies to the north of the Vaal River and includes the catchments of the Klip and Suikerbos Rivers. The catchment only contributes 273 million m³/a but has been treated in considerable detail in its own section of the VRSAU report. The report states that analysis of the catchment was complicated by the highly urbanised and regulated nature of the catchment, the inaccuracy of several gauges, the presence of large wetland areas, and high transmission losses. In addition, sewers blocked during the 1985 political unrest complicated the analysis.

The VRSAU report has been studied carefully, but it is not considered necessary to go into the same level of detail as was done for the upper and Middle Vaal catchments. The Vaal Barage Dam has a capacity of 48million m³ and small dams are calculated to have a total volume of 44 million m³. Irrigation in the catchment has not been studied in any detail and major estimates had to be made. It was estimated that irrigated hectarages increased from 14 Ha to 98 Ha in 1995.

Data on abstraction and return flows were in many cases impossible to obtain, and in the end, an approach was developed to estimate abstraction and effluent. Abstractions are significant. Rand Water alone operates eight abstraction canals/pipelines from either the Vaal River or the Vaal Dam. T otal abstraction was calculated at 401 million m³ in 1994. However, return flows are estimated at 285 million m³ for the same year. The report makes a detailed evaluation of **urbanised** areas in each of the sub-catchment since this will play an important role in the calibration process. The catchment includes a significant portion of the Johannesburg area (see **Figure 4-1**). The total urbanised area was taken to be 648 km². This figure was divided up into three levels of urban development corresponding to the degree of imperviousness of the surface. Wetland and transmission losses also received special treatment in the report. Wetland areas were estimated at 62 km².

The study reports that an adequate number of rainfall gauges (45) were available covering the entire catchment. The catchment was divided up into 8 sub-catchments for the purpose of model calibration. There are 12 gauging stations in the catchment and all were used for the purpose of model calibration. The report provides details on the status and accuracy of all the river gauges. Approximately half of them were considered to have “reasonable” records. The report goes into

considerable detail on as to how the data problems at many of the stations were solved.

Calibration of the Barrage catchment was difficult for reasons already mentioned, and a number of supplementary analyses were performed as part of the process. In most cases, the synthesised flows compared well with the sub-catchment observed flows once water demands had been taken into account. For some stations, there were significant differences. For the Vaal River at the Barrage, it was found that the Barrage overestimates flow albeit by only three per cent when results were used in conjunction with flows from the Middle Vaal and observations at Vaal Dam.

The report summarises the problems encountered in the hydrological analysis. These included having to use some records, which were too short, some records which were not very reliable (gauges on the Klip River and others). The report recommended that a new gauging weir be constructed on the Blesbokspruit, as well as a high flow station on the Suikerbosrand River. A need for a current meter gauging programme was also highlighted. It is not known whether any of these recommendations have been implemented.

4.2.4 Lower Vaal Catchment

The Lower Vaal includes several impoundments with the purpose of augmenting and stabilising water supply for irrigation. In total there are ten major dams in the Lower Vaal, the smallest being the Wentzel Dam (capacity of 6 million m^{33}) on the Harts River and the largest being the Kalfontein Dam (319 million m^3) on the Modder River. There are several other dams on the Modder and Riet Rivers, most with the purpose of supporting irrigation. The total capacity of large dams in the Lower Vaal amounts to 683 million m^3 and of farm dams to 152 million m^3.

The Lower Vaal catchment covers an area of over 88 000 km^2 and includes three distinct river systems, the Harts River to the north, the Vaal River, and the Riet and Modder Rivers to the south. The Harts River catchment is 31 000 km^2. Runoff potential is limited but nevertheless, it is a significant supplier or water for urban and especially irrigation consumption. Of the Lower Vaal incremental catchment, it is stated in the VRSAU that only 35% contributes directly to runoff in the river network. The rest drains into pans and enclosed river basins. The combined catchment areas of the Modder and Riet Rivers are 35 000 km^2. There has been extensive

dam development in the catchment.

There are a number of in-basin and inter-basin transfers. These include:

- transfers from the Caledon River to the Modder in order to supplement supplies to Thaba Nchu and Bloemfontein.
- transfers from the Vanderkoof Dam on the Orange River via the Sarel Hayward/Orange-Riet Canal to the Riet River scheme.
- transfers from the Vaal River at Riverton for water supply to Kimberley.
- short distance transfers from the Orange River for the Douglas Irrigation Scheme.

a) Literature Consulted

The 1997 VRSAU Report on the Lower Vaal was the main source for this review.

b) Water Use

The VRSAU study goes into considerable depth in its evaluation of water use and water demand in particular of irrigation.

The largest irrigation scheme is the Vaalharts Scheme (34 000 ha) situated between the Vaal and Harts Rivers. In the Modder/Riet System, there are another five Government or Irrigation Board Schemes. The report states that there is also significant diffuse and runoff river irrigation. The total hectarage under irrigation is estimated at just over 25 000 ha. In calculating the water consumption of irrigation, cognisance was taken of known application rates, cropping patterns and scheduling.

The Lower Vaal catchment is sparsely populated and urban or industrial abstraction and resultant return flows are limited to the towns of Kimberley, Bloemfontein, Botshabelo and Thaba Nchu. In addition, the Vaal-Gamagara scheme supplying water to a number of small towns, farms and some mines.

c) Transfers

While much of Bloemfontein's water is supplied from the Modder River, water is also assured via a water transfer from the Caledon sub-catchment on the Orange River. Water is also transferred into the Lower Riet River from the

Vanderkloof Dam on the Orange River. The Douglas Irrigation Scheme just upstream of the Vaal/Orange confluence also uses water transferred from the Orange River.

d) Observed Records

Approximately 98% of the rainfall records were longer than 30 years and 60% of the stations were still open. Stations were checked during the VRSAU Study for reliability, stationarity and consistency and found to be satisfactory.

17 Runoff gauging stations were considered for use in the calibration process as shown in **Table 4.5**.

Seven of these were not utilised because of poor quality data or because their catchments were considered too small. Of the selected stations, two had records going back to the 1920s. The report provides a useful in-depth review of the available data. Using standard techniques (comparisons with other stations nearby, upstream or downstream, etc.), the streamflow records were verified. Short periods of missing data for periods covered in the 1986 assessment were not re-patched.

Table 4.5: Runoff Gauges Used in 1995-1997 Upper Vaal Study

Gauge (River)	Gauge No.	Catchment Area (km²)	Date Opened	Comments
Taung (Harts)	C3H003	10990	1927	Not ideal for low flows. Some discrepancies in early record.
Espagsdrift (Harts)	C3H007	24097	1948	Not suitable for calibration due to over-estimation of high flows. Low flows used to calibrate irrigation return flows.
Schweizer Reneke (Harts)	C3R001	2919	1935	Spills from dam not gauged
Spitskop (Harts)	C3R002	26914	1975	
Shannon Valley (Renoster)	C5H007	348	1948	Record required extensive patching
Riviera (Riet)	C5H008	593	1931	Small catchment with no significant demands, hence combined with Kalkfontein
Kromdraai Rietwater (Riet)	C5H012	2372	1953	Included with Kalkfontein
Stoomhoek (Modder)	C5H015	6009	1948	Doubts over accuracy of low flows
Aucampshoop (Riet)	C5H016	33351	1952	Not completely reliable and extensive patching required

Gauge (River)	Gauge No.	Catchment Area (km²)	Date Opened	Comments
Tweerivier (Modder)	C5H018	17315	1959	Well-situated to monitor effects of Modder GWS
Tierpoort (Kaffer)	C5R001	922	1937	Reliable record requiring limited patching
Kalkfontein (Riet)	C5R002	10268	1937	Data appears reliable
Rustfontein (Modder)	C5R003	940	1954	Record was considered to be reliable
Krugersdrift (Modder)	C5R004	6315	1974	Record considered reliable
De Hoop 65 (Vaal)	C9H009	121052	1968	Record considered reliable
Vaalharts (Vaal)	C9R001	115055	1971	Record considered reliable

There are a surprisingly large number (25) of evaporation stations in the Lower Vaal catchment. It is unlikely that better estimates of evaporation could be obtained.

e) Rainfall/Runoff Modelling, Runoff Naturalisation

As is normal practice in South Africa, the well-tested Pitman Model runoff model was used for calibrating the observed record against weighted rainfall for each of the gauging stations. The process is described in sufficient detail. The usual statistics of the concurrent and observed records are presented in the report. The results are described in detail in the report for each of the stations used in the calibration process. A summary of the results has been extracted from the report and is presented in **Table 4-6**.

Table 4.6: Summary of Results from Modelling of Lower Vaal Catchment

Gauge Number	Station Name	Effective Incremental Area (km^2)	MAP (mm)	MAE (mm)	Naturalised MAR million m^3/a	Unit Runoff mm/a
C3H003	Taung	7975	530	1916	59.0	7.4
C3R002	Spitskop	9249	438	2039	77.5	8.4
C5H016	Aucampshoop	1847	350	2050	6.4	3.5
C5H018	Tweerivier	2236	422	1871	14.4	6.4
C5R001	Tierpoort	922	491	1640	23.8	25.8
C5R002	Kalkfontein	8781	412	1746	215.9	24.6
C5R003	Rustfontein	937	543	1600	30.7	32.7
C5R004	Krugersdrift	5391	508	1639	114.4	21.2
C9H009	De Hoop	3201	406	1963	12.9	4.0
C9R001	Vaalharts	2509	444	1946	11.2	4.5
-	Lower Vaal	6096	361	2210	31.5	5.2
TOTAL		**49144**			**597.7**	**143.7**

f) Conclusions

The VRSAU Report for the Lower Vaal makes a number of recommendations on the need for new river gauges and measures to improve the quality of data recorded. These include measures with respect to the need to monitor irrigation abstractions, transfers and return flows need to be monitored accurately in the Vaalharts area. Measures were also recommended to improve monitoring in the Upper Harts River, and a new gauging site was proposed for the Vaal River downstream of the Vaal and Harts River confluence and the Vaal Gamagara abstraction point. A number of recommendations to improve monitoring in the Modder/Riet catchments are also made.

Perhaps most importantly were concerns raised regarding the need to better know how much water is being used in the catchment, especially with respect to irrigation consumption. It was therefore recommended that the aerial photography and mapping of the region be updated in order to determine the extent of irrigated area. It was also recommended that a database of all current and historical irrigation information and contact names should be compiled.

More accurate and standardised estimates of effective catchment areas need to be agreed upon.

A point of caution was also raised, particularly relevant to the Lower Vaal catchment with respect to sub-catchments where flows and irrigation are primarily supported by compensation releases from an upstream reservoir rather than from runoff generated on the incremental catchment. It was stated that care must exercised during calibration and naturalisation of the catchment, and that the water demands (irrigation or other) must be supplied by the actual compensation flows rather than the catchment runoff and river flows, since failure to model the abstraction of demands in this way would result in extreme over-estimation of natural runoff when the irrigation demands are added back to the catchment runoff during the naturalisation process.

The WR90 Regional Parameters appear to give a slightly conservative estimate of natural runoff in the catchments along the Vaal River and Lower Modder and Riet catchments.

4.3 Orange River Sub-catchments

4.3.1 Senqu River Sub-system

a) General Description

The Senqu River rises in the Maluti and Drakensburg Mountains in Lesotho. Within the catchment, these mountains rise to 3 482 m. On crossing the border into South Africa, the river becomes the Orange River and makes its confluence with the Caledon River at the Gariep Dam about 220 km downstream of the border. In South African water resources studies, it is often included under the heading of the Vaal River rather than the Orange due to the fact that water transfers are made from the Senqu River across the catchment divide to the Vaal Dam. The Senqu River is therefore an essential part of the so-called “Vaal Integrated System”. The Senqu River is therefore an important water resource for South Africa for two reasons, firstly as one of the two main rivers feeding the Vanderkloof Dam, and secondly as a source of water for the industrial heartland of Gauteng. Transfers to the Vaal Dam take place as part of the Lesotho Highlands Scheme, Phase 1 of which has been implemented through the

construction of the Katse Dam and associated storage and transfer works.

In order to have been able to construct this scheme, South Africa has an agreement with the Kingdom of Lesotho, which makes provision for the payment of royalties.

b) Literature Consulted

Unlike the Vaal River Hydrology, as well as that of other parts of the Orange River, the Lesotho River Hydrology is based on relatively "new data". The first comprehensive studies of the Senqu River date back to the Lesotho Highlands Feasibility Study, carried out in the mid 1980s. An "interim" hydrology was produced for design purposes. Further studies were carried out by BKS, South Africa in 1993 and by the UK Institute of Hydrology in 1994. Finally, a study carried out jointly by BKS and the LHDA (Lesotho Highlands Development Authority) was completed in December 1998. The resultant report of this study has been the main reference document for this review.

c) Water Use

Before the construction of the Lesotho Highlands Water project (LHWP), use of water in the Senqu River was limited to water supply for small settlements. With the construction of the Katse Dam on the Malibamatso River, a 45 km transfer tunnel to Muela Power Station and the Muela Dam, which collects tailrace waters for transfer to the Vaal Dam, the situation has changed completely. From the Muela Dam water is transferred via another set of tunnels from whence the water flows into the upper reaches of the Ash River, a tributary of the Liebenbergsvlei River, which joins the Wilge River just before Vaal Dam.

It is anticipated that on average 490 million m^3/a will be transferred out of the Senqu River to the Vaal River Basin as part of Phase1A of the LHWP. This will increase when Phase 1B, the construction of a 145m high dam at Mohale on the Sequnyane River and a transfer tunnel to the Katse Reservoir, have been completed. Completion is scheduled for 2003.

d) Observed Records

The study looked at more than 120 relevant rainfall records. Of these only records, which could be patched and with a record of at least 15 years, were

utilised. It would appear that every effort was made to fully utilise the available data, even retaining parts of a record if considered acceptable and rejecting the parts considered to be unreliable. This was necessary, however, because the quality of rainfall data in the Senqu catchment was generally considerably lower than in the sub-catchments already discussed.

Most of the streamflow stations in Lesotho were set up in the middle 1960s so there are no long records. It is reported that there were 13 stations, which could be used in the analysis plus the Oranjedraai Station situated just downstream of the Lesotho/South African border. Difficult access to stations for servicing and siltation problems are two of the reasons for numerous gaps in many of the records. In general, the quality of the records is described as “fair”. Three crump weirs have been installed in recent years to improve the reliability of runoff data. It is clear that a lot of effort had to go into carefully examining the observed data and especially the water stage/discharge curves for all the stations in the catchment. The stations at Marakabei and Paray were considered to be the most complete and were therefore selected as the key reference stations. Gaps in the records of several other stations were corrected by reference to these stations. The report discusses in detail each one of the gauging stations and their associated records, the gaps and how they were patched. Another key reference station was the Oranjedraai Station, which is almost complete for the full 1960 to 1994 period.

e) Rainfall/Runoff Modelling, Runoff Naturalisation

Rainfall/runoff modelling was carried out using a modified form of the Pitman Model. Features of the version used allowed input of a number of rainfall records covering the period of interest to ensure that gaps were covered, as well as relatively short runoff records.

Table 4.7 derived from the report summarises the some of the results obtained during the modelling. It would appear from the results that the main aim was to model the MARs of each station as accurately as possible, since the observed and synthesized MARs match up quite well. A comparison of the observed and synthesized record statistics show significant differences in the standard deviations and relatively low correlations. However, it is also clear from the low number of rain gauges (between 3 and 5 for each incremental catchment)

available that it would not be possible to obtain better results.

f) Synthesized Record

Having generated the synthesized runoff records, these records were then used as inflows to the various reservoir sites agreed between the Governments of South Africa and Lesotho. In view of the fact that the reservoir sites were not the same as the gauging stations sites, the inflow records were calculated by summing the upstream incremental gauging site record with a part of the downstream incremental gauging site record.

Table 4.7: Results of Rainfall/Runoff Modelling for Selected Stations

Parameter	Seaka	Mokhotlong	Paray	Marakabei	Bokong	Orangedraai
Catchment MAP (mm)	796	908	763	944	930	781
Catchment Area (km²)	10041	1660	1028	1087	403	4806
Observed MAR (Mm³/a)	1390	280.1	181.8	359.5	100.1	813.3
Synthesized MAR (Mm³/a)	1388	280.0	180.3	348.6	100.3	812.8
Observed St. Deviation	853	208.6	117.1	181.3	50.8	560.3
Sythesized St. Deviation	820	208.0	94.2	134.2	40.0	438.9
Correlation Coefficient	0.64	0.63	0.71	0.79	0.78	0.65
No. of Rainfall Records Used	4	4	5	3	3	4

Details of how the calculations were carried out are fully described in the report. Reservoir inflow sequences are provided for the 1920 to 1995 period and hence, are consistent with the VRSAU Studies. **Figure 4-3** shows the positions of the dam sites considered in the study. **Table 4.8** summarises the calculated mean annual inflows.

Table 4.8: Calculated Mean Annual Runoffs at Considered Dam Sites

	Katse	Mohale	Mashai	Tsoelike	Malatsi	Ntoahae
MAR (Mm³/anum)	554	312	1447	1795	611	1943

g) Conclusions

Due to the sensitive nature of the hydrology of the Senqu River (amount of royalties payable to Lesotho), considerable effort has been put in to ensure the best possible result under difficult (short and incomplete records) conditions.

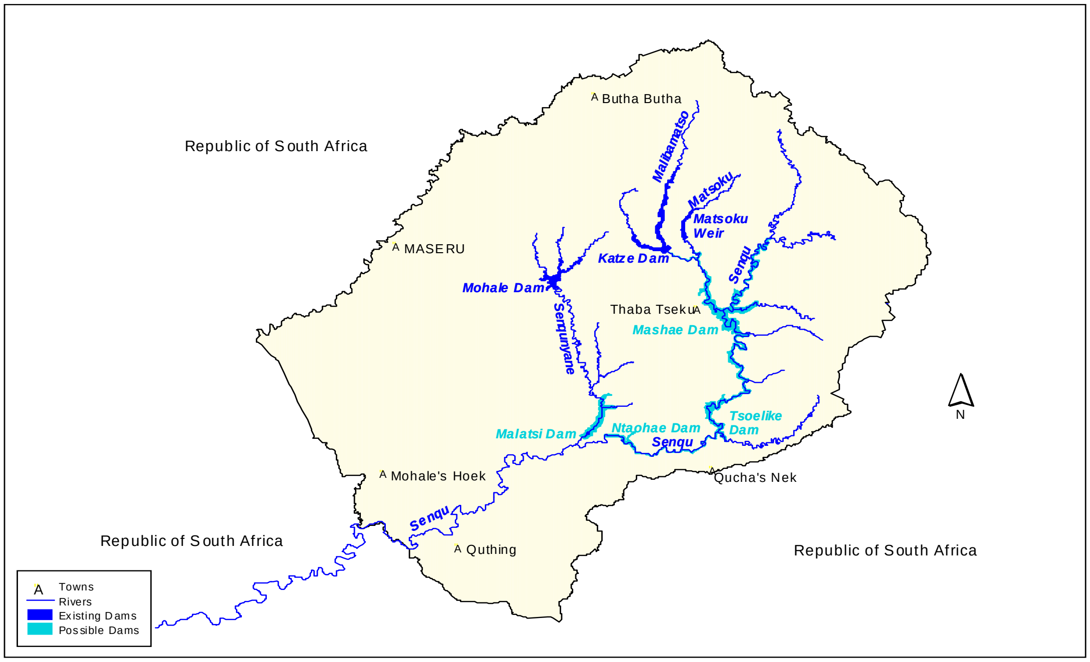

Figure 4-3: Positions of Dam Sites Considered in LHWP Systems Analysis

4.3.2 Caledon River and Upper Orange Incremental Catchment: Hydrology

a) General Description

In the nomenclature used in the South African systems analysis the Upper Orange River Incremental, catchment covers the area upstream of the Vanderkloof Dam up to Welbedacht Dam on the Caledon River and up to Oranjedraai on the Orange (Senqu in Lesotho) River. The Senqu River in Lesotho has already been discussed in the previous paragraph as far as the Oranjedraai gauging station just downstream of the Lesotho/South African border. Before making its confluence with the Caledon River, the Orange is joined by the Kraai River from the Drakensburg Mountains to the southeast. Upstream of the Wellbedacht Dam the Caledon River catchment covers an area of 15 245km², much of it in the mountains of Lesotho.

Rainfall drops off very sharply as the Orange River leaves the mountains and is down to 300mm/a at the Gariep Dam.

b) Literature Consulted

While the hydrology of the Orange/Senqu River upstream of the Orangedraai gauge was updated as part of the Lesotho Highlands Study (see paragraph) in 1999, the hydrology of the Caledon River and incremental catchments of the Vanderkloof and Gariep Dams is relatively old, dating back to a report completed in November 1992. This document, entitled "Upper Orange River : Hydrology" was the main reference document for this section of the review.

c) Water use

Water demand for Irrigation in the Upper Orange catchment was estimated at 384 million m³/a in 1990, although it would appear that this is not always met since the average water supplied was only 281 million m³/a. According to the study, total water use in the Upper Orange catchment was estimated at 1 920 million m³/a of which 885 million m³/a was estimated to be evaporation from the major storage reservoirs and farm dams. Of the remainder; it was estimated that 740 million m³/a are transferred to the Vaal catchment. Knellpoort and Welbedacht on the Caledon River are mainly used to transfer water to the Modder system to support Bloemfontein, Bothabello and other smaller urban areas with water. Welbedacht has, however, silted up to a large extent and Knelpoort Dam was built as an off-channel storage dam due to the severe silt problems. There are, however, compensation releases from Welbedacht Dam to supply irrigation downstream of the dam (irrigation that existed before the dam was built). The Welbedacht Dam is not used to support Gariep Dam at all.

d) Runoff

The incremental MAR values as calculated in the 1992 study are presented in **Table 4-9**. The natural runoff generated for this study covered the period 1920 to 1987.

Table 4.9: Incremental MAR for the Upper Orange River

River Gauge	River	Catchment Area (km²)		MAP (mm)	Incremental MAR (Mm³/annum)	Incremental Unit Runoff (mm)
		Total	Incremental			
Aliwal North	Orange	37 075	3 635	591	229	63
Roodewaal	Kraai	8 688	8 688	657	676	78
Oranjedraai	Orange	24 725	24 725	793	4 192	170
Welbedacht Dam	Caledon	15 245	15 245	755	1 217	80
Gariep Dam	Orange	70 749	18 435	456	397	22
Vanderkloof Dam	Orange	89 842	17 843	314	147	8

e) Conclusions

The report pointed out that reconciling the hydrology had been complicated by inaccurate measurement by the turbine meters at Vanderkloof Dam, and uncertainties over the accuracy of the elevation/capacity equation for the same dam. The study also recommended that combined mass balance calculations for Gariep and Vanderkloof Dams should be carried out annually.

4.3.3 Lower Orange River

a) Description

Downstream of the Vanderkloof Dam there are five incremental catchments, most of which do not make major contributions. In the South African studies, these are referred to as the Boegoeberg Incremental catchment, the Hartbees catchment, the Vioolsdrift incremental catchment, the Fish River catchment (Namibia) and the River Mouth incremental catchment.

b) Literature Consulted

A large number of reports were compiled as part of the Orange River Replanning Study (ORRS). All of these (over 30) reports were made available in electronic form for this review. Certain key reports were selected. These included the Hydrology and Systems Analysis: Orange River Basin", and the "Evaluation of Irrigation Water Use", and "Water Demands of the Orange River Basin – ORRS". While the main purpose of the first-mentioned of these studies was to carry out a large number of systems analyses in order to look at maximising yield and efficiency of the available water resources, including the inclusion of various potential reservoirs, the report also provides an overview of the hydrology.

b) Water Use

The main user of water in the Lower Orange River (and indeed of all the catchment), is the Orange River Project, which was first proposed in 1962 to irrigate thousands of hectares especially in the Eastern Cape, Northern Cape and Free State areas. This project depends on flows from the Vanderkloof and Gariep Dams. It is reported that the main functions of the Orange River Project (ORP) are to provide water for irrigation and urban users along the river, to provide irrigation water to the Great Fish and Sundays Rivers in the Eastern Cape and to the Riet River catchment. In addition, Orange River water is used to solve water quality problems in the Vaal River at Douglas, and is used to generate peak power for the Eskom Network at the Gariep and Vanderkloof Dams. The ORP also supplies water to cities and small towns such as Upington, Prieska, Port Elizabeth, Grahamstown, Alexander Bay and Port Nolloth.

In the systems analysis described, land use and associated water demand has been divided up into five areas, being:

- Area 1: Upstream of Gariep Dam (i.e., not part of ORP).
- Area 2: Area upstream of the Orange/Vaal confluence up to and including Gariep Dam.
- Area 3: Riet/Modder catchments.
- Area 4: Area downstream of Orange/Vaal confluence to 20º longitude (Namibian/RSA border).
- Area 5: From 20º longitude to River mouth.

The demands are described in the report and are summarised in **Table 4.10**.

Table 4.10: Summary of ORP Demands (excluding transfers to Riet/Modder catchments)

Area / Water Use	Area 2 (Directly from Gariep and Vanderkloof)	Area 2 (Gariep to OrangeVaal confluence	Area 4	Area 5	Total
Irrigation	882[1]	228	469	81	1 660
Urban	16	(incl. below)	(incl. below)	(incl. below)	16
Urban/ Industrial/ Stock	(incl. above)	5	13	27	45
River Requirement (Losses)	-	64	455	441	960
Canal Losses	-	9	26	-	35
Environmental Demand	-	-	-	306	306
Totals	899	306	963	855	3022

[1] 627Mm³ by Orange/Fish Tunnel; 255Mm³ by Vanderkloof canal

[2] Lesotho Highlands Water Project transfers are not included

Clearly the updating of these demands will be an important aspect of the current study in view of significant water use developments over the last decade.

In the report studied, it would appear that all the demands are described in sufficient detail and clarity to allow relatively straightforward updating for new systems analyses incorporating more up to date runoff data. The same is true of canal and rivers losses.

4.3.4 Lower Orange River and System Analysis

a) General

The hydrology used in the Lower Orange clearly relates to the hydrology of the Upper Orange and Vaal. Hence, in view of the fact that the ORRS pre-dated some of the more recent hydrological re-assessment, some of the records used are not the most recent. For example, the runoff record used for the Riet/Modder system was the one updated in 1991, rather than the one used in the 1997 study. However, in checking the runoff data files for the total Orange River catchment as it now stands, it was found that most of the records have been updated to September 1995. The only exception is the incremental area upstream of Vanderkloof Dam and downstream of the Lesotho border.

It is estimated that approximately 900 Mm³/annum originates from the Lower Orange catchment of which more than half comes from the Fish River. It is stated in the study that the hydrology of the Lower Orange was treated in a simplified manner. The Lower Orange Hydrology covers the period 1920 to 1989. A table presented in the report provides a very useful overview of the runoff contributions from the different parts of the catchment as assumed for the 1991 study. It is not presented in full here, but a summary is provided showing the sum of the incremental MARs for each of the major systems as already discussed in this review.

Table 4.11: Summary of Incremental Streamflow Data

Catchments included (see Figure 4.1 and 4.2)	Sub-system	Total Incremental Catchment Area (km²)	Total Incremental MAR (1920 – 1983)	Unit Runoff (mm)
I7, I11, I12, I13, I15, I16, I17, I19, I22, I24	Lesotho Highlands	24 752	4 014.53	162.2
I5, I8, I9, I27, I28	Caledon	15 245	1 197.98	78.58
I1, I4, I18, I20, I26	Upper Orange	48 595	1 389.125	28.586
I2, I3, I6, I10, I14, I21, I23, I25	Modder-Riet	23 277	366.21	15.77
-	Remainder of Vaal	166 235	3 521.65	21.181
-	Fish River (Namibia)	76 000	483.90	6.36
-	Remainder of Orange River*	136 909 (319 870)	219.35	1.6
TOTAL		**491 103 (685 372)**	**11 192.74**	**22.79**

b) Scenarios

One of the aims of the systems analysis was to look at combinations of new developments in the Orange River catchment to see how yield can be most usefully augmented. These scenarios have been studied as part of this review, but are too numerous to be described here. However, in order to illustrate the principle, the "base scenario" is summarised and the sort of scenario variations that were considered are briefly mentioned.

The base scenario was as follows:

- Phase 1 of LHWP at 2005-development levels.
- Compensation releases from Katse and Mohale dams of 0.5 m³/s and

0.3m³/s, respectively.

- Environmental demand at river mouth set at 100 Mm³/annum.
- Orange to Fish transfer set at 627 Mm³/annum.
- Orange/Riet transfer set at limit of 275 Mm³/annum (demand driven).
- Orange/Douglas transfer set at limit of 88 Mm³/annum (demand driven).
- Compensation flow from Gariep Dam set at 16 m³/s.
- 2005 development level spills from the Vaal Basin.
- Hydro-electric power generated in accordance with downstream system demands only.
- Dead storage level (DSL) set at 1 231.63 m for Gariep Dam and 1 147.78 m for Vanderkloof Dam.
- Total live storage at Gariep and Vanderkloof Dams = 6 883 Mm.
- Instream flow requirements taken as equal to downstream demand.
- Transfer from LHWP to Vaal basin taken as 28.6 m³/s.
- Novo transfer from Caledon to Modder in place.
- All domestic/industrial demands at 2005 levels.
- Inclusion of all possible diffuse developments in the Caledon (Lesotho and RSA).
- 2045 sedimentation levels at dams.

The results of around 50 alternative scenarios (including minor variations or sub-scenarios) were modelled in order to find out which set of operating rules was the most appropriate. These operating rules represented a combination of operating rules for existing infrastructure and operating rules for planned potential infrastructure . It should be noted that systems analyses had to take into account not just consumptive needs, but also hydropower-related scenarios.

A number of scenarios related to the inclusion of the Vioolsdrift Dam. These included for example, raising of Gariep Dam combined with a 1500 Mm³ dam at Vioolsdrift and increased transfers from the Orange River to the Vaal, or the raising of Gariep, Bosberg, Boskraai Dams combined with a large dam at Vioolsdrift.

Conclusions are too numerous and inter-dependant to go into here. The study provides a useful basis for the current study.

5. CONCLUSIONS AND RECOMMENDATIONS

Hydrological studies and systems analyses carried out in South Africa covering the entire Orange River Basin within South Africa and Lesotho have been reviewed. The general impression is that the work has been carried out thoroughly as far as the data will allow. There is no reason to disagree with the hydrological files being used as input for the systems analysis. However, as is generally the case with hydrological and associated data, given the human and financial resources, it would of course be possible and worthwhile to improve the accuracy of the data.

As stated on several occasions in the literature reviewed, the Vaal and Orange River Basins are the most important water resource systems in South Africa. They support more than 50% of the country's GDP. It is logical, therefore, that money spent on improving the accuracy of our knowledge of the system is well-spent and easily justified. Hence the current study, and the major investments being made by the Governments of South Africa and Namibia. However, in view of the fact that some of the hydrological studies studied in this review are already more than a decade old, it would seem worthwhile to utilise the new data that have been collected since their completion and to update these studies. This includes the incremental catchment upstream of Vanderkloof Dam and downstream of the Lesotho Border, as well as the Lower Orange with the exception of the Fish River in Namibia.

The need to update hydrological data and the analysis thereof should not be limited to runoff data but should also include improved collection of water demand data. The effort put over to analysis of water demand information in the studies reviewed reflects a strong awareness of the importance of water demand data. Any basin-wide efforts to update hydrology and water demand should not be undertaken lightly and will probably require a multi-disciplinary approach involving several Ministries. Consideration should be given to using a GIS-driven approach, which can be easily updated on a regular basis.

In the interest of transparency and common understanding at a technical level it is recommended that key Orange River Basin river stations in South Africa (and Namibia) be identified for common monitoring. Joint monitoring would include water level monitoring (real-time telemetry), flow measurements for station calibration, and conversion of water levels into discharge. It would seem logical to extend this transparency to include all gauging stations and also to cover water demand data.

PRE-FEASIBILITY STUDY INTO MEASURES TO IMPROVE THE MANAGEMENT OF THE LOWER ORANGE RIVER

HYDROLOGY, WATER QUALITY AND SYSTEM ANALYSIS: VOLUME B – HYDROLOGY

Part 2

Review of RSA Hydrology

PRE-FEASIBILITY STUDY INTO MEASURES TO IMPROVE THE MANAGEMENT OF THE LOWER ORANGE RIVER

HYDROLOGY, WATER QUALITY AND SYSTEM ANALYSIS: VOLUME B - HYDROLOGY

Part 2

Review of RSA Hydrology

EXECUTIVE SUMMARY

The main aim of this review is to increase the transparency of South African studies for the benefit of the Namibian Team and at the same time to ensure that they are well acquainted with the hydrology of the river basin in South Africa and Lesotho.

This review is based on three key linked information sources:

- ***Hydrological reports as obtained from the "Vaal River System Analysis Update", "Orange River Development Project Replanning" (ORRS) and the "Orange River System Analysis" studies.***
- ***The systems analysis set-ups, which facilitated understanding of priorities and transfers.***
- ***The stream flow datasets for all of the sub-catchments as derived in the studies carried out to compile the systems analysis update.***

The hydrological studies and systems analyses carried out in South Africa covering the entire Orange River Basin within South Africa and Lesotho have been reviewed. The general impression is that the work has been carried out thoroughly as far as the data will allow. There is no reason to disagree with the hydrological files being used as input for the systems analysis. However, as is generally the case with hydrological and associated data, given the human and financial resources, it would of course be possible and worthwhile to improve the accuracy of the data.

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LIST OF ABBREVIATIONS

DSL	:	Dead Storage Level
DWA	:	Department of Water Affairs (Namibia)
DWAF	:	Department of Water Affairs and Forestry (RSA)
GDP	:	Gross Domestic Product
Ha	:	Hectare
HDYP09	:	Mathematical Model for Generation of River flows from meteorological data in South Africa
LHDA	:	Lesotho Highlands Development Authority
LHWP	:	Lesotho Highlands Water Project
MAE	:	Mean annual evaporation
MAP	:	Mean annual precipitation
MAR	:	Mean annual runoff
Million m^3	:	Million cubic meter
ORP	:	Orange River Project
ORRS	:	Orange River Development Replanning Study
RSA	:	Republic of South Africa
St deviation	:	Standard deviation
VRSAU	:	Vaal River System Analysis Update Study
WRSM90	:	Water Resources Simulation Model

1. INTRODUCTION

The Orange River Basin is large, covering more than half of the land area of South Africa and the entire land area of Lesotho. Understanding the hydrology is complicated by a relatively small (considering the variability of rainfall) number of stream gauges, numerous inter-basin transfers, a large number of storage structures and high levels of demand. Given the importance of the water resources of the Orange River to South Africa, which is close to a water deficit situation, it is not surprising that numerous studies have been carried out on the hydrology of the components of the system.

In recent years, the significance of these studies has increased because of the increasing interest in the resources of the river from South Africa's neighbours, in particular Lesotho, Namibia and Swaziland. Lesotho has a water resources surplus and has reached agreement with South Africa to store and transfer water from impoundments within its territory in order to increase the yield of the system where it is needed in South Africa. Development in Namibia within the basin has increased sharply within recent years and, especially with respect to high value irrigated crops, which depend on water abstracted from the Orange River. Namibia therefore has an interest in the way in which the water resources of the system are managed further upstream in South Africa. Swaziland, while not situated within the basin is nevertheless affected by transfers from the headwaters of the Komati and Usutu Rivers. Transfers from the Usutu and Komati Basins are used to support the Vaal system, as well as Power Stations in the Upper Olifants, of which the latter also receives support from Grootdraai Dam in the Upper Vaal. Although the Komati and Usutu Rivers are not directly linked to the Orange River, the fact that they are used to augment the Vaal System will result in some effect on the Orange River. These two rivers rise in South Africa and flow eastwards through Swaziland to Moçambique and the Indian Ocean. Their water resources are critical to the sugar industry in Swaziland. The Orange River mouth at Alexander Bay/Oranjemund also has importance internationally, having been declared a RAMSAR site.

This increased international interest has resulted in a need for transparency with respect to studies on the water resources of the Orange and associated systems. There are now water allocation agreements in place between Lesotho and South

Africa, and more recently (August 2002) between South Africa and Swaziland.

The main aim of this review is to increase the transparency of South African studies for the benefit of the Namibian team and at the same time to ensure that they are well acquainted with the hydrology of the river basin in South Africa and Lesotho. This review is based on three key linked information sources:

- Hydrological reports as obtained from the "Vaal River System Analysis Update", "Orange River Development Project Replanning" and the "Orange River System Analysis" studies.
- The systems analysis set-ups, which facilitated understanding of priorities and transfers.
- The stream-flow datasets for all of the sub-catchments as derived in the studies carried out to compile the systems analysis update.

The basic approach followed in the hydrological studies is generally the same and can be summarised as follows:

- Assembly of key "observed" data. These data are essentially:
    - the observed rainfall data for the largest possible coverage of rainfall stations;
    - the observed data for the stream flow stations for each sub-catchment. These gauges are a combination of purpose-built gauging stations and dams;
    - evaporation data; and
    - demand data including irrigation, urban, industrial and mining, domestic, forestation demands, and also seepage loss and environmental requirements.

- Pre-calibration data manipulation:
    - For the rainfall data, the quality of the data at each rain gauge is checked by consideration of the record length, amount of missing data and finally using mass plots. Gauges with unacceptably short records (normally 40 years), but this may be reduced for catchments where data are lacking. Gauges with a high percentage (normally > 8%) of unreliable record are similarly rejected. Where possible, gaps in records are "patched" using a

multiple linear regression on other gauges in the sub-catchment.

- For the stream flow data, the data for all available river gauges are considered. Those with records that are too short, water stage/discharge ratings that are unreliable, or too much missing data, are rejected. Some mass balance analyses are carried out to examine the accuracy of some of the records.
- Water demand data are examined and taken back in time. For example for irrigation data, it is necessary (see later) to estimate demand as it has grown through the period of analysis (i.e., since 1920). Similarly for other demands. This is important, because rainfall/runoff modelling is based on the principle of modelling rainfall against "naturalised runoff", that is runoff unaffected by development. This is necessary, because since (it is assumed that) rainfall is unaffected by human development, it would not be possible to model it against a non-stationary time series such as observed runoff. Once modelling has been completed and an extended runoff record produced, this extended runoff can be adjusted to take into account the realities of current/future levels of demand during the systems analysis. In view of the high level of water demand within the Basin, accurate determination of water demand is critical if accurate model calibration is to be achieved.

- Model Calibration:
  - Prior to runoff simulation and record extension, Model Calibration has to be carried out. In the South African studies, a model known as the WRSM90 runoff model, has generally been used. This is an upgraded version of the Pitman (or HDYP09) model. In simplified terms, this model aims to calculate runoff based on catchment rainfall weighted according to a number of catchment parameters. Without going into detail, the principle is that these catchment parameters approximate the physical characteristics of the catchment that may have an influence on runoff. During the calibration process, the values of these parameters are modified until the best possible fit can be achieved, while at the same time respecting the physical realities of the catchment.

- Patching and Record Extension:
  - Following calibration, the model is used to patch missing periods in the observed records and to extend the record back in time, in the case of these hydrological studies to the 1920s.
  - The process is carried out for all the sub-catchments.

- System Analysis:
  - The resultant incremental runoff records are used as input to the systems analysis for the main sub-catchment area for which the hydrology is being updated.
  - The systems analysis combines the hydrology of all the sub-catchments and takes into account all the different types of water demand, including non-consumptive uses and inter-basin transfers. The systems analysis is carried out according a set of operating rules, which define priorities for different users. These "users" include the environment and natural losses such as seepage and evaporation. Operating rules can be varied until yields are optimised as desired.

2. REVIEW OF HYDROLOGICAL REPORTS AND DATA

2.1 Reports Consulted

The following reports were supplied and reviewed:

Bailey, A. K. (1999). **Vaal River System Analysis Update; Hydrology of the Vaal Barrage Catchment**. Pretoria, Department of Water Affairs and Forestry.

Basson, M. S. (1997). **Overview of Water Resources availability and utilisation in South Africa**. Pretoria.

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2.2 System Analysis and Data

In addition, the layouts of the systems analyses for the sub-systems listed below were reviewed. The layouts included the assigned penalty values so that it was possible to have an understanding of the operating rules.

- Combined Caledon, Lesotho Highlands Water Project, Upper Orange, Riet/Modder and Lower Vaal sub-systems.
- Namibia and Lower Orange sub-systems.
- Usutu, Komati, Upper Olifants, Zaaihoek, Upper Thukela, Thukela South, Upper Olifants and Upper Vaal sub-systems.
- Upper Vaal and Vaal barrage sub-systems.
- Middle Vaal sub-system.
- Lower Vaal and Riet/Modder sub-systems.

2.3 Runoff Data

The runoff files (*.inc) adopted for all the incremental catchments were provided and examined in order to get a feeling for monthly and annual variation and magnitude of flow. **Table 2.1** summarises the files, which were provided.

Table 2.1: Runoff Records Derived from Hydrological Studies for use in Systems Analysis

ALIW.INC	kat9.inc	rietf9.inc
allem9.inc	KATJE.INC	riets9.inc
auch9.inc	klerk9.inc	ROOD.INC
barbers.inc	klipb9.inc	rustf9.inc
barr9.inc	klipd9.inc	sand9.inc
bloem9.inc	klipr9.inc	spits9.inc
bosk9.inc	KNEL.INC	sterk9.inc
C3h013.inc	kop9.inc	suik9.inc
C5r5.inc	krom9.inc	tier9.inc
c9h007.inc	Krug10.inc	tso9.inc
dehoop9.inc	LORAN.INC	twee9.inc
dela9.inc	mal9.inc	uswentzd.inc
dswentzd.inc	mas9.inc	vaal9.inc
erf9.inc	mat9.inc	VERW.INC
FISH94.SPL	Mock.inc	vharts9.inc
fran9.inc	moh9.inc	WATER.INC
grootd9.inc	neser9.inc	WELBB.INC
HFDU.INC	nto9.inc	VIOOL.INC
HLOTS.INC	oran9.inc	BOEG.INC
kalkf9.inc	PKDU.INC	HARTB.INC

3. OVERVIEW OF ORANGE RIVER CATCHMENT

The Orange River rises as two main river systems, the Orange River and its associated tributaries, and the Vaal River and its associated tributaries. To the south, the Orange River rises as two main tributaries, the Caledon and the Senqu Rivers in the Drakensburg and Maluti Mountains in Lesotho and South Africa. To the north, the Vaal River rises in the Highveld in Mpumalanga and Northern Provinces of South Africa. The large majority of runoff is generated in these areas. The Vaal and the Orange (on crossing the border from Lesotho into South Africa the name changes from Senqu to Orange) Rivers make their confluence near the town of Douglas, more than a thousand kilometres upstream of the longitude 20 degrees where the Orange River becomes the border between Namibia and South Africa. Downstream of Douglas, the Orange River is joined by the Ongers/Brak River and the Hartbees River from the south and the Molopo and Fish Rivers from the north. The Molopo River has not been known to contribute surface runoff to the Orange River.

4. SUB-CATCHMENT HYDROLOGY

4.1 Overview

In representing and modelling the Orange River System, the approach adopted by South African Consultants and the Ministry has been to model the system as a whole, but to describe the hydrology and water demand on a sub-catchment basis. In some cases, these sub-catchments have grouped together as a large number of smaller sub-catchments. As is normal practice, the choice of sub-catchments has been made according to a combination of considerations including the location of gauging stations/dams and location of various demand centres.

The main source areas are covered by the Lesotho sub-catchment system; the Caledon River catchment and the Upper Vaal catchment (see **Figures 4.1 and 4.2**). However, this is complicated by the fact that part of Lesotho sub-catchment is also implicated in the Upper Vaal catchment since it is towards the Upper Vaal that water transfers are made. In addition, the Upper Vaal receives water transferred from other rivers outside of the Orange River Basin. These are also included in the analysis of the Vaal River System. The remainder of the Vaal River is divided into the Middle and Lower Vaal sub-catchment groupings. Upstream of the confluence of the Vaal River, the eleven Orange River sub-catchments are often defined by dams such as the Boskraai, Gariep, Welbedacht, Vanderkloof and Kalkfontein Dams. Downstream of the Vaal/Orange River, there are five large sub-catchments, those of the Ongers/Brak, Hartbees, Molopo, Fish and "River Mouth" catchments.

The hydrology of these sub-catchments as developed and described by or for the South African Department of Water Affairs (DWAF) has been reviewed and the findings, conclusions and recommendations are summarised on a sub-catchment (grouping) by sub-catchment (grouping) basis in **Sections 4.2.1 to 4.3.3.**

4.2 Vaal River Sub-catchments

4.2.1 Upper Vaal Sub-system

a) General Description

The Upper Vaal catchment forms part of the Vaal catchment, which is regarded as the most important water resources system in South Africa, supplying water to more than 40% of the population and supporting more than 50% of the country's gross domestic product (GDP). The Upper Vaal includes four major impoundments, the Vaal Dam (capacity of 2 603 million m^3), Grootdraai Dam (356 million m^3), Sterkfontein Dam (2 616 million m^3) and Saulspoort Dam (17 million m^3). The catchment has been divided up into five sub-catchments, Sterkfontein, Delangsdrift, Grootdraai, Wilge and Vaal Dam (incremental) sub-catchments. Reference should be made to **Figure 4-1**. The Grootdraai and Sterkfontein sub-catchment runoffs are supplemented by inter-basin transfers from the Usutu/Komati and Tugela catchments, respectively. The Vaal Dam also receives inflows from the Senqu River in Lesotho.

The Upper Vaal catchment covers an area of 38 638 km^2 with little in the way of urban development. There are thousands of small farm dams in the catchment.

b) Literature Consulted

The first major system analysis study on the Vaal River carried out in 1985 has not been reviewed in any detail, since this has been superseded by studies in 1993 and especially a study carried out between 1995 and 1997. The last-mentioned of these studies known as "Vaal River System Analysis Update Study (VRSAU)" has been reviewed in detail. The stated purpose of this study was:

> "……to revise and update the hydrological and water quality databases used in the earlier studies and to re-assess the water quantity and quality capabilities of the whole Vaal River System using the most up-to-date information and techniques."

c) Water Use

The VRSAU Study goes into considerable depth in its evaluation of water use and water demand. This is important, since only an accurate assessment of current and past water demand will allow an accurate "naturalisation" (see **Section 1**, Introduction).

Vaal Dam supplies Rand Water, South Africa's largest potable water supplier (all municipal and industrial users in Gauteng), various urban users, Grootvlei Power Station and some irrigation. Sterkfontein Dam stores water, transferred from the Tugela River System. Grootdraai Dam supplies water to various power stations and industrial users, including Sasol. It receives transfers from the Usutu catchment (Maputo River Basin).

The VRSAU included a detailed analysis of the small dams in the catchment using conventional mapping and satellite imagery. It was shown that the total capacity of all farm dams was significant. It was estimated in the study that the quantity of small (dam) storage in the basin had increased from 11.84 Mm^3 in 1920 to 166.49 Mm^3 by 1995.

The report states that there were some difficulties in accurately determining the current area under **irrigation**. The consultants made use of previous studies, Department of Water Affairs' (DWA) records and other methods to arrive at a figure of 12 200 Ha under irrigation with the majority in the Frankfort and Vaal Dam catchments. It was estimated that the area under irrigation had grown from 2 250 Ha in 1920, but that in nineties irrigation within the catchment had remained "almost constant". The report shows that considerable care was taken to model irrigation demand as accurately as possible. Cognisance was taken of different crops and monthly variations in application rates. Return flows of 10% were assumed.

Urban and industrial abstraction levels are measured by DWAF and amounted to almost 33 million m^3 from the Vaal Dam catchment in 1994.

Afforestation areas are limited. The estimated total area was only 13.4 km^2 in 1994.

d) Transfers

Since 1974, water has been pumped from the upper reaches of the Tugela River over the Drakensburg to Drieklloof Dam, a small dam adjoining Sterkfontein Dam, for hydropower generation and also for transfer to the Vaal Dam Basin. The study reports that it is not possible to accurately calculate the amount of water transferred into the Vaal Dam catchment due to the complexity of the transfer system and some unknown factors. A maximum transfer of 700 Mm³/annum has been designed for, but this is rarely possible to achieve. Historical records of annual releases are misleading since during the first 8 years of the dams life no water was released as the dam was filling. The average amount of water transferred from the Tugela Basin to Sterkfontein Dam between 1974 and 1995 was 283 million m³. Over the last 13 years, since Sterkfontein Dam has filled, an average of 183 million m³ has been released (after consideration of transmission losses). Water is also transferred from the Zaaihoek Dam on the Buffalo River System, a tributary of the Tugela River for power supply, local urban water supply and can flow into the Vaal River upstream of Grootdraai Dam. The scheme started operating in 1991 and annual transfers ranged from 8 million m³ up to 73 million m³.

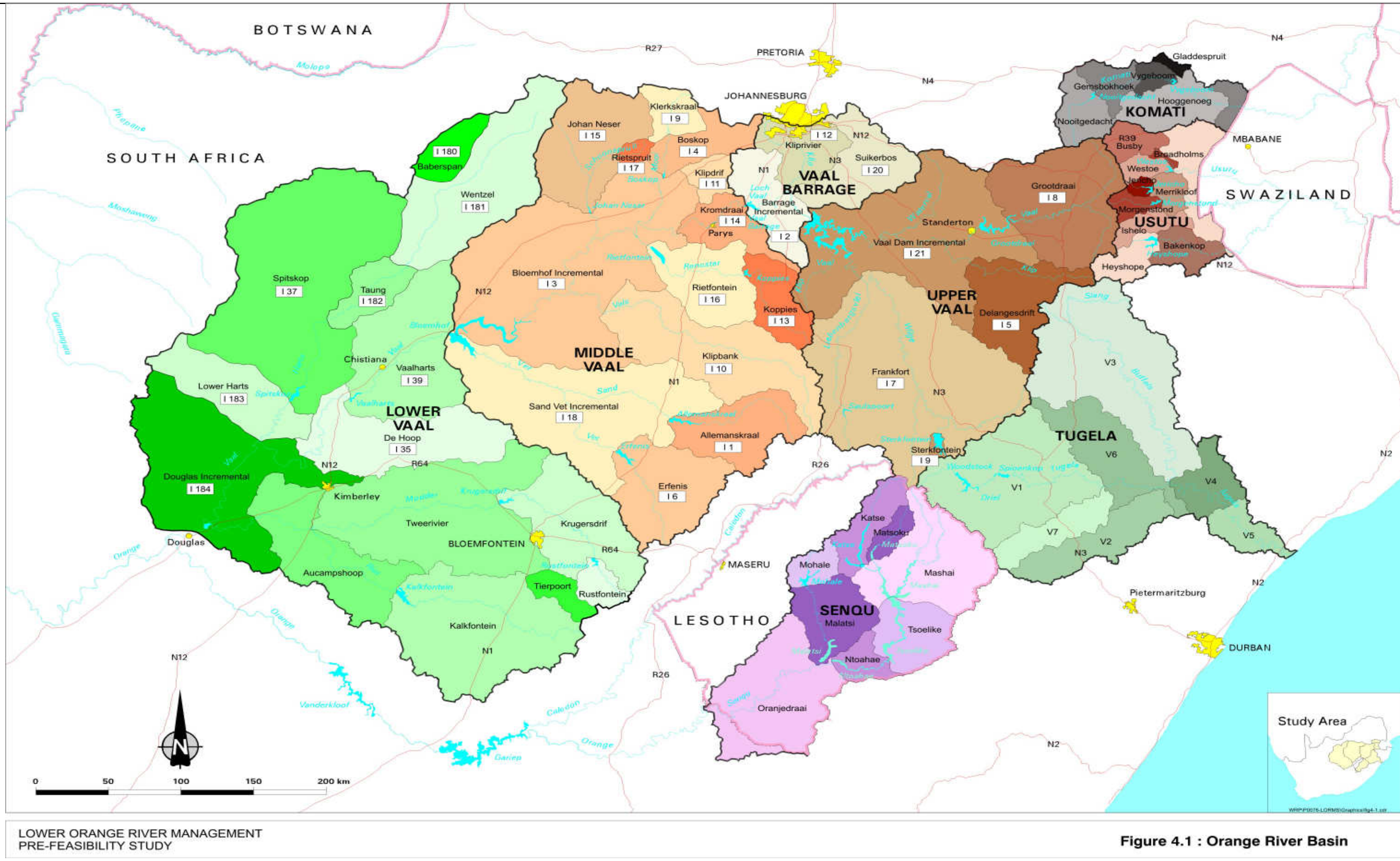

Figure 4-1: Orange River Basin

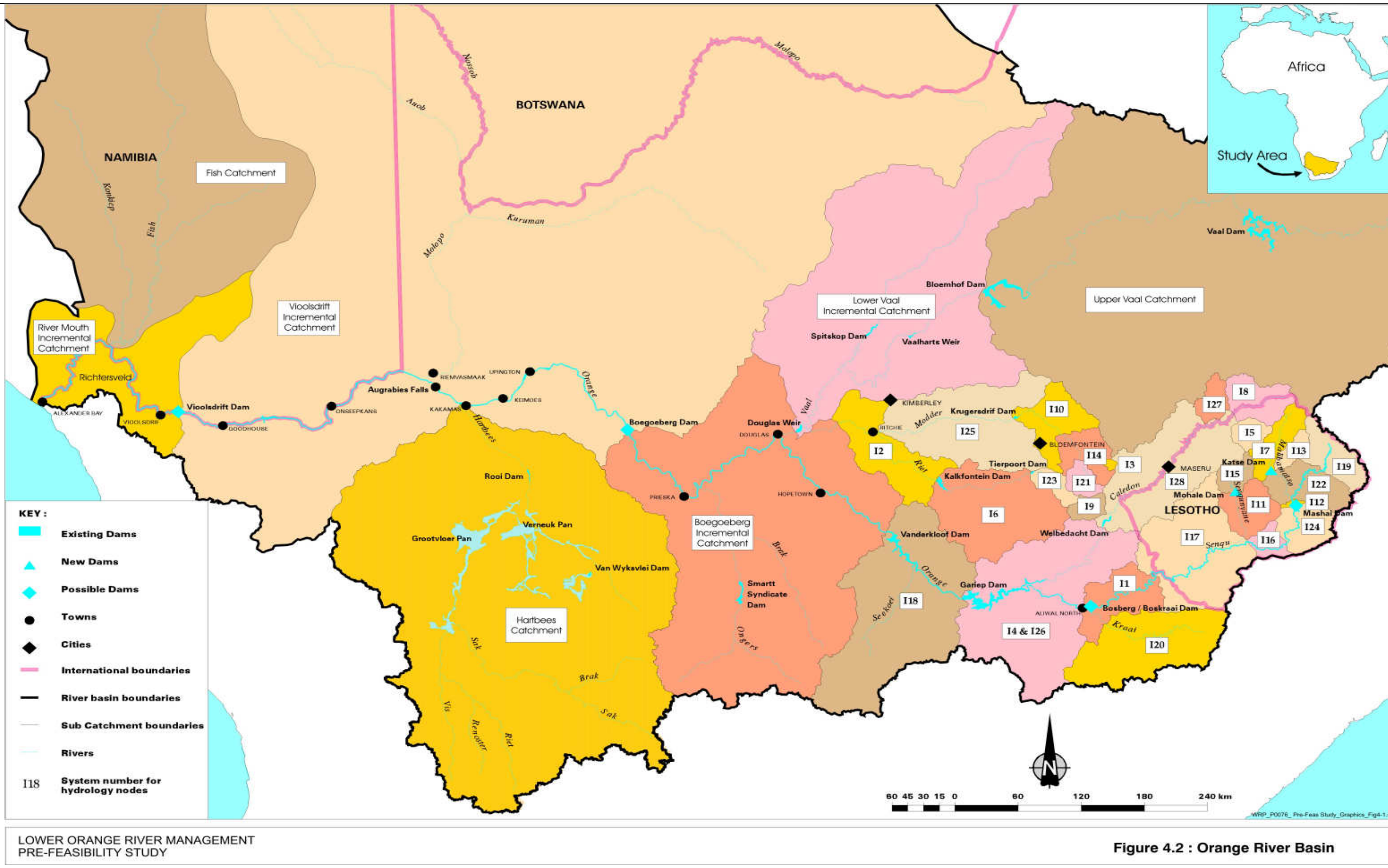

Figure 4-2: Orange River Basin

Water is transferred from Heyshope Dam in the Usutu River via a number of conveyances to the Grootdraai Dam on the Vaal River. Annual transfers between 1985 and 1994 varied from zero to 113 million m³.

e) Observed Records

In line with the generalised procedure as explained in the introduction, the observed rainfall records for as many stations as possible were examined for each of the five sub-catchments. The rainfall data for the Upper Vaal were found to be of a generally good quality and it was possible to apply exacting selection criteria. Nearly 20 gauges with records going back to 1920 or before were found. Sufficient evaporation data were also available.

Table 4.1: Runoff Gauges Used in 1995-1997 Upper Vaal Study

Gauge (River)	Gauge No.	Catchment Area (km²)	Date Opened	MAR	Comments
Standerton (Vaal)	C1H001	8 193	1920	453.70	MAR for 1920-1994 period. Only minor patching of the record was required. Record was completed with Grootdraai inflow after 1978
Delangesdrift	C1H002	4 152	1920	247.10	MAR for 1920-1994 period. Station unreliable at high flows (drowning). Very little need for patching.
Engelbrechtdrift (Vaal)	C2H003	38 564	1923	1 917.91	Only minor patching required. Years 1920-23 had to be simulated. Inflow record for Vaal Dam taken into account after 1936.
Frankfort	C6H001	15 673	1920	760.38	Extensive patching using C8H022 was required although recorded data was reliable.
Vaal Dam	C1R001	38 505	1936	1 858.25	No Patching required during period of record
Grootdraai Dam	C1R002	7 924	1978		Allowance had to be made for U/S abstractions during drought in 1983
Sterkfontein Dam (Wilge)	C8R003	58	1974		Station used only for naturalisation of Frankfort gauge.

There are 19 stream flow gauges in the catchment (including dams operating as gauging stations). Some of these have data extending back to the early 1900's, but much of the data is considered unreliable. After a critical analysis, the consultants retained only seven stations. Six stations were rejected due to unsuitably small catchment areas or poor data. Five stations were rejected due to the short records, having only been opened between 1971 and 1985. Clearly, in a revised analysis there would be considerable new data available. The report

provides a useful in-depth review of the available data. Using standard techniques (comparisons with other stations nearby, upstream or downstream etc.), the streamflow records were verified. Short periods of missing data for periods covered in the 1986 assessment were not re-patched. The utilised gauges are summarised in **Table 4.1**.

f) Rainfall/Runoff Modelling, Runoff Naturalisation

As is normal practice in South Africa, the well-tested WRSM90 runoff model was used for calibrating the observed record against weighted rainfall. The results are described in detail in the report and show high levels of correlation.

In order to achieve the required naturalised flow record, account had to be taken of the water use data described earlier in the report. This includes inter-basin transfers, which have to be subtracted from the observed flows. The report takes each one of the observed records and explains in sufficient depth how the naturalised records were calculated.

g) Synthesized Record

The details of the combined observed and synthesized records are summarised in **Table 4.2** as extracted from the report.

Table 4.2: Summary of Results for Upper Vaal Hydrological Analysis

Incremental Sub-catchment	Catchment Area (km^2)	Observed Incremental Runoff or Inflow (10^6m^3)	Natural Incremental MAR (10^6m^3)
Grootdraai	7 995	453.7	457.7
Delangesdrift	4 158	247.1	249.5
Frankfort incr.	15 498	696.2	733.3
Vaal incr.	10 792	493.2	518.7
Sterkfontein	195	97.3	18.1[(3)]
Total for Catchment	**38 638**	**1987.5**	**1977.3**

It is interesting to note that the natural incremental runoff is less than the observed. This is because of the fact that the observed runoff includes transfers from outside of the catchment.

g) Conclusions

The Upper Vaal Hydrological analysis makes use of long and generally reliable runoff records. It was found that the mean annual runoff (MAR) at Vaal Dam had not changed significantly (3%) since the less rigorous 1985 analysis. The report is very clear on the importance of correctly estimating water use/demand data since this has a significant effect on the accuracy of the record naturalisation process. Irrigation demands, which are the largest are stated as having been constant for a few years prior to 1994. While it may not be warranted to re-evaluate the hydrology, using the new data collected since 1994 (which may allow some new stations to be included in the analysis) for year or two, it is considered worthwhile to check on water demand figures, especially the irrigation demands, over the last decade.

4.2.2 Middle Vaal Sub-system

a) General Description

The Middle Vaal sub-catchment includes ten major impoundments, the most important being the Bloemhof Dam (capacity of 1 269.2 Mm^3) at the outlet of the Middle Vaal catchment. Other large impoundments are the Erfenis Dam (207.7 Mm^3), Allemanskraal Dam (174.7 Mm^3) and Koppies Dam (41.2 Mm^3). In the VRSAU Study: The catchment was divided up into 12 sub-catchments, Erfenis, Allemanskraal, Sand Vet incremental, Klipbank, Koppies, Rietfontein, Kromdraai, Klipdrif, Boskop, Klerkskraal, Johan Neser, Rietspruit and Bloemhof incremental sub-catchments. Reference should be made to **Figure 4. 1**.

The Middle Vaal catchment covers an area of just over 60 000km^2 with little in the way of relief other than the hills in the upper area of the Vals River. There are some large urban developments and mines together with extensive irrigation.

b) Literature Consulted

The 1997 VRSAU Report on the Middle Vaal was the main source for this review.

c) Water Use

As was the case with the Upper Vaal the study was particularly careful in its treatment of water demands particularly important in the Middle Vaal sub-catchment.

The VRSAU included a detailed analysis of the small dams in the catchment, on a sub-catchment by sub-catchment basis, using conventional mapping and satellite imagery. It was shown that the total capacity of all farm dams was significant at over 224 Mm^3. Older maps and the Dam Register were used to estimate historical growth in total dam capacity since 1920.

Major Irrigation schemes are sometimes part of government water schemes in which case the demand is usually monitored, or under the control of Irrigation Boards. There are also several private irrigation schemes. The report states that the Middle Vaal catchment has not been subject to any detailed irrigation investigation. Estimates were largely based on the 1988 Census of Agriculture. A number of approaches were used to derive the estimate of 23 300 ha under irrigation for 1994. The study showed that irrigation area had grown by approximately 1,78% per annum since 1920 (6 520 ha). In view of the impact of irrigation, the report goes into some detail on irrigation water usage, investigating the different water sources used, cropping patterns and seasonal demands. It was estimated that 130.6 Mm^3/annum are used for irrigation in the Middle Vaal catchment.

There was a major increase in urbanisation and urban water demand in the decade up to 1994, resulting also in significant return flows of effluent. The study clearly looked in great detail at urban and industrial abstractions and return flows and this is reported in considerable detail.

Afforestation is minimal in the Middle Vaal catchment and was not taken into account in the analysis.

Transmission losses are significant and difficult to estimate using standard approaches. A special approach was developed in the VRSAU Study. It showed that transmission losses in the Vaal River between Vaal Dam and Bloemhof are approximately 74 million m³/a.

d) Transfers

There are no transfers into the Middle Vaal Catchment.

e) Observed Records

In line with the generalised procedure as explained in the Introduction, the observed rainfall records for as many stations as possible were examined for each of the fifteen sub-catchments. The rainfall data for the Middle Vaal were found to be of a generally good quality and it was possible for the consultants to apply exacting selection criteria. The data for 140 gauges were selected for further analysis.

The report provides details on the records of all 140 gauges. 66 Gauges had records going back to 1920 or before which allows some confidence in the rainfall/runoff modelling of early years.

Table 4.3: Runoff Gauges Used in 1995-1997 Lower Vaal Study

Gauge (Catchment)	Gauge No.	Catchment Area (km^2)	Date Opened	MAR (Mm^3)	Comments
Witrand (Catchment)	C2H001	3 595	1903	-	Oldest record available. Various problems affect accuracy but record useable.
Schoemansdrift (Vaal River)	C2h018	49 120	1938	43	Record considered reasonable, water hyacinth can affect accuracy
Klipplaatdrift (Vaal River)	C2H061	79 903	1971	-	Some probably with accuracy at low flows and for high flows
Hoogekraal (Mooi River)	C2H085	5 485	1986	-	Reasonable accuracy but flows easily submerged
Boskop Dam (Mooi River)	C2R001	3 287	1957	72	
Johan Neser Dam (Schoonspruit)	C2R002	5 635	1922	87	Record ceases in 1951. Quality of record unknown
Klerkskraal Dam (Mooi River)	C2R003	1 335	1969	-	Low flow spillage cannot be measured accurately
Floorsdrift (Vet River)	C4H002	17 599	1950	413	Station closed after sub-mergence by Bloemhof Dam. Inaccurate at higher flows
Nooitgedacht (Vet River)	C4H004	16 533	1968	-	Not accurate for low flows. Okay for medium and perhaps high flows. Replaced C4H002
Allemanskraal Dam (Sand River)	C4R001	3 665	1959	-	High spillage flows are not accurately measured
Erfenis (Vet River)	C4H010	4 750	1959	-	Accurate crump weir
Roodewal (Vals River)	C6H001	5 674	1912	-	Low and medium flows reasonable, high flows could be overestimated
Mooifontein (Vals River)	C6H003	7 765	1966	155	Not suitable for low flows. Acceptable for medium flows, but not reliable for high flows
Dankbaar (Heuninghspruit)	C7H003	914	1947	-	Several problems affect the accuracy of this gauge. Record considered unreliable.
Arriesrust (Renoster River)	C7H006	5 758	1977	120	Low flows not accurate. Primarily a flood warning station
Koppies Dam (Renoster River)	C7R001	2 147	1920	59	Record accurate with no apparent anomalies
Bloemhof Dam (Vaal River)	C9R002	107 911	1968	1085	No rating for outflow measurement weir

There are 60 stream flow gauges in the catchment (including dams operating as gauging stations), although many of these have specialised purposes or have catchments too small to be of interest to the study. 19 gauging stations, of which seven were reservoir gauges were chosen for the calibration process. With the exception of the Schoonspruit River, coverage was considered to be adequate. Three gauges had records starting before 1920, two between 1921 and 1940, and the rest after 1960. Details on the records are provided in **Table 4.3**. Gaps in the records were patched using various techniques. Details on how the patching was carried out are presented in the report.

f) Rainfall/Runoff Modelling, Runoff Naturalisation

As is normal practice in South Africa, the well-tested WRSM90 runoff model was used for calibrating the observed record against weighted rainfall for 17 stations. Based on this calibration, it was possible to produce synthesized runoff records dating back to 1920. The results are described in detail in the report and show high levels of correlation

In order to achieve the naturalised flow records required for the calibration, account had to be taken of the water use data described earlier in the report. This includes inter-basin transfers, which have to be subtracted from the observed flows. The report takes each one of the sub-catchments and explains in sufficient depth how the water demands were calculated.

The naturalised stream-flows are discussed in some depth in the report. The approach adopted to produce the naturalised stream-flow for the entire record period was to take the observed record and to add all the calculated water demands (and subtract transfers received). This naturalised observed record is then extended using the synthesized record, which is any case already naturalised. The alternative approach, sometimes adopted since it usually leads to "better" correlations, of using just the synthesized record and none of the observed record was not adopted. Both approaches can be argued as being more correct, but this review concurs with the approach adopted in VRSAU.

Comparisons were made with previous studies and it was found that the overall MAR of the Middle Vaal was only one per cent different from the previous study.

However, there were significant differences for some of the sub-catchments. These differences are satisfactorily explained in the report.

g) Synthesized Record

The details of the combined observed and synthesized records are summarised in **Table 4.4** extracted from the report.

Table 4.4: Summary of results for Middle Vaal Hydrological Analysis

Sub-catchment	MAR (10^6m^3)
Mooi	134
Renoster	120
Schoonspruit	93
Vals	155
Sand-Vet	422
Other tributaries	161
TOTAL	**1085**

h) Conclusions

The Middle Vaal Hydrological analysis makes use of a mixture of long and shorter runoff records with records of varying reliability. The VRSAU represents an in depth effort to use all the available data to arrive at the best possible calibration for all thirteen of the sub-systems. It is stated in the report that simulated flows are over-estimated by a few per cent. It was found that the overall MAR at Bloemhof Dam had not changed significantly (1%) since the less rigorous 1985 analysis.

It was stated in the conclusions of the report that the natural MAR of the Middle Vaal catchment is 1085 Mm^3/annum based on the period October 1920 to September 1995. Annual flow volumes were stated to have varied from as little as 110Mm^3 in 1932 and 1991) up to nearly 3 000Mm^3 in 1932 and 1991.

4.2.3 Vaal Barrage Catchment Sub-system

The Vaal Barrage sub-catchment is an area of 8 561km^2 upstream of the Vaal Barrage on the Vaal River. The catchment covers all flows entering the Vaal River

between the Vaal Dam and the Vaal Barage. Almost all of the catchment lies to the north of the Vaal River and includes the catchments of the Klip and Suikerbos Rivers. The catchment only contributes 273 million m³/a but has been treated in considerable detail in its own section of the VRSAU report. The report states that analysis of the catchment was complicated by the highly urbanised and regulated nature of the catchment, the inaccuracy of several gauges, the presence of large wetland areas, and high transmission losses. In addition, sewers blocked during the 1985 political unrest complicated the analysis.

The VRSAU report has been studied carefully, but it is not considered necessary to go into the same level of detail as was done for the upper and Middle Vaal catchments. The Vaal Barage Dam has a capacity of 48million m³ and small dams are calculated to have a total volume of 44 million m³. Irrigation in the catchment has not been studied in any detail and major estimates had to be made. It was estimated that irrigated hectarages increased from 14 Ha to 98 Ha in 1995.

Data on abstraction and return flows were in many cases impossible to obtain, and in the end, an approach was developed to estimate abstraction and effluent. Abstractions are significant. Rand Water alone operates eight abstraction canals/pipelines from either the Vaal River or the Vaal Dam. T otal abstraction was calculated at 401 million m³ in 1994. However, return flows are estimated at 285 million m³ for the same year. The report makes a detailed evaluation of **urbanised** areas in each of the sub-catchment since this will play an important role in the calibration process. The catchment includes a significant portion of the Johannesburg area (see **Figure 4-1**). The total urbanised area was taken to be 648 km². This figure was divided up into three levels of urban development corresponding to the degree of imperviousness of the surface. Wetland and transmission losses also received special treatment in the report. Wetland areas were estimated at 62 km².

The study reports that an adequate number of rainfall gauges (45) were available covering the entire catchment. The catchment was divided up into 8 sub-catchments for the purpose of model calibration. There are 12 gauging stations in the catchment and all were used for the purpose of model calibration. The report provides details on the status and accuracy of all the river gauges. Approximately half of them were considered to have “reasonable” records. The report goes into

considerable detail on as to how the data problems at many of the stations were solved.

Calibration of the Barrage catchment was difficult for reasons already mentioned, and a number of supplementary analyses were performed as part of the process. In most cases, the synthesised flows compared well with the sub-catchment observed flows once water demands had been taken into account. For some stations, there were significant differences. For the Vaal River at the Barrage, it was found that the Barrage overestimates flow albeit by only three per cent when results were used in conjunction with flows from the Middle Vaal and observations at Vaal Dam.

The report summarises the problems encountered in the hydrological analysis. These included having to use some records, which were too short, some records which were not very reliable (gauges on the Klip River and others). The report recommended that a new gauging weir be constructed on the Blesbokspruit, as well as a high flow station on the Suikerbosrand River. A need for a current meter gauging programme was also highlighted. It is not known whether any of these recommendations have been implemented.

4.2.4 Lower Vaal Catchment

The Lower Vaal includes several impoundments with the purpose of augmenting and stabilising water supply for irrigation. In total there are ten major dams in the Lower Vaal, the smallest being the Wentzel Dam (capacity of 6 million m^{33}) on the Harts River and the largest being the Kalfontein Dam (319 million m^3) on the Modder River. There are several other dams on the Modder and Riet Rivers, most with the purpose of supporting irrigation. The total capacity of large dams in the Lower Vaal amounts to 683 million m^3 and of farm dams to 152 million m^3.

The Lower Vaal catchment covers an area of over 88 000 km^2 and includes three distinct river systems, the Harts River to the north, the Vaal River, and the Riet and Modder Rivers to the south. The Harts River catchment is 31 000 km^2. Runoff potential is limited but nevertheless, it is a significant supplier or water for urban and especially irrigation consumption. Of the Lower Vaal incremental catchment, it is stated in the VRSAU that only 35% contributes directly to runoff in the river network. The rest drains into pans and enclosed river basins. The combined catchment areas of the Modder and Riet Rivers are 35 000 km^2. There has been extensive

dam development in the catchment.

There are a number of in-basin and inter-basin transfers. These include:

- transfers from the Caledon River to the Modder in order to supplement supplies to Thaba Nchu and Bloemfontein.
- transfers from the Vanderkoof Dam on the Orange River via the Sarel Hayward/Orange-Riet Canal to the Riet River scheme.
- transfers from the Vaal River at Riverton for water supply to Kimberley.
- short distance transfers from the Orange River for the Douglas Irrigation Scheme.

a) Literature Consulted

The 1997 VRSAU Report on the Lower Vaal was the main source for this review.

b) Water Use

The VRSAU study goes into considerable depth in its evaluation of water use and water demand in particular of irrigation.

The largest irrigation scheme is the Vaalharts Scheme (34 000 ha) situated between the Vaal and Harts Rivers. In the Modder/Riet System, there are another five Government or Irrigation Board Schemes. The report states that there is also significant diffuse and runoff river irrigation. The total hectarage under irrigation is estimated at just over 25 000 ha. In calculating the water consumption of irrigation, cognisance was taken of known application rates, cropping patterns and scheduling.

The Lower Vaal catchment is sparsely populated and urban or industrial abstraction and resultant return flows are limited to the towns of Kimberley, Bloemfontein, Botshabelo and Thaba Nchu. In addition, the Vaal-Gamagara scheme supplying water to a number of small towns, farms and some mines.

c) Transfers

While much of Bloemfontein's water is supplied from the Modder River, water is also assured via a water transfer from the Caledon sub-catchment on the Orange River. Water is also transferred into the Lower Riet River from the

Vanderkloof Dam on the Orange River. The Douglas Irrigation Scheme just upstream of the Vaal/Orange confluence also uses water transferred from the Orange River.

d) Observed Records

Approximately 98% of the rainfall records were longer than 30 years and 60% of the stations were still open. Stations were checked during the VRSAU Study for reliability, stationarity and consistency and found to be satisfactory.

17 Runoff gauging stations were considered for use in the calibration process as shown in **Table 4.5**.

Seven of these were not utilised because of poor quality data or because their catchments were considered too small. Of the selected stations, two had records going back to the 1920s. The report provides a useful in-depth review of the available data. Using standard techniques (comparisons with other stations nearby, upstream or downstream, etc.), the streamflow records were verified. Short periods of missing data for periods covered in the 1986 assessment were not re-patched.

Table 4.5: Runoff Gauges Used in 1995-1997 Upper Vaal Study

Gauge (River)	Gauge No.	Catchment Area (km^2)	Date Opened	Comments
Taung (Harts)	C3H003	10990	1927	Not ideal for low flows. Some discrepancies in early record.
Espagsdrift (Harts)	C3H007	24097	1948	Not suitable for calibration due to over-estimation of high flows. Low flows used to calibrate irrigation return flows.
Schweizer Reneke (Harts)	C3R001	2919	1935	Spills from dam not gauged
Spitskop (Harts)	C3R002	26914	1975	
Shannon Valley (Renoster)	C5H007	348	1948	Record required extensive patching
Riviera (Riet)	C5H008	593	1931	Small catchment with no significant demands, hence combined with Kalkfontein
Kromdraai Rietwater (Riet)	C5H012	2372	1953	Included with Kalkfontein
Stoomhoek (Modder)	C5H015	6009	1948	Doubts over accuracy of low flows
Aucampshoop (Riet)	C5H016	33351	1952	Not completely reliable and extensive patching required

Gauge (River)	Gauge No.	Catchment Area (km²)	Date Opened	Comments
Tweerivier (Modder)	C5H018	17315	1959	Well-situated to monitor effects of Modder GWS
Tierpoort (Kaffer)	C5R001	922	1937	Reliable record requiring limited patching
Kalkfontein (Riet)	C5R002	10268	1937	Data appears reliable
Rustfontein (Modder)	C5R003	940	1954	Record was considered to be reliable
Krugersdrift (Modder)	C5R004	6315	1974	Record considered reliable
De Hoop 65 (Vaal)	C9H009	121052	1968	Record considered reliable
Vaalharts (Vaal)	C9R001	115055	1971	Record considered reliable

There are a surprisingly large number (25) of evaporation stations in the Lower Vaal catchment. It is unlikely that better estimates of evaporation could be obtained.

e) Rainfall/Runoff Modelling, Runoff Naturalisation

As is normal practice in South Africa, the well-tested Pitman Model runoff model was used for calibrating the observed record against weighted rainfall for each of the gauging stations. The process is described in sufficient detail. The usual statistics of the concurrent and observed records are presented in the report. The results are described in detail in the report for each of the stations used in the calibration process. A summary of the results has been extracted from the report and is presented in **Table 4-6**.

Table 4.6: Summary of Results from Modelling of Lower Vaal Catchment

Gauge Number	Station Name	Effective Incremental Area (km²)	MAP (mm)	MAE (mm)	Naturalised MAR million m³/a	Unit Runoff mm/a
C3H003	Taung	7975	530	1916	59.0	7.4
C3R002	Spitskop	9249	438	2039	77.5	8.4
C5H016	Aucampshoop	1847	350	2050	6.4	3.5
C5H018	Tweerivier	2236	422	1871	14.4	6.4
C5R001	Tierpoort	922	491	1640	23.8	25.8
C5R002	Kalkfontein	8781	412	1746	215.9	24.6
C5R003	Rustfontein	937	543	1600	30.7	32.7
C5R004	Krugersdrift	5391	508	1639	114.4	21.2
C9H009	De Hoop	3201	406	1963	12.9	4.0
C9R001	Vaalharts	2509	444	1946	11.2	4.5
-	Lower Vaal	6096	361	2210	31.5	5.2
TOTAL		**49144**			**597.7**	**143.7**

f) Conclusions

The VRSAU Report for the Lower Vaal makes a number of recommendations on the need for new river gauges and measures to improve the quality of data recorded. These include measures with respect to the need to monitor irrigation abstractions, transfers and return flows need to be monitored accurately in the Vaalharts area. Measures were also recommended to improve monitoring in the Upper Harts River, and a new gauging site was proposed for the Vaal River downstream of the Vaal and Harts River confluence and the Vaal Gamagara abstraction point. A number of recommendations to improve monitoring in the Modder/Riet catchments are also made.

Perhaps most importantly were concerns raised regarding the need to better know how much water is being used in the catchment, especially with respect to irrigation consumption. It was therefore recommended that the aerial photography and mapping of the region be updated in order to determine the extent of irrigated area. It was also recommended that a database of all current and historical irrigation information and contact names should be compiled.

More accurate and standardised estimates of effective catchment areas need to be agreed upon.

A point of caution was also raised, particularly relevant to the Lower Vaal catchment with respect to sub-catchments where flows and irrigation are primarily supported by compensation releases from an upstream reservoir rather than from runoff generated on the incremental catchment. It was stated that care must exercised during calibration and naturalisation of the catchment, and that the water demands (irrigation or other) must be supplied by the actual compensation flows rather than the catchment runoff and river flows, since failure to model the abstraction of demands in this way would result in extreme over-estimation of natural runoff when the irrigation demands are added back to the catchment runoff during the naturalisation process.

The WR90 Regional Parameters appear to give a slightly conservative estimate of natural runoff in the catchments along the Vaal River and Lower Modder and Riet catchments.

4.3 Orange River Sub-catchments

4.3.1 Senqu River Sub-system

a) General Description

The Senqu River rises in the Maluti and Drakensburg Mountains in Lesotho. Within the catchment, these mountains rise to 3 482 m. On crossing the border into South Africa, the river becomes the Orange River and makes its confluence with the Caledon River at the Gariep Dam about 220 km downstream of the border. In South African water resources studies, it is often included under the heading of the Vaal River rather than the Orange due to the fact that water transfers are made from the Senqu River across the catchment divide to the Vaal Dam. The Senqu River is therefore an essential part of the so-called “Vaal Integrated System”. The Senqu River is therefore an important water resource for South Africa for two reasons, firstly as one of the two main rivers feeding the Vanderkloof Dam, and secondly as a source of water for the industrial heartland of Gauteng. Transfers to the Vaal Dam take place as part of the Lesotho Highlands Scheme, Phase 1 of which has been implemented through the

construction of the Katse Dam and associated storage and transfer works.

In order to have been able to construct this scheme, South Africa has an agreement with the Kingdom of Lesotho, which makes provision for the payment of royalties.

b) Literature Consulted

Unlike the Vaal River Hydrology, as well as that of other parts of the Orange River, the Lesotho River Hydrology is based on relatively "new data". The first comprehensive studies of the Senqu River date back to the Lesotho Highlands Feasibility Study, carried out in the mid 1980s. An "interim" hydrology was produced for design purposes. Further studies were carried out by BKS, South Africa in 1993 and by the UK Institute of Hydrology in 1994. Finally, a study carried out jointly by BKS and the LHDA (Lesotho Highlands Development Authority) was completed in December 1998. The resultant report of this study has been the main reference document for this review.

c) Water Use

Before the construction of the Lesotho Highlands Water project (LHWP), use of water in the Senqu River was limited to water supply for small settlements. With the construction of the Katse Dam on the Malibamatso River, a 45 km transfer tunnel to Muela Power Station and the Muela Dam, which collects tailrace waters for transfer to the Vaal Dam, the situation has changed completely. From the Muela Dam water is transferred via another set of tunnels from whence the water flows into the upper reaches of the Ash River, a tributary of the Liebenbergsvlei River, which joins the Wilge River just before Vaal Dam.

It is anticipated that on average 490 million m^3/a will be transferred out of the Senqu River to the Vaal River Basin as part of Phase1A of the LHWP. This will increase when Phase 1B, the construction of a 145m high dam at Mohale on the Sequnyane River and a transfer tunnel to the Katse Reservoir, have been completed. Completion is scheduled for 2003.

d) Observed Records

The study looked at more than 120 relevant rainfall records. Of these only records, which could be patched and with a record of at least 15 years, were

utilised. It would appear that every effort was made to fully utilise the available data, even retaining parts of a record if considered acceptable and rejecting the parts considered to be unreliable. This was necessary, however, because the quality of rainfall data in the Senqu catchment was generally considerably lower than in the sub-catchments already discussed.

Most of the streamflow stations in Lesotho were set up in the middle 1960s so there are no long records. It is reported that there were 13 stations, which could be used in the analysis plus the Oranjedraai Station situated just downstream of the Lesotho/South African border. Difficult access to stations for servicing and siltation problems are two of the reasons for numerous gaps in many of the records. In general, the quality of the records is described as "fair". Three crump weirs have been installed in recent years to improve the reliability of runoff data. It is clear that a lot of effort had to go into carefully examining the observed data and especially the water stage/discharge curves for all the stations in the catchment. The stations at Marakabei and Paray were considered to be the most complete and were therefore selected as the key reference stations. Gaps in the records of several other stations were corrected by reference to these stations. The report discusses in detail each one of the gauging stations and their associated records, the gaps and how they were patched. Another key reference station was the Oranjedraai Station, which is almost complete for the full 1960 to 1994 period.

e) Rainfall/Runoff Modelling, Runoff Naturalisation

Rainfall/runoff modelling was carried out using a modified form of the Pitman Model. Features of the version used allowed input of a number of rainfall records covering the period of interest to ensure that gaps were covered, as well as relatively short runoff records.

Table 4.7 derived from the report summarises the some of the results obtained during the modelling. It would appear from the results that the main aim was to model the MARs of each station as accurately as possible, since the observed and synthesized MARs match up quite well. A comparison of the observed and synthesized record statistics show significant differences in the standard deviations and relatively low correlations. However, it is also clear from the low number of rain gauges (between 3 and 5 for each incremental catchment)

available that it would not be possible to obtain better results.

f) Synthesized Record

Having generated the synthesized runoff records, these records were then used as inflows to the various reservoir sites agreed between the Governments of South Africa and Lesotho. In view of the fact that the reservoir sites were not the same as the gauging stations sites, the inflow records were calculated by summing the upstream incremental gauging site record with a part of the downstream incremental gauging site record.

Table 4.7: Results of Rainfall/Runoff Modelling for Selected Stations

Parameter	Seaka	Mokhotlong	Paray	Marakabei	Bokong	Orangedraai
Catchment MAP (mm)	796	908	763	944	930	781
Catchment Area (km²)	10041	1660	1028	1087	403	4806
Observed MAR (Mm³/a)	1390	280.1	181.8	359.5	100.1	813.3
Synthesized MAR (Mm³/a)	1388	280.0	180.3	348.6	100.3	812.8
Observed St. Deviation	853	208.6	117.1	181.3	50.8	560.3
Sythesized St. Deviation	820	208.0	94.2	134.2	40.0	438.9
Correlation Coefficient	0.64	0.63	0.71	0.79	0.78	0.65
No. of Rainfall Records Used	4	4	5	3	3	4

Details of how the calculations were carried out are fully described in the report. Reservoir inflow sequences are provided for the 1920 to 1995 period and hence, are consistent with the VRSAU Studies. **Figure 4-3** shows the positions of the dam sites considered in the study. **Table 4.8** summarises the calculated mean annual inflows.

Table 4.8: Calculated Mean Annual Runoffs at Considered Dam Sites

	Katse	Mohale	Mashai	Tsoelike	Malatsi	Ntoahae
MAR (Mm³/anum)	554	312	1447	1795	611	1943

g) Conclusions

Due to the sensitive nature of the hydrology of the Senqu River (amount of royalties payable to Lesotho), considerable effort has been put in to ensure the best possible result under difficult (short and incomplete records) conditions.

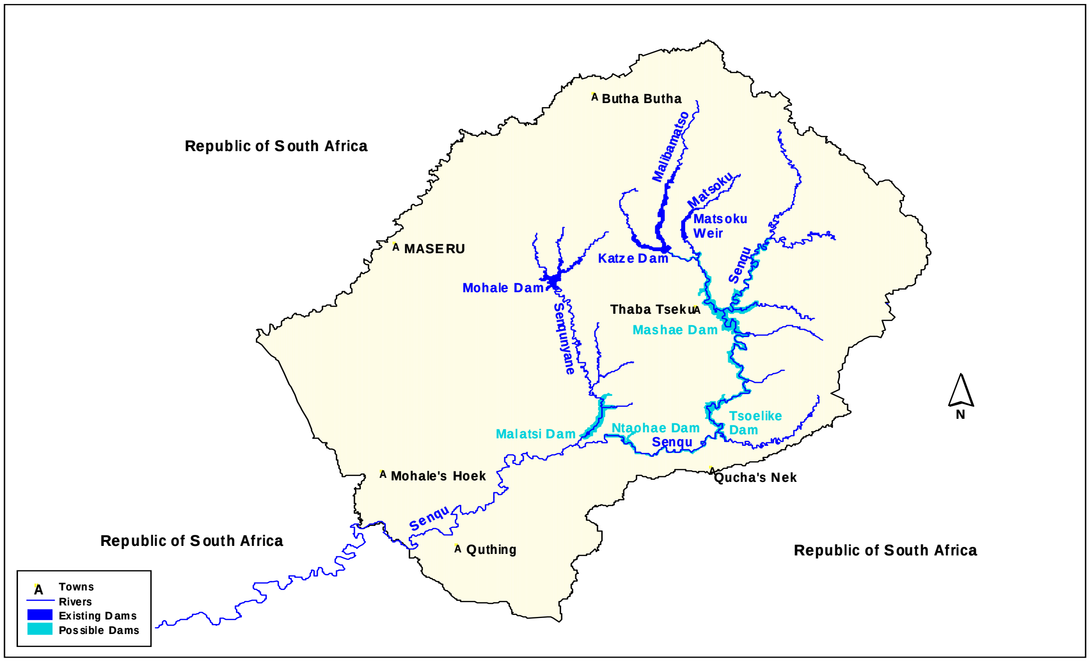

Figure 4-3: Positions of Dam Sites Considered in LHWP Systems Analysis

4.3.2 Caledon River and Upper Orange Incremental Catchment: Hydrology

a) General Description

In the nomenclature used in the South African systems analysis the Upper Orange River Incremental, catchment covers the area upstream of the Vanderkloof Dam up to Welbedacht Dam on the Caledon River and up to Oranjedraai on the Orange (Senqu in Lesotho) River. The Senqu River in Lesotho has already been discussed in the previous paragraph as far as the Oranjedraai gauging station just downstream of the Lesotho/South African border. Before making its confluence with the Caledon River, the Orange is joined by the Kraai River from the Drakensburg Mountains to the southeast. Upstream of the Wellbedacht Dam the Caledon River catchment covers an area of 15 245km², much of it in the mountains of Lesotho.

Rainfall drops off very sharply as the Orange River leaves the mountains and is down to 300mm/a at the Gariep Dam.

b) Literature Consulted

While the hydrology of the Orange/Senqu River upstream of the Orangedraai gauge was updated as part of the Lesotho Highlands Study (see paragraph) in 1999, the hydrology of the Caledon River and incremental catchments of the Vanderkloof and Gariep Dams is relatively old, dating back to a report completed in November 1992. This document, entitled "Upper Orange River : Hydrology" was the main reference document for this section of the review.

c) Water use

Water demand for Irrigation in the Upper Orange catchment was estimated at 384 million m³/a in 1990, although it would appear that this is not always met since the average water supplied was only 281 million m³/a. According to the study, total water use in the Upper Orange catchment was estimated at 1 920 million m³/a of which 885 million m³/a was estimated to be evaporation from the major storage reservoirs and farm dams. Of the remainder; it was estimated that 740 million m³/a are transferred to the Vaal catchment. Knellpoort and Welbedacht on the Caledon River are mainly used to transfer water to the Modder system to support Bloemfontein, Bothabello and other smaller urban areas with water. Welbedacht has, however, silted up to a large extent and Knelpoort Dam was built as an off-channel storage dam due to the severe silt problems. There are, however, compensation releases from Welbedacht Dam to supply irrigation downstream of the dam (irrigation that existed before the dam was built). The Welbedacht Dam is not used to support Gariep Dam at all.

d) Runoff

The incremental MAR values as calculated in the 1992 study are presented in Table 4-9**. The natural runoff generated for this study covered the period 1920 to 1987.**

Table 4.9: Incremental MAR for the Upper Orange River

River Gauge	River	Catchment Area (km²)		MAP (mm)	Incremental MAR (Mm³/annum)	Incremental Unit Runoff (mm)
		Total	Incremental			
Aliwal North	Orange	37 075	3 635	591	229	63
Roodewaal	Kraai	8 688	8 688	657	676	78
Oranjedraai	Orange	24 725	24 725	793	4 192	170
Welbedacht Dam	Caledon	15 245	15 245	755	1 217	80
Gariep Dam	Orange	70 749	18 435	456	397	22
Vanderkloof Dam	Orange	89 842	17 843	314	147	8

e) Conclusions

The report pointed out that reconciling the hydrology had been complicated by inaccurate measurement by the turbine meters at Vanderkloof Dam, and uncertainties over the accuracy of the elevation/capacity equation for the same dam. The study also recommended that combined mass balance calculations for Gariep and Vanderkloof Dams should be carried out annually.

4.3.3 Lower Orange River

a) Description

Downstream of the Vanderkloof Dam there are five incremental catchments, most of which do not make major contributions. In the South African studies, these are referred to as the Boegoeberg Incremental catchment, the Hartbees catchment, the Vioolsdrift incremental catchment, the Fish River catchment (Namibia) and the River Mouth incremental catchment.

b) Literature Consulted

A large number of reports were compiled as part of the Orange River Replanning Study (ORRS). All of these (over 30) reports were made available in electronic form for this review. Certain key reports were selected. These included the Hydrology and Systems Analysis: Orange River Basin", and the "Evaluation of Irrigation Water Use", and "Water Demands of the Orange River Basin – ORRS". While the main purpose of the first-mentioned of these studies was to carry out a large number of systems analyses in order to look at maximising yield and efficiency of the available water resources, including the inclusion of various

potential reservoirs, the report also provides an overview of the hydrology.

b) Water Use

The main user of water in the Lower Orange River (and indeed of all the catchment), is the Orange River Project, which was first proposed in 1962 to irrigate thousands of hectares especially in the Eastern Cape, Northern Cape and Free State areas. This project depends on flows from the Vanderkloof and Gariep Dams. It is reported that the main functions of the Orange River Project (ORP) are to provide water for irrigation and urban users along the river, to provide irrigation water to the Great Fish and Sundays Rivers in the Eastern Cape and to the Riet River catchment. In addition, Orange River water is used to solve water quality problems in the Vaal River at Douglas, and is used to generate peak power for the Eskom Network at the Gariep and Vanderkloof Dams. The ORP also supplies water to cities and small towns such as Upington, Prieska, Port Elizabeth, Grahamstown, Alexander Bay and Port Nolloth.

In the systems analysis described, land use and associated water demand has been divided up into five areas, being:

- **Area 1: Upstream of Gariep Dam (i.e., not part of ORP).**
- **Area 2: Area upstream of the Orange/Vaal confluence up to and including Gariep Dam.**
- **Area 3: Riet/Modder catchments.**
- **Area 4: Area downstream of Orange/Vaal confluence to 20º longitude (Namibian/RSA border).**
- **Area 5: From 20º longitude to River mouth.**

The demands are described in the report and are summarised in Table 4.10**.**

Table 4.10: Summary of ORP Demands (excluding transfers to Riet/Modder catchments)

Water Use \ Area	Area 2 (Directly from Gariep and Vanderkloof)	Area 2 (Gariep to OrangeVaal confluence	Area 4	Area 5	Total
Irrigation	882[1]	228	469	81	1 660
Urban	16	(incl. below)	(incl. below)	(incl. below)	16
Urban/ Industrial/ Stock	(incl. above)	5	13	27	45
River Requirement (Losses)	-	64	455	441	960
Canal Losses	-	9	26	-	35
Environmental Demand	-	-	-	306	306
Totals	899	306	963	855	3022

[1] 627Mm³ by Orange/Fish Tunnel; 255Mm³ by Vanderkloof canal

[2] Lesotho Highlands Water Project transfers are not included

Clearly the updating of these demands will be an important aspect of the current study in view of significant water use developments over the last decade.

In the report studied, it would appear that all the demands are described in sufficient detail and clarity to allow relatively straightforward updating for new systems analyses incorporating more up to date runoff data. The same is true of canal and rivers losses.

4.3.4 Lower Orange River and System Analysis

a) General

The hydrology used in the Lower Orange clearly relates to the hydrology of the Upper Orange and Vaal. Hence, in view of the fact that the ORRS pre-dated some of the more recent hydrological re-assessment, some of the records used are not the most recent. For example, the runoff record used for the Riet/Modder system was the one updated in 1991, rather than the one used in the 1997 study. However, in checking the runoff data files for the total Orange River catchment as it now stands, it was found that most of the records have been updated to September 1995. The only exception is the incremental area upstream of Vanderkloof Dam and downstream of the Lesotho border.

It is estimated that approximately 900 Mm³/annum originates from the Lower Orange catchment of which more than half comes from the Fish River. It is stated in the study that the hydrology of the Lower Orange was treated in a simplified manner. The Lower Orange Hydrology covers the period 1920 to 1989. A table presented in the report provides a very useful overview of the runoff contributions from the different parts of the catchment as assumed for the 1991 study. It is not presented in full here, but a summary is provided showing the sum of the incremental MARs for each of the major systems as already discussed in this review.

Table 4.11: Summary of Incremental Streamflow Data

Catchments included (see Figure 4.1 and 4.2)	Sub-system	Total Incremental Catchment Area (km²)	Total Incremental MAR (1920 – 1983)	Unit Runoff (mm)
I7, I11, I12, I13, I15, I16, I17, I19, I22, I24	Lesotho Highlands	24 752	4 014.53	162.2
I5, I8, I9, I27, I28	Caledon	15 245	1 197.98	78.58
I1, I4, I18, I20, I26	Upper Orange	48 595	1 389.125	28.586
I2, I3, I6, I10, I14, I21, I23, I25	Modder-Riet	23 277	366.21	15.77
-	Remainder of Vaal	166 235	3 521.65	21.181
-	Fish River (Namibia)	76 000	483.90	6.36
-	Remainder of Orange River*	136 909 (319 870)	219.35	1.6
TOTAL		**491 103 (685 372)**	**11 192.74**	**22.79**

b) Scenarios

One of the aims of the systems analysis was to look at combinations of new developments in the Orange River catchment to see how yield can be most usefully augmented. These scenarios have been studied as part of this review, but are too numerous to be described here. However, in order to illustrate the principle, the "base scenario" is summarised and the sort of scenario variations that were considered are briefly mentioned.

The base scenario was as follows:

- **Phase 1 of LHWP at 2005-development levels.**
- **Compensation releases from Katse and Mohale dams of 0.5 m³/s and**

0.3m³/s, respectively.

- Environmental demand at river mouth set at 100 Mm³/annum.
- Orange to Fish transfer set at 627 Mm³/annum.
- Orange/Riet transfer set at limit of 275 Mm³/annum (demand driven).
- Orange/Douglas transfer set at limit of 88 Mm³/annum (demand driven).
- Compensation flow from Gariep Dam set at 16 m³/s.
- 2005 development level spills from the Vaal Basin.
- Hydro-electric power generated in accordance with downstream system demands only.
- Dead storage level (DSL) set at 1 231.63 m for Gariep Dam and 1 147.78 m for Vanderkloof Dam.
- Total live storage at Gariep and Vanderkloof Dams = 6 883 Mm.
- Instream flow requirements taken as equal to downstream demand.
- Transfer from LHWP to Vaal basin taken as 28.6 m³/s.
- Novo transfer from Caledon to Modder in place.
- All domestic/industrial demands at 2005 levels.
- Inclusion of all possible diffuse developments in the Caledon (Lesotho and RSA).
- 2045 sedimentation levels at dams.

The results of around 50 alternative scenarios (including minor variations or sub-scenarios) were modelled in order to find out which set of operating rules was the most appropriate. These operating rules represented a combination of operating rules for existing infrastructure and operating rules for planned potential infrastructure . It should be noted that systems analyses had to take into account not just consumptive needs, but also hydropower-related scenarios.

A number of scenarios related to the inclusion of the Vioolsdrift Dam. These included for example, raising of Gariep Dam combined with a 1500 Mm³ dam at Vioolsdrift and increased transfers from the Orange River to the Vaal, or the raising of Gariep, Bosberg, Boskraai Dams combined with a large dam at Vioolsdrift.

Conclusions are too numerous and inter-dependant to go into here. The study provides a useful basis for the current study.

5. CONCLUSIONS AND RECOMMENDATIONS

Hydrological studies and systems analyses carried out in South Africa covering the entire Orange River Basin within South Africa and Lesotho have been reviewed. The general impression is that the work has been carried out thoroughly as far as the data will allow. There is no reason to disagree with the hydrological files being used as input for the systems analysis. However, as is generally the case with hydrological and associated data, given the human and financial resources, it would of course be possible and worthwhile to improve the accuracy of the data.

As stated on several occasions in the literature reviewed, the Vaal and Orange River Basins are the most important water resource systems in South Africa. They support more than 50% of the country's GDP. It is logical, therefore, that money spent on improving the accuracy of our knowledge of the system is well-spent and easily justified. Hence the current study, and the major investments being made by the Governments of South Africa and Namibia. However, in view of the fact that some of the hydrological studies studied in this review are already more than a decade old, it would seem worthwhile to utilise the new data that have been collected since their completion and to update these studies. This includes the incremental catchment upstream of Vanderkloof Dam and downstream of the Lesotho Border, as well as the Lower Orange with the exception of the Fish River in Namibia.

The need to update hydrological data and the analysis thereof should not be limited to runoff data but should also include improved collection of water demand data. The effort put over to analysis of water demand information in the studies reviewed reflects a strong awareness of the importance of water demand data. Any basin-wide efforts to update hydrology and water demand should not be undertaken lightly and will probably require a multi-disciplinary approach involving several Ministries. Consideration should be given to using a GIS-driven approach, which can be easily updated on a regular basis.

In the interest of transparency and common understanding at a technical level it is recommended that key Orange River Basin river stations in South Africa (and Namibia) be identified for common monitoring. Joint monitoring would include water

level monitoring (real-time telemetry), flow measurements for station calibration, and conversion of water levels into discharge. It would seem logical to extend this transparency to include all gauging stations and also to cover water demand data.

PRE-FEASIBILITY STUDY INTO MEASURES TO IMPROVE THE MANAGEMENT OF THE LOWER ORANGE RIVER

HYDROLOGY, WATER QUALITY AND SYSTEM ANALYSIS: VOLUME B – HYDROLOGY

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Review of RSA Hydrology

EXECUTIVE SUMMARY

The main aim of this review is to increase the transparency of South African studies for the benefit of the Namibian Team and at the same time to ensure that they are well acquainted with the hydrology of the river basin in South Africa and Lesotho.

This review is based on three key linked information sources:

- **Hydrological reports as obtained from the "Vaal River System Analysis Update", "Orange River Development Project Replanning" (ORRS) and the "Orange River System Analysis" studies.**
- **The systems analysis set-ups, which facilitated understanding of priorities and transfers.**
- **The stream flow datasets for all of the sub-catchments as derived in the studies carried out to compile the systems analysis update.**

The hydrological studies and systems analyses carried out in South Africa covering the entire Orange River Basin within South Africa and Lesotho have been reviewed. The general impression is that the work has been carried out thoroughly as far as the data will allow. There is no reason to disagree with the hydrological files being used as input for the systems analysis. However, as is generally the case with hydrological and associated data, given the human and financial resources, it would of course be possible and worthwhile to improve the accuracy of the data.

As stated on several occasions in the literature reviewed, the Vaal and Orange River Basins are the most important water resource systems in South Africa. They support more than 50% of the country's GDP. It is logical; therefore, that money spent on improving the accuracy of our knowledge of the system is well-spent and can be easily justified. Hence, the current study, and the major investments being made by the Governments of South Africa and Namibia. However, in view of the fact that some of the hydrological studies studied in this review are already more than a decade old, it would seem worthwhile to utilise any new data that have been collected since their completion and to update these studies. This includes the incremental catchment upstream of Vanderkloof Dam and downstream of the Lesotho Border, as well as the Lower Orange with the exception of the Fish River in Namibia.

The need to update hydrological data and the analysis thereof should not be limited to runoff data, but should also include improved collection of water demand data. The effort put over to analysis of water demand information in the studies reviewed reflects a strong awareness of the importance of water demand data. Any basin-wide efforts to update hydrology and water demand should not be undertaken lightly and will probably require a multi-disciplinary approach involving several Ministries. Consideration should be given to using a GIS-driven approach, which can be easily updated on a regular basis.

In the interest of transparency and common understanding at a technical level, it is recommended that key Orange River Basin river stations in South Africa (and Namibia) be identified for common monitoring. Joint monitoring would include water level monitoring (real-time telemetry), flow measurements for station calibration, and conversion of water levels into discharge. It would seem logical to extend this transparency to include all gauging stations and also to cover water demand data.

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LIST OF ABBREVIATIONS

DSL	**:**	**Dead Storage Level**
DWA	**:**	**Department of Water Affairs (Namibia)**
DWAF	**:**	**Department of Water Affairs and Forestry (RSA)**
GDP	**:**	**Gross Domestic Product**
Ha	**:**	**Hectare**
HDYP09	**:**	**Mathematical Model for Generation of River flows from meteorological data in South Africa**
LHDA	**:**	**Lesotho Highlands Development Authority**
LHWP	**:**	**Lesotho Highlands Water Project**
MAE	**:**	**Mean annual evaporation**
MAP	**:**	**Mean annual precipitation**
MAR	**:**	**Mean annual runoff**
Million m^3	**:**	**Million cubic meter**
ORP	**:**	**Orange River Project**
ORRS	**:**	**Orange River Development Replanning Study**
RSA	**:**	**Republic of South Africa**
St deviation	**:**	**Standard deviation**
VRSAU	**:**	**Vaal River System Analysis Update Study**
WRSM90	**:**	**Water Resources Simulation Model**

1. INTRODUCTION

The Orange River Basin is large, covering more than half of the land area of South Africa and the entire land area of Lesotho. Understanding the hydrology is complicated by a relatively small (considering the variability of rainfall) number of stream gauges, numerous inter-basin transfers, a large number of storage structures and high levels of demand. Given the importance of the water resources of the Orange River to South Africa, which is close to a water deficit situation, it is not surprising that numerous studies have been carried out on the hydrology of the components of the system.

In recent years, the significance of these studies has increased because of the increasing interest in the resources of the river from South Africa's neighbours, in particular Lesotho, Namibia and Swaziland. Lesotho has a water resources surplus and has reached agreement with South Africa to store and transfer water from impoundments within its territory in order to increase the yield of the system where it is needed in South Africa. Development in Namibia within the basin has increased sharply within recent years and, especially with respect to high value irrigated crops, which depend on water abstracted from the Orange River. Namibia therefore has an interest in the way in which the water resources of the system are managed further upstream in South Africa. Swaziland, while not situated within the basin is nevertheless affected by transfers from the headwaters of the Komati and Usutu Rivers. Transfers from the Usutu and Komati Basins are used to support the Vaal system, as well as Power Stations in the Upper Olifants, of which the latter also receives support from Grootdraai Dam in the Upper Vaal. Although the Komati and Usutu Rivers are not directly linked to the Orange River, the fact that they are used to augment the Vaal System will result in some effect on the Orange River. These two rivers rise in South Africa and flow eastwards through Swaziland to Moçambique and the Indian Ocean. Their water resources are critical to the sugar industry in Swaziland. The Orange River mouth at Alexander Bay/Oranjemund also has importance internationally, having been declared a RAMSAR site.

This increased international interest has resulted in a need for transparency with respect to studies on the water resources of the Orange and associated systems. There are now water allocation agreements in place between Lesotho and South

Africa, and more recently (August 2002) between South Africa and Swaziland.

The main aim of this review is to increase the transparency of South African studies for the benefit of the Namibian team and at the same time to ensure that they are well acquainted with the hydrology of the river basin in South Africa and Lesotho. This review is based on three key linked information sources:

- **Hydrological reports as obtained from the "Vaal River System Analysis Update", "Orange River Development Project Replanning" and the "Orange River System Analysis" studies.**
- **The systems analysis set-ups, which facilitated understanding of priorities and transfers.**
- **The stream-flow datasets for all of the sub-catchments as derived in the studies carried out to compile the systems analysis update.**

The basic approach followed in the hydrological studies is generally the same and can be summarised as follows:

- **Assembly of key "observed" data. These data are essentially:**
  - **the observed rainfall data for the largest possible coverage of rainfall stations;**
  - **the observed data for the stream flow stations for each sub-catchment. These gauges are a combination of purpose-built gauging stations and dams;**
  - **evaporation data; and**
  - **demand data including irrigation, urban, industrial and mining, domestic, forestation demands, and also seepage loss and environmental requirements.**

- **Pre-calibration data manipulation:**
  - **For the rainfall data, the quality of the data at each rain gauge is checked by consideration of the record length, amount of missing data and finally using mass plots. Gauges with unacceptably short records (normally 40 years), but this may be reduced for catchments where data are lacking. Gauges with a high percentage (normally > 8%) of unreliable record are similarly rejected. Where possible, gaps in records are "patched" using a**

multiple linear regression on other gauges in the sub-catchment.

- For the stream flow data, the data for all available river gauges are considered. Those with records that are too short, water stage/discharge ratings that are unreliable, or too much missing data, are rejected. Some mass balance analyses are carried out to examine the accuracy of some of the records.
- Water demand data are examined and taken back in time. For example for irrigation data, it is necessary (see later) to estimate demand as it has grown through the period of analysis (i.e., since 1920). Similarly for other demands. This is important, because rainfall/runoff modelling is based on the principle of modelling rainfall against "naturalised runoff", that is runoff unaffected by development. This is necessary, because since (it is assumed that) rainfall is unaffected by human development, it would not be possible to model it against a non-stationary time series such as observed runoff. Once modelling has been completed and an extended runoff record produced, this extended runoff can be adjusted to take into account the realities of current/future levels of demand during the systems analysis. In view of the high level of water demand within the Basin, accurate determination of water demand is critical if accurate model calibration is to be achieved.

- Model Calibration:
  - Prior to runoff simulation and record extension, Model Calibration has to be carried out. In the South African studies, a model known as the WRSM90 runoff model, has generally been used. This is an upgraded version of the Pitman (or HDYP09) model. In simplified terms, this model aims to calculate runoff based on catchment rainfall weighted according to a number of catchment parameters. Without going into detail, the principle is that these catchment parameters approximate the physical characteristics of the catchment that may have an influence on runoff. During the calibration process, the values of these parameters are modified until the best possible fit can be achieved, while at the same time respecting the physical realities of the catchment.

- **Patching and Record Extension:**
  - **Following calibration, the model is used to patch missing periods in the observed records and to extend the record back in time, in the case of these hydrological studies to the 1920s.**
  - **The process is carried out for all the sub-catchments.**

- **System Analysis:**
  - **The resultant incremental runoff records are used as input to the systems analysis for the main sub-catchment area for which the hydrology is being updated.**
  - **The systems analysis combines the hydrology of all the sub-catchments and takes into account all the different types of water demand, including non-consumptive uses and inter-basin transfers. The systems analysis is carried out according a set of operating rules, which define priorities for different users. These "users" include the environment and natural losses such as seepage and evaporation. Operating rules can be varied until yields are optimised as desired.**

2. REVIEW OF HYDROLOGICAL REPORTS AND DATA

2.1 Reports Consulted

The following reports were supplied and reviewed:

Bailey, A. K. (1999). Vaal River System Analysis Update; Hydrology of the Vaal Barrage Catchment**. Pretoria, Department of Water Affairs and Forestry.**

Basson, M. S. (1997). Overview of Water Resources availability and utilisation in South Africa**. Pretoria.**

BKS and Ninham Shand (1998). Potential Dam Developments and Hydro Power Options - Orange River Development Replanning Study**. Pretoria, Department of Water Affairs and Forestry.**

Loxton Venn & Associates and Agrimodel (1998). Evaluation of Irrigation Water Use Volume 3 : Possible New Irrigation Developments - Orange River Development Replanning Study**. Pretoria, Department of Water Affairs and Forestry.**

Loxton Venn & Associates and Agrimodel (1998). Evaluation of Irrigation Water Use Volume 2 : Existing Irrigated Agriculture - Orange River Development Replanning Study**. Pretoria, Department of Water Affairs and Forestry.**

Loxton Venn & Associates and Agrimodel (1998). Evaluation of Irrigation Water Use Volume 1 : Present Water Demand - Orange River Development Replanning Study**. Pretoria, Department of Water Affairs and Forestry.**

Maré, H. G. and O. J. Viljoen (1999). Irrigation and Farm Dam Information for the Vaal River System**. Pretoria, Department of Water Affairs and Forestry.**

McKenzie, R. S., N. W. Schäfer, et al. (1992). Upper Orange River : Hydrology**. Pretoria, Department of Water Affairs.**

McKenzie, R. S. (1998). Vaal River System Analysis Update; Lesotho Highlands Hydrology**. Pretoria, Department of Water Affairs and Forestry.**

McKenzie, R. S. and H. G. Maré (1998). Hydrology and Systems Analysis - Orange River Basin - Orange River Development Replanning Study**. Pretoria, Department of Water Affairs and Forestry.**

McKenzie, R. S. and F. G. B. d. Jager (1999). Vaal River System Analysis Update; Hydrology of the Upper Vaal Catchment**. Pretoria, Department of Water Affairs and Forestry.**

McKenzie, R. S., H. G. Maré, et al. (1999). Vaal River System Analysis Update; Hydrology of the Usutu River Catchment upstream of Swaziland**. Pretoria, Department of Water Affairs and Forestry.**

Pitman, W. V. (1999). Vaal River System Analysis Update; Hydrology of the Tugela Catchment and Hydrology of Zaaihoek Dam**. Pretoria, Department of Water Affairs and Forestry.**

Pitman, W. V., C. E. Herold, et al. (1999). Vaal River System Analysis Update; Hydrology of the Middle Vaal Catchment**. Pretoria, Department of Water Affairs and Forestry.**

Rossouw, J. D. (1997). Water Demands of the Orange River Basin - Orange River Development Project Replanning Study**. Pretoria, Department of Water Affairs and Forestry.**

Stassen, R., G. Hemme, et al. (1997). Hydrology and Systems Analysis - Eastern Cape Rivers - Orange River Development Replanning Study**. Pretoria, Department of Water Affairs and Forestry.**

Tukker, M. J. (1999). Vaal River System Analysis Update; Hydrology of the Lower Vaal Catchment**. Pretoria, Department of Water Affairs and Forestry**

2.2 System Analysis and Data

In addition, the layouts of the systems analyses for the sub-systems listed below were reviewed. The layouts included the assigned penalty values so that it was possible to have an understanding of the operating rules.

- **Combined Caledon, Lesotho Highlands Water Project, Upper Orange, Riet/Modder and Lower Vaal sub-systems.**
- **Namibia and Lower Orange sub-systems.**
- **Usutu, Komati, Upper Olifants, Zaaihoek, Upper Thukela, Thukela South, Upper Olifants and Upper Vaal sub-systems.**
- **Upper Vaal and Vaal barrage sub-systems.**
- **Middle Vaal sub-system.**
- **Lower Vaal and Riet/Modder sub-systems.**

2.3 Runoff Data

The runoff files (*.inc) adopted for all the incremental catchments were provided and examined in order to get a feeling for monthly and annual variation and magnitude of flow. Table 2.1 **summarises the files, which were provided.**

Table 2.1: Runoff Records Derived from Hydrological Studies for use in Systems Analysis

ALIW.INC	kat9.inc	rietf9.inc
allem9.inc	KATJE.INC	riets9.inc
auch9.inc	klerk9.inc	ROOD.INC
barbers.inc	klipb9.inc	rustf9.inc
barr9.inc	klipd9.inc	sand9.inc
bloem9.inc	klipr9.inc	spits9.inc
bosk9.inc	KNEL.INC	sterk9.inc
C3h013.inc	kop9.inc	suik9.inc
C5r5.inc	krom9.inc	tier9.inc
c9h007.inc	Krug10.inc	tso9.inc
dehoop9.inc	LORAN.INC	twee9.inc
dela9.inc	mal9.inc	uswentzd.inc
dswentzd.inc	mas9.inc	vaal9.inc
erf9.inc	mat9.inc	VERW.INC
FISH94.SPL	Mock.inc	vharts9.inc
fran9.inc	moh9.inc	WATER.INC
grootd9.inc	neser9.inc	WELBB.INC
HFDU.INC	nto9.inc	VIOOL.INC
HLOTS.INC	oran9.inc	BOEG.INC
kalkf9.inc	PKDU.INC	HARTB.INC

3. OVERVIEW OF ORANGE RIVER CATCHMENT

The Orange River rises as two main river systems, the Orange River and its associated tributaries, and the Vaal River and its associated tributaries. To the south, the Orange River rises as two main tributaries, the Caledon and the Senqu Rivers in the Drakensburg and Maluti Mountains in Lesotho and South Africa. To the north, the Vaal River rises in the Highveld in Mpumalanga and Northern Provinces of South Africa. The large majority of runoff is generated in these areas. The Vaal and the Orange (on crossing the border from Lesotho into South Africa the name changes from Senqu to Orange) Rivers make their confluence near the town of Douglas, more than a thousand kilometres upstream of the longitude 20 degrees where the Orange River becomes the border between Namibia and South Africa. Downstream of Douglas, the Orange River is joined by the Ongers/Brak River and the Hartbees River from the south and the Molopo and Fish Rivers from the north. The Molopo River has not been known to contribute surface runoff to the Orange River.

4. SUB-CATCHMENT HYDROLOGY

4.1 Overview

In representing and modelling the Orange River System, the approach adopted by South African Consultants and the Ministry has been to model the system as a whole, but to describe the hydrology and water demand on a sub-catchment basis. In some cases, these sub-catchments have grouped together as a large number of smaller sub-catchments. As is normal practice, the choice of sub-catchments has been made according to a combination of considerations including the location of gauging stations/dams and location of various demand centres.

The main source areas are covered by the Lesotho sub-catchment system; the Caledon River catchment and the Upper Vaal catchment (see Figures 4.1 and 4.2**). However, this is complicated by the fact that part of Lesotho sub-catchment is also implicated in the Upper Vaal catchment since it is towards the Upper Vaal that water transfers are made. In addition, the Upper Vaal receives water transferred from other rivers outside of the Orange River Basin. These are also included in the analysis of the Vaal River System. The remainder of the Vaal River is divided into the Middle and Lower Vaal sub-catchment groupings. Upstream of the confluence of the Vaal River, the eleven Orange River sub-catchments are often defined by dams such as the Boskraai, Gariep, Welbedacht, Vanderkloof and Kalkfontein Dams. Downstream of the Vaal/Orange River, there are five large sub-catchments, those of the Ongers/Brak, Hartbees, Molopo, Fish and "River Mouth" catchments.**

The hydrology of these sub-catchments as developed and described by or for the South African Department of Water Affairs (DWAF) has been reviewed and the findings, conclusions and recommendations are summarised on a sub-catchment (grouping) by sub-catchment (grouping) basis in Sections 4.2.1 to 4.3.3.

4.2 Vaal River Sub-catchments

4.2.1 Upper Vaal Sub-system

a) General Description

The Upper Vaal catchment forms part of the Vaal catchment, which is regarded as the most important water resources system in South Africa, supplying water to more than 40% of the population and supporting more than 50% of the country's gross domestic product (GDP). The Upper Vaal includes four major impoundments, the Vaal Dam (capacity of 2 603 million m³), Grootdraai Dam (356 million m³), Sterkfontein Dam (2 616 million m³) and Saulspoort Dam (17 million m³). The catchment has been divided up into five sub-catchments, Sterkfontein, Delangsdrift, Grootdraai, Wilge and Vaal Dam (incremental) sub-catchments. Reference should be made to Figure 4-1**. The Grootdraai and Sterkfontein sub-catchment runoffs are supplemented by inter-basin transfers from the Usutu/Komati and Tugela catchments, respectively. The Vaal Dam also receives inflows from the Senqu River in Lesotho.**

The Upper Vaal catchment covers an area of 38 638 km² with little in the way of urban development. There are thousands of small farm dams in the catchment.

b) Literature Consulted

The first major system analysis study on the Vaal River carried out in 1985 has not been reviewed in any detail, since this has been superseded by studies in 1993 and especially a study carried out between 1995 and 1997. The last-mentioned of these studies known as "Vaal River System Analysis Update Study (VRSAU)" has been reviewed in detail. The stated purpose of this study was:

> **"……to revise and update the hydrological and water quality databases used in the earlier studies and to re-assess the water quantity and quality capabilities of the whole Vaal River System using the most up-to-date information and techniques."**

c) Water Use

The VRSAU Study goes into considerable depth in its evaluation of water use and water demand. This is important, since only an accurate assessment of current and past water demand will allow an accurate "naturalisation" (see Section 1**, Introduction).**

Vaal Dam supplies Rand Water, South Africa's largest potable water supplier (all municipal and industrial users in Gauteng), various urban users, Grootvlei Power Station and some irrigation. Sterkfontein Dam stores water, transferred from the Tugela River System. Grootdraai Dam supplies water to various power stations and industrial users, including Sasol. It receives transfers from the Usutu catchment (Maputo River Basin).

The VRSAU included a detailed analysis of the small dams in the catchment using conventional mapping and satellite imagery. It was shown that the total capacity of all farm dams was significant. It was estimated in the study that the quantity of small (dam) storage in the basin had increased from 11.84 Mm³ in 1920 to 166.49 Mm³ by 1995.

The report states that there were some difficulties in accurately determining the current area under irrigation**. The consultants made use of previous studies, Department of Water Affairs' (DWA) records and other methods to arrive at a figure of 12 200 Ha under irrigation with the majority in the Frankfort and Vaal Dam catchments. It was estimated that the area under irrigation had grown from 2 250 Ha in 1920, but that in nineties irrigation within the catchment had remained "almost constant". The report shows that considerable care was taken to model irrigation demand as accurately as possible. Cognisance was taken of different crops and monthly variations in application rates. Return flows of 10% were assumed.**

Urban and industrial **abstraction levels are measured by DWAF and amounted to almost 33 million m³ from the Vaal Dam catchment in 1994.**

Afforestation **areas are limited. The estimated total area was only 13.4 km² in 1994.**

d) Transfers

Since 1974, water has been pumped from the upper reaches of the Tugela River over the Drakensburg to Drieklloof Dam, a small dam adjoining Sterkfontein Dam, for hydropower generation and also for transfer to the Vaal Dam Basin. The study reports that it is not possible to accurately calculate the amount of water transferred into the Vaal Dam catchment due to the complexity of the transfer system and some unknown factors. A maximum transfer of 700 Mm³/annum has been designed for, but this is rarely possible to achieve. Historical records of annual releases are misleading since during the first 8 years of the dams life no water was released as the dam was filling. The average amount of water transferred from the Tugela Basin to Sterkfontein Dam between 1974 and 1995 was 283 million m³. Over the last 13 years, since Sterkfontein Dam has filled, an average of 183 million m³ has been released (after consideration of transmission losses). Water is also transferred from the Zaaihoek Dam on the Buffalo River System, a tributary of the Tugela River for power supply, local urban water supply and can flow into the Vaal River upstream of Grootdraai Dam. The scheme started operating in 1991 and annual transfers ranged from 8 million m³ up to 73 million m³.

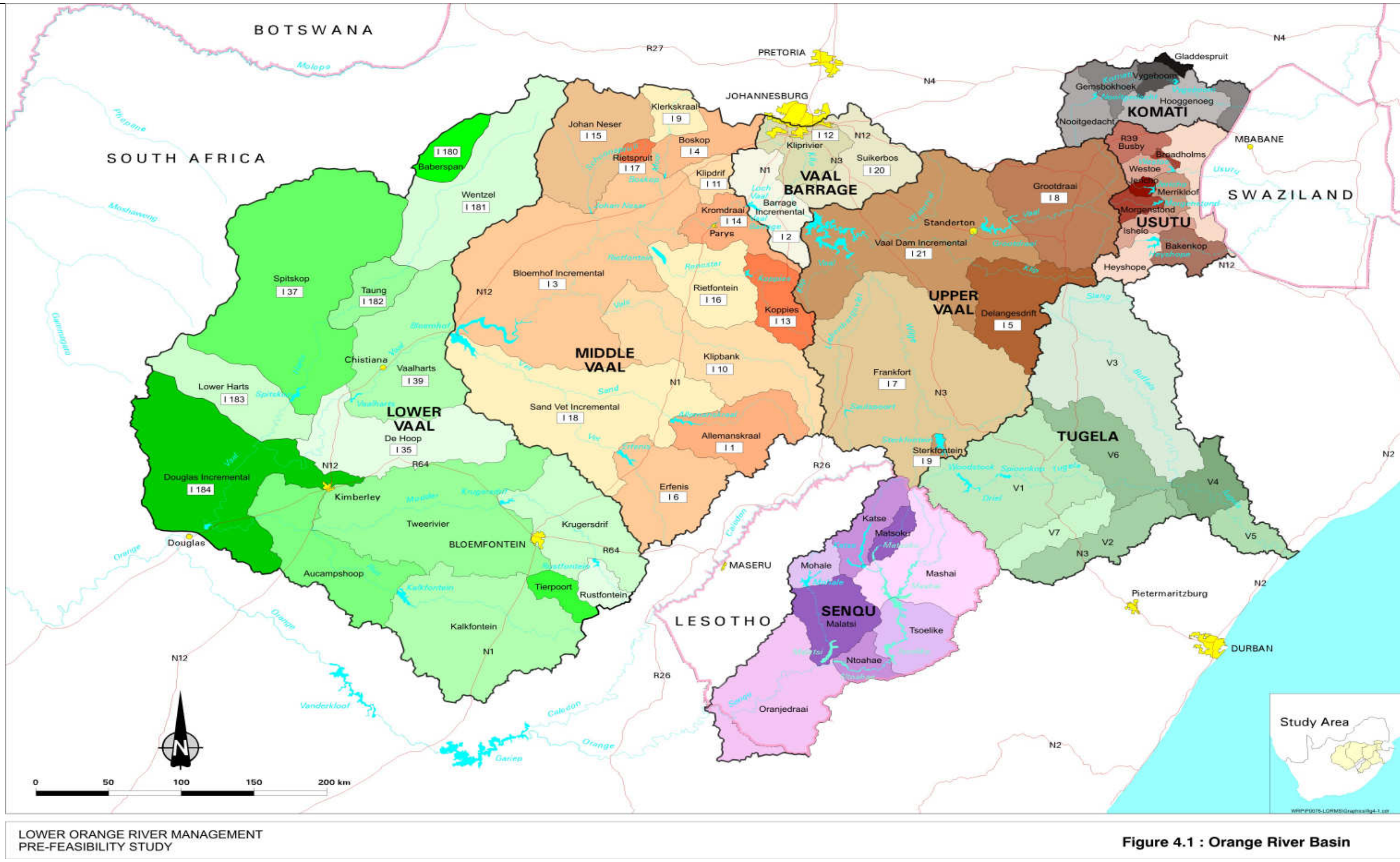
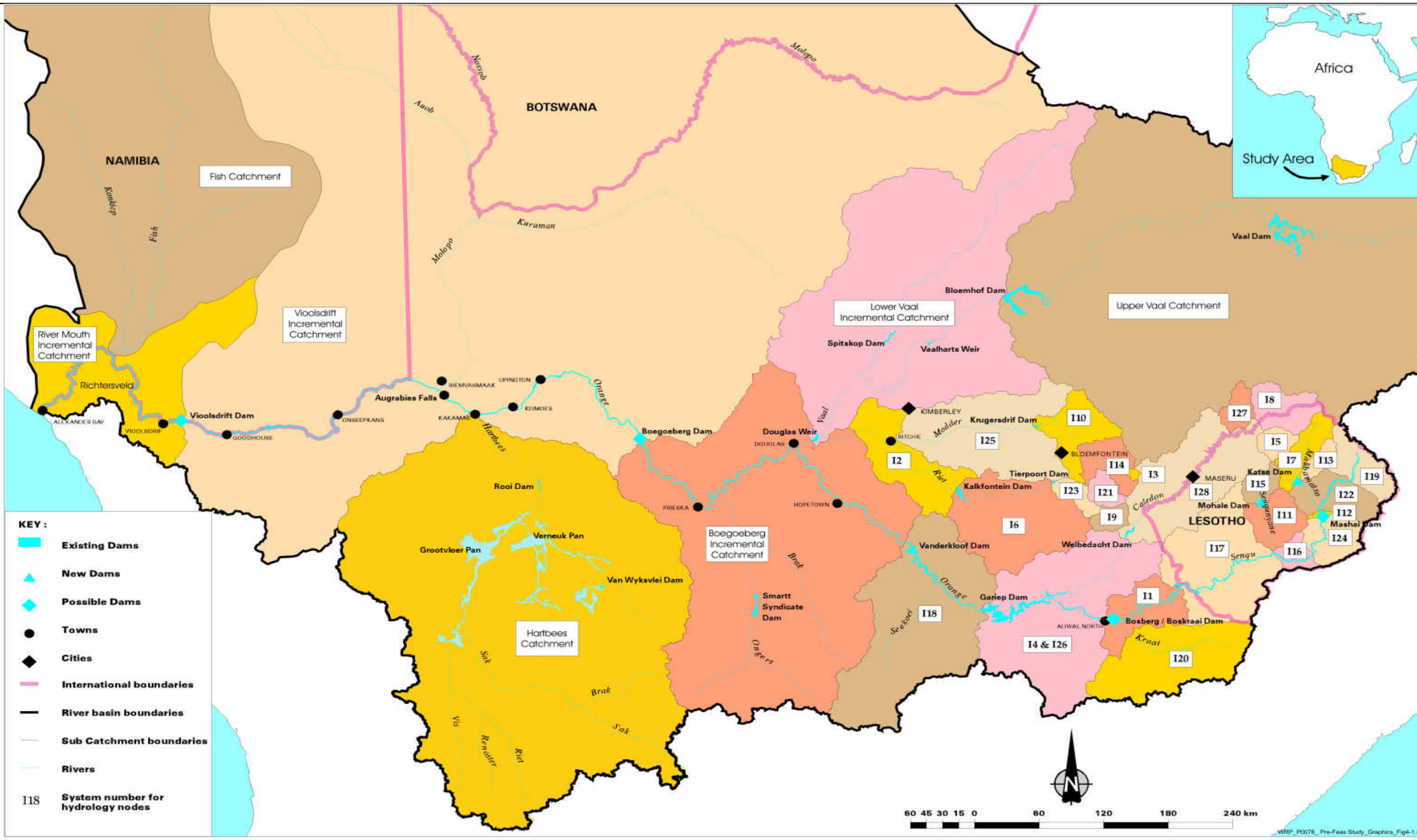


Figure 4-1: Orange River Basin



LOWER ORANGE RIVER MANAGEMENT
PRE-FEASIBILITY STUDY

Figure 4.2 : Orange River Basin

Figure 4-2: Orange River Basin

Water is transferred from Heyshope Dam in the Usutu River via a number of conveyances to the Grootdraai Dam on the Vaal River. Annual transfers between 1985 and 1994 varied from zero to 113 million m³.

e) Observed Records

In line with the generalised procedure as explained in the introduction, the observed rainfall records for as many stations as possible were examined for each of the five sub-catchments. The rainfall data for the Upper Vaal were found to be of a generally good quality and it was possible to apply exacting selection criteria. Nearly 20 gauges with records going back to 1920 or before were found. Sufficient evaporation data were also available.

Table 4.1: Runoff Gauges Used in 1995-1997 Upper Vaal Study

Gauge (River)	Gauge No.	Catchment Area (km²)	Date Opened	MAR	Comments
Standerton (Vaal)	C1H001	8 193	1920	453.70	MAR for 1920-1994 period. Only minor patching of the record was required. Record was completed with Grootdraai inflow after 1978
Delangesdrift	C1H002	4 152	1920	247.10	MAR for 1920-1994 period. Station unreliable at high flows (drowning). Very little need for patching.
Engelbrechtdrift (Vaal)	C2H003	38 564	1923	1 917.91	Only minor patching required. Years 1920-23 had to be simulated. Inflow record for Vaal Dam taken into account after 1936.
Frankfort	C6H001	15 673	1920	760.38	Extensive patching using C8H022 was required although recorded data was reliable.
Vaal Dam	C1R001	38 505	1936	1 858.25	No Patching required during period of record
Grootdraai Dam	C1R002	7 924	1978		Allowance had to be made for U/S abstractions during drought in 1983
Sterkfontein Dam (Wilge)	C8R003	58	1974		Station used only for naturalisation of Frankfort gauge.

There are 19 stream flow gauges in the catchment (including dams operating as gauging stations). Some of these have data extending back to the early 1900's, but much of the data is considered unreliable. After a critical analysis, the consultants retained only seven stations. Six stations were rejected due to unsuitably small catchment areas or poor data. Five stations were rejected due to the short records, having only been opened between 1971 and 1985. Clearly, in a revised analysis there would be considerable new data available. The report

provides a useful in-depth review of the available data. Using standard techniques (comparisons with other stations nearby, upstream or downstream etc.), the streamflow records were verified. Short periods of missing data for periods covered in the 1986 assessment were not re-patched. The utilised gauges are summarised in Table 4.1**.**

f) Rainfall/Runoff Modelling, Runoff Naturalisation

As is normal practice in South Africa, the well-tested WRSM90 runoff model was used for calibrating the observed record against weighted rainfall. The results are described in detail in the report and show high levels of correlation.

In order to achieve the required naturalised flow record, account had to be taken of the water use data described earlier in the report. This includes inter-basin transfers, which have to be subtracted from the observed flows. The report takes each one of the observed records and explains in sufficient depth how the naturalised records were calculated.

g) Synthesized Record

The details of the combined observed and synthesized records are summarised in Table 4.2 **as extracted from the report.**

Table 4.2: Summary of Results for Upper Vaal Hydrological Analysis

Incremental Sub-catchment	Catchment Area (km^2)	Observed Incremental Runoff or Inflow ($10^6 m^3$)	Natural Incremental MAR ($10^6 m^3$)
Grootdraai	7 995	453.7	457.7
Delangesdrift	4 158	247.1	249.5
Frankfort incr.	15 498	696.2	733.3
Vaal incr.	10 792	493.2	518.7
Sterkfontein	195	97.3	18.1(3)
Total for Catchment	**38 638**	**1987.5**	**1977.3**

It is interesting to note that the natural incremental runoff is less than the observed. This is because of the fact that the observed runoff includes transfers from outside of the catchment.

g) Conclusions

The Upper Vaal Hydrological analysis makes use of long and generally reliable runoff records. It was found that the mean annual runoff (MAR) at Vaal Dam had not changed significantly (3%) since the less rigorous 1985 analysis. The report is very clear on the importance of correctly estimating water use/demand data since this has a significant effect on the accuracy of the record naturalisation process. Irrigation demands, which are the largest are stated as having been constant for a few years prior to 1994. While it may not be warranted to re-evaluate the hydrology, using the new data collected since 1994 (which may allow some new stations to be included in the analysis) for year or two, it is considered worthwhile to check on water demand figures, especially the irrigation demands, over the last decade.

4.2.2 Middle Vaal Sub-system

a) General Description

The Middle Vaal sub-catchment includes ten major impoundments, the most important being the Bloemhof Dam (capacity of 1 269.2 Mm³) at the outlet of the Middle Vaal catchment. Other large impoundments are the Erfenis Dam (207.7 Mm³), Allemanskraal Dam (174.7 Mm³) and Koppies Dam (41.2 Mm³). In the VRSAU Study: The catchment was divided up into 12 sub-catchments, Erfenis, Allemanskraal, Sand Vet incremental, Klipbank, Koppies, Rietfontein, Kromdraai, Klipdrif, Boskop, Klerkskraal, Johan Neser, Rietspruit and Bloemhof incremental sub-catchments. Reference should be made to Figure 4. 1**.**

The Middle Vaal catchment covers an area of just over 60 000km² with little in the way of relief other than the hills in the upper area of the Vals River. There are some large urban developments and mines together with extensive irrigation.

b) Literature Consulted

The 1997 VRSAU Report on the Middle Vaal was the main source for this review.

c) Water Use

As was the case with the Upper Vaal the study was particularly careful in its treatment of water demands particularly important in the Middle Vaal sub-catchment.

The VRSAU included a detailed analysis of the small dams in the catchment, on a sub-catchment by sub-catchment basis, using conventional mapping and satellite imagery. It was shown that the total capacity of all farm dams was significant at over 224 Mm³. Older maps and the Dam Register were used to estimate historical growth in total dam capacity since 1920.

Major Irrigation schemes are sometimes part of government water schemes in which case the demand is usually monitored, or under the control of Irrigation Boards. There are also several private irrigation schemes. The report states that the Middle Vaal catchment has not been subject to any detailed irrigation investigation. Estimates were largely based on the 1988 Census of Agriculture. A number of approaches were used to derive the estimate of 23 300 ha under irrigation for 1994. The study showed that irrigation area had grown by approximately 1,78% per annum since 1920 (6 520 ha). In view of the impact of irrigation, the report goes into some detail on irrigation water usage, investigating the different water sources used, cropping patterns and seasonal demands. It was estimated that 130.6 Mm³/annum are used for irrigation in the Middle Vaal catchment.

There was a major increase in urbanisation and urban water demand in the decade up to 1994, resulting also in significant return flows of effluent. The study clearly looked in great detail at urban and industrial abstractions and return flows and this is reported in considerable detail.

Afforestation is minimal in the Middle Vaal catchment and was not taken into account in the analysis.

Transmission losses are significant and difficult to estimate using standard approaches. A special approach was developed in the VRSAU Study. It showed that transmission losses in the Vaal River between Vaal Dam and Bloemhof are approximately 74 million m³/a.

d) Transfers

There are no transfers into the Middle Vaal Catchment.

e) Observed Records

In line with the generalised procedure as explained in the Introduction, the observed rainfall records for as many stations as possible were examined for each of the fifteen sub-catchments. The rainfall data for the Middle Vaal were found to be of a generally good quality and it was possible for the consultants to apply exacting selection criteria. The data for 140 gauges were selected for further analysis.

The report provides details on the records of all 140 gauges. 66 Gauges had records going back to 1920 or before which allows some confidence in the rainfall/runoff modelling of early years.

Table 4.3: Runoff Gauges Used in 1995-1997 Lower Vaal Study

Gauge (Catchment)	Gauge No.	Catchment Area (km²)	Date Opened	MAR (Mm³)	Comments
Witrand (Catchment)	C2H001	3 595	1903	-	Oldest record available. Various problems affect accuracy but record useable.
Schoemansdrift (Vaal River)	C2h018	49 120	1938	43	Record considered reasonable, water hyacinth can affect accuracy
Klipplaatdrift (Vaal River)	C2H061	79 903	1971	-	Some probably with accuracy at low flows and for high flows
Hoogekraal (Mooi River)	C2H085	5 485	1986	-	Reasonable accuracy but flows easily submerged
Boskop Dam (Mooi River)	C2R001	3 287	1957	72	
Johan Neser Dam (Schoonspruit)	C2R002	5 635	1922	87	Record ceases in 1951. Quality of record unknown
Klerkskraal Dam (Mooi River)	C2R003	1 335	1969	-	Low flow spillage cannot be measured accurately
Floorsdrift (Vet River)	C4H002	17 599	1950	413	Station closed after sub-mergence by Bloemhof Dam. Inaccurate at higher flows
Nooitgedacht (Vet River)	C4H004	16 533	1968	-	Not accurate for low flows. Okay for medium and perhaps high flows. Replaced C4H002
Allemanskraal Dam (Sand River)	C4R001	3 665	1959	-	High spillage flows are not accurately measured
Erfenis (Vet River)	C4H010	4 750	1959	-	Accurate crump weir
Roodewal (Vals River)	C6H001	5 674	1912	-	Low and medium flows reasonable, high flows could be overestimated
Mooifontein (Vals River)	C6H003	7 765	1966	155	Not suitable for low flows. Acceptable for medium flows, but not reliable for high flows
Dankbaar (Heuninghspruit)	C7H003	914	1947	-	Several problems affect the accuracy of this gauge. Record considered unreliable.
Arriesrust (Renoster River)	C7H006	5 758	1977	120	Low flows not accurate. Primarily a flood warning station
Koppies Dam (Renoster River)	C7R001	2 147	1920	59	Record accurate with no apparent anomalies
Bloemhof Dam (Vaal River)	C9R002	107 911	1968	1085	No rating for outflow measurement weir

There are 60 stream flow gauges in the catchment (including dams operating as gauging stations), although many of these have specialised purposes or have catchments too small to be of interest to the study. 19 gauging stations, of which seven were reservoir gauges were chosen for the calibration process. With the exception of the Schoonspruit River, coverage was considered to be adequate. Three gauges had records starting before 1920, two between 1921 and 1940, and the rest after 1960. Details on the records are provided in Table 4.3**. Gaps in the records were patched using various techniques. Details on how the patching was carried out are presented in the report.**

f) Rainfall/Runoff Modelling, Runoff Naturalisation

As is normal practice in South Africa, the well-tested WRSM90 runoff model was used for calibrating the observed record against weighted rainfall for 17 stations. Based on this calibration, it was possible to produce synthesized runoff records dating back to 1920. The results are described in detail in the report and show high levels of correlation

In order to achieve the naturalised flow records required for the calibration, account had to be taken of the water use data described earlier in the report. This includes inter-basin transfers, which have to be subtracted from the observed flows. The report takes each one of the sub-catchments and explains in sufficient depth how the water demands were calculated.

The naturalised stream-flows are discussed in some depth in the report. The approach adopted to produce the naturalised stream-flow for the entire record period was to take the observed record and to add all the calculated water demands (and subtract transfers received). This naturalised observed record is then extended using the synthesized record, which is any case already naturalised. The alternative approach, sometimes adopted since it usually leads to "better" correlations, of using just the synthesized record and none of the observed record was not adopted. Both approaches can be argued as being more correct, but this review concurs with the approach adopted in VRSAU.

Comparisons were made with previous studies and it was found that the overall MAR of the Middle Vaal was only one per cent different from the previous study.

However, there were significant differences for some of the sub-catchments. These differences are satisfactorily explained in the report.

g) Synthesized Record

The details of the combined observed and synthesized records are summarised in Table 4.4 **extracted from the report.**

Table 4.4: Summary of results for Middle Vaal Hydrological Analysis

Sub-catchment	MAR ($10^6 m^3$)
Mooi	134
Renoster	120
Schoonspruit	93
Vals	155
Sand-Vet	422
Other tributaries	161
TOTAL	**1085**

h) Conclusions

The Middle Vaal Hydrological analysis makes use of a mixture of long and shorter runoff records with records of varying reliability. The VRSAU represents an in depth effort to use all the available data to arrive at the best possible calibration for all thirteen of the sub-systems. It is stated in the report that simulated flows are over-estimated by a few per cent. It was found that the overall MAR at Bloemhof Dam had not changed significantly (1%) since the less rigorous 1985 analysis.

It was stated in the conclusions of the report that the natural MAR of the Middle Vaal catchment is 1085 Mm³/annum based on the period October 1920 to September 1995. Annual flow volumes were stated to have varied from as little as 110Mm³ in 1932 and 1991) up to nearly 3 000Mm³ in 1932 and 1991.

4.2.3 Vaal Barrage Catchment Sub-system

The Vaal Barrage sub-catchment is an area of 8 561km² upstream of the Vaal Barrage on the Vaal River. The catchment covers all flows entering the Vaal River

between the Vaal Dam and the Vaal Barage. Almost all of the catchment lies to the north of the Vaal River and includes the catchments of the Klip and Suikerbos Rivers. The catchment only contributes 273 million m³/a but has been treated in considerable detail in its own section of the VRSAU report. The report states that analysis of the catchment was complicated by the highly urbanised and regulated nature of the catchment, the inaccuracy of several gauges, the presence of large wetland areas, and high transmission losses. In addition, sewers blocked during the 1985 political unrest complicated the analysis.

The VRSAU report has been studied carefully, but it is not considered necessary to go into the same level of detail as was done for the upper and Middle Vaal catchments. The Vaal Barage Dam has a capacity of 48million m³ and small dams are calculated to have a total volume of 44 million m³. Irrigation in the catchment has not been studied in any detail and major estimates had to be made. It was estimated that irrigated hectarages increased from 14 Ha to 98 Ha in 1995.

Data on abstraction and return flows were in many cases impossible to obtain, and in the end, an approach was developed to estimate abstraction and effluent. Abstractions are significant. Rand Water alone operates eight abstraction canals/pipelines from either the Vaal River or the Vaal Dam. T otal abstraction was calculated at 401 million m³ in 1994. However, return flows are estimated at 285 million m³ for the same year. The report makes a detailed evaluation of urbanised areas in each of the sub-catchment since this will play an important role in the calibration process. The catchment includes a significant portion of the Johannesburg area (see Figure 4-1). The total urbanised area was taken to be 648 km². This figure was divided up into three levels of urban development corresponding to the degree of imperviousness of the surface. Wetland and transmission losses also received special treatment in the report. Wetland areas were estimated at 62 km².

The study reports that an adequate number of rainfall gauges (45) were available covering the entire catchment. The catchment was divided up into 8 sub-catchments for the purpose of model calibration. There are 12 gauging stations in the catchment and all were used for the purpose of model calibration. The report provides details on the status and accuracy of all the river gauges. Approximately half of them were considered to have “reasonable” records. The report goes into

considerable detail on as to how the data problems at many of the stations were solved.

Calibration of the Barrage catchment was difficult for reasons already mentioned, and a number of supplementary analyses were performed as part of the process. In most cases, the synthesised flows compared well with the sub-catchment observed flows once water demands had been taken into account. For some stations, there were significant differences. For the Vaal River at the Barrage, it was found that the Barrage overestimates flow albeit by only three per cent when results were used in conjunction with flows from the Middle Vaal and observations at Vaal Dam.

The report summarises the problems encountered in the hydrological analysis. These included having to use some records, which were too short, some records which were not very reliable (gauges on the Klip River and others). The report recommended that a new gauging weir be constructed on the Blesbokspruit, as well as a high flow station on the Suikerbosrand River. A need for a current meter gauging programme was also highlighted. It is not known whether any of these recommendations have been implemented.

4.2.4 Lower Vaal Catchment

The Lower Vaal includes several impoundments with the purpose of augmenting and stabilising water supply for irrigation. In total there are ten major dams in the Lower Vaal, the smallest being the Wentzel Dam (capacity of 6 million m^{33}) on the Harts River and the largest being the Kalfontein Dam (319 million m^3) on the Modder River. There are several other dams on the Modder and Riet Rivers, most with the purpose of supporting irrigation. The total capacity of large dams in the Lower Vaal amounts to 683 million m^3 and of farm dams to 152 million m^3.

The Lower Vaal catchment covers an area of over 88 000 km^2 and includes three distinct river systems, the Harts River to the north, the Vaal River, and the Riet and Modder Rivers to the south. The Harts River catchment is 31 000 km^2. Runoff potential is limited but nevertheless, it is a significant supplier or water for urban and especially irrigation consumption. Of the Lower Vaal incremental catchment, it is stated in the VRSAU that only 35% contributes directly to runoff in the river network. The rest drains into pans and enclosed river basins. The combined catchment areas of the Modder and Riet Rivers are 35 000 km^2. There has been extensive

dam development in the catchment.

There are a number of in-basin and inter-basin transfers. These include:

- transfers from the Caledon River to the Modder in order to supplement supplies to Thaba Nchu and Bloemfontein.
- transfers from the Vanderkoof Dam on the Orange River via the Sarel Hayward/Orange-Riet Canal to the Riet River scheme.
- transfers from the Vaal River at Riverton for water supply to Kimberley.
- short distance transfers from the Orange River for the Douglas Irrigation Scheme.

a) Literature Consulted

The 1997 VRSAU Report on the Lower Vaal was the main source for this review.

b) Water Use

The VRSAU study goes into considerable depth in its evaluation of water use and water demand in particular of irrigation.

The largest irrigation scheme is the Vaalharts Scheme (34 000 ha) situated between the Vaal and Harts Rivers. In the Modder/Riet System, there are another five Government or Irrigation Board Schemes. The report states that there is also significant diffuse and runoff river irrigation. The total hectarage under irrigation is estimated at just over 25 000 ha. In calculating the water consumption of irrigation, cognisance was taken of known application rates, cropping patterns and scheduling.

The Lower Vaal catchment is sparsely populated and urban or industrial abstraction and resultant return flows are limited to the towns of Kimberley, Bloemfontein, Botshabelo and Thaba Nchu. In addition, the Vaal-Gamagara scheme supplying water to a number of small towns, farms and some mines.

c) Transfers

While much of Bloemfontein's water is supplied from the Modder River, water is also assured via a water transfer from the Caledon sub-catchment on the Orange River. Water is also transferred into the Lower Riet River from the

Vanderkloof Dam on the Orange River. The Douglas Irrigation Scheme just upstream of the Vaal/Orange confluence also uses water transferred from the Orange River.

d) Observed Records

Approximately 98% of the rainfall records were longer than 30 years and 60% of the stations were still open. Stations were checked during the VRSAU Study for reliability, stationarity and consistency and found to be satisfactory.

17 Runoff gauging stations were considered for use in the calibration process as shown in Table 4.5**.**

Seven of these were not utilised because of poor quality data or because their catchments were considered too small. Of the selected stations, two had records going back to the 1920s. The report provides a useful in-depth review of the available data. Using standard techniques (comparisons with other stations nearby, upstream or downstream, etc.), the streamflow records were verified. Short periods of missing data for periods covered in the 1986 assessment were not re-patched.

Table 4.5: Runoff Gauges Used in 1995-1997 Upper Vaal Study

Gauge (River)	Gauge No.	Catchment Area (km²)	Date Opened	Comments
Taung (Harts)	C3H003	10990	1927	Not ideal for low flows. Some discrepancies in early record.
Espagsdrift (Harts)	C3H007	24097	1948	Not suitable for calibration due to over-estimation of high flows. Low flows used to calibrate irrigation return flows.
Schweizer Reneke (Harts)	C3R001	2919	1935	Spills from dam not gauged
Spitskop (Harts)	C3R002	26914	1975	
Shannon Valley (Renoster)	C5H007	348	1948	Record required extensive patching
Riviera (Riet)	C5H008	593	1931	Small catchment with no significant demands, hence combined with Kalkfontein
Kromdraai Rietwater (Riet)	C5H012	2372	1953	Included with Kalkfontein
Stoomhoek (Modder)	C5H015	6009	1948	Doubts over accuracy of low flows
Aucampshoop (Riet)	C5H016	33351	1952	Not completely reliable and extensive patching required

Gauge (River)	Gauge No.	Catchment Area (km²)	Date Opened	Comments
Tweerivier (Modder)	C5H018	17315	1959	Well-situated to monitor effects of Modder GWS
Tierpoort (Kaffer)	C5R001	922	1937	Reliable record requiring limited patching
Kalkfontein (Riet)	C5R002	10268	1937	Data appears reliable
Rustfontein (Modder)	C5R003	940	1954	Record was considered to be reliable
Krugersdrift (Modder)	C5R004	6315	1974	Record considered reliable
De Hoop 65 (Vaal)	C9H009	121052	1968	Record considered reliable
Vaalharts (Vaal)	C9R001	115055	1971	Record considered reliable

There are a surprisingly large number (25) of evaporation stations in the Lower Vaal catchment. It is unlikely that better estimates of evaporation could be obtained.

e) Rainfall/Runoff Modelling, Runoff Naturalisation

As is normal practice in South Africa, the well-tested Pitman Model runoff model was used for calibrating the observed record against weighted rainfall for each of the gauging stations. The process is described in sufficient detail. The usual statistics of the concurrent and observed records are presented in the report. The results are described in detail in the report for each of the stations used in the calibration process. A summary of the results has been extracted from the report and is presented in Table 4-6**.**

Table 4.6: Summary of Results from Modelling of Lower Vaal Catchment

Gauge Number	Station Name	Effective Incremental Area (km²)	MAP (mm)	MAE (mm)	Naturalised MAR million m³/a	Unit Runoff mm/a
C3H003	Taung	7975	530	1916	59.0	7.4
C3R002	Spitskop	9249	438	2039	77.5	8.4
C5H016	Aucampshoop	1847	350	2050	6.4	3.5
C5H018	Tweerivier	2236	422	1871	14.4	6.4
C5R001	Tierpoort	922	491	1640	23.8	25.8
C5R002	Kalkfontein	8781	412	1746	215.9	24.6
C5R003	Rustfontein	937	543	1600	30.7	32.7
C5R004	Krugersdrift	5391	508	1639	114.4	21.2
C9H009	De Hoop	3201	406	1963	12.9	4.0
C9R001	Vaalharts	2509	444	1946	11.2	4.5
-	Lower Vaal	6096	361	2210	31.5	5.2
TOTAL		**49144**			**597.7**	**143.7**

f) Conclusions

The VRSAU Report for the Lower Vaal makes a number of recommendations on the need for new river gauges and measures to improve the quality of data recorded. These include measures with respect to the need to monitor irrigation abstractions, transfers and return flows need to be monitored accurately in the Vaalharts area. Measures were also recommended to improve monitoring in the Upper Harts River, and a new gauging site was proposed for the Vaal River downstream of the Vaal and Harts River confluence and the Vaal Gamagara abstraction point. A number of recommendations to improve monitoring in the Modder/Riet catchments are also made.

Perhaps most importantly were concerns raised regarding the need to better know how much water is being used in the catchment, especially with respect to irrigation consumption. It was therefore recommended that the aerial photography and mapping of the region be updated in order to determine the extent of irrigated area. It was also recommended that a database of all current and historical irrigation information and contact names should be compiled.

More accurate and standardised estimates of effective catchment areas need to be agreed upon.

A point of caution was also raised, particularly relevant to the Lower Vaal catchment with respect to sub-catchments where flows and irrigation are primarily supported by compensation releases from an upstream reservoir rather than from runoff generated on the incremental catchment. It was stated that care must exercised during calibration and naturalisation of the catchment, and that the water demands (irrigation or other) must be supplied by the actual compensation flows rather than the catchment runoff and river flows, since failure to model the abstraction of demands in this way would result in extreme over-estimation of natural runoff when the irrigation demands are added back to the catchment runoff during the naturalisation process.

The WR90 Regional Parameters appear to give a slightly conservative estimate of natural runoff in the catchments along the Vaal River and Lower Modder and Riet catchments.

4.3 Orange River Sub-catchments

4.3.1 Senqu River Sub-system

a) General Description

The Senqu River rises in the Maluti and Drakensburg Mountains in Lesotho. Within the catchment, these mountains rise to 3 482 m. On crossing the border into South Africa, the river becomes the Orange River and makes its confluence with the Caledon River at the Gariep Dam about 220 km downstream of the border. In South African water resources studies, it is often included under the heading of the Vaal River rather than the Orange due to the fact that water transfers are made from the Senqu River across the catchment divide to the Vaal Dam. The Senqu River is therefore an essential part of the so-called "Vaal Integrated System". The Senqu River is therefore an important water resource for South Africa for two reasons, firstly as one of the two main rivers feeding the Vanderkloof Dam, and secondly as a source of water for the industrial heartland of Gauteng. Transfers to the Vaal Dam take place as part of the Lesotho Highlands Scheme, Phase 1 of which has been implemented through the

construction of the Katse Dam and associated storage and transfer works.

In order to have been able to construct this scheme, South Africa has an agreement with the Kingdom of Lesotho, which makes provision for the payment of royalties.

b) Literature Consulted

Unlike the Vaal River Hydrology, as well as that of other parts of the Orange River, the Lesotho River Hydrology is based on relatively "new data". The first comprehensive studies of the Senqu River date back to the Lesotho Highlands Feasibility Study, carried out in the mid 1980s. An "interim" hydrology was produced for design purposes. Further studies were carried out by BKS, South Africa in 1993 and by the UK Institute of Hydrology in 1994. Finally, a study carried out jointly by BKS and the LHDA (Lesotho Highlands Development Authority) was completed in December 1998. The resultant report of this study has been the main reference document for this review.

c) Water Use

Before the construction of the Lesotho Highlands Water project (LHWP), use of water in the Senqu River was limited to water supply for small settlements. With the construction of the Katse Dam on the Malibamatso River, a 45 km transfer tunnel to Muela Power Station and the Muela Dam, which collects tailrace waters for transfer to the Vaal Dam, the situation has changed completely. From the Muela Dam water is transferred via another set of tunnels from whence the water flows into the upper reaches of the Ash River, a tributary of the Liebenbergsvlei River, which joins the Wilge River just before Vaal Dam.

It is anticipated that on average 490 million m³/a will be transferred out of the Senqu River to the Vaal River Basin as part of Phase1A of the LHWP. This will increase when Phase 1B, the construction of a 145m high dam at Mohale on the Sequnyane River and a transfer tunnel to the Katse Reservoir, have been completed. Completion is scheduled for 2003.

d) Observed Records

The study looked at more than 120 relevant rainfall records. Of these only records, which could be patched and with a record of at least 15 years, were

utilised. It would appear that every effort was made to fully utilise the available data, even retaining parts of a record if considered acceptable and rejecting the parts considered to be unreliable. This was necessary, however, because the quality of rainfall data in the Senqu catchment was generally considerably lower than in the sub-catchments already discussed.

Most of the streamflow stations in Lesotho were set up in the middle 1960s so there are no long records. It is reported that there were 13 stations, which could be used in the analysis plus the Oranjedraai Station situated just downstream of the Lesotho/South African border. Difficult access to stations for servicing and siltation problems are two of the reasons for numerous gaps in many of the records. In general, the quality of the records is described as "fair". Three crump weirs have been installed in recent years to improve the reliability of runoff data. It is clear that a lot of effort had to go into carefully examining the observed data and especially the water stage/discharge curves for all the stations in the catchment. The stations at Marakabei and Paray were considered to be the most complete and were therefore selected as the key reference stations. Gaps in the records of several other stations were corrected by reference to these stations. The report discusses in detail each one of the gauging stations and their associated records, the gaps and how they were patched. Another key reference station was the Oranjedraai Station, which is almost complete for the full 1960 to 1994 period.

e) Rainfall/Runoff Modelling, Runoff Naturalisation

Rainfall/runoff modelling was carried out using a modified form of the Pitman Model. Features of the version used allowed input of a number of rainfall records covering the period of interest to ensure that gaps were covered, as well as relatively short runoff records.

Table 4.7 **derived from the report summarises the some of the results obtained during the modelling. It would appear from the results that the main aim was to model the MARs of each station as accurately as possible, since the observed and synthesized MARs match up quite well. A comparison of the observed and synthesized record statistics show significant differences in the standard deviations and relatively low correlations. However, it is also clear from the low number of rain gauges (between 3 and 5 for each incremental catchment)**

available that it would not be possible to obtain better results.

f) Synthesized Record

Having generated the synthesized runoff records, these records were then used as inflows to the various reservoir sites agreed between the Governments of South Africa and Lesotho. In view of the fact that the reservoir sites were not the same as the gauging stations sites, the inflow records were calculated by summing the upstream incremental gauging site record with a part of the downstream incremental gauging site record.

Table 4.7: Results of Rainfall/Runoff Modelling for Selected Stations

Parameter	Seaka	Mokhotlong	Paray	Marakabei	Bokong	Orangedraai
Catchment MAP (mm)	796	908	763	944	930	781
Catchment Area (km²)	10041	1660	1028	1087	403	4806
Observed MAR (Mm³/a)	1390	280.1	181.8	359.5	100.1	813.3
Synthesized MAR (Mm³/a)	1388	280.0	180.3	348.6	100.3	812.8
Observed St. Deviation	853	208.6	117.1	181.3	50.8	560.3
Sythesized St. Deviation	820	208.0	94.2	134.2	40.0	438.9
Correlation Coefficient	0.64	0.63	0.71	0.79	0.78	0.65
No. of Rainfall Records Used	4	4	5	3	3	4

Details of how the calculations were carried out are fully described in the report. Reservoir inflow sequences are provided for the 1920 to 1995 period and hence, are consistent with the VRSAU Studies. Figure 4-3 **shows the positions of the dam sites considered in the study.** Table 4.8 **summarises the calculated mean annual inflows.**

Table 4.8: Calculated Mean Annual Runoffs at Considered Dam Sites

	Katse	Mohale	Mashai	Tsoelike	Malatsi	Ntoahae
MAR (Mm³/anum)	554	312	1447	1795	611	1943

g) Conclusions

Due to the sensitive nature of the hydrology of the Senqu River (amount of royalties payable to Lesotho), considerable effort has been put in to ensure the best possible result under difficult (short and incomplete records) conditions.

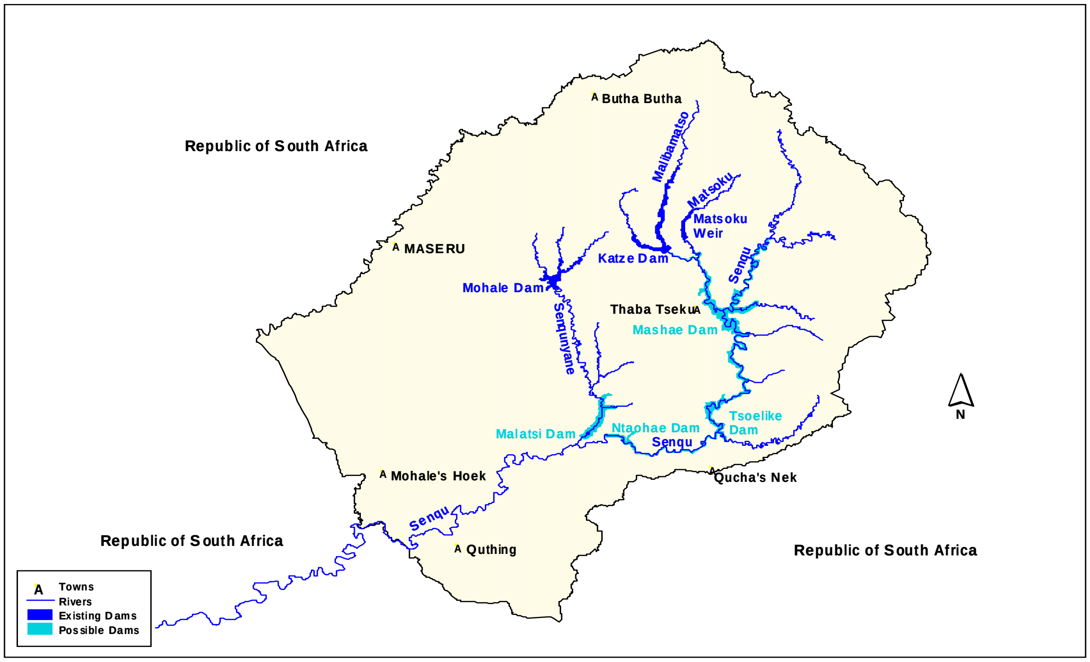


Figure 4-3: Positions of Dam Sites Considered in LHWP Systems Analysis

4.3.2 Caledon River and Upper Orange Incremental Catchment: Hydrology

a) General Description

In the nomenclature used in the South African systems analysis the Upper Orange River Incremental, catchment covers the area upstream of the Vanderkloof Dam up to Welbedacht Dam on the Caledon River and up to Oranjedraai on the Orange (Senqu in Lesotho) River. The Senqu River in Lesotho has already been discussed in the previous paragraph as far as the Oranjedraai gauging station just downstream of the Lesotho/South African border. Before making its confluence with the Caledon River, the Orange is joined by the Kraai River from the Drakensburg Mountains to the southeast. Upstream of the Wellbedacht Dam the Caledon River catchment covers an area of 15 245km², much of it in the mountains of Lesotho.

Rainfall drops off very sharply as the Orange River leaves the mountains and is down to 300mm/a at the Gariep Dam.

b) Literature Consulted

While the hydrology of the Orange/Senqu River upstream of the Orangedraai gauge was updated as part of the Lesotho Highlands Study (see paragraph) in 1999, the hydrology of the Caledon River and incremental catchments of the Vanderkloof and Gariep Dams is relatively old, dating back to a report completed in November 1992. This document, entitled "Upper Orange River : Hydrology" was the main reference document for this section of the review.

c) Water use

Water demand for Irrigation in the Upper Orange catchment was estimated at 384 million m³/a in 1990, although it would appear that this is not always met since the average water supplied was only 281 million m³/a. According to the study, total water use in the Upper Orange catchment was estimated at 1 920 million m³/a of which 885 million m³/a was estimated to be evaporation from the major storage reservoirs and farm dams. Of the remainder; it was estimated that 740 million m³/a are transferred to the Vaal catchment. Knellpoort and Welbedacht on the Caledon River are mainly used to transfer water to the Modder system to support Bloemfontein, Bothabello and other smaller urban areas with water. Welbedacht has, however, silted up to a large extent and Knelpoort Dam was built as an off-channel storage dam due to the severe silt problems. There are, however, compensation releases from Welbedacht Dam to supply irrigation downstream of the dam (irrigation that existed before the dam was built). The Welbedacht Dam is not used to support Gariep Dam at all.

d) Runoff

The incremental MAR values as calculated in the 1992 study are presented in Table 4-9**. The natural runoff generated for this study covered the period 1920 to 1987.**

Table 4.9: Incremental MAR for the Upper Orange River

River Gauge	River	Catchment Area (km²)		MAP (mm)	Incremental MAR (Mm³/annum)	Incremental Unit Runoff (mm)
		Total	Incremental			
Aliwal North	Orange	37 075	3 635	591	229	63
Roodewaal	Kraai	8 688	8 688	657	676	78
Oranjedraai	Orange	24 725	24 725	793	4 192	170
Welbedacht Dam	Caledon	15 245	15 245	755	1 217	80
Gariep Dam	Orange	70 749	18 435	456	397	22
Vanderkloof Dam	Orange	89 842	17 843	314	147	8

e) Conclusions

The report pointed out that reconciling the hydrology had been complicated by inaccurate measurement by the turbine meters at Vanderkloof Dam, and uncertainties over the accuracy of the elevation/capacity equation for the same dam. The study also recommended that combined mass balance calculations for Gariep and Vanderkloof Dams should be carried out annually.

4.3.3 Lower Orange River

a) Description

Downstream of the Vanderkloof Dam there are five incremental catchments, most of which do not make major contributions. In the South African studies, these are referred to as the Boegoeberg Incremental catchment, the Hartbees catchment, the Vioolsdrift incremental catchment, the Fish River catchment (Namibia) and the River Mouth incremental catchment.

b) Literature Consulted

A large number of reports were compiled as part of the Orange River Replanning Study (ORRS). All of these (over 30) reports were made available in electronic form for this review. Certain key reports were selected. These included the Hydrology and Systems Analysis: Orange River Basin", and the "Evaluation of Irrigation Water Use", and "Water Demands of the Orange River Basin – ORRS". While the main purpose of the first-mentioned of these studies was to carry out a large number of systems analyses in order to look at maximising yield and efficiency of the available water resources, including the inclusion of various

potential reservoirs, the report also provides an overview of the hydrology.

b) Water Use

The main user of water in the Lower Orange River (and indeed of all the catchment), is the Orange River Project, which was first proposed in 1962 to irrigate thousands of hectares especially in the Eastern Cape, Northern Cape and Free State areas. This project depends on flows from the Vanderkloof and Gariep Dams. It is reported that the main functions of the Orange River Project (ORP) are to provide water for irrigation and urban users along the river, to provide irrigation water to the Great Fish and Sundays Rivers in the Eastern Cape and to the Riet River catchment. In addition, Orange River water is used to solve water quality problems in the Vaal River at Douglas, and is used to generate peak power for the Eskom Network at the Gariep and Vanderkloof Dams. The ORP also supplies water to cities and small towns such as Upington, Prieska, Port Elizabeth, Grahamstown, Alexander Bay and Port Nolloth.

In the systems analysis described, land use and associated water demand has been divided up into five areas, being:

- **Area 1: Upstream of Gariep Dam (i.e., not part of ORP).**
- **Area 2: Area upstream of the Orange/Vaal confluence up to and including Gariep Dam.**
- **Area 3: Riet/Modder catchments.**
- **Area 4: Area downstream of Orange/Vaal confluence to 20º longitude (Namibian/RSA border).**
- **Area 5: From 20º longitude to River mouth.**

The demands are described in the report and are summarised in Table 4.10**.**

Table 4.10: Summary of ORP Demands (excluding transfers to Riet/Modder catchments)

Water Use \ Area	Area 2 (Directly from Gariep and Vanderkloof)	Area 2 (Gariep to OrangeVaal confluence	Area 4	Area 5	Total
Irrigation	882[1]	228	469	81	1 660
Urban	16	(incl. below)	(incl. below)	(incl. below)	16
Urban/ Industrial/ Stock	(incl. above)	5	13	27	45
River Requirement (Losses)	-	64	455	441	960
Canal Losses	-	9	26	-	35
Environmental Demand	-	-	-	306	306
Totals	899	306	963	855	3022

[1] 627Mm³ by Orange/Fish Tunnel; 255Mm³ by Vanderkloof canal

[2] Lesotho Highlands Water Project transfers are not included

Clearly the updating of these demands will be an important aspect of the current study in view of significant water use developments over the last decade.

In the report studied, it would appear that all the demands are described in sufficient detail and clarity to allow relatively straightforward updating for new systems analyses incorporating more up to date runoff data. The same is true of canal and rivers losses.

4.3.4 Lower Orange River and System Analysis

a) General

The hydrology used in the Lower Orange clearly relates to the hydrology of the Upper Orange and Vaal. Hence, in view of the fact that the ORRS pre-dated some of the more recent hydrological re-assessment, some of the records used are not the most recent. For example, the runoff record used for the Riet/Modder system was the one updated in 1991, rather than the one used in the 1997 study. However, in checking the runoff data files for the total Orange River catchment as it now stands, it was found that most of the records have been updated to September 1995. The only exception is the incremental area upstream of Vanderkloof Dam and downstream of the Lesotho border.

It is estimated that approximately 900 Mm³/annum originates from the Lower Orange catchment of which more than half comes from the Fish River. It is stated in the study that the hydrology of the Lower Orange was treated in a simplified manner. The Lower Orange Hydrology covers the period 1920 to 1989. A table presented in the report provides a very useful overview of the runoff contributions from the different parts of the catchment as assumed for the 1991 study. It is not presented in full here, but a summary is provided showing the sum of the incremental MARs for each of the major systems as already discussed in this review.

Table 4.11: Summary of Incremental Streamflow Data

Catchments included (see Figure 4.1 and 4.2)	Sub-system	Total Incremental Catchment Area (km²)	Total Incremental MAR (1920 – 1983)	Unit Runoff (mm)
I7, I11, I12, I13, I15, I16, I17, I19, I22, I24	Lesotho Highlands	24 752	4 014.53	162.2
I5, I8, I9, I27, I28	Caledon	15 245	1 197.98	78.58
I1, I4, I18, I20, I26	Upper Orange	48 595	1 389.125	28.586
I2, I3, I6, I10, I14, I21, I23, I25	Modder-Riet	23 277	366.21	15.77
-	Remainder of Vaal	166 235	3 521.65	21.181
-	Fish River (Namibia)	76 000	483.90	6.36
-	Remainder of Orange River*	136 909 (319 870)	219.35	1.6
TOTAL		**491 103 (685 372)**	**11 192.74**	**22.79**

b) Scenarios

One of the aims of the systems analysis was to look at combinations of new developments in the Orange River catchment to see how yield can be most usefully augmented. These scenarios have been studied as part of this review, but are too numerous to be described here. However, in order to illustrate the principle, the "base scenario" is summarised and the sort of scenario variations that were considered are briefly mentioned.

The base scenario was as follows:

- **Phase 1 of LHWP at 2005-development levels.**
- **Compensation releases from Katse and Mohale dams of 0.5 m³/s and**

0.3m³/s, respectively.

- **Environmental demand at river mouth set at 100 Mm³/annum.**
- **Orange to Fish transfer set at 627 Mm³/annum.**
- **Orange/Riet transfer set at limit of 275 Mm³/annum (demand driven).**
- **Orange/Douglas transfer set at limit of 88 Mm³/annum (demand driven).**
- **Compensation flow from Gariep Dam set at 16 m³/s.**
- **2005 development level spills from the Vaal Basin.**
- **Hydro-electric power generated in accordance with downstream system demands only.**
- **Dead storage level (DSL) set at 1 231.63 m for Gariep Dam and 1 147.78 m for Vanderkloof Dam.**
- **Total live storage at Gariep and Vanderkloof Dams = 6 883 Mm.**
- **Instream flow requirements taken as equal to downstream demand.**
- **Transfer from LHWP to Vaal basin taken as 28.6 m³/s.**
- **Novo transfer from Caledon to Modder in place.**
- **All domestic/industrial demands at 2005 levels.**
- **Inclusion of all possible diffuse developments in the Caledon (Lesotho and RSA).**
- **2045 sedimentation levels at dams.**

The results of around 50 alternative scenarios (including minor variations or sub-scenarios) were modelled in order to find out which set of operating rules was the most appropriate. These operating rules represented a combination of operating rules for existing infrastructure and operating rules for planned potential infrastructure . It should be noted that systems analyses had to take into account not just consumptive needs, but also hydropower-related scenarios.

A number of scenarios related to the inclusion of the Vioolsdrift Dam. These included for example, raising of Gariep Dam combined with a 1500 Mm³ dam at Vioolsdrift and increased transfers from the Orange River to the Vaal, or the raising of Gariep, Bosberg, Boskraai Dams combined with a large dam at Vioolsdrift.

Conclusions are too numerous and inter-dependant to go into here. The study provides a useful basis for the current study.

5. CONCLUSIONS AND RECOMMENDATIONS

Hydrological studies and systems analyses carried out in South Africa covering the entire Orange River Basin within South Africa and Lesotho have been reviewed. The general impression is that the work has been carried out thoroughly as far as the data will allow. There is no reason to disagree with the hydrological files being used as input for the systems analysis. However, as is generally the case with hydrological and associated data, given the human and financial resources, it would of course be possible and worthwhile to improve the accuracy of the data.

As stated on several occasions in the literature reviewed, the Vaal and Orange River Basins are the most important water resource systems in South Africa. They support more than 50% of the country's GDP. It is logical, therefore, that money spent on improving the accuracy of our knowledge of the system is well-spent and easily justified. Hence the current study, and the major investments being made by the Governments of South Africa and Namibia. However, in view of the fact that some of the hydrological studies studied in this review are already more than a decade old, it would seem worthwhile to utilise the new data that have been collected since their completion and to update these studies. This includes the incremental catchment upstream of Vanderkloof Dam and downstream of the Lesotho Border, as well as the Lower Orange with the exception of the Fish River in Namibia.

The need to update hydrological data and the analysis thereof should not be limited to runoff data but should also include improved collection of water demand data. The effort put over to analysis of water demand information in the studies reviewed reflects a strong awareness of the importance of water demand data. Any basin-wide efforts to update hydrology and water demand should not be undertaken lightly and will probably require a multi-disciplinary approach involving several Ministries. Consideration should be given to using a GIS-driven approach, which can be easily updated on a regular basis.

In the interest of transparency and common understanding at a technical level it is recommended that key Orange River Basin river stations in South Africa (and Namibia) be identified for common monitoring. Joint monitoring would include water

level monitoring (real-time telemetry), flow measurements for station calibration, and conversion of water levels into discharge. It would seem logical to extend this transparency to include all gauging stations and also to cover water demand data.