ORANGE - SENQU RIVER COMMISSION
BOTSWANA LESOTHO
ORASECOM
NAMIBIA SOUTH AFRICA
Established 2000

Water Resources Modelling, Baseline Scenario, Yield Analysis, Stochastic Verification and Validation

Integrated Water Resources Management Plan for the Orange-Senqu River Basin

2014

Report No. ORASECOM 013/2014

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Support to Phase 3 of the ORASECOM Basin-wide integrated Water Resources Management Plan

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Integrated Water Resource Management Plan for the Orange-Senqu River Basin

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WATER RESOURCES MODELLING, BASELINE SCENARIO, YIELD ANAYSIS, STOCHASTIC VERIFICATION AND VALIDATION

Integrated Water Resources Management Plan for the Orange-Senqu River Basin – Phase 3

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1 Introduction

1.1 CONTEXT AND OBJECTIVES OF THE STUDY

1.1.1 General Context

Southern Africa has fifteen (15) transboundary watercourse systems of which thirteen exclusively stretch over SADC Member States. The Orange–Senqu is one of these thirteen. The Southern African Development Community (SADC) embraces the ideals of utilising the water resources of these transboundary watercourses for the regional economic integration of SADC and for the mutual benefit of riparian states. The region has demonstrated a great deal of goodwill and commitment towards collaboration on water issues. Thus, SADC has adopted the principle of basin–wide management of the water resources for sustainable and integrated water resources development. The proposed ORASECOM basin-wide IWRM fits into this background.

1.1.2 Water resources context

The Orange - Senqu River originates in the highlands of Lesotho on the slopes of its highest peak, Thabana Ntlenyana, at 3 482masl, and it runs for over 2 300km to its mouth on the Atlantic Ocean. The river system is one of the largest river basins in Southern Africa with a total catchment area of more than 975,000km^{2}and includes the whole of Lesotho as well as portions of Botswana, Namibia and South Africa. The natural mean annual runoff at the mouth is estimated to be in the order of 11,500Million m^3, but this has been significantly reduced by extensive water utilisation for domestic, industrial and agricultural purposes to such an extent that the current flow reaching the river mouth is now in the order of half the natural flow. The basin is shown in Figure 1-1.

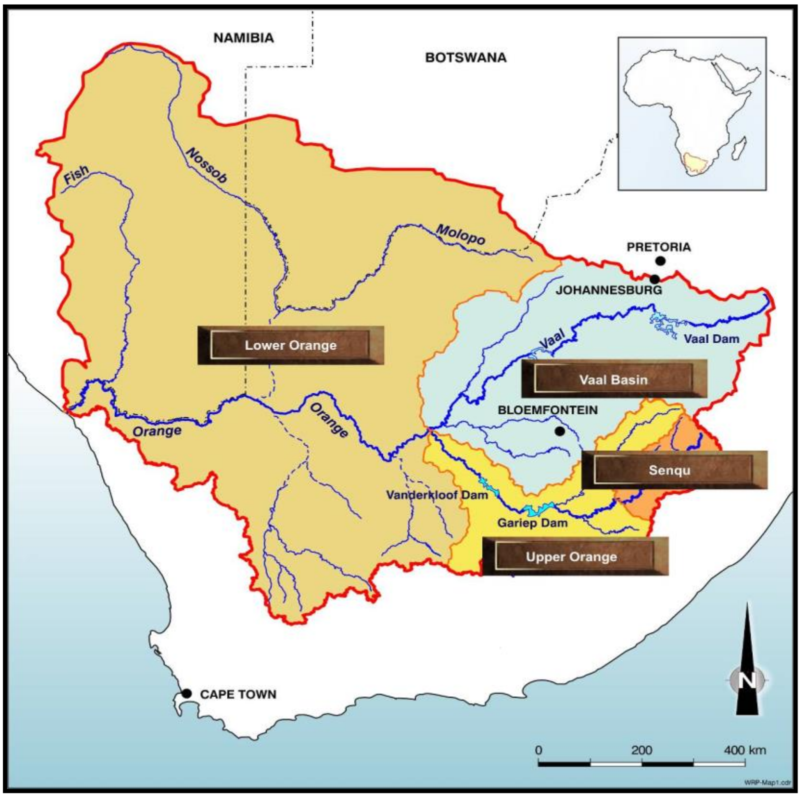


Figure 1-1: Orange – Senqu River Basin

REGULATION AND INTER-BASIN TRANSFERS

The Orange-Senqu system is regulated by more than thirty-one major dams. Two of these dams are situated in Lesotho, five in Namibia and 24 in South Africa. The largest five reservoirs are those formed by the Gariep, Vanderkloof, Sterkfontein, Vaal and Katse Dams with capacities ranging from 1 950 Mm^3 to 5 675 Mm^3. The Orange-Senqu river basin is a highly complex and integrated water resource system with numerous large inter-basin transfers which allow water to be moved from one part of the basin to another as well as into and out of neighbouring basins. For example, the Sterkfontein Dam (2 617Mm^3) is supplied from the adjacent Tugela basin and the Katse-Mohale dams system (2 910Mm^3) located in Lesotho augment the Vaal Dam (2 122Mm^3) which supplies water to the industrial heartland of South Africa. The Gariep Dam (5 675 Mm^3) and Vanderkloof Dam (3 237 Mm^3) on the Orange River downstream of Lesotho are the largest reservoirs in the Orange-Senqu river system respectively. Both dams are used to regulate the river flow for irrigation purposes as well as to generate hydro-electricity during the peak demand periods with a combined installed capacity of 600 MW. Releases from Vanderkloof Dam into the Orange River are dictated by the downstream flow requirements.

The tributaries downstream of the Vaal confluence are the Molopo-Nossob sub-basin system. Surface flow from this system has not reached the main stem of the Orange River in living memory. Further downstream, the Fish River sub-basin, entirely located within Namibia accounts for the two (Hardap, Naute Dams) of the five dams regulating the flows from Namibia into the Orange River.

The most important and highly utilised tributary of the Orange-Senqu system is the Vaal River which supplies water to the industrial heartland of Southern Africa, the Vaal Triangle including Pretoria. The Vaal River System also provides water to 12 large thermal power stations which produce more than 90% of South Africa's electricity, as well as water to some of the world's largest gold, platinum and coal mines.

The Orange-Senqu river basin is clearly one of the most developed and certainly most utilised river basins in the SADC region, with at least 9 major intra - and inter - basin water transfer schemes.

The complexity of this transboundary systemy and the resultant need for a sophisticated management system in the Orange-Senqu river basin is one of the key drivers of the proposed project to develop an Integrated Water Resources Management Plan for the basin.

1.1.3 Phase 3 of the Basin-wide IWRM Plan

The basin-wide Integrated Water Resources Management (IWRM) Plan will provide a framework for management, development and conservation of water resources in the Orange-Senqu River Basin, serving to advise Parties on optimising overall water resource utilisation.

Since the establishment of ORASECOM in 2000, a significant number of studies have been completed or are in process and have provided the building blocks for the Basin-wide IWRM Plan. Phase I of the ORASECOM IWRM planning programme was implemented between 2004 and 2007 and focused on collating existing information that described the water resources of the Basin. Phase II of the IWRM Planning Programme (2009 to 2011) focused on bridging the planning gaps identified in Phase I. A Transboundary diagnostic analysis (TDA) has been carried out under the ongoing UNDP-GEF project and National and Strategic Action Plans are in the process of being finalised.

Strategically, ORASECOM has approached the point where, with some exceptions, sufficient preparatory work has been done to move towards drafting a Basin-Wide IWRM Plan. Representatives of the four member countries have tentatively defined an “overall objective” for preparing a Basin-wide IWRM Plan:

“To provide a framework for sustainable development and management of the water resources, taking into account the need for improved distribution and equitable allocation of benefits, in order to contribute towards socio-economic upliftment of communities within the basin, and ensure future water security for the basin States.”

The plan will set out the actions necessary to achieve the strategic objectives of ORASECOM as well as those of the basin States. Some of these will be short term and others longer term. In the context of IWRM planning, once approved, “the Plan” will signify a transition from planning to implementation of the actions that are determined in the Plan. Moreover it will signify the transition of ORASECOM from a reactive to a pro-active mode, technically competent advisor to the Parties as envisaged in the ORASECOM Agreement.

The IWRM Plan will include an implementation plan that identifies activities that will be implemented collectively by all the Parties through ORASECOM and the existing bilateral institutions and those that will be implemented separately by the Parties. The IWRM Plan will be forward looking (10 years in scope) and provide a framework that enables the basin to realise economic and social benefits associated with better water resources management. In addition, the IWRM Plan should strive to link the water sector with national economic growth and poverty alleviation strategies based on the fact that the IWRM is not an end in itself but rather a means to achieve economic and social development.

In summary, the objective of this consultancy is to develop a comprehensive 10 year IWRM Plan for the whole of the Orange-Senqu Vaal River Basin. The IWRM Plan will include an implementation plan that identifies activities that will be implemented collectively by all the Parties through ORASECOM and the existing bilateral institutions and those that will be implemented separately by the Parties.

1.2 THIS REPORT

1.2.1 Rationale

This study consists of five Work Packages to address all the requirements and actions for the preparation, tabling and approval of the IWRMP. This report focus on Work Package 4c-i, which is one of the sub-work packages of Work Package 4. Work package 4 comprises the following sub-work packages, effectively the technical studie components of the Phase 3 work.:

- **Work Package 4a:** Conduct an economic analysis of water use based on water accounting.
- **Work Package 4b: Consolidate water demands and infrastructure development plans.** The task comprises consolidation into a database, updating and filling of gaps for some parts of the basin.
- **Work Package 4c-i: Update the basin planning model and conduct a model based situation analysis.** 4c-Part i comprises the modelling work that has to be done before any new scenarios can be investigated
- **Work Package 4c-ii:** Application of the basin planning model for testing and evaluation of scenarios
- **Work Package 4d: Update ORASECOM Water Information System:** All information collected as well as results generated will be consolidated in the WIS.
- **Work Package 4e: Consolidate available knowledge on environmental flow requirements and water quality assessments.** The consolidation work will form part of the SAP work but the results will be required for consolidation in the water resources models.
- **Work Package 4f:** Consolidate knowledge on economic approaches to water management

These Sub-Work Packages are critical to finalising the inputs required for the drafting of the IWRM Plan.

The Senqu, Orange Vaal system is a highly complex and largely integrated system. It also includes several transfers into and out of the basin and therefore requires the inclusion of parts of other neighbouring river basins into the water resources modelling setup.

A proper detailed model representative of the water use and water resource activities within this integrated system is an absolute necessity, as it is not possible to effectively and efficiently plan and operate this large and complicated system without the aid of such a tool. Two models are used to simulate the entire integrated system, the Water Resources Yield Model (WRYM) and the Water Resources Planning Model (WRPM). As the names indicate, the WRYM is used to determine the yield of the system and sub-systems within the system. The WRPM uses these yield results as input and are used for planning and operating purposes. Two separate reports will be produced from Work Package 4c, the “System Yield Analysis” Report that focus on the WRYM related work and the “System Planning Analyses and Evaluation of Scenarios” Report which summarises the work related to the WRPM analyses.

Since the completion of Phase 2 of the ORASECOM IWRM Study the WRYM and WRPM models setups that were deliverables from the Phase 2 study, were already used as the basis for further studies in South Africa and Lesotho. Updated information and more detailed layouts were introduced, which will form part of the final updated WRYM and WRPM to be used in this study. In a large and complex system such as this, there are always new developments and updates taking place. The scenarios that will be investigated in order that recommendations can be taken forward to the draft IWRM Plan will be evaluated, using the most up-to-date model configurations.

1.2.2 Tasks undertaken under Work Package 4c

The following main tasks were undertaken as part of **Work Package 4c**:

- Obtain the latest model versions and update the central models accordingly.
- Integrate the demand-side information as obtained from Work Package 4b and from Work package 3 where applicable
- Verify and validate the stochastic flow sequences before using the models in stochastic analysis mode.
- Carry out yield analysis using the WRYM with the base scenario data sets for several of the sub-systems within the Orange Senqu Vaal basin and carry forward results to draft the IWRM Plan.
- Carry out scenario analysis using the WRPM and carry forward results to the draft IWRM Plan.
- Refine chosen scenario(s) depending on feedback received during discussion of the draft IWRM Plan with stakeholders
- Install the final updated and tested models on work stations in each Basin State and provide training.
- Reports to be compiled as a result of the work carried out as indicated in the above mentioned tasks.

1.2.3 Objective of this report

The objective of this report is therefore to include a summary of all the configurations that have been consolidated in order to create the latest version of the WRYM for output in this study. A current situation simulation will be carried out to test the model, the results of which will be included in this report. The results of the stochastic verification tests will also be included in this report as well as historic and stochastic yield analyses results.

1.2.4 Structure of the report

This report comprises eight main sections, covering the entire scope of work required for the System Yield Analysis and Stochastic Validation and Verification processes as well as the relatedresults. Section 1 has given an introduction to the study, the objective of this report as well as an overview of the contents of the report. The crux of the report is covered in sections 2 to 7 with the conclusions and way forward provided in Section 8.

- Section 2: This section provides a brief description of the modelling process and models used as well as the model input requirement and typical applications of the models.
- Section 3: Background on the current operation and related operating rules are given in this section. For this purpose the entire basin was sub-divided into three main components, the Vaal River, the Orange River and the Senqu River component.
- Section 4: A summary of the hydrology (natural flow per sub-catchment) is given in this section. This section will provide the reader with a clear understanding of which area each of the hydrology files represent, what the file names are as well as the mean annual runoff and related statistics of each flow record.
- Section 5: This section briefly explains the process behind the generation of the stochastic flows and discussed the validation en verifications tests that are carried out to ensure that the generated stochastic flow sequences indeed mimic the historic flow sequences well. The different tests are reviewed and a summary of the results is provided.
- Section 6: A summary of the model components is given in this section. Details are included on the transfers within the systems, the demands imposed on the key sub-systems. The importance and reasons for stochastic yield analyses are briefly described.
- Section 7: This section covers the yield analyses, giving a description of the scenario analysed and providing the related yield results.

2 The WRYM and WRPM models

Water resources modelling can be divided into three main modelling processes, namely:

- **Rainfall-runoff modelling:** objective to produce naturalized hydrology that covers the entire historical record period based on observed stream flow and rainfall data for input into yield and planning models;
- **Yield modelling:** objective to determine yields of individual sub-systems for input into planning model; and
- **Planning and operations modelling:** objective to operate and manage and plan sub-systems and catchments in an integrated manner using individual sub-system yield characteristics.

The application of these types of models for the Orange-Senqu Basin has been as follows:

- The Pitman model was used in the Integrated Water Resources Management Plan Phase 2 Study to generate natural hydrology for the entire Orange basin. The models used for the systems analyses for this Phase 3 study are as follows:
  - The **WRYM (Water Resources Yield Model)**: Used to determine sub-system yields;
  - The **WRPM (Water Resources Planning Model)**: Configured for future management and scenario analyses of the Integrated Orange-Senqu River catchment.

2.1 OVERVIEW OF THE MODELS

2.1.1 Pitman model

The application of the Pitman model formed part of the Phase 2 work and was presented and discussed as part of that work.

2.1.2 WRYM

The WRYM is a monthly stochastic yield reliability model used to determine the system yield capability at a fixed development level with present day development level being used in most cases. The model allows for scenario-based historical firm and stochastic long-term yield reliability analysis. In addition, short term reservoir yield reliability can be determined, at selected starting conditions.

The WRYM was developed by the South African Department of Water Affairs (SA-DWA) for the purpose of modelling complex water resource systems and is used together with other simulation models, pre-processors and utilities for the purpose of planning and operating the country's water resources.

The WRYM uses a sophisticated network solver in order to analyse complex multi-reservoir water resource systems for a variety of operating policies and is designed for the purpose of assessing a system's long- and short-term resource capability (or yield). Analyses are undertaken based on a monthly time-step and for constant development levels, i.e. the system configuration and modelled demands remain unchanged over the simulation period. The major strength of the model lies in the fact that it enables the user to configure most water resource system networks using basic building blocks, which means that the configuration of a system network and the relationships between its elements are defined by means of input data, rather than by fixed algorithms embedded in the complex source code of the model.

SA-DWA has developed a software system for the structured storage and utilisation of hydrological and water resource system network model information. The system, referred to as the WRYM Information Management System (IMS), serves as a user friendly interface with the Fortran-based WRYM and substantially improves the performance and ease of use of the model. It incorporates the WRYM data storage structure in a database and provides users with an interface which allows for system configuration and run result interpretation within a Microsoft Windows environment.

SA-DWA made available WRYM Release 7.5.6.7 which incorporates a number of new sub-models designed to support the explicit modelling of water resource system components in various studies. Detailed information in this regard may be obtained from the Water Resources Yield Model (WRYM) User Guide – Release 7.4 (WRP, 2007).

2.1.3 WRPM

The WRPM is similar to the WRYM, but uses short term yield reliability relationships of sub-systems to determine for a specific planning horizon what the likely water supply volumes will be, given starting storages, operating rules, user allocation and curtailment rules. The model is used for operational and future planning of reservoirs and inter-dependent systems, and provides insight into infrastructure scheduling, probable curtailment interventions and salt blending options.

A unique feature of the analysis methodology is the capability of the WRPM to simulate drought curtailments for water users with different risk requirements (profiles) receiving water from the same resource (see Basson et. Al, 1994 for a technical description). This methodology makes it possible to evaluate and implement adaptive operating rules (transfer rules and drought curtailments) that can accommodate changing water requirements (growth in water use) as well as future changes in infrastructure (new transfers, dams and/or dam raisings) in a single simulation model. By combining these simulation features in one model gives the WRPM the ability to undertake risk based projection analysis for **operation** and **development** planning of water resource systems. The WRPM therefore simulates all the interdependencies of the aforementioned variables and allow management decisions (operational and/or developmental) to be informed by results where all these factors are properly taken into consideration.

2.1.4 Model input requirements

Both the WRYM and WRPM require inputs in order to carry out a simulation. These inputs are included in specific data files which can be modified to cater for varying scenarios. The executable version of the model remains unchanged per scenario, is not "hard coded" to simulate a specific operating rule, these are defined in the data files. The inputs required include the following:

- Natural hydrology time series files for each sub-catchment, obtained as outputs from the rainfall-runoff calibration exercise;
- Climate data including rainfall and evaporation for each hydrological sub-catchment;
- Infrastructure details including reservoir sizes and characteristics and water conveyance structure capacity constraints;
- Current and future demand projections;
- Current and future operating rules for dams, order or preference of use for multi resource schemes;
- Current and future operating rules for users, required assurance of supply, priority of various users and access to resources;
- Future potential schemes to be analysed;
- Parameter file specifying stochastic parameters for each hydrological catchment.

2.1.5 Model output and applications

The WRYM and WRPM provide results for specific purposes as described in the following points:

- **WRYM:** The WRYM provides historic and stochastic yields available from a specific resource or combined set of resources. The model is used to assess which operating rule provides the highest yield for a scheme and is used to determine short term yield capabilities based on varying starting storages of the resource.
- **WRPM:** The WRPM uses the results of the WRYM to carry out future projection scenarios based on increasing demands and potential scheme augmentations. Short term operation is carried out based on starting storages and the model provides results of whether or not the scheme can expect a shortfall or surplus in a 5 to 10 year operating period. Longer projection periods assess whether the planned future schemes are sufficient to supply users at their required assurance levels and when new intervention options will be required to achieve this over the long term.

2.2 PREVIOUS WORK AND CURRENT UPDATE

This report focusses on the WRYM analyses. This and the following sections will therefore address the WRYM related work and results. The WRPM related work will be covered in a future separate report.

The WRYM was configured as part of the Integrated Water Resources Management Plan for the Orange-Senqu Basin Phase 2 study. The main focus of that study was to incorporate the newly updated hydrology (also part of the study) into the WRYM, to update demands based on recent information and finally to confirm that the model was operating correctly by comparing the main system historic yields with previous results.

The WRYM has been taken one step further in this study, where again updates to demands have taken place based on new information gathered as part of Work Package 4b of this study. The model was then used to determine yields, both historic and stochastic, for selected sub-systems of the Orange-Senqu Basin.

3 Current general operation of the system

The general operating rules of the system as explained in this section, refer to the basic operating rules used for yield analysis purposes. These rules are further refined in the WRPM where rules are added to protect the resource by implementing restrictions at times when the reservoir levels get too low. Details of these refined operating rules will be given in the second report to be produced as part of this work package. The second report will focus on the WRPM scenario analysis.

3.1 VAAL RIVER COMPONENT

The Bloemhof sub-system (see Figures 6, 7 and 9 in Annex 1) forms the core of the Integrated Vaal River System and includes Grootdraai Dam, Vaal Dam, Vaal Barrage, Bloemhof Dam and Sterkfontein Dam as the main storage dams as well as Woodstock and Driel Barrage in the Upper Thukela that forms part of the Thukela transfer system. The operating rules used for the WRYM analysis of the Bloemhof sub-system include the following:

- Grootdraai Dam does not support Vaal Dam. Only spills from Grootdraai can therefore be utilised by Vaal Dam. Grootdraai Dam is used mainly to supply SASOL and Eskom power stations with water.
- Transfers from Tugela continue until Sterkfontein Dam is full
- Sterkfontein Dam start to support Vaal Dam only when Vaal Dam is at 15% or lower storage
- Vaal Dam releases water to support the abstractions at Sedibeng and Midvaal if local runoff and spills are insufficient.
- Vaal Dam only starts to support Bloemhof Dam when Bloemhof reaches its m.o.l.

The demands imposed on the Bloemhof sub-system are replaced by “yield channels” when carrying out a yield analyses to be able to determine the yield available from this entire sub-system. All the smaller sub-systems located on the tributaries of the Vaal River are included in the data sets. The 2010 demands are imposed on these sub-systems. These sub-systems do not support the Bloemhof sub-system and only spills from these sub-systems enter the Bloemhof sub-system and can contribute to the Bloemhof sub-system yield. These sub-systems (see Figures 10, 7 and 9 in Annex 1) include:

- Schoonspruit sub-system with Rietspruit, Elandskuil and Johan Neser dams
- Renoster sub-system with Koppies Dam
- Sand-Vet sub-system including Allemanskraal and Erfenis dams
- Mooi River sub-system that includes the Mooi River Government Scheme comprising of Klerkskraal, Boskop and Lakeside dams as well as the Klipdrift Irrigation scheme using Klipdrift Dam in the Loopspruit River, a tributary of the Mooi River.

Operating rules and related penalties for these sub-systems are selected to allow them to be operated as individual systems without supporting the main Vaal system. In the WRYM setup these sub-systems will supply the demand imposed on them until the dam reaches the defined minimum operating level whereafter only the water available will be supplied to it’s users.

For the Lower Vaal sub-system, Bloemhof Dam is used to support various demands downstream of the dam. The largest of these demands is that of the Vaalharts Irrigation scheme, which also generates a considerable volume of return flows. The different sub-systems in the Lower Vaal were treated in the same manner as those located in the Middle and Upper Vaal. These sub-systems (see Figure 10 in Annex 1) include:

- Wentzel Dam sub-system on the Upper Harts River
- Taung Dam sub-system on the Middle Harts River
- Spitskop Dam sub-system on the Lower Harts River receiving return flows from the Vaalharts scheme

3.2 THE ORANGE RIVER COMPONENT

Although the Modder/Riet rivers are tributaries to the Vaal River, this catchment and related sub-systems are seen as part of the Orange River System due to transfers and support from the Orange to the Modder/Riet catchment.

The Orange River System includes two major water supply systems, the Orange River Project (ORP) (Figures 2 and 5 in Annex 1) and the Caledon Modder sub-system (Figures 1 and 2 Annex 1). The ORP comprises Gariep and Vanderkloof dams with its entire supply area, covering the Eastern Cape Sundays/Fish area, the entire Orange River from Gariep Dam to the river mouth at Alexander Bay and Oranjemund as well as transfers to the Riet/Modder.

The ORP sub-system is set up so that the Vaal River system is not used to support any of the demands in the Orange River as the Vaal River is in practice operated as such. The Vaal River system is supported by several transfer systems and the operating rules were therefore developed to minimise the spilling of expensive transferred water into the Orange River. Spills from the Vaal can also not be utilized by Lower Orange demands as in practice the total demand for the Lower Orange is released from Vanderkloof Dam, without taking into account inflows from the Vaal as the Vanderkloof releases take approximately one month to reach the river mouth. To be able to model this in the WRYM, channels parallel to the main Orange are included in the model setup so that Orange River demands cannot utilize these spills. Inflows from tributaries along the Lower Orange are also routed through these parallel channels.

The demands in the Eastern Cape as well as demands between Gariep and Vanderkloof dams can only be supplied from Gariep Dam. The remainder of the demands imposed on the ORP is supplied from Vanderkloof Dam with support from Gariep Dam. Releases from these two dams into the river to supply downstream demands are simultaneously used to generate hydro-power. The releases from Vanderkloof Dam follows the monthly distribution pattern of the demands downstream which is mainly driven by irrigation, thus high requirements in the summer and low requirements in the winter. For hydro-power purposes an inverse pattern is in general required as the power demand in the winter is higher than in the summer. To accommodate this requirement, the release pattern from Gariep Dam follows the inverse pattern of the irrigation requirement, allowing more power to be generated in the winter months from Gariep Dam. The monthly distribution pattern is then again corrected by the releases from Vanderkloof Dam located not far downstream of Gariep Dam.The volume of water released from Gariep Dam is however limited to the total downstream requirement plus the short-term surplus available in the system. The surplus available over the short-term is determined every year by means of a detail WRPM analysis and it depends on the storage level and the total demand imposed on the two dams in the particular year under consideration.

3. CURRENT GENERAL OPERATION OF THE SYSTEM

To protect the users that can only obtain water from Gariep Dam, the operating rule dictates that releases in support of Vanderkloof Dam will not take place when Gariep Dam is below 15% of its live storage. The only releases that will then be made from Gariep Dam will the water required to supply the users between Gariep and Vanderkloof Dam. When Vanderkloof Dam however reaches its minimum operating level (m.o.l.) releases will again be made from Gariep Dam in support of Vanderkloof Dam, keeping Vanderkloof just above its m.o.l.

The m.o.l.'s for hydro-power generation purposes are in both dams slightly higher than the m.o.l. for releases in support of the demands in Eastern Cape (Orange Fish tunnel intake) in Gariep Dam and the releases into the Vanderkloof main canal. For yield purposes the lower m.o.l. were used in both dams to determine the maximum yield available for the users, not for hydro-power purposes. None of the dams located upstream of Gariep Dam in the Caledon or in the Senqu basin are used to support the ORP.

The Caledon/Modder sub-system comprise the Knellpoort and Welbedacht dams in the Caledon River catchment with Rustfontein and Mockes dams in the Modder River catchment. This sub-system is used to supply Bloemfontein, Mangaung, Botshabelo, Thaba N'chu and several other small towns with water (See Figures 1 and 2 Annex 1).

The bulk of the water supplied from the Caledon/Modder sub-system comes from the Caledon due to significantly higher runoff produced in the Caledon catchment. To be able to obtain the maximum possible yield from the combined system (Caledon plus Modder river dams) spesific operating rules were developed to achieve this. These operating rules also take into account the limited transfer capacities from Knellpoort to Rustfontein Dam and from Welbedacht Dam to Bloemfontein. The operating rule therefore dictates that water is taken first from Welbedacht Dam to the maximum capacity of the transfer system. When there is not sufficient water in Welbedacht Dam, releases will be made from Knellpoort Dam to support the maximum transfer rate from Welbedacht Dam. This will be followed by taking water from Mockes Dam until Mockes reaches 25% storage level. At that Level releases will be made from Rustfontein Dam in support of Mockes, keeping Mockes at its 25% live storage level. When Rustfontein drops below its 90% live storage level, transfers from Knellpoort to Rustfontein starts at the maximum transfer capacity of the system, trying to keep Rustfontein at 90%. As some demands can only be supplied from Rustfontein Dam, an operating level at 5% of its live storage was introduced in Rustfontein Dam at which releases in support of Mockes Dam will stop. The remainder of the storage in Mockes Dam below the 25% level will then be used. Only when Mockes Dam reaches its m.o.l will releases from Rustfontein Dam in support of Mocked Dam be made.

Knellpoort Dam is an off channel storage dam and is filled mainly by means of water pumped from Tienfontein pump station in the Caledon River. The operating rule dictates that whenever sufficient water is available in the Caledon River, water must be pumped into Knellpoort Dam until Knellpoort Dam reaches its 90% storage level. Only then pumping will be stopped.

The 2012 demands for Bloemfontein, Botshabelo and small towns are imposed on the Caledon Modder sub-system and transfers from the Caledon to the Modder as described above are in place. It is however important to note that whenever any of the transfer or pump capacities changes, the operating rule will need to be revised.

A number of smaller sub-systems are located in the Modder/Riet catchment (See Figure 2 Annex 1). These smaller sub-systems were treated in the same manner as those located in the Middle and Upper Vaal and include the following:

- Krugersdrift Dam on Modder River
- Groothoek Dam on a tributary of the Modder River
- Tierpoort Dam Upper Riet River tributary
- Kalkfontein Dam on the Riet River

Several smaller sub-systems are also found in the Upper, Middle and Lower Orange which is operated as individual systems that are not used to support any of the ORP demands. These typically include:

- Caledon/Mohokare Maseru supply system, river abstraction and off channel storage (Maqalika Dam) with Metolong Dam recently completed
- Ongers sub-system including Smartt Syndicate and Victoria Wes dams
- Hartbees River sub-system including Modderpoort, Loxton, Van Wyksvlei and Rooiberg dams
- Molopo sub-system RSA including Lotlamoreng, Setumo and Disaneng dams
- Molopo sub-system Namibia including Daan & Tilda Viljoen and Otjivero dams
- Fish River sub-system (Namibia) including Hardap and Naute dams with Neckartal Dam of which the construction just started,

Operating rules and related penalties for these sub-systems were selected to allow them to be operated as individual systems without supporting the demands related to the ORP. These sub-systems will supply the demand imposed on them until the dam reaches the defined minimum operating level, when only the water available will be supplied to it's users..

3.3 THE SENQU COMPONENT

The Senqu catchment includes only one major water supply system referred to as the Lesotho Highlands Water Project (LHWP) used to transfer water to the Vaal system. This system currently comprises Katse and Mohale dams as well as the Matsoku diversion weir (See Figure 1 Annex 1).

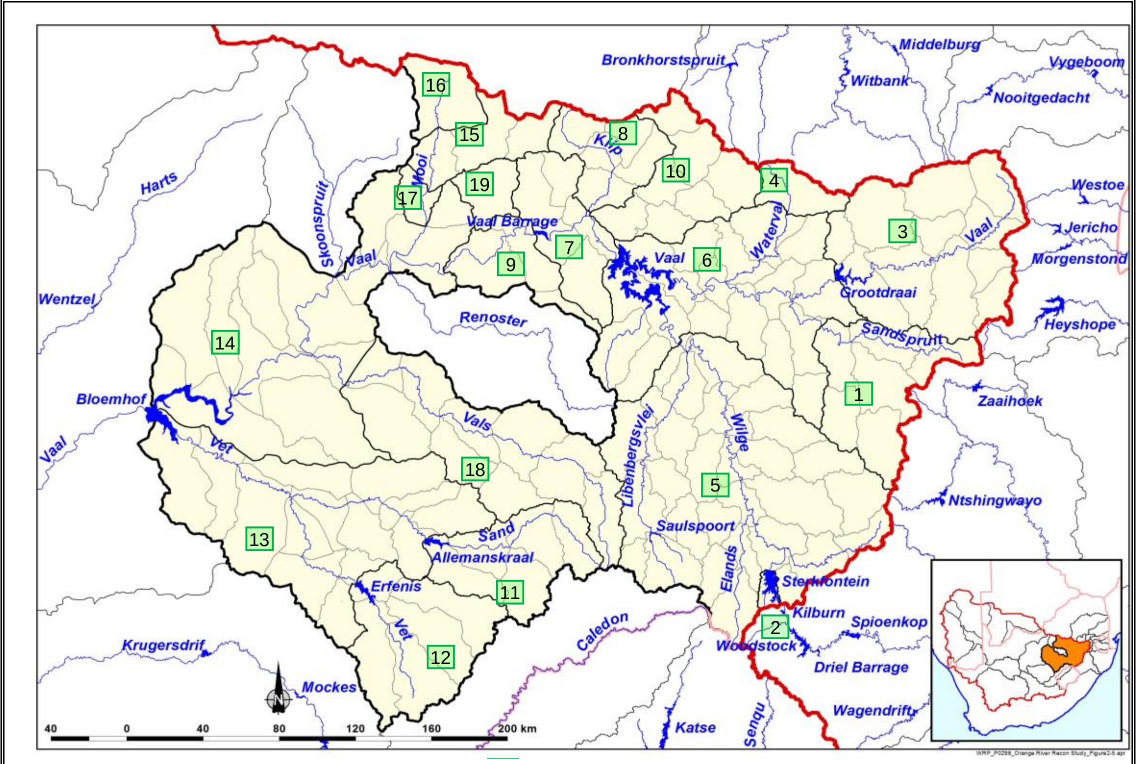
The operating rules are set up in such a manner that Katse and Mohale dams are not able to support Gariep and Vanderkloof dams. Only spills and environmental releases from these dams can flow into Gariep Dam. The 2012 transfer rate of 780.19 million m^3/a that is applicable to the Lesotho Highlands project, was imposed on Katse and Mohale dams. The operating rule between Katse and Mohale dams dictates that water is first taken from Katse Dam to supply the full transfer to the Vaal until Katse Dam reaches the 86% storage level. Below this level Mohale Dam starts to support Katse Dam. The flow volume from Mohale Dam to Katse Dam is controlled by the tunnel capacity and the difference in the water level between Katse and Mohale dams. Available river flow is diverted from Matsoku Weir to Katse Dam, after allowing for environmental requirements downstream of Matsoku Weir. The maximum flow through the tunnel between Matsoku Weir and Katse Dam is governed by the tunnel capacity and difference in the water level between Katse Dam and Matsoku Weir.

There are no smaller sub-systems currently existing in the Senqu catchments except for several run-off river abstractions for small towns and villages in the catchment.

4 Hydrology

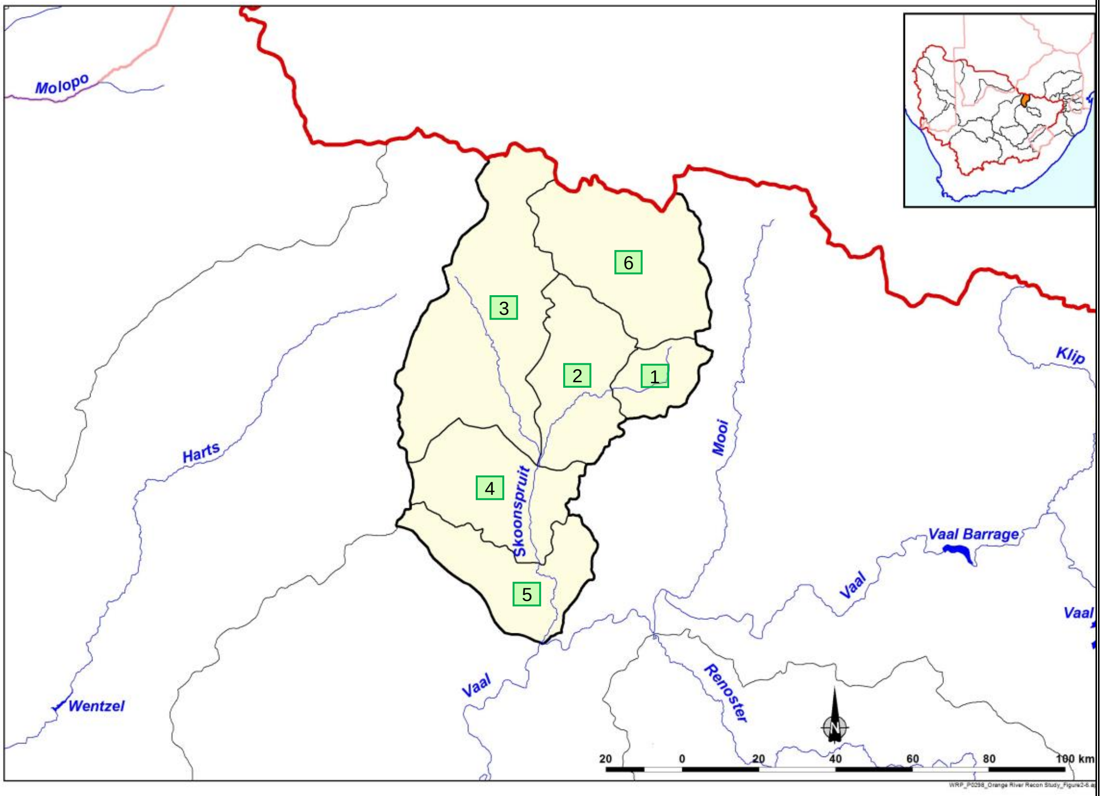
A set of 212 hydrology's cover the integrated Orange-Senqu River catchment and when Eastern Cape is added it increases to 248. The Orange-Senqu is divided into 16 main catchment areas, as presented in Figure 1 of Annex 3. The figures and tables which follow present the locations and statistics of the hydrologies of all these catchment areas.

4.1 VAAL RIVER



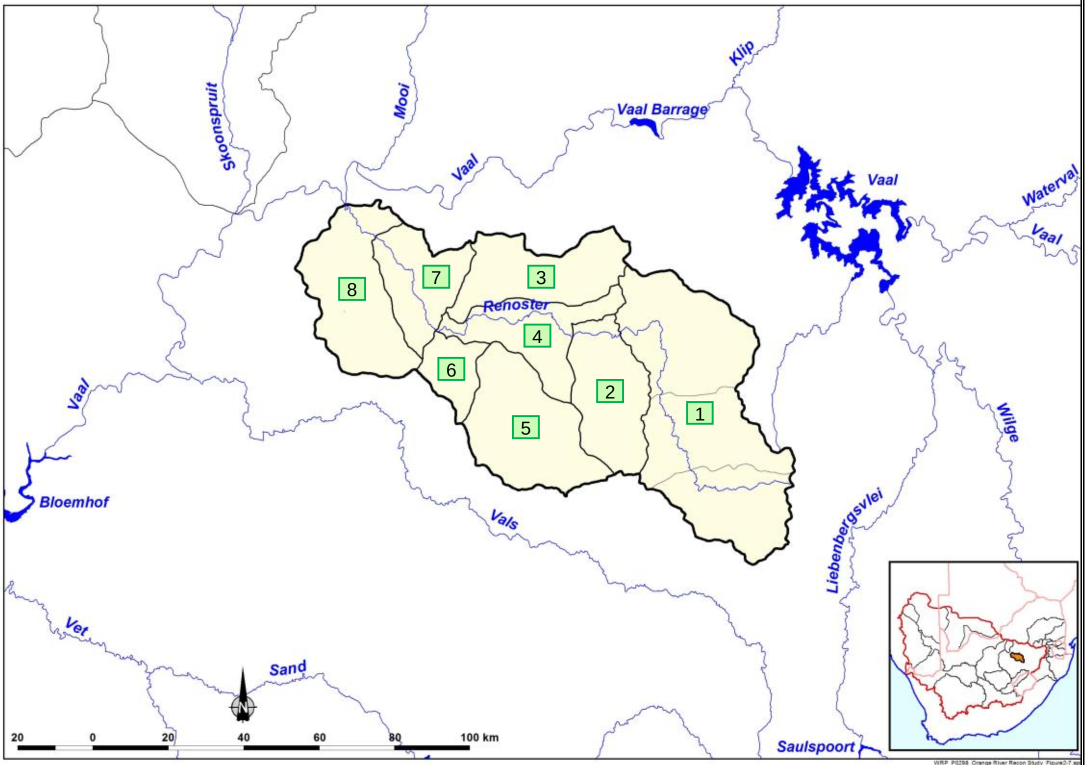
Locality map reference	Param.dat order no.	Hydrology reference name	MAR (million m3/annum)	Standard deviation	Coefficient of variation
1	7	FRAN4	760.01	645.15	0.85
2	19	STERK4	19.53	14.83	0.76
3	8	GROOTD4	462.02	375.21	0.81
4	205	C12D4	77.38	49.17	0.64
5	5	DELA4	261.14	216.56	0.83
6	21	VAAL4	493.19	463.45	0.94
7	2	BARR4	72.24	55.66	0.77
8	12	KLIPR4	102.66	79.22	0.77
9	14	KROMN4	42.04	40.23	0.96
10	20	SUIK4	99.87	98.20	0.98
11	1	ALLEM4	94.90	85.21	0.90
12	6	ERF4	163.59	151.48	0.93
13	18	SANDN4	160.21	162.66	1.02
14	3	BLOEMN3D4	130.60	148.06	1.13
15	4	BOSK4	37.54	17.24	0.46
16	9	KLERK4	39.73	29.17	0.73
17	197	LAKESN4	9.68	7.32	0.76
18	10	KLIPBN4	153.29	147.05	0.96
19	11	KLIPDN4	21.19	23.10	1.09

4.2 SCHOONSPRUIT



Locality map reference	Param.dat order no.	Hydrology reference name	MAR (million m^3/annum)	Standard deviation	Coefficient of variation
1	128	C24D4	7.35	10.35	1.41
2	129	C24E4	9.81	14.78	1.51
3	130	C24F4	19.55	28.77	1.47
4	131	C24G4	16.91	24.68	1.46
5	132	C24H4	8.50	13.41	1.58
6	59	C24CEYE4	46.82	24.94	0.53

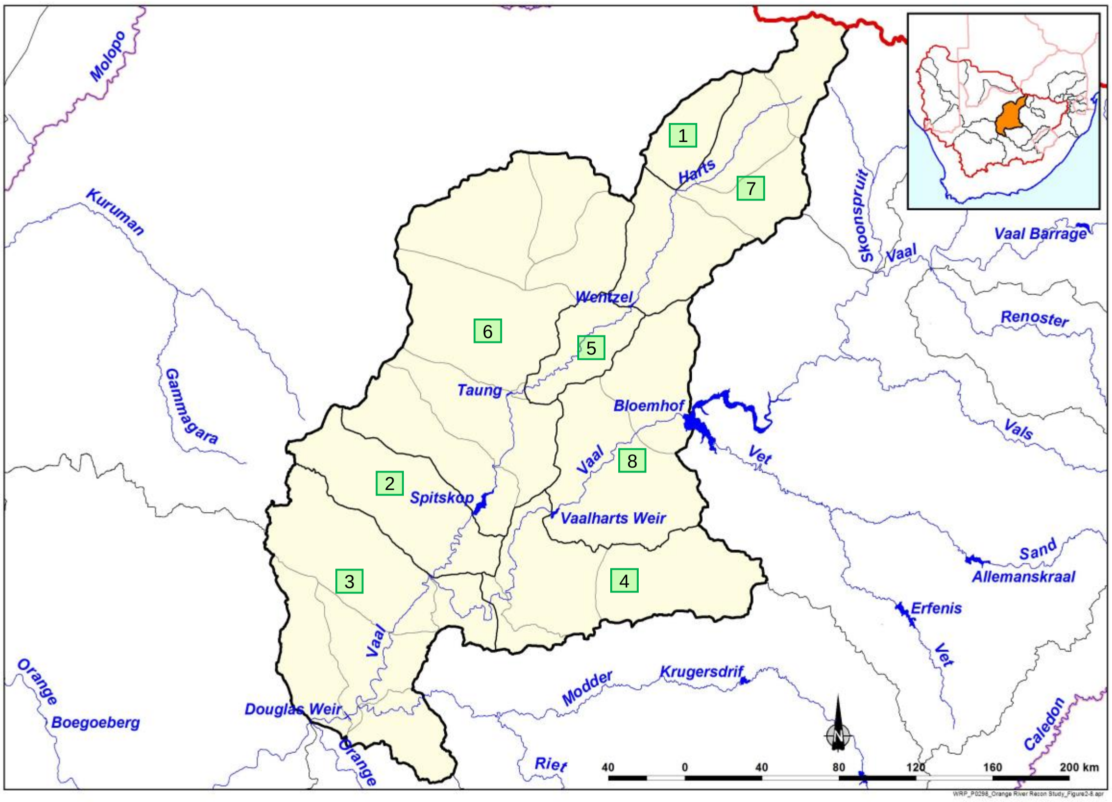
4.3 RENOSTER



WRP_P0298_Orange River Recon Study_Figure2-7.ap

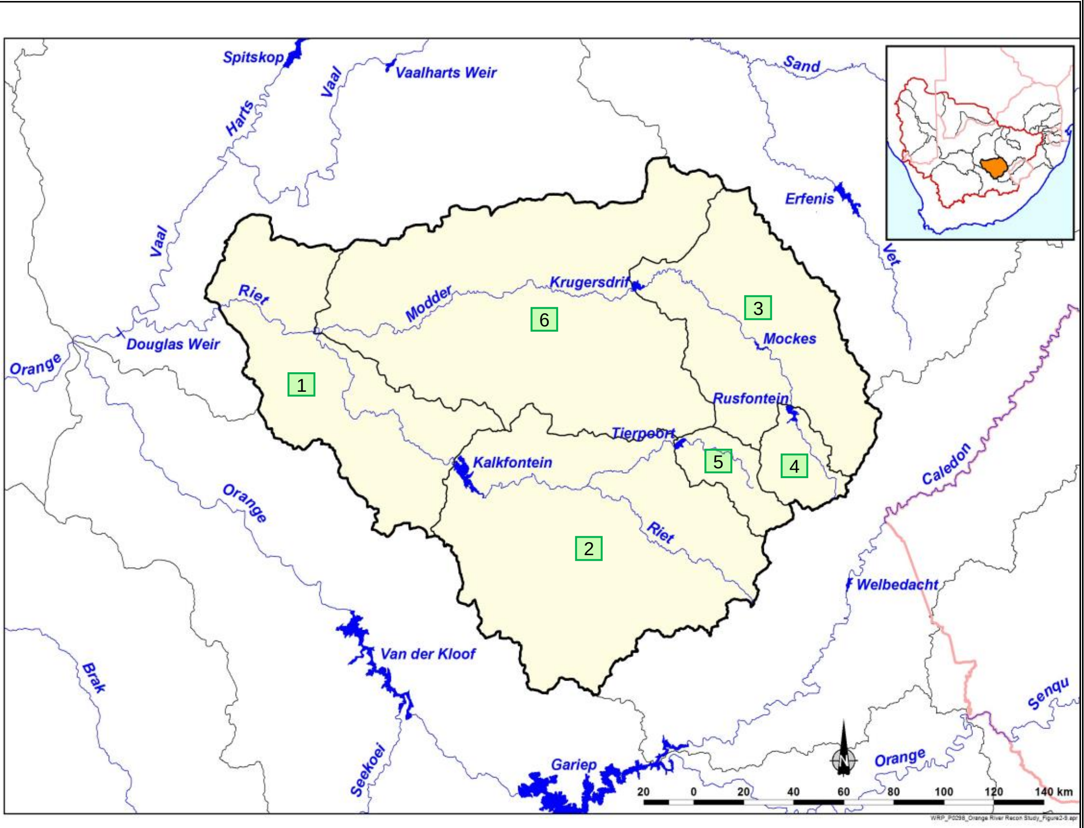
Locality map reference	Param.dat order no.	Hydrology reference name	MAR (million m^3/annum)	Standard deviation	Coefficient of variation
1	13	C70ABC4	61.11	52.91	0.87
2	191	C70D4	12.60	11.52	0.91
3	192	C70E4	11.97	10.89	0.91
4	193	C70F4	9.46	8.60	0.91
5	194	C70G4	14.16	12.64	0.89
6	195	C70H4	3.98	3.62	0.91
7	196	C70J4	8.58	7.76	0.90
8	127	C70K4	10.25	11.08	1.08

4.4 LOWER VAAL



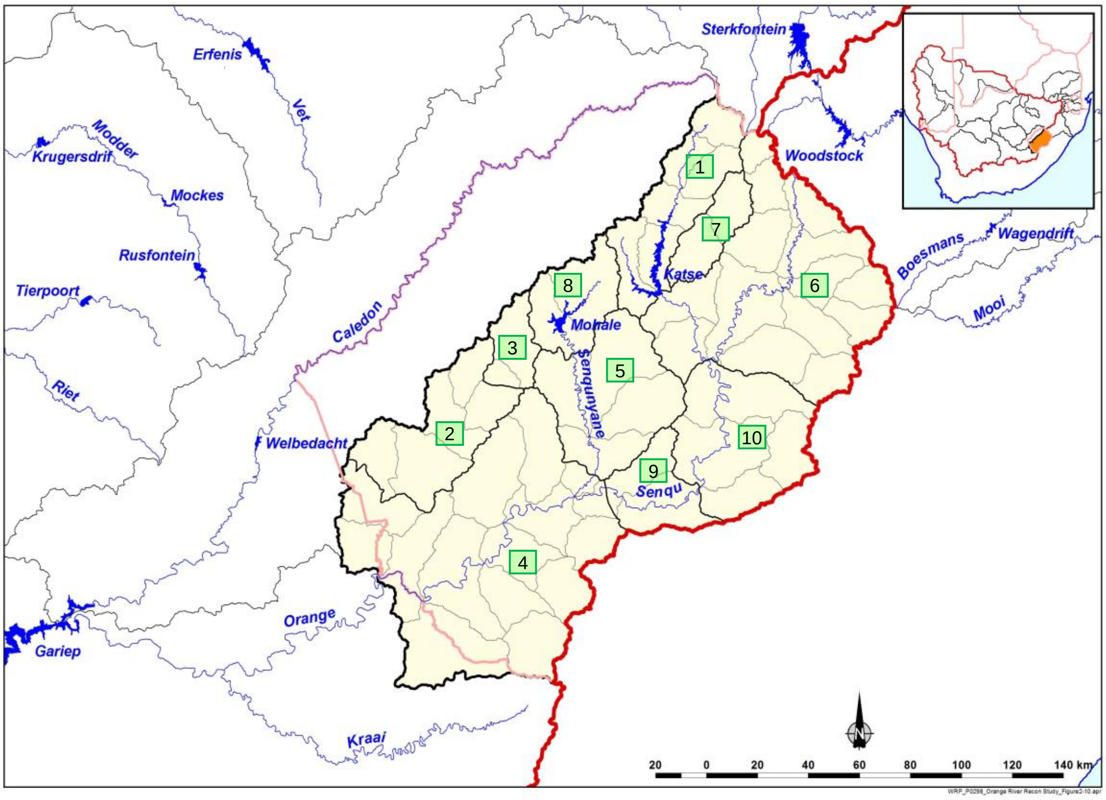
Locality map reference	Param.dat order no.	Hydrology reference name	MAR (million m^3/annum)	Standard deviation	Coefficient of variation
1	180	BARBERS4	2.94	4.44	1.51
2	183	C3H0134	11.71	39.08	3.34
3	184	C9H0074	18.63	62.15	3.34
4	35	DEHOOP4	15.32	25.07	1.64
5	182	DSWENTZD4	12.11	18.27	1.51
6	37	SPITS4	81.29	141.23	1.74
7	181	USWENTZD4	39.49	59.58	1.51
8	39	VHARTS4	9.97	18.29	1.84

4.5 RIET - MODDER



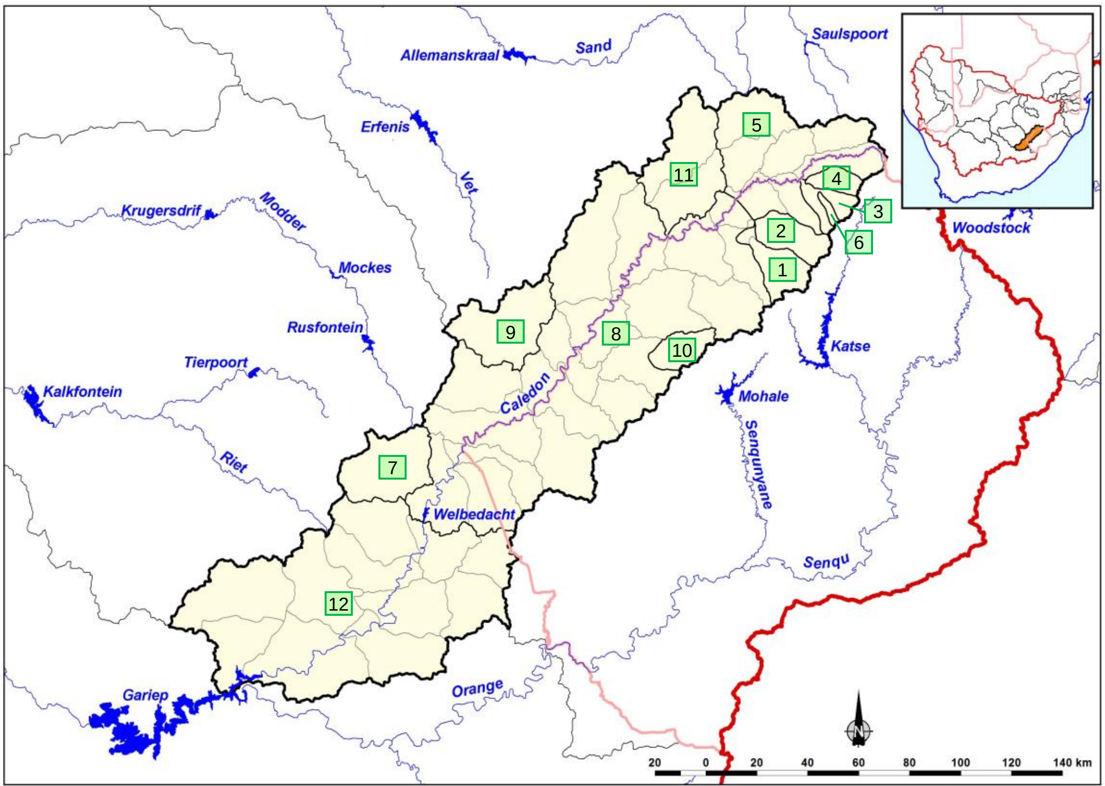
Locality map reference	Param.dat order no.	Hydrology reference name	MAR (million m^3/annum)	Standard deviation	Coefficient of variation
1	40	AUCH4	5.80	18.13	3.12
2	41	KALKF4	185.85	270.33	1.45
3	42	KRUG4	118.06	129.84	1.10
4	43	RUSTF4	30.96	41.80	1.35
5	44	TIER4	23.23	29.43	1.27
6	45	TWEE4	15.67	24.36	1.56

4.6 SENQU



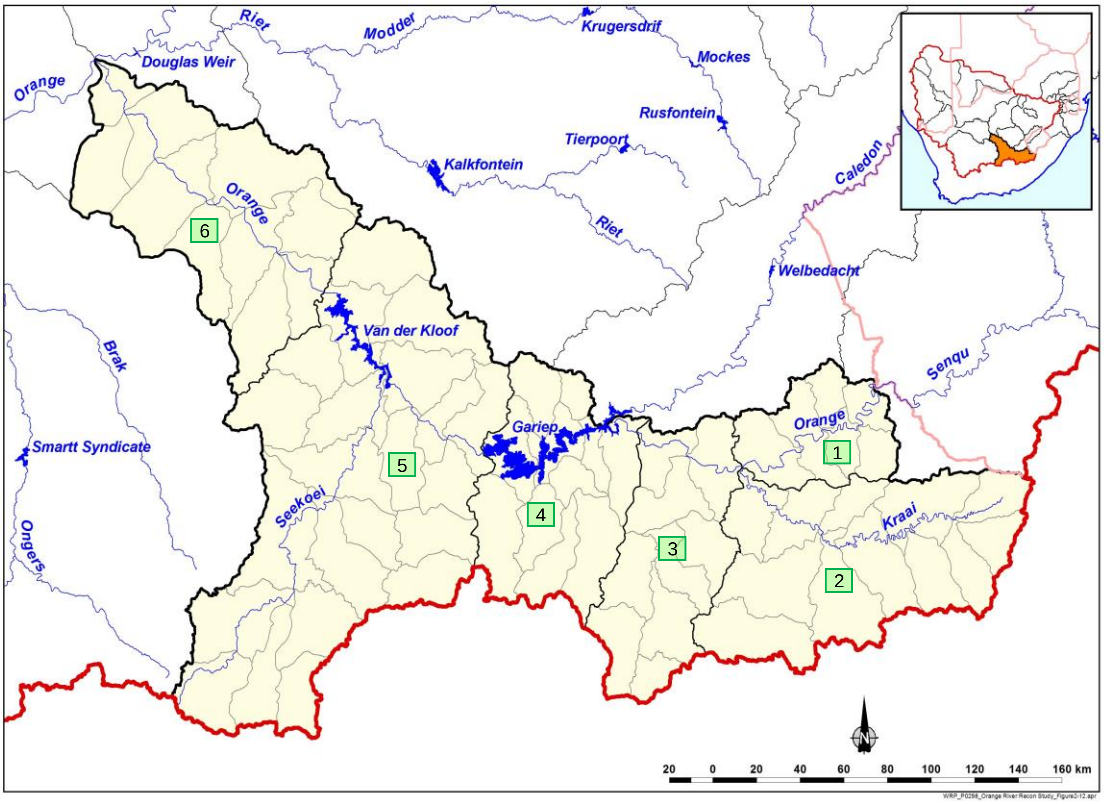
Locality Map Ref.	Param.dat order no	Hydrology reference name	MAR (million m^3/annum)	Standard deviation	Coefficient of Variation
1	27	KAT10	559.44	231.28	0.41
2	178	MAKABS	354.83	182.01	0.51
3	179	MAKDAM	169.70	87.05	0.51
4	33	ORAN10	1018.20	522.31	0.51
5	28	MAL10	291.72	146.16	0.50
6	29	MAS10	792.91	440.50	0.56
7	30	MAT10	98.11	51.36	0.52
8	31	MOH10	303.24	125.23	0.41
9	32	NTO10	154.55	87.00	0.56
10	34	TSO10	362.64	180.92	0.50

4.7 CALEDON



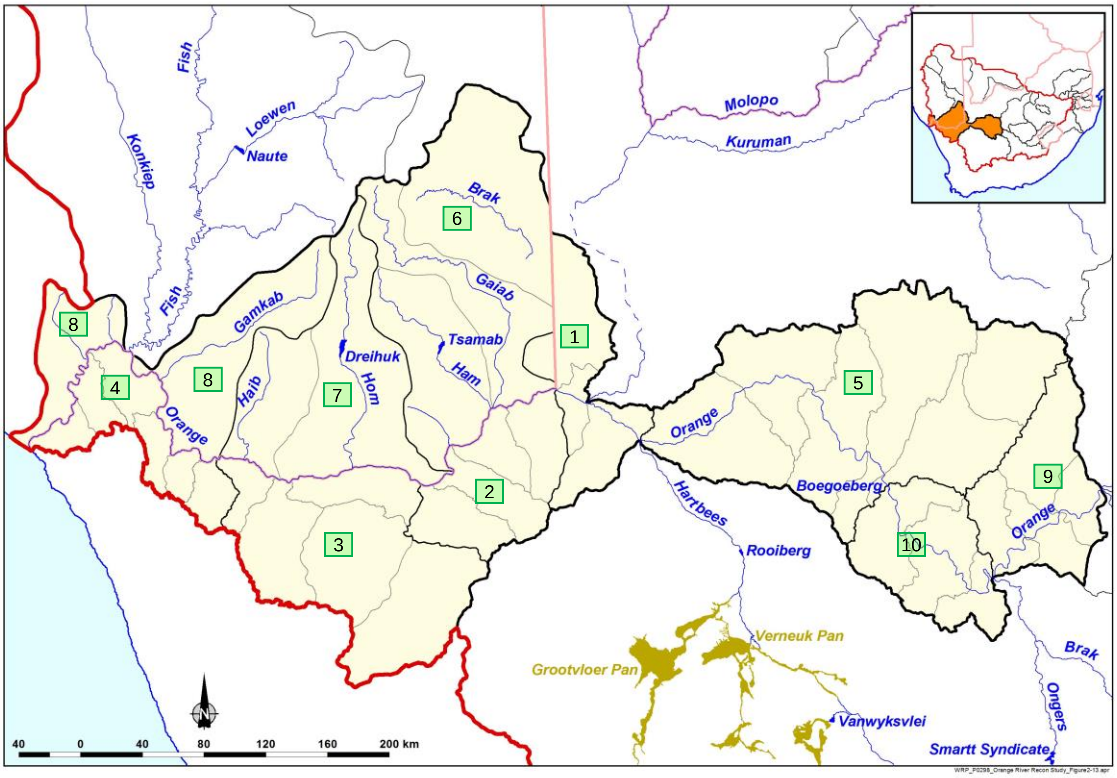
Locality map reference	Param.dat order no.	Hydrology reference name	MAR (million m^3/annum)	Standard deviation	Coefficient of variation
1	173	HLOABS	103.94	43.72	0.42
2	70	HLODAM	99.48	43.39	0.44
3	175	HOLABS	43.72	24.71	0.57
4	174	HOLDAM	36.34	16.59	0.46
5	71	KATJREST	206.83	138.47	0.67
6	177	MUELA	5.91	3.34	0.57
7	72	KNELL	17.57	23.20	1.32
8	78	WELINC	556.42	430.91	0.77
9	176	ARMEN	30.08	27.63	0.92
10	172	METO	61.83	47.88	0.77
11	77	WATER	63.64	59.84	0.94
12	207	D24	151.65	221.84	1.46

4.8 UPPER ORANGE



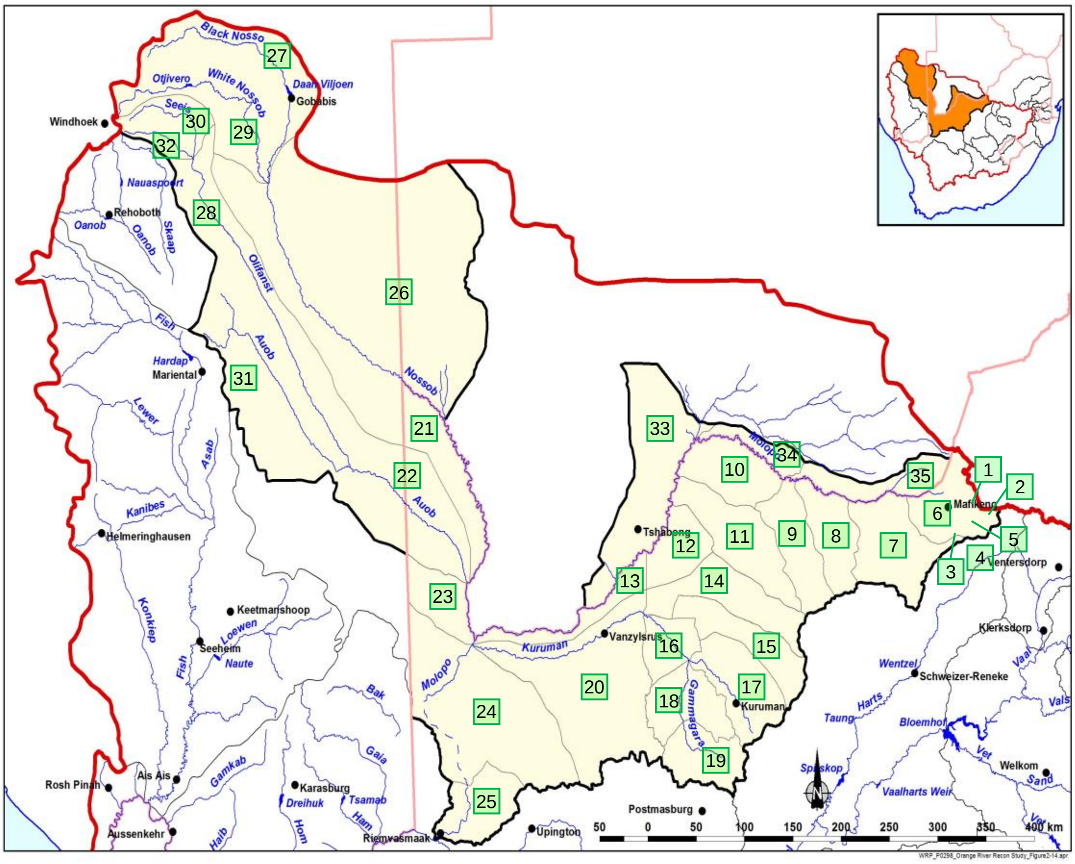
Locality map reference	Param.dat order no.	Hydrology reference name	MAR (million m^3/annum)	Standard deviation	Coefficient of variation
1	67	D12	165.74	167.66	1.01
2	74	D13	719.01	509.55	0.71
3	75	D14	127.82	193.47	1.51
4	69	D35	56.62	106.97	1.89
5	73	VDK	108.05	258.49	2.39
6	15	D33	14.24	29.95	2.10

4.9 LOWER ORANGE MAIN STEM



Locality map reference	Param.dat order no.	Hydrology reference name	MAR (million m^3/annum)	Standard deviation	Coefficient of variation
1	165	LOGR13	4.48	9.84	2.20
2	166	LOGR14	3.14	5.84	1.86
3	167	LOGR16	4.59	9.42	2.05
4	169	LOGR18	1.60	5.71	3.58
5	157	LOGR5	21.07	47.98	2.28
6	171	LOGR15	53.08	123.63	2.33
7	168	LOGR17	13.02	31.75	2.44
8	170	LOGR19	4.49	11.02	2.45
9	155	LOGR3	17.45	41.89	2.40
10	156	LOGR4	11.60	28.39	2.45

4.10 MOLOPO

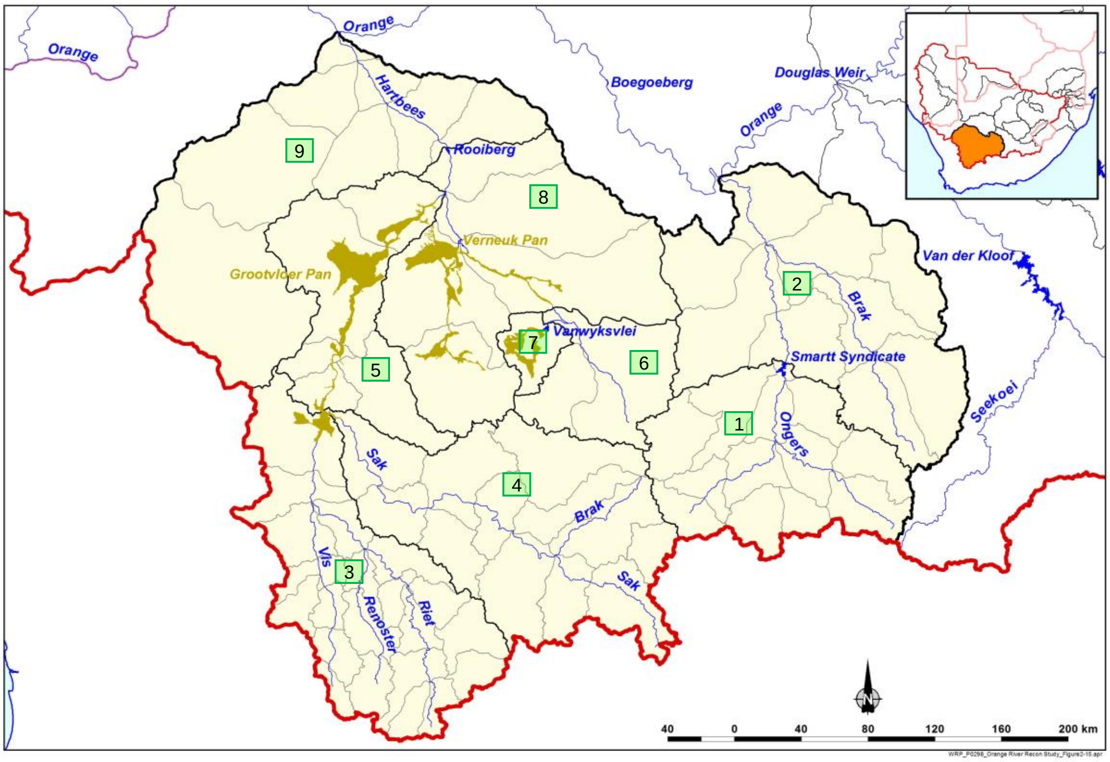


Locality map reference	Param.dat order no.	Hydrology reference name	MAR (million m^3/annum)	Standard deviation	Coefficient of variation
1	151	COM1113	0.27	0.88	3.30
2	66	COM2124	10.82	4.95	0.46
3	154	COM22	2.78	1.21	0.43
4	153	COM2327	0.02	0.14	6.89
5	152	GRO	0.12	0.74	6.22
6	17	D41ARED	5.06	8.12	1.61
7	48	D41B	12.76	18.49	1.45
8	49	D41C	9.65	17.03	1.76
9	50	D41D	5.99	11.05	1.84
10	51	D41E	0.67	1.30	1.94
11	52	D41F	1.94	3.81	1.96
12	60	D41G	0.85	1.86	2.21
13	139	D41J	0.10	0.40	3.96
14	61	D42A	1.58	3.43	2.18
15	53	D42B	7.13	12.67	1.78
16	65	D42C	0.89	1.64	1.85
17	64	D42D	18.02	45.45	2.52
18	63	D42E	4.53	12.37	2.73
19	62	D42F	3.66	10.07	2.75
20	140	D42G	1.05	3.89	3.69
21	136	D43C	0.22	0.88	3.97
22	137	D44C	0.01	0.05	5.51
23	138	D44D	0.01	0.06	4.80

4.10 MOLOPO

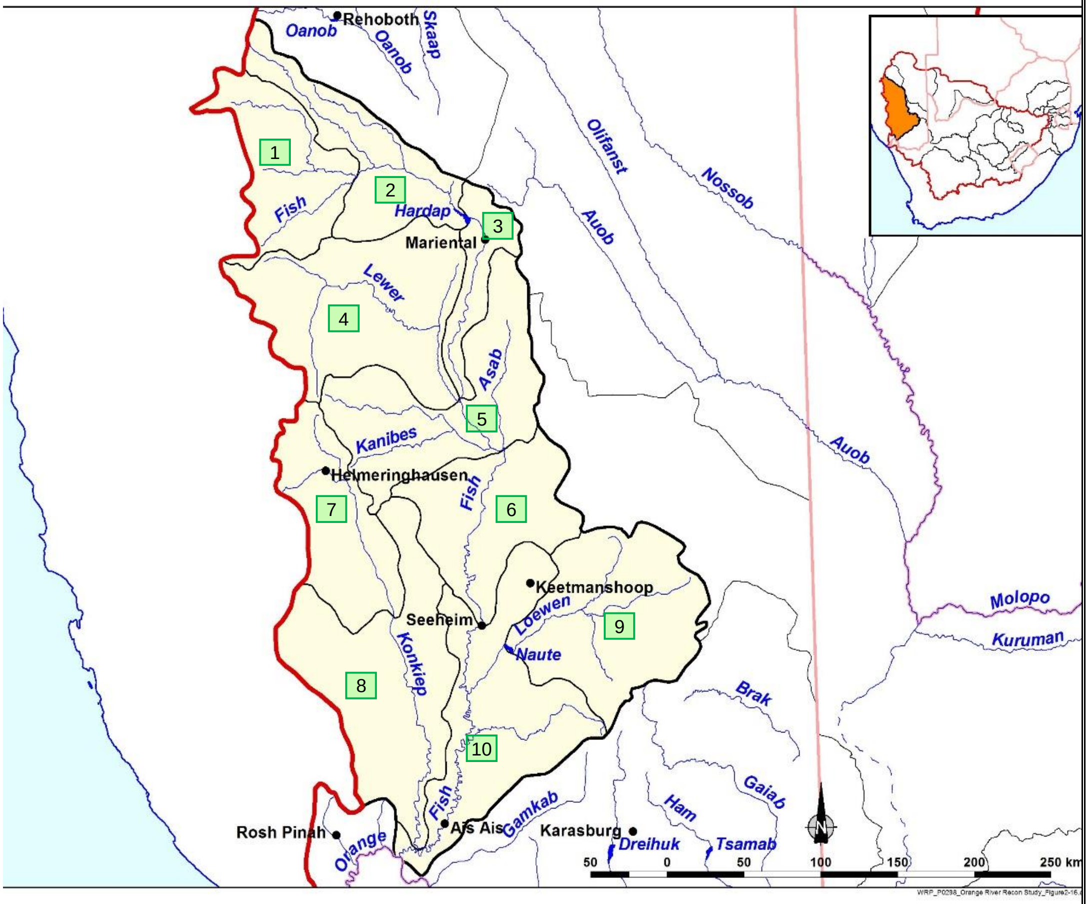
24	141	D45C	0.03	0.12	4.42
25	142	D45D	0.24	1.04	4.29
26	150	D43B	15.83	38.37	2.42
27	144	DVILJ	1.15	2.53	2.19
28	36	LOLIF	2.10	7.73	3.67
29	143	OTJV	1.15	2.53	2.19
30	56	SEEIS	0.88	2.48	2.82
31	24	UAUB	4.17	15.01	3.60
32	55	UOLIF	0.59	1.66	2.82
33	47	D41K	0.64	1.52	2.37
34	46	D41M	3.57	11.38	3.19
35	38	D41N	16.84	56.73	3.37

4.11 LOWER ORANGE TRIBUTARIES



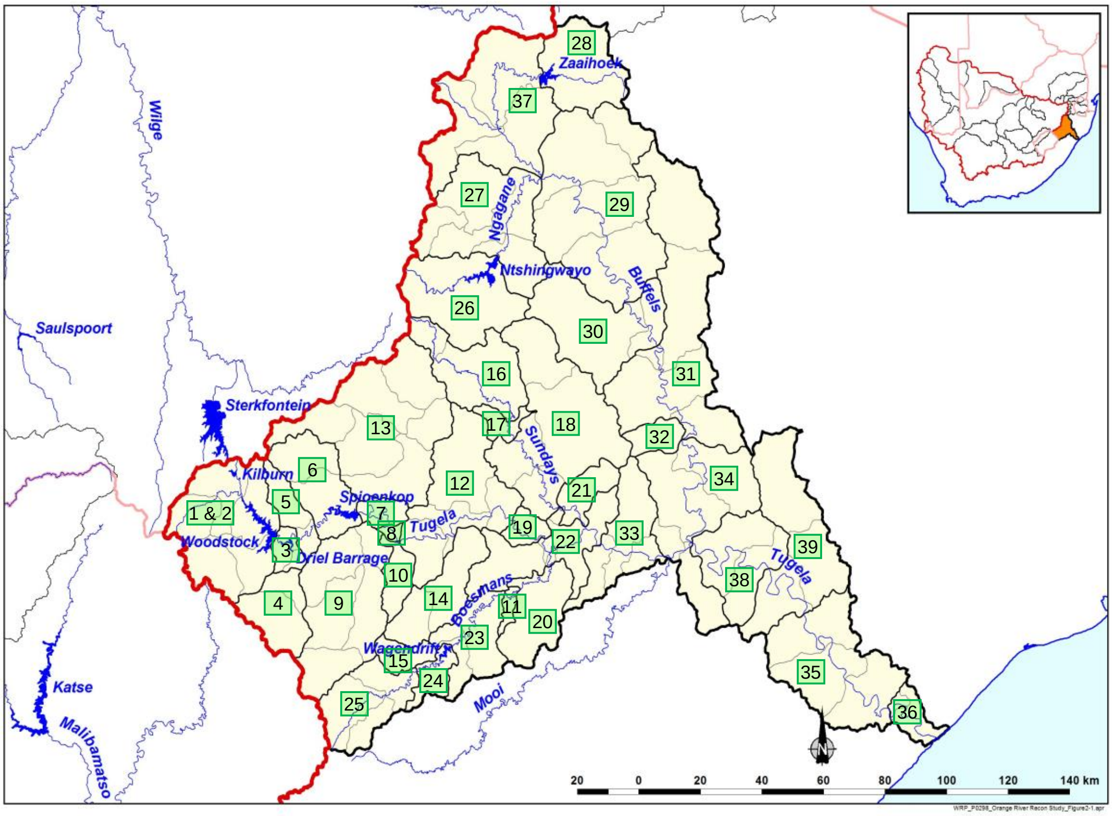
Locality map reference	Param.dat order no.	Hydrology reference name	MAR (million m^3/annum)	Standard deviation	Coefficient of variation
1	68	LOGR1	22.12	50.99	2.31
2	76	LOGR2	30.20	64.97	2.15
3	158	LOGR6	46.36	99.09	2.14
4	159	LOGR7	22.11	45.52	2.06
5	160	LOGR8	3.89	8.89	2.28
6	161	LOGR9	9.58	25.54	2.67
7	162	LOGR10	1.37	3.65	2.67
8	163	LOGR11	15.95	42.10	2.64
9	164	LOGR12	10.88	31.34	2.88

4.12 FISH RIVER



Locality map reference	Param.dat order no.	Hydrology reference name	MAR (million m^3/annum)	Standard deviation	Coefficient of variation
1	186	F1	94.63	162.42	1.72
2	187	F2	101.97	174.16	1.71
3	188	F3	36.70	65.52	1.79
4	189	F4	107.13	214.37	2.00
5	190	F5	82.56	135.14	1.64
6	208	F6	84.68	143.28	1.69
7	209	F7	4.74	17.03	3.60
8	210	F8	3.37	10.38	3.08
9	211	F9	76.21	157.32	2.06
10	212	F10	24.13	52.80	2.19

4.13 THUKELA



Locality map reference	Param.dat order no.	Hydrology reference name	MAR (million m^3/annum)	Standard deviation	Coefficient of variation
1	79	TM0194	76.30	31.62	0.41
2	80	TM0294	372.50	154.40	0.41
3	81	TM0394	20.24	9.96	0.49
4	82	TM0494	227.95	87.53	0.38
5	83	TM05A4	37.86	21.18	0.56
6	84	TM05B4	81.50	47.06	0.58
7	198	TM07A4	12.86	10.20	0.79
8	85	TM07B4	2.82	2.24	0.79
9	86	TM08A4	289.30	143.51	0.50
10	202	TM08B4	16.23	12.12	0.75
11	87	TM0994	7.10	6.26	0.88
12	88	TM1094	91.60	73.99	0.81
13	89	TM1194	231.30	132.94	0.57
14	90	TM1294	37.27	31.87	0.86
15	91	TM1394	20.05	10.30	0.51
16	92	TM1494	85.52	58.18	0.68
17	99	TM15A4	7.78	6.22	0.80
18	93	TM15B4	107.00	74.55	0.70
19	101	TM16A4	7.66	7.47	0.98
20	100	TM16B4	15.66	13.81	0.88
21	94	TM16C4	3.81	3.72	0.98
22	203	TM16D4	56.00	47.47	0.85
23	95	TM1794	33.55	23.29	0.69
24	96	TM1894	26.25	14.74	0.56

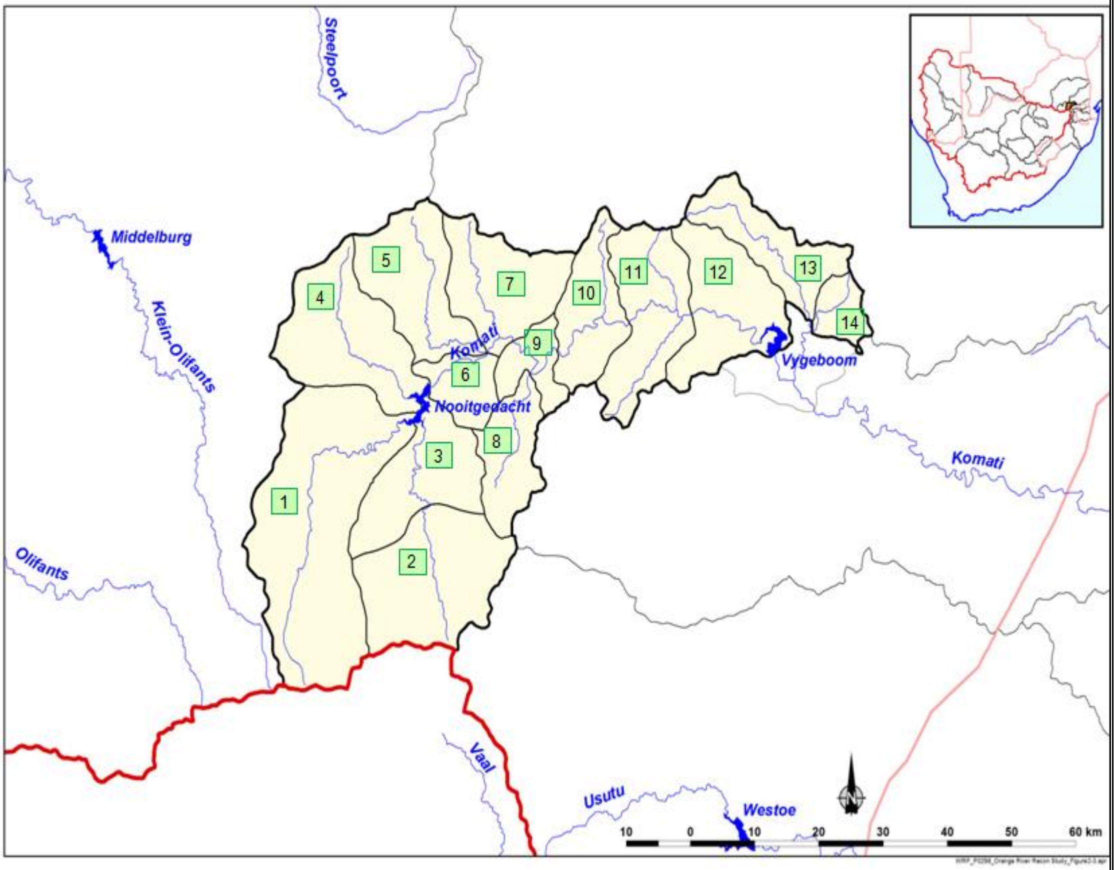
4.13 THUKELA

25	97	TM1994	207.10	80.12	0.39
26	102	TM2494	110.83	67.84	0.61
27	103	TM2594	140.39	84.11	0.60
28	104	TM2694	99.99	60.56	0.61
29	105	TM2794	164.72	145.25	0.88
30	106	TM289_A4	65.93	47.33	0.72
31	199	TM289_B4	142.69	113.47	0.80
32	200	TM289_C4	13.59	10.51	0.77
33	98	TM29A4	38.52	40.02	1.04
34	107	TM29B4	81.19	58.65	0.72
35	108	TM30A4	160.98	111.52	0.69
36	204	TM30B4	35.33	24.48	0.69
37	109	TM3194	148.16	98.53	0.67
38	110	TM329_A4	63.79	44.49	0.70
39	201	TM329_B4	97.95	68.32	0.70

4.14 OLIFANTS

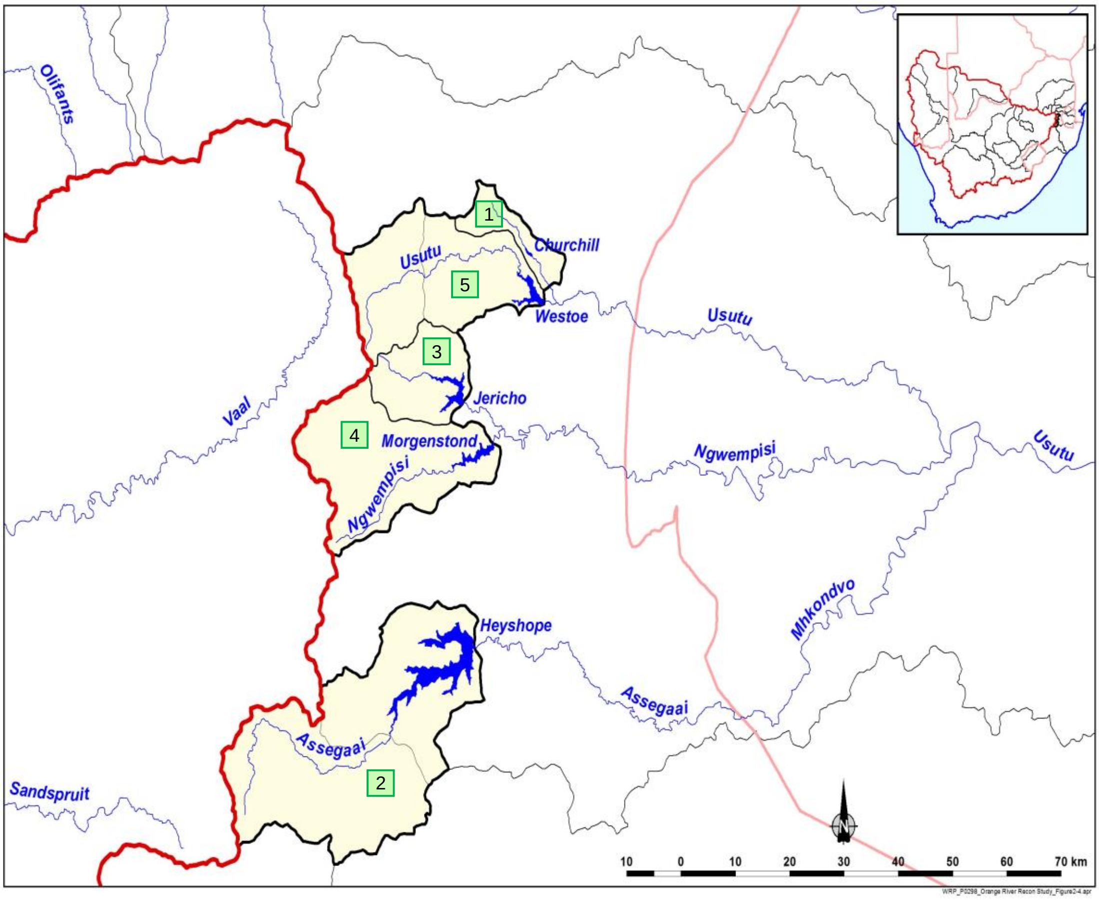
Locality map reference	Param.dat order no.	Hydrology reference name	MAR (million m^3/annum)	Standard deviation	Coefficient of variation
1	121	MU1	3.51	3.72	1.06
2	122	MU2	11.75	12.38	1.05
3	123	MU3	5.31	5.51	1.04
4	124	MU4	4.16	4.40	1.06
5	125	MU5	12.22	12.75	1.04
6	126	MU6	2.98	3.17	1.07
7	145	MU7	27.62	29.43	1.07
8	146	MU8	49.76	50.90	1.02
9	147	MU9	9.55	9.84	1.03
10	148	MU10	12.92	11.68	0.90
11	149	MU11	2.73	2.46	0.90
12	16	MU12	1.71	1.54	0.90
13	133	MU13	9.26	8.37	0.90
14	134	MU14	12.47	11.27	0.90
15	135	MU15	2.10	1.91	0.91

4.15 KOMATI



Locality map reference	Param.dat order no.	Hydrology reference name	MAR (million m^3/annum)	Standard deviation	Coefficient of variation
1	25	X11A1	26.31	24.63	0.94
2	206	X11B1	17.73	15.21	0.86
3	111	X11B2	12.01	10.52	0.88
4	112	X11C1	11.35	10.08	0.89
5	26	X11D1	21.03	12.44	0.59
6	22	X11D2	6.22	3.73	0.60
7	113	X11D3	20.24	11.95	0.59
8	116	X11E1	14.76	8.47	0.57
9	118	X11E2	6.84	4.10	0.60
10	185	X11F1	22.13	12.40	0.56
11	54	X11G1	45.28	20.17	0.45
12	57	X11H1	54.48	24.73	0.45
13	23	X11J1	49.20	20.22	0.41
14	58	X11K1	13.74	5.96	0.43

4.16 USUTU



Locality map reference	Param.dat order no.	Hydrology reference name	MAR (million m^3/annum)	Standard deviation	Coefficient of variation
1	114	CHURCH9	6.88	3.87	0.56
2	115	HEYS9	129.03	83.54	0.65
3	117	JERI9	23.69	15.58	0.66
4	119	MORG9	56.33	38.51	0.68
5	120	WEST9	43.61	29.04	0.67

5 Verification and validation of stochastic flow sequences

5.1 STOCHASTIC ANALYSIS OF STREAM FLOW DATA

5.1.1 Background

As the need for information on the assurance of water supply grows, the use of stochastic flow sequences is becoming increasingly popular in water resource studies. It is no longer satisfactory to say that the yield from a system is 20 million m^3/a. Such a figure could for example indicate 20 million m^3/a, with a risk of failure of either once in every 10 years or once in every 200 years. Clearly the reliabilities of the two yields are completely different, hence the need to be more specific and to relate each yield value to a particular reliability or assurance.

The major objective of using stochastic generation software is to provide alternative realistic flow sequences that can be analysed in the same manner as the historic flow sequence. One of the main problems associated with the use of generated flow sequences concerns the validity of such sequences. Before the end user can place his/her confidence in results based on stochastically generated flow sequences, it is first necessary to provide confirmation that the stochastic flow sequences are in fact realistic and plausible.

The statistical analysis of stream flows was undertaken in this Study using the Stochastic Model of South Africa (STOMSA). STOMSA incorporates Mark 7.1 of the ANNUAL and CROSSYR programs, both of which have been used extensively in South Africa over the past ten years for such purposes. The analysis was based on the natural historical stream flow sequences for the sub-catchments within the integrated Orange-Vaal catchment, obtained from the hydrological analysis undertaken as part of the ORASECOM Phase II Study.

Each sequence covers the period 1920 to 2004 (hydrological years) in all catchments except the Namibian Fish, which covers the period 1930 to 1994. After having performed the cross correlation analysis, STOMSA was used to create the statistical parameter file called the PARAM.DAT-file, which summarises the results of the statistical analyses, including the marginal distribution and serial correlation parameters as well as the B-matrix of the cross correlation. The PARAM.DAT-file provides direct input data to the WRYM and WRPM and is used by the models, at runtime, to generate the stochastic stream flow sequences applied in a stochastic yield and planning analysis. Included in the PARAM.DAT-file is control information for the verification and validation testing. A combined PARAM.DAT file was created for the entire integrated Orange-Vaal system. The file contains parameters for all 248 hydrology time series files when the Eastern Cape hydrology was added for the WRPM analysis purposes.

5.1.2 Estimation of annual stream flow parameters

The marginal distribution of a stream flow sequence provides a measure of the relationship between its annual total flows. The appropriate distribution for modelling annual flows is selected using the so-called *Hill Algorithm* (HILL, HILL and HOLDER, 1976). The Hill algorithm is based on the *Johnson Transform Suite*, which uses the first four moments of the marginal distribution to classify the type of distribution function as one of the following:

- 2-parameter Log-normal (LN2);
- 3-parameter Log-normal (LN3);
- 3-parameter Bounded (SB3);
- 4-parameter Bounded (SB4).

The Log-normal (LN) and Bounded (SB) distribution functions are defined as shown in Equations 3.1 and 3.2, respectively. More information in this regard is provided in the document Stochastic Modelling of Stream flow (BKS, 1986):

$$y = \gamma + \delta * \mathrm{Ln}(x - \xi), \text{ where } x > \xi (3.1)$$

$$y = \gamma + \delta * \mathrm{Ln}(x - \xi) \;/\; (\lambda + x - \xi), \text{ where } \lambda > x > \xi (3.2)$$

It should be noted that each of the above distributions has its strengths and weaknesses with the result that careful checking is undertaken by the program to ensure that realistic and meaningful results are produced. An example summary of the selected Johnson-Transform distributions and the values of the associated model parameters, as determined by STOMSA for the sub-quaternary catchments, are provided in the following Table. The complete Table is given in Annex 3 – Hydrology and Stochastic Validation and Verification.

Table 5-1: Example of selected Johnson-Transform distributions and values of associated model parameters for selected (1) simulated catchments

Catchment	Selected Distribution	Johnson	Transform	Parameters	
		γ	δ	λ	ξ
ALLEM4	LN3	-5.0324095	1.1962513	1.0000000	0.0000000
ARMEN	SB4	2.0237190	0.9136617	216.7413689	0.0000000
AUCH4	LN3	-0.1014556	0.5615228	1.0000000	0.0000000
BARBERS4	LN3	-0.4029140	0.8976931	1.0000000	0.0000000
BARR4	SB4	1.1264274	0.7463220	268.5964115	7.4331160
BLOEMN3D4	SB4	1.7920447	0.6910949	949.2854887	11.0879088
BOSK4	LN3	-8.2404410	2.3331421	1.0000000	0.0000000
C12D4	SB4	0.6721991	0.7441580	228.6229968	0.0000000
C24CEYE4	SB4	0.6181649	0.6449110	100.9355834	13.1037226
C24D4	SB4	1.6511545	0.5550652	56.9050988	0.2341942
C24E4	LN3	-0.7940559	0.6733485	1.0000000	0.3978835
C24F4	SB4	1.8477440	0.5764144	179.5782764	0.8019454
C24G4	SB4	1.8144248	0.5729379	150.7783773	0.6794406

Note: Only catchments having direct impact on Orange System presented, eg. No Olifants or Thukela downstream of Driel is included.

SB4: 4-parameter bounded, LN3: 3-parameter log normal

The Johnson-Transform parameters are applied in STOMSA to transform the annual total flows of each stream flow sequence to normalised flow residuals so that the data exhibit zero mean and unit variance. This transformation is undertaken by means of the linear stochastic difference equation models of time-series, called ARMA (Φ,Θ), which are defined as follows (see BKS, 1986):

$$\mathbf{x}t - \Phi 1 * xt-1 - \Phi 2 * \mathbf{x}t-2 = at - \Theta 1 * at-1 - \Theta 2 * at-2 \quad (3.3)$$

Any one of nine ARMA models may be selected, based on a set of standard selection criteria applied in STOMSA. These models are ARMA(0,0), ARMA(0,1), ARMA(1,0), ARMA(1,1), ARMA(0,2), ARMA(1,2), ARMA(2,0), ARMA(2,2) and ARMA(2,2). It should be noted that, as part of the Vaal River System Analysis Update study (DWAF, 2001a), a new selection criterion was developed in addition to the standard set applied in previous versions of STOMSA. The new criterion evaluates the particular performance of each ARMA model with respect to the yield-capacity validation test.

An example summary of the selected ARMA distributions and the values of the associated model parameters, as determined by STOMSA, are provided in the following Table for each sub-quaternary catchment. The complete Table is given in Annex 3 – Hydrology and Stochastic Validation and Verification.

Table 5-2: Summary of selected ARMA distributions and values of associated model parameters for selected [(1)] simulated catchments

Catchment		ARMA	Parameters	
	Φ1	**Φ2**	**Θ1**	**Θ2**
ALLEM4	-0.67890	0.00000	-0.74780	0.22290
ARMEN	0.85943	0.00000	0.97633	0.00000
AUCH4	0.00000	0.00000	0.00000	0.00000
BARBERS4	0.00000	0.00000	0.00000	0.00000
BARR4	0.00000	0.00000	0.00000	0.00000
BLOEMN3D4	0.00000	0.00000	0.00000	0.00000
BOSK4	0.41490	0.00000	0.00000	0.00000
C12D4	0.00000	0.00000	0.00000	0.00000
C24CEYE4	1.11347	-0.21281	0.00000	0.00000
C24D4	0.00000	0.00000	0.00000	0.00000

5.2 CROSS- CORRELATION

A major problem encountered, when generating stochastic flow sequences at multiple sites consecutively, is the preservation of the appropriate cross-correlation between the various records. Unless the cross-correlations are preserved, the flow sequences generated will be of little use in the subsequent analyses since flood and drought sequences at nearby gauges will not correspond.

The CROSSYR-program computes the inter-dependence between the annual flow residuals from the various stations. This is done under the assumption of normality of the residuals, so that their cross-covariance matrix is the measure of the extent of their inter-dependence. This cross-covariance matrix is decomposed into its (non-unique) square root B-matrix using a technique called singular value decomposition (BKS, 1986).

CROSSYR creates a file called PARAM.DAT, containing the parameters of the transformations together with B-matrix and control information for GENTST (discussed in Section 2.5). The PARAM.DAT file created for the Integrated Orange/Senqu/Vaal River System, containing parameters for all 248 incremental sub-catchments, is included in electronic format on the CD created along with this report to form part of the deliverable.

5.2.1 Monthly Disaggregation

As explained in Section 5.1.2, the ANNUAL-program generates annual stream flow parameters and consequently only allows stochastic stream flow generation as annual totals. A separate technique was developed to disaggregate the annual totals into the 12 monthly values. Several different approaches were initially considered after which the approach currently used was adopted.

In order to distribute the annual totals at each gauge for a single year into monthly totals, one appropriate year in the historic sequence is selected, by means of a relatively complicated operation, for every year of the stochastically generated flow. In order to select the year, several key gauges must first be defined. For example, if the system includes 40 stream flow records, perhaps 10 of these will be identified as the most important and can therefore be selected as the key gauges.

For each key gauge, the annual recorded flow closest to the stochastically generated annual flow is selected. If there are 10 key gauges, then 10 years will be identified - some of which may be the same (for example: the year 1956 may be selected for 4 of the gauges) although it is not unusual for 10 different years to be selected. Having selected the 10 key years, a simple exercise of "least squares fit" is used to select the single year which provides the smallest difference between the annual recorded flows and annual simulated flows for the 10 key gauges.

After the single historical year for disaggregation is selected in this manner, the monthly distribution for that year is used to distribute the annual totals at all gauges. In other words, if 1956 is selected, the distribution for 1956 at gauge 1 is used to disaggregate the annual total at gauge 1 while the distribution for 1956 at gauge 2 is used to distribute the annual total at gauge 2 etc.

In this manner it was found that realistic monthly flows were generated without the necessity of developing a monthly stochastic flow generator.

It should be noted that the stochastic flow generation techniques used are considered to be appropriate for a wide variety of hydrological conditions experienced in South Africa. In areas with critical periods of less than one year or greater than 20 years, the methodology may not be applicable.

In certain cases, a short critical period is experienced as a result of reservoir storage that is small relative to the annual inflow. In such cases it may be found that a stochastic model based on monthly flows rather than annual flows is required since the critical drought period may continue from the end of one year into the beginning of the next year. Unfortunately the current stochastic model was not designed to simulate such conditions and therefore cannot be used with confidence when critical periods of less than one year are experienced.

5.3 VERIFICATION AND VALIDATION TESTS

The program used to caary out the validation tests is called GENTST. GENTST uses a subroutine called ANNSIM to generate 41 replicate sets of stream flow sequences, each as long as the original historical sample. Each of the 41 flow sequences for each gauge is re-sampled and its basic statistics computed – the first two moments of the annual flows, the first two moments of the monthly flows and then some more sophisticated storage-based tests. Also included is a grouped capacity-yield diagram for each station

The GENTST-program can only test up to 15 different hydrology's at a time, while the testing of 248 hydrologies is required for the analysis of the Integrated Orange/Senqu/Vaal River System. To accommodate this, the 207 hydrologies were divided into 14 sets and each set tested separately.

In the stochastic checks the historic values are usually positioned between the 25% and 75% limits suggested by the stochastic sequences. In some instances, however, this is not the case and the explanation can lie with an error in the historic flow record, problems with the stochastic flow generation or a legitimate natural anomaly.

In cases where the historic value is outside the normally accepted limits, it is the responsibility of the analyst to decide whether or not there is an error. It should be remembered that no stochastic model is perfect, particularly one in which stochastic sequences are generated simultaneously at multiple sites. The model used in this study is considered to be one of the most reliable models available and has been thoroughly tested over the years. It is, however, not necessarily applicable to every water resource system and modifications may sometimes be required. In view of this, the model is continually being modified and upgraded as part of the overall quality control procedures.

No model is capable of producing perfect results at all gauges and any possible errors or anomalies should be judged individually to ensure that they are not data errors or large enough to have a significant influence on the overall results. The time and effort required to address a possible problem should also be compared to the benefit to be gained.

All major problems with the stochastic flow sequences have been corrected and the sequences included in this report are considered to be acceptable. More effort could be spent making finer adjustments to certain flow sequences, however, this was not considered necessary to the overall objectives of the study or productive in view of the limited budget available.

The standard stochastic verification and validation plots were carried out on each hydrology. A set of ten plots were prepared. These include the:

- Yield Capacity test plots (validation);
- N-month run sums box plots (validation);
- Maximum deficit plot (validation);
- Duration of maximum deficit plot (validation);
- Duration of longest depletion plot (validation);
- Monthly and annual means box plot (verification)
- Monthly and annual standard deviations box plot (verifivation);
- Two sampled cumulative distributions (verification); and
- Correlogram of normalized annual stream flow (verification).

5.3.1 Monthly and Annual Means

The first and most basic verification test carried out on the stochastically generated flow sequences involves comparing the monthly and annual means of each stochastic flow sequence with those of the historic flow record. The test is based on 41 stochastically generated flow sequences – each of the same length as the historic flow sequence. The number of 41 sequences was originally selected during the Vaal River System Analysis Study and this is still considered to be acceptable. The mean annual run-off (MAR) of each sequence is calculated together with the 12 monthly averages. The results are then displayed in the form of box plots with the historic values indicated by arrowheads.

The results are discussed in Section 5.4.1

5.3.2 Monthly and Annual Standard Deviations

The second verification test carried out involves the assessment of the monthly and annual standard deviations (SDs) of the generated and historic flow sequences.

The annual SDs is particularly important in water resource studies where reservoir yield calculations are involved. The yield from a reservoir will be considerably greater for a low annual SD compared to that obtained when the SD of the annual totals is high. The results of the SD check are discussed in Section 5.4.2.

5.3.3 Minimum Run-sums

Minimum run-sums are usually given for a particular time period such as 12 months, 24 months, 36 months etc. The 12-month minimum run-sum for a given sequence is the lowest flow to occur during the complete sequence for 12 consecutive months. This is a validation test since the run-sum characteristics of the historic flow sequence are not used in any way to generate the stochastic flow sequences.

It is sometimes found that the historic minimum run-sums are greater or less than the maximum or minimum simulated values respectively. When examining the minimum run-sum results however, the general lengths of critical period experienced in the catchment area (also a function of reservoir storage) should be taken into account. If, for example, the average historical critical periods experienced in a given catchment are in the order of two years, it is more important to produce realistic 12 month, 24 month and 36 month minimum run-sums. Obviously it is desirable to match the minimum run-sums for all durations. This is often not achieved, however, in these cases more significance should be placed on the minimum run-sums most appropriate to the given catchment area.

The results of the minimum run-sum checks are discussed in Section 5.4.3.

5.3.4 Maximum Deficits and Deficit durations

The maximum deficit and deficit duration tests are validation tests where a given draft expressed as a percentage of the MAR is applied to a semi-infinite reservoir starting full. Three tests are undertaken, the maximum deficit test, the duration of maximum deficit test and the duration of longest depletion test. The results are again simply a variation on the presentation of the results depicted in the minimum run-sum plots and the yield-capacity diagrams.

The maximum deficit test provides a record of the minimum reservoir storage required for each sequence to provide an uninterrupted supply for demands of 40 %, 50 %, 60 %, 70 % and 80 % of each generated MAR. The duration of maximum deficit test records the duration in months of the drought event causing the maximum deficit. The duration is the period from full supply to maximum deficit and back to full supply. The maximum duration is obviously the total record length (= 85 years or 1 020 months in this case).

The third and final test in this set is the duration of the longest depletion that again can be equal to the total record length. The depletion is given in months and does not necessarily tie in with the drought event causing the maximum deficit, although in many cases the same event causes both maximum deficit and longest depletion.

The results of the deficit and depletion tests are discussed in Section 5.4.4.

5.3.5 Yield Capacity

The yield-capacity test is a storage based validation test and is simply the minimum reservoir capacity required to meet a given yield for each of the 41 stochastically generated sequences. This test is simply a different form of presenting the results derived from the minimum run-sum test with the variation that the yields are expressed as percentages of the historical MAR, whereas in the minimum run-sum test, the drafts are a function of the generated MAR. The results are expressed in terms of the historic MAR and yields of 20 %, 40 %, 60 %, 80 % and 100 % of the MAR are used. The yield-capacity test assumes that there are no evaporation losses from the reservoir surface.

The results of the yield-capacity test are discussed in Section 5.4.5.

5.3.6 Serial Correlation of Annual Totals

In many catchments it often appears that there is some form of cyclic pattern associated with the annual flows, resulting in a series of wet and dry periods. Many different explanations for this phenomenon have been suggested ranging from sun-spots to the warming of the oceans.

In order to determine if there is strong serial correlation in the annual totals, a test is carried out for serial correlations with lags ranging from 1 year to 20 years. Usually in arid or semi-arid areas the serial and partial serial correlations are zero, indicating no serial correlation. Values other than zero will usually be estimated from even a purely independent sequence possibly indicating some degree of serial correlation. In general, however, the serial correlations are low enough to be ignored.

The serial correlation should not be confused with the cross-correlation discussed in Section 5.2. The former relates to the successive annual values for an individual record while the latter is based on the corresponding simultaneous annual values at two different gauges.

The results of the serial correlation and partial serial correlation tests are discussed in Section 5.4.6.

5.3.7 Normalisation of Annual totals

One of the first steps required to generate stochastic flow sequences is the normalisation of the naturalised recorded annual flow values from which the stochastic annual flows will be generated. The normalisation can be carried out using a variety of different distributions such as the 3- parameter Log-normal or the Bounded Sb distributions of the Johnson family.

To ensure that the distribution has in fact correctly normalised the recorded annual totals, the original values and the normalised values are plotted on a normal probability axis. The original values generally show a distinct skewness caused mainly by a few very high annual values. The normalised values should lie on a reasonably straight line if the normalisation procedure is successful.

The results of the normalisation tests are discussed in Section 5.4.7.

5.3.8 Cross-Correlations

One of the most important considerations to be taken into account when generating stochastic stream flows is the preservation of the cross-correlations between different flow records. In cases where only a single flow record is being analysed there is obviously no problem. In multi-site stream flow generation, however, it is essential that the appropriate cross-correlations existing in nature are preserved. If preservation of the cross-correlations is not achieved, the results from the analysis will be meaningless since the model may generate high flows at certain gauges while generating low flows at other gauges, when in reality both sets of flows should be similar. In such cases, the severe drought sequences experienced regionally in nature are "smoothed" out by the inclusion of higher flows at some nodes which in turn produces over-optimistic yield estimates.

The results of the cross-correlation tests are discussed in Section 5.4.8.

5.4 REVIEW OF STOCHASTIC RESULTS

The entire integrated Vaal, Orange Senqu system contains 248 sub-catchments (**see Figure 1, Annex 4)**. The natural incremental stream flow time series are available electronically on the Report CD. Only 144 of these sub-catchments are located within the Orange/Senqu/Vaal basin and another 18 sub-catchments from neighbouring catchments are having a direct impact on the Orange/Senqu system. Only the hydrology for sub-catchments located within the Orange/Senqu Vaal were extended and in some cases completely updated as part of Phase II of the ORASECOM Integrated Water Resources Management Plan. For the purpose of reviewing the generated stochastic flows it was therefore only necessary to carry out validation and verification tests on the 144 sub-catchments within the basin and the 18 neighbour catchments impacting on the Orange Senqu systems.

All plots are available in electronic form as part of a CD submitted with this report.

5.4.1 Monthly and Annual Means

The acceptability criteria require that the annual historic means are generally between the 25 percentile and the 75 percentile limits of the stochastically generated flows.

Comparing box plots of the mean annual values of the recorded flow data sets to the median values of the corresponding stochastically generated flows shows that there are no obvious or serious problems with the stochastic flows, as only eleven of the 212 cases not meeting the acceptability criteria. They are F2, F5, F6, F7, F8, F9, C24D4, C24G4, D42G, LOLIF, UAUB. Five of these sub-catchments represents extremely arid areas with a MAR of less than 5 million m^3/a and have therefore almost no impact on the overall system.

5.4.2 Monthly and Annual Standard Deviations

In 13 out of 212 cases, the historic record is not positioned between the 25 and 75 percentile limits. They are F2, F5, F6, F7, F9, SPITS4, C3H0134, C9H0074, KALK4, TWEE4, C24D4, C24G4 and D42G. Except for C24D4 and C24G4 all these sub-catchments represent fairly arid catchments. When detailed analyses focussed on those areas are required, it is recommended to rather use the Bootstrap method, which is an option that can be selected in the WRYM and WRPM. Based on the experience gained during previous simulation of stochastic stream flows in this system as well as other parts of Southern Africa, however, these results are considered to be acceptable.

It is difficult to specify when a possible problem becomes large enough to investigate in more detail. All such problems were already addressed in the preliminary analyses and do not appear in this report. It is simply a matter of judgment and a balance between accuracy and level of effort.

A few cases do however deserve additional comment. For most of these sub-catchments listed above the yield capacity tests produced excellent plots showing a very good fit between the historic and mean as well as median stochastic results. The only exceptions were F7 where the flow is so small that a yield capacity test could not be carried out and the TWEE4 catchment with a MAR of 15.67 million m^3/a, showing a reasonable fit on the yield capacity test curve.

5.4.3 Minimum Run-sums

The results of the minimum run-sum tests in general appear to be satisfactory. The only exceptions are TWEE4, C24H4, LOGR1, LOGR5, LOGR17 and D41N.

One problem that can occur concerns the fact that the model generates annual totals that are then disaggregated into monthly values using the historical distribution from a selected year. The monthly serial correlation for a specific gauge may result in a severe dry period continuing from the end of one water year into the beginning of the next water year. Unfortunately when dealing with a model which is based on the generation of annual values which are then disaggregated, it is not possible to take such monthly serial correlation into account.

In cases, where the critical periods are reasonably long (i.e. several years) the non-continuity of monthly serial correlation between consecutive water years does not present a problem. In cases where critical periods of less than 12 months are experienced, however, it may be necessary to consider an alternative stochastic model which generates stream flow on a monthly basis.

5.4.4 Maximum Deficits and Deficit durations

As with the previous tests, the results are satisfactory and in most instances the recorded values are between the 25% and 75% limits of the stochastic values. Exceptions are C3H0134, TWEE4, D41N, C24D4, C24G4, C24H4 and D13. The first three of these sub-catchments are fairly arid catchments and improved fittings might be obtained by using the Bootstrap method. The other four sub-catchments represents wetter catchments, in particular D13, with an MAR of 719 million m^3/a deserves more attention (see **Section 5.4.5** for more detail).

5.4.5 Yield Capacity

The yield-capacity test is a most useful visual validation test because it summarizes so much of the behaviour of both the historical flows and of the generated flows. Ideally the stochastic points (indicated by the small circles) should show a reasonable spread around the values obtained from the historic flow sequence. This is assuming that the historic record contained periods of average severity as would be expected from the available record length. In such cases historic values should also be reasonably close to the median values of the stochastic flow sequences. If the results from the historic record are considerably lower than the median values from the stochastic sequences or even outside the range of generated values, it would indicate that the recorded data contain a period of extreme severity. In such cases the critical period in question should be carefully examined for possible errors.

From examination of the yield capacity graphs there are generally very good matches between the historical and generated values. This is usually an indication that the historical records have been well prepared are homogeneous and sound. There are few exceptions that are discussed below.

A review of the stochastic verification plots highlighted some issues that required further analyses. The issue occurred for a number of hydrology's where the selected default ARMA model differed from the previous selected default (VRSAU, DWAF, 2001a) as a result of adding the 10 additional years of data. The issue is illustrated using the Katse hydrology as an example.

A default ARMA 0-1 model was previously selected for the Katse hydrology with the record dating 1920 to 1994. Having extended the record to 2004 (the first part of the record remained unchanged) the ARMA default shifted to an ARMA 1-2 model. The impact of this was quite severe on the system, resulting in higher stochastic flows being generated. **Figure 5 1** and **Figure 5 2** present the yield capacity curves for the two cases, previous and extended hydrology.

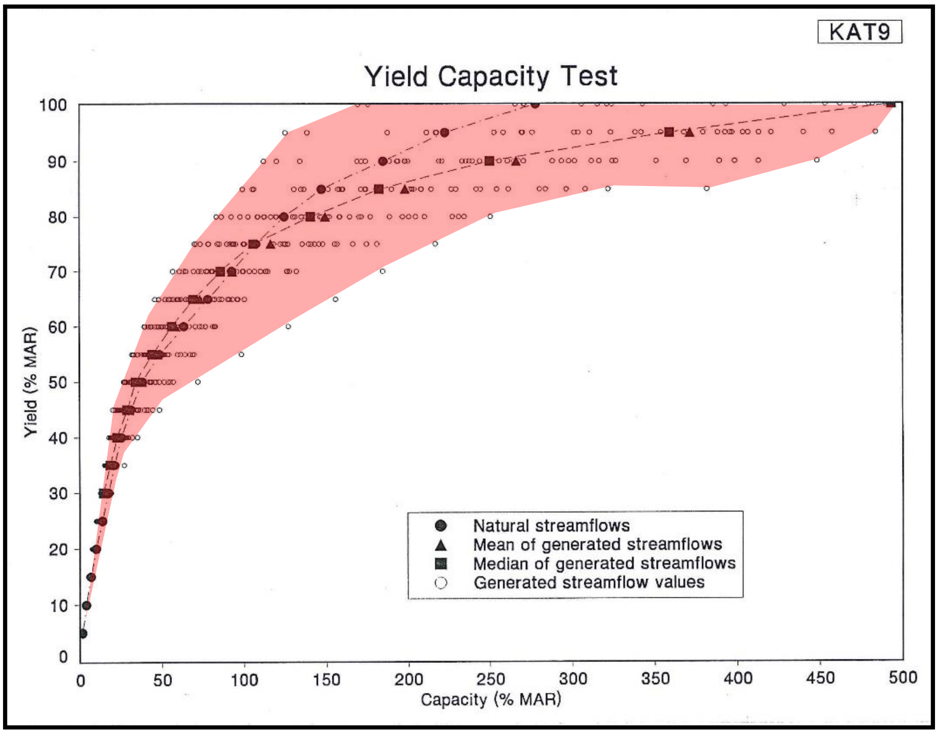


Figure 5-1: Yield capacity test on Katse hydrology dating 1920 to 1994, default ARMA 0-1

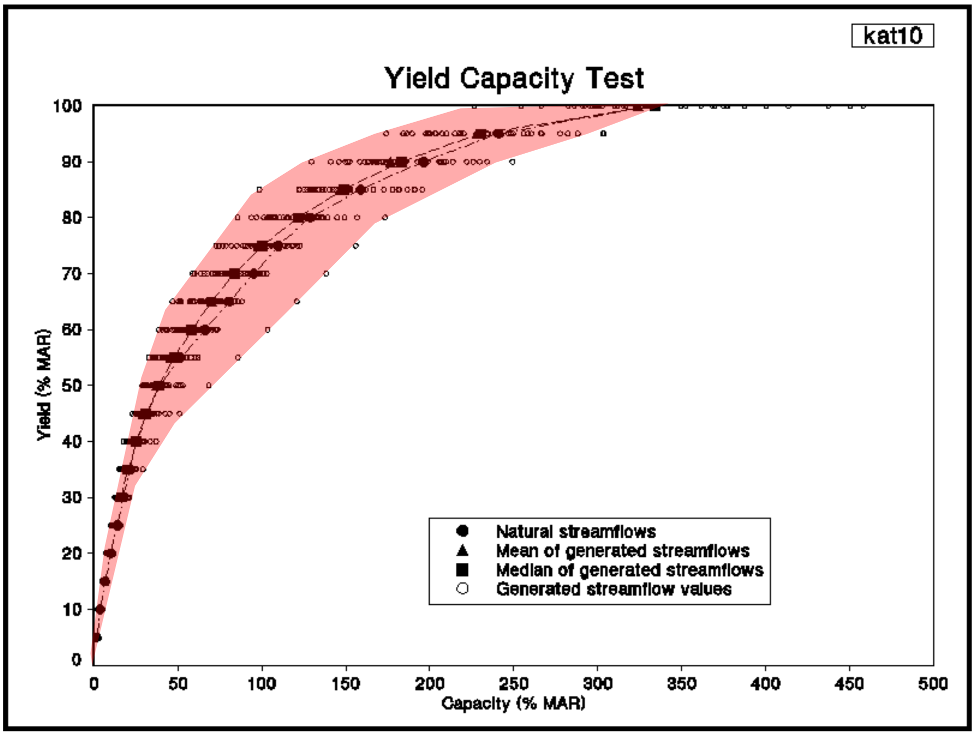


Figure 5-2: Yield capacity test on Katse hydrology dating 1920 to 2004, default ARMA 1-2

The figures show the wider range of stochastic flow sequences generated using the ARMA 0-1 model, with a much narrower range from the ARMA 1-2 default selection. This resulted in significantly higher flows for the Katse catchment in a test WRPM simulation, resulting in Katse Dam projections operating at a higher level than previous simulations.

In most cases, the 10 additional years of data are wet years, and one would expect higher stochastic flows as a result. However, the severity of the impact was extreme, and in many situations completely changed the projections that have been used as a basis for future augmentation planning for a number of years.

As a result, Professor Geoff Pegram was requested to assist by carrying out a review of the issue, focusing on the Senqu hydrologies. The review document is presented in **Annex 5** Two significant conclusions were drawn based on the assessment.

- ARMA model 2-2 should no longer be used as an option; and
- Where the default ARMA model that was selected differed from the previously selected ARMA model as a result of the additional 10 years of data, (i.e. the first part of the record remained unchanged), the original ARMA selection should be used. This should be the case until further analyses and research work can take place on the stochastic procedure.

Other exceptions that were still evident are for sub-catchments D13, LOGR1, D43B, DVILJ and OTJV. Except for D43B all these represents catchments upstream of existing dams or possible future dams. It is therefore important that those yield capacity comparisons be improved. Except for sub-catchment D13 all the other sub-catchments are representative of semi-arid to arid catchments and better comparison might be obtained by using the Bootstrap method.

Improvement on the stochastic flow generations for D13 is however important and requires more attention.

5.4.5.1 Modifications to Default Selections

During the review it was determined that the ARMA 2-2 model should no longer be used as an option. In addition, as a result of the differences in stochastic results, it was decided to default back to the originally selected ARMA model for any case where a new ARMA model was selected based on the extended hydrological record. If either the new or previous model selected ARMA 2-2, the second best option fit was used. Hydrologies where this occurred are listed in the table below.

Table 5 3: ARMA default selection modifications

Catchment	Original ARMA default based on hydrology record 1920 - 1994	New ARMA default based on hydrology record 1920 - 2004	Selected ARMA model
ALLEM4	1-2	2-2	1-2
BARBERS4	2-2	2-2	0-0
BLOEMN3D4	2-2	2-2	0-0
C12D4	0-0	2-2	0-0
C24D4	2-2	2-2	0-0
C24E4	2-2	2-2	0-0
C24F4	2-2	2-2	2-1
C24G4	2-2	2-2	2-1
C24H4	2-1	2-2	2-1
C70ABC4	0-0	1-1	0-0
C70D4	2-2	2-2	1-1
C70E4	2-2	2-2	1-1
C70F4	2-2	2-2	1-1
C70G4	2-2	2-2	1-1
C70H4	2-2	2-2	1-1
C70J4	2-2	2-2	1-1
CHURCH9	0-2	'2-0	0-2
D13	NA	2-2	'2-0
DSWENTZD4	2-2	2-2	0-0
ERF4	0-0	1-1	0-0
GROOTD4	0-2	0-0	0-2
KAT10	0-1	1-2	0-1
KLERK4	'2-0	1-0	'2-0
KLIPBN4	1-2	2-2	1-2
KLIPDN4	0-0	2-1	0-0
LAKESN4	0-2	2-2	0-2
MAS10	2-2	1-0	1-0
MAT10	0-1	1-2	0-1
NTO10	1-0	0-0	1-0
SANDN4	2-2	2-2	0-0
SPITS4	2-2	2-2	1-2
STERK4	0-0	0-1	0-0
SUIK4	0-0	1-1	0-0
TM0194	2-2	0-0	0-0
TM0294	2-2	0-0	0-0
TM0394	2-1	0-0	2-1
TM0494	1-2	0-0	1-2
TM08A4	2-2	2-2	0-0
TM16C4	2-2	2-2	0-0
TM1994	2-2	2-2	0-0
TM29A4	2-2	2-2	0-0
USWENTZD4	2-2	2-2	0-0
VAAL4	2-2	1-0	'2-0

5.4.6 Serial Correlation of Annual Totals

The results of the serial correlation test are stored on the Report CD. From the figures it can be seen that the serial correlations rarely exceed the upper or lower bounds, which are indicated by two additional horizontal lines. Many of the flow records indicate a reasonably high negative serial correlation with lag times of between 5 and 10 years, indicating that there may be some evidence of a cyclic nature. There appears to be no general pattern indicating cycles however and the evidence of cycles is not strong enough to warrant further investigation.

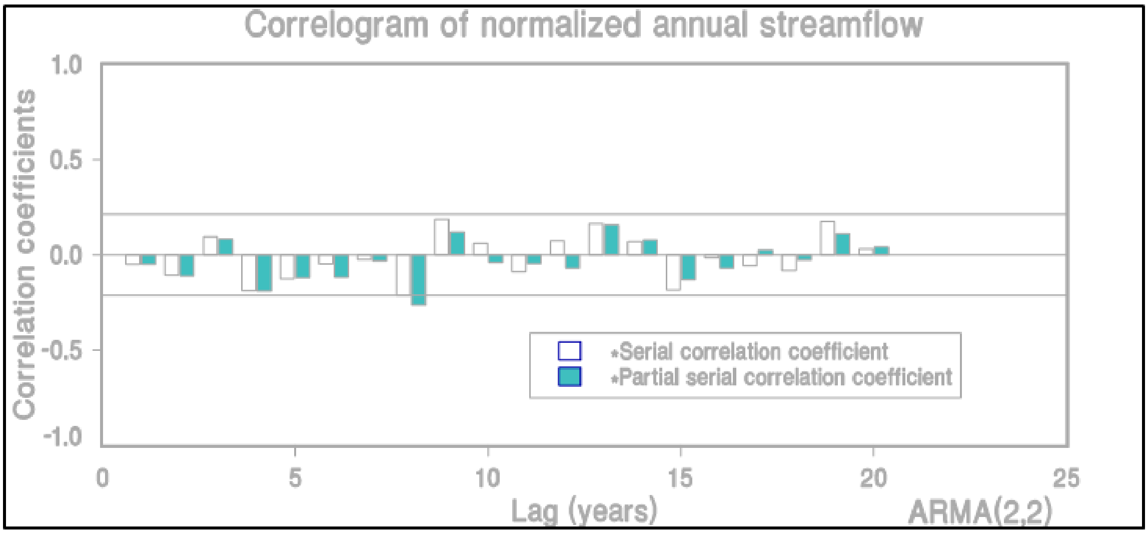


Figure 5-3 :Example of serial correlation test

As a result of the experience gained in previous analyses of the Vaal River System it has become standard practice to model whatever time series structure is present in the data, even if it is weak. If the time series structure is ignored it will bias the estimation of the reliability of the system as analysed by the stochastic sequences relative to the historical sequences.

Exceptions experienced included C24EYE4 that showed serial correlation exceeding the upper bound by far. This is due to the surface flow in this sub-catchment that originates entirely from the Schoonspruit Eye, receiving water from a dolomite compartments with a large storage capacity, so that flows from one year is very strongly correlated with those from the previous years. Similar correlations were found in other sub-catchments such as COM2121 and COM22 where the surface water flow is predominately driven by out flows from dolomitic eyes.

5.4.7 Normalisation of Annual totals

The results of the normalisation test are also available on the Report CD. Ideally the transformed points should form a relatively straight line and pass through the origin of the axes. From examination of the figures it can be seen that in general the transformations have been successful.

Exceptions that were identified include the following sub-catchments, TWEE4, C24D4 and C24G4.

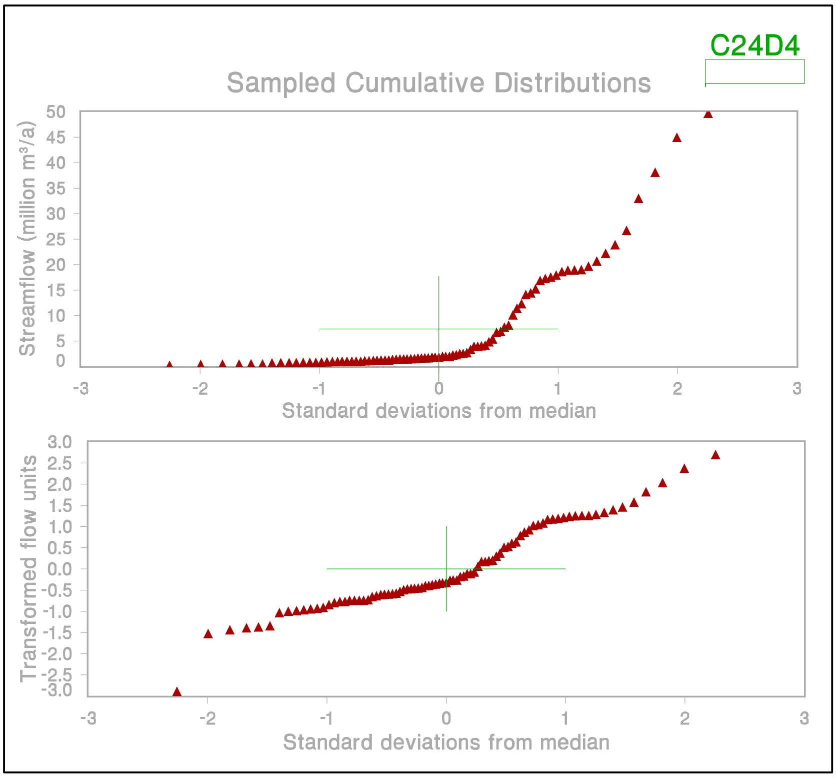


Figure 5-4: Example of normalisation test

5.5 SUMMARY AND CONCLUSIONS

From the results in **Section 5.4** it is evident that the stochastic flows generated for most of the sub-catchments did mimic the historic flow sequences quite well. In the arid areas where years with zero flow for the entire year often occurs resulted in the serial correlation of annual totals graphs not generated. Quite a number of the sub-catchments in the arid catchments such as the Molopo and Lower Orange the flows are so small that it was not always possible to generate sensible graphs, in particular the yield capacity graphs.

If the need to carry out detail modelling within the extreme arid areas using stochastic flows in future, it is recommended that the bootstrap method rather be used, specifically for those areas where the current stochastic model did not mimic the historic sequences that well.

In general however the contributions of these arid areas are negligible and will have hardly any impact on the system results.

6 Consolidation of base scenario

6.1 CONSOLIDATION OF MODEL COMPONENTS

The WRYM is set up to cover the entire Orange Senqu Vaal system, and it focusses on the yield available from the many sub-systems located within the river basin. The purpose of the yield model is to determine the yield available from a sub-system and sometimes for a combination of sub-systems. To decide which sub-systems need a separate yield analysis and in which cases one requires the combined yield from more than one sub-system, depends on modeler's understanding of the system, the way how its operated as well as possible future developments that are expected to come into play in future. The yield results are finally used as input to the WRPM and it is therefore also important to have a good understanding of how the different sub-systems will be modelled in the WRPM, to allow support from one sub-system to another, where it is designed for that purpose. This will also play a role in the decisions regarding how the yields of sub-systems that need to be determined and in particular the short-term stochastic yield results that forms a vital part of the operating rules used in the WRPM.

Some sub-systems are operated as stand-alone systems, although they are embedded along with many other sub-systems within the entire river system. It basically means that this stand-alone sub-system is not supported from any other sub-system nor is it being used to support another sub-system. It is possible that the spills and water use from an upstream system can impact on the yield available from this stand-alone sub-system. For this reason it is important that the stand-alone sub-system is simulated within the context of the other sub-systems around it, so that related impacts are taken into account when the yield is determined. When the yield of such a sub-system is determined, the demands supplied from that sub-system are in general set to zero. A yield channel is then linked to the sub-system and the target draft on the yield channel is increased until failure occurs. The historic firm yield represents the maximum target draft that will just not result in a failure. The demands at a selected development level, in most cases the current day development levels, are imposed on all the other sub-systems so that a realistic impact of these sub-systems will be modelled on the sub-system of which the yield is determined.

In the case of larger sub-systems comprising several major dams, the yield of the combined system is in general also determined. A good example is that of the Vaal sub-system referred to as the Bloemhof sub-system, which includes Grootdraai Dam, Vaal Dam, Bloemhof Dam and Sterkontein Dam. The operating rules followed between these dams are crucial and can significantly affect the yield available from the sub-system.

Inter-basin transfers are seldom forming part of a sub-system yield, as it is more important to determine the yield of the sub-system from where the water is transferred from. One then knows what the yield capability is of the transfer system and can on that basis request support from the transfer system without causing the transfer system to fail.

6.2 INTER-BASIN TRANSFERS

Several transfer systems form part of the integrated Vaal/Orange/Senqu system. Only some of these transfer systems are included in the WRYM setup that is used for determining the yield characteristics of different sub-systems within the Orange/Senqu basin. All the transfers are however included in the WRPM setup where it is required to supply the entire current and future demands imposed on the system. Only the transfer systems that need to be in place when the yields of the different sub-systems are determined, were included. These are mainly the transfer systems that are using water resources located within the Orange/Senqu basin. All the transfer systems will be listed in this section, although details will only be given on the ones included in the WRYM setup. Details of the remainder of the transfer systems will be provided in the WRPM report.

Transfer sub-systems linked to the Vaal system include the following:

- Thukela-Vaal Transfer Scheme: This scheme transfers water from Woodstock Dam and Driel Barrage in the Upper Tugela Catchment to Sterkfontein Dam in the Upper Vaal Catchment. The maximum transfer capacity is 20 m^3/s. This is the only transfer system in the Vaal that is included in the yield analysis and forms part of the Bloemhof sub-system yield. (see section 7.3)
- The Heyshope to Grootdraai Transfer Scheme: Water is transferred from Heyshope in the Upper Usutu catchment located in the Assegaai River in support of Grootdraai Dam in the Upper Vaal. The system has a design capacity of 135million m^3/a, but is limited to a maximum transfer rate of 3.8 m^3/s due to the pumping station and rising mains. This transfer was not included when modelling the yield of the Vaal sub-systems as the sub-system yield of Grootdraai on its own was required.
- The Zaaihoek Transfer Scheme: Water from Zaaihoek Dam in the Slang River a tributary of the larger Buffalo River within the Tukela basin is transferred to the Upper Vaal catchment. This scheme has a maximum transfer capacity of 2.16 m^3/s and is mainly used to supply Majuba Power Station in the Upper Vaal with water. The transfer is also used to support Grootdraai Dam when required. This transfer was not included when modelling yield of the Vaal sub-systems as the sub-system yield of Grootdraai on its own was required.
- The Vaal-Olifants Transfer Scheme (Grootdraai Dam): Water is transferred from Grootdraai Dam to the Upper Olifants catchment in support of the Sasol Secunda complex and Eskom Power Stations, which forms the bulk of the users supplied from Grootdraai Dam. The maximum transfer capacity of this scheme is 6.5 m^3/s. In the WRYM setup this transfer is replaced by the yield channel used to determine the yield available from Grootdraai Dam.
- The Inkomati Transfer system: This system transfers water from the Nooitgedacht and Vygeboom Dams in the Komati West catchment to the Upper Olifants catchment in support of the Eskom Power stations. The design capacity of this system is 3.59m^3/s. This transfer system is not used to support the Vaal system as such but also supply water to the power stations in the Upper Olifants as for the Vaal-Olifants transfer system. This transfer was not included when modelling yield of the Vaal sub-systems as it is not affecting the yield in the Vaal.
- The Vaal Eastern sub-system Augmentation Project (VRESAP): Water is transferred from Vaal Dam to the Sasol Secunda complex as well as the Eskom Power Stations in the Upper Olifants, as the water from Grootdraai Dam in not sufficient for this purpose. The maximum transfer capacity of this system is 5.07 m^3/s. In the WRYM setup this transfer forms part of the yield channel and related yield to be supplied from Vaal Dam.

- The Usutu transfer system: This system transfer's water from Morgenstond, Jericho and Westoe dams to the Eskom Power Stations in the Upper Olifants. The Usutu sub-system can also receive support from the Heyshope Transfer System and can in turn also support the Komati sub-system. These transfer links than in effect allows water to be transferred from Heyshope Dam to Nooitgedacht Dam in the upper Komati system. This transfer was not included when modelling yield of the Vaal sub-systems as it is not affecting the yield in the Vaal.
- The Lesotho Highlands Transfer System: Water is transferred from Katse and Mohale dams in the Lesotho Highlands in support of Vaal Dam. The maximum transfer capacity of this system is 35.7 m^3/s. With the current full Phase 1 of the LHWP in place, the current fixed transfer is 780.19 million m^3/a or 24.7 m^3/s. This transfer is included in the WRYM setup as a demand imposed on Katse Dam when the yield of the Orange River Project is determined. This transfer however does not enter the Vaal system when the yield of the Bloemhof sub-system is determined, as the Bloemhof sub-system yield is required on its own, without the contribution from the LHWP.

Transfer sub-systems linked to the Orange system include the following:

- Caledon-Modder transfer: Bloemfontein and surrounding areas pull water from the Caledon system (Welbedacht and Knellpoort dams) when there is insufficient water in the Modder system. The transfer differs according to the required demand and availability in the Modder system. The transfer from Knellpoort Dam in the Caledon catchment to Rustfontein Dam in the Modder River is referred to as the Novo transfer scheme. The maximum transfer capacity is currently 1.4 m^3/s and will be increased to 2.3 m^3/s by March 2015. The second transfer component of this scheme is the pipeline from Welbedacht Dam to Bloemfontein with a current capacity of 1.61 m^3/s which is the limitation of the main pump line from the water treatment plant. This transfer was in place in the WRYM data setup when the yield of the ORP was determined. When the yield of the Caledon Modder sub-system was determined the two transfer channels were linked to the yield node and channel to determine the yield of the Caledon component of the system separately. The transfers from the Caledon to the Modder system were disconnected when the yield of the Modder River component (Rustfontein and Mockes dams) was determined.
- Orange-Fish (Eastern Cape) Transfer: Water is transferred from Gariep Dam in the Orange River to Fish and eventually also to the Sundays River in the Eastern Cape. The water is mainly used for irrigation purposes, but also supplies several towns with water as well as Port Elizabeth by means of an abstraction at the downstream end of this system. The maximum capacity of the transfer tunnel is 54 m^3/s although currently an average of in the order of 21 m^3/s is transferred on an annual basis. This transfer was simulated as part of the yield channel when the yield for the ORP was determined.
- Orange-Riet Transfer: Water is transferred by means of a canal and pump system from Vanderkloof Dam over the water shed to the Riet River catchment. The water is primarily used for irrigation purposes, but also supplies urban requirements of Koffiefontein, Ritchie and Jacobsdal. The first 74km of the Orange Riet canal has a capacity of 15.6 m^3/s. Approximately 8.3 m^3/s on average is currently transferred . The tail end of the canal ends in the Riet River from where water flows further downstream in support of irrigation along the Riet River. This transfer was simulated as part of the yield channel when the yield for the ORP was determined.

- Orange-Vaal Transfer: Water is transferred from Marksdrift Weir in the Orange River to Douglas Weir at the downstream end of the Vaal River. The bulk of the transfers are used for irrigation purposes, with a small portion also supplied to the town of Douglas. The Vaal system is not used to support the requirements imposed on Douglas Weir and only spills and some Vaal return flows end up in Douglas Weir. This water is most of the time not sufficient and is then supplemented by the transfers from the Orange. The scheme has a transfer capacity of 6 m^3/s. This transfer was simulated as part of the yield channel when the yield for the ORP was determined.

Transfer sub-systems linked to the Senqu system include the following:

- The Lesotho Highlands Transfer System: This transfer system is already described as part of the transfer systems linked to the Vaal, as it links the Senqu to the Vaal. See detail description under Vaal Transfer Systems Section.

6.3 DEMANDS

The total gross demand imposed on the entire Orange Senqu Vaal Basin is in the order of 7 500 million m^3/a, of which 52% is located in the Orange/Senqu basin (Modder/Riet included) and 48% in the Vaal (Modder/Riet excluded). The demands supplied from the Vaal River basin depends on water generated in the Vaal basin as well as on transfers from the LHWP, the Upper Tukela, Zaaihoek, Heyshope, Usutu and Komati sub-systems. The Orange/Senqu demands are all supplied from water generated in the Orange Senqu basin, without any transfers from outside of the basin. Water is in fact transferred from the Orange Senqu basin to other basins to support the local demands there.

All the demands supplied from the Vaal are located within South Africa. The bulk of the demands supplied from the Orange Senqu are located in South Africa, with the remainder in Lesotho, Namibia and Botswana. Currently approximately 63% of the Orange Senqu demand is located in South Africa, 3% in Namibia, 1.4 % in Lesotho, 0.02% in Botswana. The remainder of the demands are made up of losses to be shared among the basin states as well as shared EWRs. These typically include river bed losses mainly in the Molopo catchment, river evaporation and evapo-transpiration along the main Orange River, river mouth environmental requirements, etc.

6. CONSOLIDATION OF BASE SCENARIO

Table 6-1: Summary of demands supplied by main sub-systems

Sub-system and Dams	Demand (M m^3/a)			Comments
	2013	2025	2040	
Grootdraai Dam	170	185.6	192.4	Grootdraai demands are also supported with transfers from Heyshope, Zaaihoek and Vaal dam
Bloemhof sub-system (Bloemhof Dam, Grootdraai, Vaal Dam, Sterkfontein, Tugela transfer from Driel Barrage)	2 454	2 666	2 985	Bloemhof sub-system is supported with transfers from LHWP, Heyshope and Zaaihoek dams. (Net demand)
Caledon Modder sub-system	96	134	213	Includes 10% losses for transfers
Orange River Project (Gariep & Vanderkloof dams)	3 089	3 290	3 312	Net demand
LHWP Phase 1)Katse & Mohale dams & Matsoku Weir	780	780 (460)	780 (450)	Volume transferred to the Vaal and excludes the EWR releases from Katse and Mohale dams which are on average 68 and 31 million m^3/a respectively
Koppies Dam	10	10	10	
Boskop & Lakeside dams	45	47	47	
Klipdrift Dam	6.4	6.4	6.4	
Rietspruit & Elandskuil dams	28.8	29.2	29.7	
Allemanskraal Dam	52	52	52	
Spitskop Dam	13.7	13.7	13.7	
Taung Dam	0	0	0	
Wentzel Dam	1.7	2.8	3.9	
Krugersdrift Dam	36.6	36.6	36.7	Net demand
Kalkfontein Dam	50.1	52.1	54.5	
Hardap Dam	44.9	44.9	44.9	
Naute Dam	8.2	11.7	11.7	

Note (1) –Transfer volume can increase by 460 million m3/a when Phase II of LHWP (Polihali Dam) is completed.

Demands imposed on the main sub-systems or dams within the Orange Senqu Vaal basin are summarised in **Table 6-1.**

6.4 STOCHASTICS

Historic records are available for a limited record period. All of the hydrological records except for those representing the Fish River in Namibia, cover the period 1920 to 2004 (hydrological years), thus an eighty five year record period. This is quite a reasonable length to be used for historic yield analysis purposes. The shorter the available record period, the less information on the characteristics will be available that represents the runoff generated from a particular sub-catchment. The longer the record period, the more information can be captured and will obviously also result in a more accurate prediction of the yield available from the sub-system.

The difficulty with working only with natural historical flow records is the following:

- It is almost certain that the natural historical flow record will never be repeated.
- For water supply purposes strategic industries, drinking water for urban areas, etc. a high assurance of supply of 1 in 100 or 1 in 200 years are required. It si not possible to determine the yield representing that assurance, if you only have an 85 year record period available?
- When we want to do future planning, what will future natural runoff flow sequences look like, what should be used? Without climate change impacts, the future natural flow records will have similar characteristics than the historical record, but will be different in detail. In the future, one can also expect to experience worse flood events and worse droughts than those captured in the historic record.
- Different yield results are obtained when different lengths of historic records are used. Which result is then the correct one to use for planning purposes, and why do they differ.

The example of historic yield results as determined for Midmar Dam on the Mgeni River clearly illustrates the difference in yield results as obtained for different record periods (See **Table 6-1**).

After considering the yield results for the 10, 20 and 40 year period as given in **Table 6-1**, one can easily be misled to base the planning of the entire Midmar System on the 69 million m^3/a yield. By adding another 20years to the record period the firm yield is reduced almost by half, which is painting a total different picture.

Table 6-2 : Firm yield versus record Period

Period of analysis (hydrological years)	Number of Years	Historic Firm Yield (million m^3/a)
1930 - 1934	5	81
1930 - 1939	10	69
1930 - 1949	20	69
1930 - 1969	40	69
1930 - 1989	60	36

The methodology used to determine each of these firm yields is exactly the same, and technically speaking all these results are correct. The key to the difference of these results is the reliability or assurance of each of these yields. The assurance of the 69 million m^3/a yield is obviously much lower than that of the 36 million m^3/a yield.

It is important that the assurance of the yield one uses, is in line with the assurance of supply required by the users. Stochastically generated flow sequences are generated artificially based on the statistical characteristics of the historic natural flow sequence. The stochastic flow sequences are in general of the same period length as the historic flow sequence, so that one can compare the results from the two types of analyses. In the order of 200 to 500 stochastic flow sequences are analysed to obtain a good definition of the available yield at different assurance levels.

Two types of stochastic yield analyses are used, the long-term stochastic yield and the short-term stochastic yield. The long-term stochastic yield is used to obtain the expected yield over the long term at different assurance levels. (See **section 7** for more detail).

The short-term stochastic yield results are used as part of the operating rule for the water resource systems. The yield of the resource is then determined at different starting storage levels. These results clearly show that over the short-term the yield from a resource will be much higher when the resource is full at the beginning of the analysis period than for the event when the storage is low at the start of the analysis. These yield results can then very effectively be used to determine when restrictions need to be imposed on a system and how severe these restrictions should be (See **section 7** for more detail).

7 System yield analyses

Various yield analyses were carried out on the Orange-Senqu-Vaal River basin. Selected analyses were carried out for different sub-catchments depending on the relevance and requirements of the sub-catchments. The analyses carried out were one or more of the following:

- Historic yield analysis: This analysis is based on the historical actual time series, and as a result only represents one, single sequence of flows for each sub-catchment. The historical analysis was undertaken over an 85 year period dating from October 1920 to September 2005. A historic yield is defined as the maximum target draft that can be removed from the resource prior to the resource just touching empty one time over the analysis period. As a result of its definition the historical analysis is generally fairly conservative, and the yield obtained is at a fairly high assurance level. The yield is, however, quick to obtain and is a good comparative indicator with previous yields obtained, and various options to be analysed.
- Long-Term Stochastic analysis: This analysis is carried out for the entire record period of 85 years, however, a number of differing stochastic flow sequences are analysed for each sub-catchment and the system behaviour is assessed under these differing sequences. 201 sequences have been used for this study. As a result of this, yields can be quoted at various assurances of supply levels which provide a better indicator of the available yield from the system. A long-term stochastic analysis takes a number of days to complete for the system the size on the Orange-Senqu basin, due to the many sequences and long time period that need to be covered. Not all sub-catchments are therefore analysed under long-term conditions due to this.
- Short-Term Stochastic analysis: As with the long-term, a number of sequences are analysed for short-term stochastic analyses, however only a five year record period is assessed. Starting storages of the resources are set at varying levels, and the short-term yields determined are thus based on the various starting storages. 501 sequences are used for short-term analyses, and again the process is lengthy. The results of the short-term stochastic analysis are used as a direct input into the WRPM. Not all sub-catchments are analysed under short-term conditions.

7.1 SCENARIO DESCRIPTIONS

To date, only existing operating rule scenarios have been assessed as part of this study. The demands imposed on the entire system were based on the 2013 development level demands and infrastructure. Based on these results, varying potential future scenarios will be defined and a second round of analysis will then take place. The following sections present details of the yield analyses that have been undertaken for various sub-catchments. The sections are divided per catchment, and a description of the yields undertaken and results obtained is presented under each section.

7.2 GROOTDRAAI DAM

The scenario considered when determining the yield for Grootdraai Dam included the following:

- Existing compensation release from Grootdraai Dam included;
- Current Standerton demand downstream of Grootdraai Dam included, this demand has access to the compensation release;
- 6% loss included prior to water available to the yield channel;
- Unlawful irrigation abstractions upstream of Grootdraai Dam set at 2014 target level volume.

Under these conditions, a historic firm yield of 96 million m^3/annum was determined for Grootdraai Dam. **Table 7-1** presents the long-term stochastic yield results, and **Table 7-2** the short-term stochastic yield results that were obtained for the dam.

Table 7-1 : Long-Term Stochastic yield results for Grootdraai Dam

Dam	Long-term stochastic firm yield at indicated recurrence intervals			
	1:20 year (million m^3/a)	1:50 year (million m^3/a)	1:100 year (million m^3/a)	1:200 year (million m^3/a)
Grootdraai	146.20	119.15	106.54	93.25

Table 7-2 : Short-Term Stochastic yield results for Grootdraai Dam

Starting storage (as % of live FSC$^{(1)}$)	Selected period length (years) $^{(2)}$	Yield (Million m^3/annum) at indicated RI $^{(3)}$				
		1:200	1:100	1:50	1:20	1:10
100%	5	113.67	124.77	146.01	176.08	204.14
80%	5	104.61	117.61	134.30	165.65	196.17
60%	3	91.93	101.32	110.24	143.31	177.08
40%	3	61.77	69.01	83.30	110.67	144.88
20%	2	30.40	37.96	49.88	66.41	89.96
10%	2	11.40	18.57	28.99	38.79	45.41

Note:(1) Live full supply capacity (FSC) of Dam.

(2) Selected period length, from 1 to 5 years, that provides the most conservative result.

(3) Recurrence interval of failure, in years.

7.3 BLOEMHOF SUB-SYSTEM

When determining the yield of the Bloemhof sub-system, the yield obtained for Grootdraai Dam as presented in **Section 7.2** is removed from Grootdraai Dam and linked directly with the Bloemhof sub-system yield node. This is because Grootdraai Dam is not used to support Vaal Dam and therefore its individual yield should be added to the remaining system yield in order to obtain the total yield for the Bloemhof sub-system.

Abstractions from the Vaal River downstream of Vaal Barrage take place at two main points in the river. In order to account for this, channels representing these abstractions are configured at their respective points, and are linked to the yield node. Demands supported from Bloemhof Dam is abstracted from the dam and the related demand channel linked to the yield node.An “open” channel that represents all additional yields over and above the 2013 development level abstractions already removed is then placed on Vaal Dam and linked to the yield node. The following assumptions are considered when determining the yield of the Bloemhof system.

- Yield from Grootdraai Dam linked to yield node, Grootdraai Dam does not support Vaal Dam;
- Grootdraai Dam compensation release included;
- Transfer from Thukela system into Sterkfontein Dam included; Sterkfontein Dam supports Vaal Dam when Vaal Dam empties;
- Unlawful irrigation in all sub-catchments upstream of Bloemhof Dam set at 2014 target level volume;
- 2013 development level demands for Midvaal, small towns, Sedibeng and main stem irrigation upstream of Bloemhof Dam all abstracted at their relevant points and linked to yield node;
- Demands supported from Bloemhof Dam set at 2013 development level and abstracted from Bloemhof Dam and linked to yield node;
- Open channel linked to yield node from Vaal Dam;
- No return flows in place in any upstream catchments;
- Loss from Bloemhof Dam not included.

Under these conditions, a historic firm yield of 1 801 million m^3/annum was determined for the total Bloemhof system.

Table 7-3 presents the long-term stochastic yield results, and **Table 7-4** the short-term stochastic yield results obtained from the analysis.

Table 7-3 : Long-Term Stochastic yield results for Bloemhof system

Dam	Long-term stochastic firm yield at indicated recurrence intervals			
	1:20 year (million m^3/a)	1:50 year (million m^3/a)	1:100 year (million m^3/a)	1:200 year (million m^3/a)
Bloemhof system	2170.24	1937.77	1798.52	1687.07

Table 7-4 : Short-Term Stochastic yield results for Bloemhof system

Starting storage (as % of live FSC(1))	Selected period length (years) (2)	Yield Mill m^3/annum at indicated RI (3)				
		1:200	1:100	1:50	1:20	1:10
100%	5	2188.39	2328.95	2496.49	2761.06	3085.53
80%	5	1948.72	2109.37	2284.33	2562.27	2869.75
60%	5	1707.96	1838.54	2007.10	2290.80	2604.40
40%	4	1419.40	1523.42	1664.90	1923.62	2210.45
20%	3	1017.39	1098.47	1192.35	1380.92	1643.59
10%	2	689.99	752.56	819.57	984.98	1134.09

Note:(1) Live full supply capacity (FSC) of Dam.

(2) Selected period length, from 1 to 5 years, that provides the most conservative result.

(3) Recurrence interval of failure, in years.

7.4 MODDER SUB-SYSTEM COMPONENT OF THE CALEDON MODDER SUB-SYSTEM

A yield analysis was carried out on the Modder sub-system component of the greater Caledon Modder sub-system. The configuration was such that the yield channel was placed on Mockes Dam, which was supported by Rustfontein Dam when it reached 20% storage capacity. The upstream demands were set at 2013 development level, including a portion of the Thaba Nchu demand from Groothoek Dam. A historic firm yield of 13.6 million m³/annum was determined for the Modder sub-system component. **Table 7-5** presents the long-term stochastic yield results, and **Table 7-6** the short-term stochastic yield results obtained for the system.

Table 7-5 : Long-Term Stochastic yield results for Riet-Modder sub-system

Dam	Long-term stochastic firm yield at indicated recurrence intervals			
	1:20 year (million m³/a)	1:50 year (million m³/a)	1:100 year (million m³/a)	1:200 year (million m³/a)
Rustfontein and Mockes	19.31	16.14	14.23	12.42

Table 7-6 : Short-Term Stochastic yield results for Riet-Modder sub-system

Starting storage (as % of live FSC⁽¹⁾)	Selected period length (years) ⁽²⁾	Yield Mill m³/annum at indicated RI ⁽³⁾			
		1:200	1:100	1:50	1:20
100%	5	18.68	20.07	23.15	27.67
80%	5	16.13	17.79	20.97	25.64
60%	5	13.75	15.21	18.21	22.50
40%	5	10.87	12.46	14.72	18.97
20%	3	7.68	8.79	10.31	12.87
10%	2	4.18	5.29	6.71	8.35

Note:(1) Live full supply capacity (FSC) of Dam.

(2) Selected period length, from 1 to 5 years, that provides the most conservative result.

(3) Recurrence interval of failure, in years.

7.5 VAAL RIVER SMALLER TRIBUTARIES

Some large dams exist on a number of smaller tributaries to the Vaal River. The hydrology for these areas was merely updated, and it is not anticipated that the yields for these dams will be significantly different from previous determinations. The yields obtained for these dams are summarised in **Table 7-7**. These yields were sourced from other studies and are merely included here for completeness. Some of the other studies used the recently extended hydrology and system configurations from the Phase 2 of the IWRMP ORASECOM study, whereas some were carried out prior to the hydrology extension. This is indicated in the **Table 7-7**. It is recommended that the yields not yet updated with the new hydrology record period be carried out at some stage.

Table 7-7 : Historic firm yields of large Dams on Vaal River tributaries

Catchment	Dam	Historic Firm Yield	Yield carried out with updated hydrology 1920 - 2004
Harts	Wentzel Dam	0.94	yes
Harts	Taung Dam	7.82	yes
Harts	Spitskop Dam	30.35	yes
Renoster	Koppies Dam	13.0	no
Sand	Allemanskraal Dam	41.1	no
Vet	Erfenis Dam	51.1	no
Mooi	KlerkskraalDam	17.5	no
Mooi	BoskopDam	33.1	no
Mooi	LakesideDam	6.1	no
Klipdrift	KlipdriftDam	3.5	no
Schoonspruit	Rietspruit & ElandskuilDams	21.3	yes
Wilge	Fika PatsoDam	15.5	yes
Wilge	MetsimatshoDam	2.5	yes
Modder	KrugersdriftDam	23.9	yes
Riet	KalkfonteinDam	39.0	yes

Table 7-8 Long-Term yields of large Dams on Vaal River tributaries

Dam	Long-term stochastic firm yield at indicated recurrence intervals			
	1:20 year (million m^3/a)	1:50 year (million m^3/a)	1:100 year (million m^3/a)	1:200 year (million m^3/a)
Wentzel	2.01	1.49	1.26	1.08
Taung	12.65	10.35	9.15	8.25
Spitskop	35.20	33.20	31.90	30.70
Rietspruit & Elandskuil	30.3	28.8	27.1	25.1
Fika Patso	19.59	17.64	16.72	15.85
Metsimatsho	3.15	2.85	2.68	2.56
Kalkfontein	54.34	43.67	35.88	30.17
Krugersdrift	37.01	33.41	30.76	28.91

Table 7-9: Short-Term characteristics of large Dams on Vaal River tributaries

Starting storage (as % of live FSC(1))	Selected period length (years) (2)	Yield Mill m^3/annum at indicated RI (3)			
		1:200	1:100	1:50	1:20
Wentzel Dam					
100%	5	1.32	1.70	2.04	2.39
80%	5	1.15	1.60	1.94	2.24
60%	5	1.06	1.36	1.77	2.10
40%	4	0.96	1.12	1.28	1.72
20%	3	0.52	0.60	0.72	1.14
10%	2	0.30	0.36	0.48	0.88
Taung Dam					
100%	5	7.90	9.40	10.30	12.80
80%	5	6.10	7.10	8.05	11.25
60%	5	3.70	4.70	5.60	8.50
40%	4	1.60	2.50	3.40	5.70
20%	3	0.00	0.30	0.95	2.40
Spitskop Dam					
100%	5	32.30	33.00	34.10	36.70
80%	5	32.30	32.80	33.70	36.00
60%	5	31.70	32.30	33.00	35.20
40%	4	30.90	31.20	32.20	34.30
20%	3	29.90	30.20	31.40	33.20
10%	2	29.30	29.60	30.30	31.70
Fika Patso Dam					
100%	5	17.06	18.04	19.28	21.04
80%	5	16.05	16.94	18.14	20.07
60%	4	14.29	15.06	16.29	17.91
40%	2	11.30	12.50	13.36	14.85
20%	2	7.97	8.91	9.56	10.79
10%	1	5.67	5.80	6.11	6.60
Metsimatsho Dam					
100%	5	2.71	2.86	3.06	3.38
80%	5	2.54	2.70	2.87	3.18
60%	3	2.26	2.37	2.56	2.86
40%	2	1.70	1.96	2.09	2.37
20%	1	1.43	1.48	1.52	1.64
10%	1	0.87	0.89	0.93	1.01
Kalkfontein Dam					
100%	5	59.79	66.19	72.90	85.91
80%	5	53.13	58.73	66.30	78.04
60%	5	43.87	48.89	57.05	68.77
40%	5	34.34	38.89	45.61	57.58
20%	4	22.42	26.39	32.29	41.06
10%	3	15.87	19.01	22.71	28.20
Krugersdrift Dam					
100%	5	14.58	17.31	19.80	26.02
80%	5	12.58	15.35	18.30	23.75
60%	4	12.42	14.16	16.85	22.08
40%	3	9.40	10.68	12.66	17.68
20%	2	4.98	6.50	7.33	10.91
10%	2	2.95	3.71	4.49	6.90

Note:(1) Live full supply capacity (FSC) of Dam.
(2) Selected period length, from 1 to 5 years, that provides the most conservative result.
(3) Recurrence interval of failure, in years.

7.6 LESOTHO HIGHLANDS SUB-SYSTEM

The original hydrological records for the Lesotho Highlands system dating from 1920 to 1995 **were not modified in any way** as part of the ORASECOM Integrated Water Resources Management Plan Phase 2 Study, and additional years from 1996 to 2004 were merely added, based on the original calibrated hydrology parameters. Only a stochastic yield analysis was carried out previously, with a result of 780.19 million m^3/annum determined to be the volume available for transfer to the Vaal system. This yield is referred to as the nominal annual yield and represents approximately a 1 in 50 year recurrence interval. The historic firm yield for the combined Katse and Mohale Dams was determined as part of this study to be 796 million m^3/annum. The existing operating rule of transfers between Mohale and Katse Dam was used for the analysis, as well as the diversion from Matsoku weir into Katse Dam. The environmental releases for the two dams were included in the analyses, and were allowed for prior to the yield being determined.

It was decided to check the short-term stochastic analysis at two starting storage levels with that previously used. The results of this is summarised in **Table 7-10**.

Table 7-10 : Short-Term Stochastic yield results for the Senqu system

Starting storage (as % of live FSC(1))	Selected period length (years) (2)	Yield (Million m^3/annum) at indicated RI (3)			
		1:200	1:100	1:50	1:20
100%	5	964.57	1011.36	1054.12	1112.83
40%	5	651.61	686.76	744.65	803.61

Note:(1) Live full supply capacity (FSC) of Dam.
(2) Selected period length, from 1 to 5 years, that provides the most conservative result.
(3) Recurrence interval of failure, in years.

7.7 CALEDON SUB-SYSTEM COMPONENT OF CALEDON MODDER SUB-SYSTEM

New hydrology for the Caledon sub-system component of the greater Caledon Modder sub-system was produced as part of the ORASECOM Integrated Water Resources Management Plan Phase 2 Study, and for this reason all yields were reproduced. The water resources of the Caledon sub-system are a combination of Knellpoort and Welbedacht dams. These dams are both used to support the Bloemfontein Botshabelo urban demand centre in South Africa. Knellpoort is an off channel storage dam and is supplied with water from the Caledon River through the Tienfontein Pump Station. Knellpoort transfers water through the Novo transfer scheme to Rustfontein Dam in the Modder catchment. Welbedacht Dam transfers water directly to Bloemfontein via a pipeline. The infrastructure capacities of these transfers were included in the model when carrying out the yield analysis as follows:

- Tienfontein pump capacity: pump capacity differs depending on flow in Caledon river, with maximum capacity set on 4.17 m^3/s;
- Novo transfer capacity:72.6 million m^3/annum (2.3 m^3/s)
- **Welbedacht pipeline capacity**: 56.2 million m^3/annum(1.78 m^3/s)

The two transfers from Knellpoort and Welbedacht Dams were combined into one yield node in order to determine the total yield from the Caledon resources.

The historic firm yield was determined to be 69 million m^3/annum. The long-term stochastic yields obtained are presented in **Table 7-11** and the short-term stochastic yields in **Table 7-12**.

Table 7-11 : Long-Term Stochastic yield results for the Caledon system

Dam	Long-term stochastic firm yield at indicated recurrence intervals			
	1:20 year (million m^3/a)	1:50 year (million m^3/a)	1:100 year (million m^3/a)	1:200 year (million m^3/a)
Knellpoort and Welbedacht	93.01	85.28	78.17	72.52

Table 7-12: Short-Term Stochastic yield results for the Caledon system

Starting storage (as % of live FSC(1))	Selected period length (years) (2)	Yield Mill m^3/annum at indicated RI (3)			
		1:200	1:100	1:50	1:20
100%	5	80.73	86.74	92.40	103.56
80%	5	75.68	85.16	91.69	102.56
60%	5	73.87	80.97	89.61	99.18
40%	2	67.99	76.03	80.71	91.18
20%	1	39.05	46.51	53.30	60.41
10%	1	22.02	26.88	31.22	37.46

7.8 ORANGE RIVER PROJECT (GARIEP & VANDERKLOOF DAMS)

New hydrology for the Upper Orange sub-system was produced as part of the ORASECOM Integrated Water Resources Management Plan Phase 2 Study, and for this reason all yields were reproduced. The water resources of the Orange River project (ORP) are a combination of Gariep and Vanderkloof dams. The following is considered when carrying out the yield analysis for the Orange River Project:

- The full transfer to the Vaal is removed from Katse and Mohale Dams, and these dams are not used to support the Orange River Project. Only the agreed on environmental requirement releases are releasedfrom these dams.
- All upstream demands were set at 2013 development level, except for the Bloemfontein urban area which was set at a 2023 development level and the infrastructure capacity constraints were removed from the Caledon/Modder transfers. This was so that the Bloemfontein demand could be fully supplied before any spills from the Caledon system reach Gariep Dam, and will therefore result in a more conservative yield for ORP.
- An additional future demand was placed on the Metolong Dam, and the dam was switched on in the analysis.

The historic firm yield was determined to be 3 252 million m^3/annum. The long-term stochastic yields obtained are presented in **Table 7-13** and the short term stochastic yields in **Table 7-14**.

Table 7-13 : Long-Term Stochastic yield results for the Orange River Project

Dam	Long-term stochastic firm yield at indicated recurrence intervals			
	1:20 year (million m^3/a)	1:50 year (million m^3/a)	1:100 year (million m^3/a)	1:200 year (million m^3/a)
Gariep and Vanderkloof	3716	3332	3084	2892

Table 7-14 : Short-Term Stochastic yield results for the Orange River Project

Starting storage (as % of live FSC$^{(1)}$)	Selected period length (years) $^{(2)}$	Yield Mill m^3/annum at indicated RI $^{(3)}$			
		1:200	1:100	1:50	1:20
100%	5	3392	3593	3848	4350
80%	5	3205	3410	3670	4143
60%	5	2887	3090	3420	3836
40%	3	2386	2574	2896	3308
20%	2	1660	1877	2131	2479
10%	1	1204	1247	1491	1705

7.9 FISH RIVER

New hydrology for the Namibian Fish River sub-system was produced as part of the ORASECOM Study "Orange-Senqu Strategic Action Programme: Research Project on Environmental Flow Requirements of the Fish River and the Orange-Senqu River Mouth" funded by the UNDP-GEF. The WRSM2000 model was used to carry out this work, due to complications with obtaining the NAMRON model at the time. New yields were reproduced for Hardap and Naute Dams as part of this study. These initial historic firm yields differ significantly from previous results.The main reason for the lower yields obtained from the updated hydrology was lower flows produced by the simulated record over the critical period. Observed records were available for both Hardap and Neckartal dams that completely cover the critical periods. The simulated portion of the record that overlaps with the observed records was then replaced with the observed record. These combined flow records (simulated and observed) were then used for the yield assessments and produced far more realistic results.

The historic firm yield for Hardap Dam was now determined to be 35.5 million m^3/annum and for Naute Dam 9.6 million m^3/annum in comparison with the initial results of 24.9 and 8.2 million m^3/a respectively.

Table 7-15: Long-Term Stochastic yield results for the Hardap Dam

Dam	Long-term stochastic firm yield at indicated recurrence intervals			
	1:20 year (million m^3/a)	1:50 year (million m^3/a)	1:100 year (million m^3/a)	1:200 year (million m^3/a)
Hardap Dam	48.77	33.74	26.63	22.63

Table 7-16: Long-Term Stochastic yield results for the Naute Dam

Dam	Long-term stochastic firm yield at indicated recurrence intervals			
	1:20 year (million m^3/a)	1:50 year (million m^3/a)	1:100 year (million m^3/a)	1:200 year (million m^3/a)
Naute Dam	15.64	11.78	9.78	8.15

7.10 ORANGE RIVER SMALLER TRIBUTARIES

Two additional medium large dams exist on smaller tributaries to the Orange River. The yields obtained for these dams are summarised in **Table 7-17**. These yields were sourced from other studies and are merely included here for completeness. Both of the other studies used the recently extended hydrology and system configurations.

Table 7-17 : Historic firm yields of large Dams on Orange River tributaries

Catchment	Dam	Historic Firm Yield	Yield carried out with updated hydrology 1920 - 2004
Caledon	Armenia Dam	4.0	yes
Upper Orange	Hololhatsi Dam	6.7	yes

Table 7-18 Long-Term yields of large Dams on Orange River tributaries

Dam	Long-term stochastic firm yield at indicated recurrence intervals			
	1:20 year (million m^3/a)	1:50 year (million m^3/a)	1:100 year (million m^3/a)	1:200 year (million m^3/a)
Armenia Dam	5.11	4.44	4.01	3.74
Holohlatsi Dam	8.91	7.70	7.12	6.59

Table 7-19: Short-Term characteristics of large Dams on Orange River tributaries

Starting storage (as % of live FSC⁽¹⁾)	Selected period length (years) ⁽²⁾	Yield Mill m^3/annum at indicated RI ⁽³⁾			
		1:200	1:100	1:50	1:20
Armenia Dam					
100%	5	4.29	4.67	5.11	6.15
80%	5	4.14	4.53	4.96	5.96
60%	5	3.79	4.16	4.69	5.55
40%	2	3.40	3.70	4.08	4.84
20%	2	2.28	2.60	2.93	3.56
10%	2	1.80	2.05	2.33	2.67
Holohlatsi Dam					
100%	5	7.11	7.68	8.61	9.95
80%	5	6.75	7.46	8.34	9.47
60%	3	5.96	6.55	7.31	8.56
40%	2	4.66	5.21	5.63	6.99
20%	2	3.26	3.65	3.94	4.52
10%	1	1.96	2.15	2.30	2.58

Note:(1) Live full supply capacity (FSC) of Dam.

(2) Selected period length, from 1 to 5 years, that provides the most conservative result.

(3) Recurrence interval of failure, in years.

7.11 SUMMARY OF YIELD RESULTS

A summary of the yields and demands for the main sub-systems or dams is given in **Table 7-18**. The Grootdraai and Bloemhof sub-system yields are significantly less than the current and future demands imposed on these sub-systems. For this reason several transfers systems were introduced over the years to augment the shortages within these two sub-systems. These include the transfers from Heyshope Dam, Zaaihoek Dam, the Upper Tukela transfer via Sterkfontein Dam and the LHWP which are all used to directly support these two sub-systems. The Komati and Usutu transfer systems are used to assist the Grootdraai sub-system in supplying several power stations in the Upper Olifants catchment (Limpopo Basin), but is not providing direct support to the Grootdraai sub-system. Results from the Vaal River System Reconciliation Study indicated that the Integrated Vaal River System will require augmentation by approximately 2021. For this reason Phase II of the LHWP is currently in its planning stages to address this problem.

In the Caledon River catchment the Novo transfer capacity and the Tienfontein pump-station capacity are in the process of being increased and they are expected to be functional by 2015 and 2016 respectively. The yield analyses carried out as part of this study already included the increased transfer and pump capacities. As this system is used to supply urban/industrial requirements it should be reasonable to compare the demand with the 1 in 50 year stochastic yield of 101.4 million m^3/a. This clearly illustrates that with the increased capacities in place the yield should still be sufficient to supply in the demand, but shortages will be expected before 2025.

Although the Orange River Project yield seems approximately in balance with the current and expected future demands, there are a number of other aspects that need to be taken into account. The significant increase in demand between 2013 and 2015 is mainly as result of increased irrigation that was already allocated for the development of resource poor farmers in South Africa (approximately 120 million m^3/a) which has not yet been taken up. The LHWP Phase II is planned to be in place by around 2022. This comprises Polihali Dam in Lesotho with a tunnel linking Polihali Dam to Katse Dam. Polihali Dam will transfer additional water to the Vaal system and thereby taking water away from the Senqu system resulting in less flows entering Gariep and Vanderkloof Dam. Results from the Orange Reconciliation Strategy Study currently undertaken by the DWA RSA showed that this will result in a decrease in the ORP yield and shortages are then expected to occur in the ORP sub-system. There would therefore also be a greater risk of shortages further downstream along the main Orange River, including the Namibian/South African shared portion of the Lower Orange. The current releases from the ORP to address the EWR in the Orange are based on outdated methods. These EWRs need to be replaced by more recent estimations of the EWRs. These EWRs were recently determined by ORASECOM through the "Orange-Senqu Strategic Action Programme: Research Project on Environmental Flow Requirements of the Fish River and the Orange-Senqu River Mouth" study funded by the UNDP-GEF. Results from ongoing work on the Orange Reconciliation Strategy Study and under this project show that the inclusion of these updated EWR's as demands on the ORP result in a significant decrease in the ORP project yield, which will further increases the deficit in the ORP..

Table 7-20: Summary of yield results

Sub-system and Dams	Yield (1) (million m^3/a)	Demand (million m^3/a)			Comments
		2013	2025	2040	
Grootdraai Dam	96.0 (119.2 - 106.5)	170	185.6	192.4	Grootdraai yield is significantly less than the demand. This is the reason why several transfers are used to support Grootdraai.
Bloemhof sub-system (Bloemhof Dam, Grootdraai, Vaal Dam, Sterkfontein, Tugela transfer from Driel Barrage)	1 801 (1 938 – 1 798)	2 454	2 666	2 985	Bloemhof sub-system is supported with transfers from LHWP, Heyshope and Zaaihoek dams. (Net demand)
Caledon Modder sub-system	13.6+69=82.6 (2) (101.4 – 92.4)	96	134	213	The demands include 10% losses related to the transfers
Orange River Project (Gariep & Vanderkloof dams)	3 252 (3 332 – 3084)	3 089	3 290	3 312	The net demand is given as a significant volume of return flows are generated that are again used by downstream irrigators.
LHWP Phase 1)Katse & Mohale dams & Matsoku Weir	796	780	780	780	Volume transferred to the Vaal is based on the nominal annual yield which is close to the 1 in 50 year stochastic yield.
Koppies Dam	13.0	10	10	10	Stochastic yield not available
Boskop & Lakeside	33.1+6.1=39.2 (2)	45	47	47	Stochastic yield not available
Klipdrift Dam	3.5	6.4	6.4	6.4	Stochastic yield not available
Rietspruit & Elandskuil	21.3(28.8 - 27.1)	28.8	29.2	29.7	
Allemanskraal Dam	41.1	52	52	52	Stochastic yield not available
Spitskop Dam	30.4 (33.2 - 31.9)	13.7	13.7	13.7	
Taung Dam	7.82 (10.4 - 9.2)	0	0	0	
Wentzel Dam	0.94 (1.49 - 1.26)	1.7	2.8	3.9	
Krugersdrift Dam	23.9 (33.4 - 30.8)	36.6	36.6	36.7	Net demand
Kalkfontein Dam	39.0 (43.7 - 35.9)	50.1	52.1	54.5	
Armenia Dam	4.0 (4.4 – 4.0)	0.48	0.54	0.61	
Holohlatsi Dam	6.7 (7.7 - 7.1)	5.4	6.5	7.4	
Hardap Dam	35.5 (33.7 – 26.6)	44.9	44.9	44.9	The 1 in 20 year is 48.8 and is more applicable to the irrigation demand for Hardap
Naute Dam	9.6 (11.78 – 9.78)	8.2	11.7	11.7	

Note:(1) Yield in brackets refer to 1 in 50 and 1 in 100 year stochastic yield respectively. The other yield refers to the historic firm yield
(2) Combined yield of two dams or sub-systems.

7. SYSTEM YIELD ANALYSES

The historic firm yield as determined for the LHWP Phase I is well in line with the current agreed transfer volume to the Vaal sub-system, and no yield related problems are foreseen for this sub-system.

For several of the medium size dams the demands are already exceeding the 1 in 50 year stochastic yield. These include Allemanskraal, Wentzel, Krugersdrift, Kalkfontein and Hardap dams. Allemanskraal, Krugersdrift and Kalkfontein dams primarily supply water to irrigators which have adapted to the lower assurance of supply. Wentzel Dam seems to have a problem as it is used for urban water supply purposes.

Hardap Dam in Namibia is mainly used for irrigation purposes which requires a lower assurance of supply. In general a 1 in 20 year assurance (95% assurance) is regarded as sufficient for irrigation purposes. Although the 1 in 50 year yield of Hardap is significantly less than the current demand imposed on the dam, the 1 in 20 year yield of 48.8 million m^3/a is thus more than sufficient.

8 Conclusions and next steps

The updated yield results from this study are in general fairly in line with the previous estimated yields..

Most of the existing sub-systems are fairly in balance with the available yield. To be able to maintain this balance over time, interventions will be required in future, in particular for the Integrated Vaal River System and the ORP. The inclusion of EWRs on the Orange will also result in significant deficits in the ORP.

Lesotho has currently completed the Metolong Dam that will address current and future shortages in the Maseru and surrounding towns and settlements. Namibia started with the construction of Neckartal Dam in the Fish River to supply water to a new irrigation scheme. Vioolsdrift Dam on the Lower Orange is in the planning process, and will be a combined project between Namibia and South Africa to address water requirements and operational improvements along the Lower Orange for both of the basin states. Botswana is currently looking at the possibility to obtain water from Lesotho to address needs within Botswana.

All the above mentioned aspects are of importance for the next stage of this task which will be focussed on scenario analyses. These aspects need to be discussed with the stakeholders as it will provide valuable input in the process of defining scenarios that need to be analysed as part of the next stage of this task.

The bulk of the scenario analyses will be carried out with the use of the WRPM. The short-term stochastic yield characteristics as already determined and described in this report forms a critical input to the WRPM as part of the operating rule for the various sub-systems.

9 References

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ANNEXES

ANNEXES