DWA REPORT NUMBER: P RSA D000/00/18312/13

water affairs

Department:
Water Affairs
REPUBLIC OF SOUTH AFRICA

Directorate: National Water Resource Planning

DEVELOPMENT OF RECONCILIATION STRATEGIES FOR LARGE BULK WATER SUPPLY SYSTEMS: ORANGE RIVER

RESERVE REQUIREMENT SCENARIOS AND SCHEME YIELDS

JANUARY 2015

DEVELOPMENT OF RECONCILIATION STRATEGIES FOR BULK WATER SUPPLY SYSTEMS

ORANGE RIVER

REFERENCE

This report is to be referred to in bibliographies as:

Department of Water Affairs, South Africa, 2013. ***DEVELOPMENT OF RECONCILLIATION STRATEGIES FOR LARGE BULK WATER SUPPLY SYSTEMS: RESERVE REQUIREMENT SCENARIOS AND SCHEME YIELDS***

Prepared by:

WRP Consulting Engineers, Aurecon, Golder Associates Africa, and Zitholele Consulting.

Report No. P RSA D000/00/18312/13

Title:	***Reserve Requirement Scenarios and Scheme Yield***
Authors:	*C Seago & HG Maré*
Project Name:	***Development of Water of Reconciliation Strategies for Large Bulk Water Supply Systems: Orange River***
DWA Report No:	*P RSA D000/00/18312/13*
Status of Report:	*Final*
First Issue:	*September 2014*
Final:	*January 2015*

Consultants: WRP Consulting Engineers (Pty) Ltd in association with Aurecon, Golder Associates Africa and Zitholele Consulting

Approved for the Consultants by:

....

PG van Rooyen

Study Leader

DEPARTMENT OF WATER AFFAIRS

Directorate: National Water Resource Planning

Approved for DWA by:

....

ST Makombe

Production Engineer: National Water Resource Planning

....

JI Rademeyer

Chief Engineer: National Water Resource Planning

....

T Nditwani

Acting Director: National Water Resource Planning

LIST OF REPORTS

The following reports form part of this study:

Report Title	Report number
Inception Report	P RSA D000/00/18312/1
Literature Review Report	P RSA D000/00/18312/2
International obligations	P RSA D000/00/18312/3
Current and future Water Requirements	P RSA D000/00/18312/4
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Reserve Requirement Scenarios and Scheme Yield	**P RSA D000/00/18312/13**
Preliminary Screening Options Agreed: Workshop of February 2013	P RSA D000/00/18312/14

DEVELOPMENT OF RECONCILIATION STRATEGIES FOR LARGE BULK WATER SUPPLY SYSTEMS: ORANGE RIVER

Reserve Requirement Scenarios and Scheme Yield

EXECUTIVE SUMMARY

The Department of Water Affairs (DWA) has identified the need for detailed water resource management strategies as part of their Internal Strategic Perspective (ISP) planning initiative, which recommended studies to identify and formulate intervention measures that will ensure enough water can be made available to supply the water requirements for the next three to four decades.

As part of this process the need for the Reconciliation Strategy Study for the Large Bulk Water Supply Systems in the Orange River was also defined. Given the location of the Orange River System and its interdependencies with other WMAs as well as other countries, various water resource planning and management initiatives compiled during the past few years as well as those currently in progress will form an integral part of the strategy development process.

Since 1994, a significant driver of change in the water balance of the Orange River System was brought about by the storing of water in Katse Dam as the first component of the multi-phase Lesotho Highlands Water Project (LHWP). Currently Phase 1 of the LHWP (consisting of Katse, and Mohale dams, Matsoku Weir and associated conveyance tunnels) transfers 780 million cubic metres per annum via the Liebenbergsvlei River into the Vaal Dam to augment the continuously growing water needs of the Gauteng Province. Phase 2 of the LWHP comprising of Polihali Dam and connecting tunnel to Katse Dam is already in its planning stages. Polihali Dam is expected to be in place by around 2022. Flows that are currently still entering into Gariep and Vanderkloof dams will then be captured by Polihali Dam, thus reducing the inflow to Gariep and Vanderkloof dams. This will result in a reduction in yield of the Orange River Project (Gariep and Vanderkloof dams) to such an extent that

shortages will be experienced in the ORP system. Some sort of yield replacement is then required in the Orange River to correct the yield versus demand imbalance in the ORP system. The objective of the study is to develop a reconciliation strategy for the bulk water resources of the Orange River System, to ensure that sufficient water can be made available to supply the current and future water needs for a 25 year planning horizon. This Strategy must be flexible to accommodate future changes in the actual water requirements and transfers, with the result that the Strategy will evolve over time as part of an on-going planning process.

Appropriate integration with other planning and management processes as well as cooperation among stakeholders will be key success factors in formulating coherent recommendations and action plans.

The purpose of this report

*The Task reported on in this document is Task 12 of the study and is titled **Reserve Requirement Scenarios and Scheme Yield**. As part of the recently completed ORASECOM Study "Support to Phase ll ORASECOM Basin Wide Integrated Water Resources Management Plan" (**ORASECOM, 2011**) the hydrology for the entire Orange basin was extended and improved in some places, now covering the total record period 1920 to 2004 hydrological years. The objective of this task was to use this hydrology, configured it into the WRYM and WRPM and to determine the system yields as well as the required timing of intervention options.*

Yield analysis

Yield analyses were undertaken for the existing system as well as for the identified intervention as agreed upon during the screening workshop involving all SSC members earlier in this study.

The ORP System yield (historic firm yield) was determined under current conditions as 3 325 million m^3/a and reduce to 3 038 million m^3/a when the current EWR releases are supplied. The ORP system is currently for practical purposes just in balance. The small surplus available will be utilized by the further development of the 120 million m^3/a already allocated to the resource poor farmers.

Polihali Dam, the phase ll component of the LHWP will significantly impact on the Orange ORP System yield (reduction of 284 million m3/a), which will result in a deficit in the Orange ORP system. The increased transfer from the LHWP to the Vaal as result of Polihali Dam was determined as 437 million m^3/a. It is however important to note that the Integrated Vaal River System (IVRS) do not initially require the full yield available from Polihali Dam, which *will result in a surplus available in Polihali Dam for quite a long time before the full yield is taken up by the growth in the IVRS requirement. It was therefore recommended to use Polihali Dam to initially support both the IVRS as well as the Orange ORP System.*

When the recommended EWRs on the Lower Orange we included in the yield analysis, a significant reduction in the yield available from the ORP (Gariep and Vanderkloof dams) was evident. The reduction in the yield is very sensitive to the EWR class used as well as related assumptions. The recommended EWR reduce the yield by as much as1060 million m^3/a, but if only the summer month (excluding high flows) flows are considered with no winter flows, the yield reduction is 722 million m^3/a. This impact further reduces to 479 million m^3/a when the PES EWR is used.

The yield available from Vioolsdrift Dam as well as the sizing of Vioolsdrift Dam is very sensitive to the EWR used, the demands downstream of the dam as well as the development of large upstream storage dams. These will typically include the raising of Gariep Dam, Bosberg or Boskraai Dam and Verbeeldingskraal Dam.

*Details of the yield analysis results are given in **Table 4-1** in **Section 4.3** of this report.*

These yield results were used for the water balances presented in the preliminary reconciliation strategy. The preliminary reconciliation strategy was presented to DWA and the stakeholders. Feedback from the meetings and comments on the reports were received and the preliminary reconciliation strategy was updated accordingly.

WRPM analysis

The agreed intervention options forming part of the updated preliminary strategy also formed part of the final detailed WRPM analyses. The WRPM was used to carry out risk based analyses that take into account the required assurances of supply to the different user sectors over an analysis period 2013 to 2040. The WRPM take into account the growth in the demands that are supplied from the resource as well as those located upstream of the resource, impacting on the yield available from the resource. Changed infrastructure changes over time are included in the WRPM as they can significantly impact on the water supply characteristics of a system.

Results from the WRPM analyses showed that Vanderkloof Dam lower level storage need to be in operation by 2019, Vioolsdrift Dam must be in place by 2025 followed by the implementation of the final agreed EWRs (Reserve) in 2026. The next recommended intervention option can be the raised Gariep Dam or the building of Verbeeldingskraal Dam, and must be able to deliver water in 2026 when the agreed EWRs are implemented.

The following important conclusions and recommendations can be drawn from the WRYM and WRPM analyses results.

- *To be able to effectively supply the EWR at the Orange River estuary a control structure on the Lower Orange is required. The possible future Vioolsdrift Dam will be ideal for this purpose.*
- *The yield available from Vioolsdrift Dam as well as the sizing of Vioolsdrift dam is very sensitive to the EWR used, the demands downstream of the dam as well as the development of large upstream storage dams.*
- *By reducing the assurance of supply in particular to irrigation, which is currently receiving a fairly high supply assurance, can significantly increase the water availability in the system. Discussing the assurance of water supply requirements with the stakeholders to find agreement on lower assurances of supply in particular for irrigation purposes is very important.*
- *Operating rules can play a significant role in the yield available in the Orange ORP System. This is in particular important when development of dams upstream of Gariep is considered as an intervention option. Due to very high evaporation losses from Gariep Dam, a rule that keep the water for as long as possible in the upstream dam, should increase the yield available due to the reduction in evaporation losses.*
- *The filling periods for the large storage dams such as the raised Gariep and Polihali dam can be quite long as evident from the WRPM analyses results, and will thus impact on the supply capability in the initial years.*
- *Utilizing the Lower Level Storage in Vanderkloof Dam impact on the hydro-power generated at the dam. This impact can be reduced significantly by using the correct operating rule when an upstream storage dam is used to support Gariep and Vanderkloof dams.*
- *Although Verbeeldingskraal Dam storage is significantly less that that obtained by the raising of Gariep Dam, the performance of Verbeelingskraal Dam in system context is very good and is almost as good as the raised Gariep. This is most probably due to much lower evaporation losses from the entire system, when the Verbeeldingskraal option is used.*
- *The identified intervention options as included in the WRPM analyses are sufficient to maintain the water balance over the planning period.*
- *The operating rule imposed on Polihali Dam to manage the duel support from the*

dam is be very important and will significantly impact on the water availability in both the IVRS and the Orange ORP System. Further work is recommended to refine this operating rule, which in the end need to be agreed upon by both Lesotho and the RSA.

- *A classification study is required to obtain a decision on the final agreed EWRs to be imposed on the Orange ORP system. This need to be done as soon as possible as it significantly influences decisions on the future developments.*
- *The impacts of large upstream developments on the environment, specifically along the Lower Orange and the estuary need to be evaluated in more detail, to prevent further deterioration of the environment.*

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1 INTRODUCTION

1.1 Background

The Department of Water Affairs (DWA) has identified the need for detail water resource management strategies as part of their Internal Strategic Perspective (ISPs) planning initiative which recommended studies to identify and formulate intervention measures that will ensure enough water can be made available to supply the water requirements for the next three to four decades.

The DWA Directorate: National Water Resource Planning (NWRP) therefore commenced the strategy development process in 2004 by initially focusing on the water resources supporting the large metropolitan clusters, followed by the systems supplying the smaller urban areas to systematically cover all the municipalities in the country.

Giving the location of the Orange River System and its interdependencies with other WMAs as well as other countries, various water resource planning and management initiatives compiled during the past few years or in progress will form an integral part of the strategy development process, with particular reference to the following:

- Vaal River Reconciliation Strategy (**DWAF, 2009a**), currently being implemented under the guidance of the Strategy Steering Committee.
- Greater Bloemfontein Reconciliation Strategy (**DWA, 2012a**), currently being finalized.
- Various water resource planning and management initiatives commissioned under the auspices of the Orange-Senqu River Basin Commission (ORASECOM, 2011), such as:
  - ORACESOM Basin Wide Integrated Water Resource Management Plan.
  - Trans Boundary Diagnostic Analysis (TDA) followed by a Strategic Action Plan (SAP) and National Action Plans (NAP).
  - UNDP-GEF Orange-Senqu Strategic Action Programme: Determining the environmental flow requirements of the lower Orange River with special focus on the Orange Estuary and coastal marine environment.
- Water quality (salinity) model calibration study to enable the analysis for water quality management scenarios with the Water Resources Planning Model (WRPM).
- Development of an Integrated Water Quality Management Plan for the Orange River System.
- Validation and Verification of water use in the Upper Orange Water

Management Area.
- Feasibility study of a potential dam at Vioolsdrift.

1.2 Objectives

The objective of the study is to develop a reconciliation strategy for the bulk water resources of the Orange River System to ensure sufficient water can be made available to supply the current and future water needs of all the users up to the year 2040. This Strategy must be flexible to accommodate future changes in the actual water requirements and transfers with the result that the Strategy will evolve over time as part of an on-going planning process. Appropriate integration with other planning and management processes as well as cooperation among stakeholders will be key success factors in formulating coherent recommendations and action plans. The outcomes of the Strategy will be specific interventions with particular actions needed to balance the water needs with the availability through the implementation of regulations, demand management measures as well as infrastructure development options.

The Task reported on in this document is Task 12 of the study and is titled **Reserve Requirement Scenarios and Scheme Yield**. As part of the recently completed ORASECOM Study ''Support to Phase II ORASECOM Basin Wide Integrated Water Resources Management Plan" (ORASECOM, 2011) the hydrology for the entire Orange basin was extended and improved in some places, now covering the total record period 1920 to 2004 hydrological years. The objective of this task was using this hydrology, configured into the WRYM and WRPM, to determine system yields and future augmentation scheme timings. The WRYM and WRPM were updated to represent the most recent information in terms of system configurations and projected demands.

1.3 Structure of Report

This report has been structured into a number of different sections. Following this introduction is a section where the background information used to configure the WRYM and WRPM is described. **Section 3** presents and discusses the reserve requirement scenarios in more detail. **Section 4** deals with the yield analyses and results obtained using the Water Resources Yield Model (WRYM) while **Section 5** presents the Water Resources Planning Analyses scenarios and results. Finally, **Section 6** includes conclusions and recommendations resulting from the work. The report also includes **Appendices** which contain additional and supporting information.

2 BACKGROUND INFORMATION USED FOR WYRM AND WRPM

This chapter includes references to all the background information used in the WRYM and WRPM.

2.1 Model versions

2.1.1 WRYM

The water resources yield analyses carried out as part of this study took place in July 2013. The base version of the yield model configuration that was used was obtained from the ORASECOM Phase 2 Study (ORASECOM, 2011), which was completed in April 2011. That WRYM version included all the updated hydrology and water requirements that were available at the time. Subsequent to the completion of the ORASECOM Phase 2 Study however, the detailed Upper Orange and Caledon hydrology recalibration took place. This new hydrology and more detailed system configurations were included into the WRYM as part of this study. This updated WRYM version was considered the base scenario for this study.

2.1.2 WRPM

The water resources planning analyses carried out as part of this study took place in May 2014. The base version of the planning model configuration that was used was obtained from the ORASECOM Phase 3 study, which was ongoing at the time of carrying out the analyses. That WRPM version included all the most recent hydrology and water requirements. Additions to the WRPM that were not included in the WRYM analyses (of July 2013) included, for example, the most recent Namibian-Fish hydrology and configuration and the latest validated irrigation demands for the Upper Orange and Caledon catchments.

2.2 Hydrology

Due to the fact that the ORASECOM Phase 3 Study is running in parallel to this study, the models are constantly being updated in the two studies based on new available information and efforts. The hydrology (prepared as part of the ORASECOM Phase 2 Study (ORASECOM, 2011)) that was used in the WRYM analyses included 207 updated and extended hydrology files, all described in detail and presented in the report produced as part of this study titled Development of Reconciliation Strategies for Large Bulk Water Supply Systems: Orange River: Surface Water Hydrology and System Analysis Report (DWA, 2013a).

Subsequent to the yield analyses, and as part of the ORASECOM Phase 3 study, additional hydrology updates took place, and the hydrology that was used in the WRPM analyses included 248 updated and extended hydrology files, all described in detail and presented in the report produced as part of the ORASECOM Phase 3 study titled Integrated Water Resources Management Plan For The Orange-Senqu River Basin, Work Package 4c: Water Resources Modelling; Base Scenario. Yield Analysis, Stochastic Verification and Validation (ORASECOM, 2014). The additional 41 files were a result of modified Namibian Fish hydrology files (previously five files, updated to ten files), and an additional 36 files representing the hydrology of the Eastern Cape, a new configuration included in the WRPM. A summary of the hydrology used in the WRPM is provided in **Table 2-1** per sub-catchment.

Table 2-1: Summary of average natural historic surface runoff per sub-catchment

Sub-catchment	Average surface runoff (million m^3/a)	Catchment area (km^2)
Senqu	4 105	27 647
Renoster	132	6 157
Riet - Modder	380	33 294
Vaal	3 201	94 456
Lower Orange Main stem	135	116 539
Fish	567	81 630
Caledon	1377	21 884
Molopo	135	351 553
Upper Orange	1 191	49 746
Schoonspruit	109	7 512
Lower Orange Tributaries	162	126 774
Lower Vaal	191	55 019
Total	**11 687**	**972 211**

2.3 Water Requirements and Return Flows

Details of the water requirements and return flows obtained as part of this study are documented in the report “Current and future Water Requirements” (DWA, 2014a). Demands and return flows are, however, constantly being updated as new information becomes available and is received. An example of this is the irrigation information for the Upper Orange and Caledon catchments, obtained from the Validation study (DWA, 2014b). An initial set of demands was obtained and utilized as part of the WRYM analyses. These demands were later updated, as the Validation study progressed. The WRYM analyses were carried out using a 2012 constant development level demand. The WRPM analyses used the starting year demands of 2014.

A detailed demand and return flow spreadsheet for the entire catchment area (including the neighboring catchments of the Usutu, Komati, Thukela and Eastern Cape) was prepared as part of the ORASECOM Phase 3 Study, and maintained and updated as part of this study and the Vaal and Orange Annual Operating Analyses study (also running in parallel to this).

There are currently close to 900 demand and return flow entries in the data base, of which just over half represent Orange system demand and return flows, and the other belong to the Vaal catchment (a tributary of the Orange). These are far too many to include as a table in this report, and the demands have rather been added together and summarized in **Table 2-2**, at 5 year increments.

Table 2-2: Summary of Orange River requirements (million m^3/annum)

Description	2014	2020	2025	2030	2035	2040
IRRIGATION DEMANDS (Including net canal losses)						
Upper Orange Irrigation	101.95	105.18	107.87	110.57	110.57	110.57
From Gariep only	599.12	617.12	635.12	635.12	635.12	635.12
From Vanderkloof (RSA)	1,402.77	1,486.50	1,487.48	1,487.48	1,487.48	1,487.48
From Vanderkloof (Namibia)	41.35	46.35	51.05	58.35	58.35	58.35
Total Irrigation Demands	**2,145.18**	**2,255.15**	**2,281.53**	**2,291.52**	**2,291.52**	**2,291.52**
DOMESTIC/URBAN DEMANDS						
Bloemfontein Botshabelo	87.39	103.82	122.15	143.39	168.01	193.68
Upper Orange	11.77	12.82	13.20	13.81	14.41	15.02
From Gariep Only	74.58	76.21	77.67	79.15	80.61	82.06
From Vanderkloof (RSA)	63.79	71.12	78.64	82.06	85.49	88.93
From Vanderkloof (Namibia)	16.50	19.66	18.67	17.65	16.81	16.98
Total Domestic / Urban Demands	**254.03**	**283.64**	**310.33**	**336.06**	**365.33**	**396.66**
Katse Dam to Vaal Dam	**780.19**	**780.19**	**854.79**	**939.84**	**1008.43**	**1055.56**
Total River & Operating requirements	**1082.70**	**1082.70**	**1082.70**	**1082.70**	**1082.70**	**1082.70**
Demand Imposed Gariep & Vanderkloof	**3280.81**	**3399.66**	**3431.33**	**3442.52**	**3446.56**	**3451.62**
Total Orange River Demand	**4262.10**	**4401.68**	**4529.34**	**4650.12**	**4747.99**	**4826.44**

2.4 Physical System Components

2.4.1 Impoundments

There are currently 366 dams included in the Integrated Orange-Vaal WRPM configuration. Most of these have been documented before. The focus of this section will therefore be on the proposed dams simulated as part of the yield analyses scenarios. **Table 2-3** presents a summary of this information.

Table 2-3: Proposed dams simulated in WRYM analysis

Dam	Live * capacity	Dead* capacity	Total * capacity	Full supply area (km^2)
Vioolsdrift Reregulating	110	260	370	10.2
Vioolsdrift yield	250	260	510	10.2
Polihali	1 904	417	2 322	50.4
Raised Gariep (by 10m)	9 060	623	9 683	552.8
Bosberg	3 065	37	3 102	101.0
Boskraai	8 288	55	8 343	303.1
Ntoahae	1 700	20	1 720	35.0
Malatsi	870	8	878	19.2
Vanderkloof	2 173	1 015	3 188	133.4
Vanderkloof utilizing lower level	3 023	165	3 188	133.4
Kraai (small)	929	18	947	66.6
Kraai (large)	2 971	18	2 989	142.0
Verbeeldelingskraal	1 363	0	1 363	65.4

Note: * - Storage capacity given in million m^3

2.4.2 Transfer Infrastructure

The main transfer infrastructure relevant to the Orange systems analyses is included in the Caledon catchment. The infrastructure capacities were updated based on information from the Bloemfontein Reconciliation Strategy Study (DWA, 2012a). All other transfer infrastructure, for example the Vanderkloof canal and Mohale-Katse transfer capacities remained unchanged as previously simulated in the system. The modifications to the Caledon-Modder transfer in the WRPM configuration included an increase in capacity of the Novo transfer from 1.67 m^3/s to 2.3 m^3/s, and at the Tienfontein pump station from 2.35 m^3/s to 4.17 m^3/s. In the WRYM analyses, no capacity constraints were included, as this would represent the most conservative flows into Gariep Dam.

3 RESERVE REQUIREMENT SCENARIOS

Currently environmental requirements for the estuary are released from Vanderkloof Dam in support of the estuary. These release volumes were determined during the middle 1990's and are based on outdated methods. These environmental releases for the estuary amounts to 288 million m^3/a during normal years and 195.8 million m^3/a during drought years.

As part of the ORASECOM Study "Support to Phase 2 of the ORASECOM Basin-wide Integrated Water Resources Management Plan" (ORASECOM, 2011b) the environmental flow requirements (EFR) was assessed at selected key areas of the Orange River Basin at an Intermediate Level (DWA RSA criteria). Previous WRYM analysis showed that the EFR at the Augrabies site was the main driver and resulted in a significant reduction in the ORP of 1060 million m^3/a (net reduction 1060 – 288 = 772 million m^3/a) when the recommended EFR is imposed on the system. This ORASECOM EFR study did not provide information on the river mouth environmental requirements or the EFRs applicable to the Fish River in Namibia.

ORASECOM introduced a follow up study (ORASECOM, 2012) focusing on the Namibia Fish River environmental flows, the Orange River Mouth environmental requirements as well as on the Lower Orange downstream of Vioolsdrift. The recently determined EFRs for the from this ORASECOM study (ORASECOM, 2012) provided valuable information on the EWRs on the main Lower Orange River, the Namibia Fish River and the Orange River mouth environmental requirements. Scenario analyses carried out as part of the follow up ORASECOM study showed that too much low flows were reaching the estuary, the result of which is that the mouth will never close. To be able to provide the estuary team with a flow scenario which met their criteria, the EFR at site 5 on the Lower Orange was manipulated in order to provide the required low flows. This manipulation entailed shifting excess low flow into a period of floods until the desired duration curves were achieved. To avoid too much low flows from the Augrabies site reaching EFR 5, the Augrabies winter flow EFR were set to zero, thus only requesting flows during the summer months.

The manipulated EFR5 flows only become available later in the Orange Reconciliation Strategy Study, and the initial WRYM analyses used the Augrabies EFRs, just without the winter flow requirements. It seemed that the winter month releases from Vanderkloof Dam to supply irrigation and river losses along the lower Orange was sufficient. The scenario where only summer EFR flows were requested at the Augrabies site, reduced the impact of the EFR on the system yield to 722 million m^3/a (net reduction 722 – 288 = 434 million m^3/a).

4 WATER RESOURCES YIELD ANALYSIS

4.1 Configuration of the WRYM

As already mentioned, the WRYM was configured as part of the ORASECOM Phase 2 study (ORASECOM, 2011) and was merely updated as part of this study with the latest information. The main configuration updates took place on the Caledon and Upper Orange systems (upstream of Gariep Dam).

4.1.1 Overview of the WRYM

The yield analysis of the study area was undertaken using the Water Resources Yield Model (WRYM). The WRYM was developed by 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 analyze 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.

Recently, DWA has developed a software system for the structured storage and utilization 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.

4.1.2 Development of a representative system network model

Developing a representative network model for a water resource system involves a process whereby the modeler creates a synthetic representation of reality, in the form of a schematic diagram. This is achieved by indicating the connectivity between and nature of the various components that make up the system in question. This process of synthesis, however, always implies a trade-off between the need to simulate the behavior of individual system components at a sufficient level of detail, on the one hand, and practical modelling limitations on the other.

The process of developing a representative system network model therefore includes three main aspects, (a) the identification of physical system features, (b) assessing the appropriate spatial resolution and (c) the lumping and aggregation of system components until the appropriate spatial resolution is achieved. These aspects are discussed below.

(a) Identification of physical system features

The process of identifying the physical features in the Caledon/Upper Orange systems for the purpose of the hydrological analysis involved a visual study of Google Earth images covering the specific catchments. In order to enhance these images, the location and extent of the main land use activity in the catchment, which is irrigation, was plotted on the images as polygons, together with polygons representing water bodies.

(b) Spatial resolution

While the hydrology for the Caledon and Upper Orange was done at a fairly high resolution (per quaternary), the final WRYM was configured at a lower resolution, more in line with the rest of the study area's configuration, in order to limit model run time. The lower resolution was considered suitable for the purposes of the WRYM and WRPM which mainly focus on the water resources of the larger schemes. If users would want to narrow in on small individual sub-catchments, some refinements would need to take place to the current resolution.

(c) Aggregation of system components

In cases where a large number of similar system elements are located within a catchment it is generally considered to be impractical to model each element individually. It was therefore inevitable that certain system elements had to be combined and simulated as single network elements in the yield analysis of the study area. This is of particular importance in the case of the irrigation demands, as well as impoundments. In this regard, the following overriding principles were followed:

- Water abstractions of the same type that have access to the same surface flow were grouped and represented by a single system component;
- Farm dams located in tributary catchments were combined to form a single dummy dam in the network model;
- The process of combining individual system elements was undertaken in such a way that the impact of the resulting element mimics, as closely as possible, the combined impact of the individual elements that it represents.

4.1.3 System network diagram

System schematic diagrams of the WRYM configuration of the study area are presented in **Figures A-1** to **A-5** of **Appendix A**. It should be noted that these diagrams are representative of the base scenario, but that the network definition of other scenarios are essentially the same and differ only with regard to the inclusion or exclusion of a particular system element or land use development.

4.1.4 WRYM system configuration testing

Great care was taken to ensure that the network configuration definition input into the WRYM was correct and accurately represented the intended configuration. This included four main processes which are discussed below:

- Extensive checking was undertaken to verify that the sub-catchment hydrology data was applied correctly in the WRYM system. This involved comparing simulated node inflows with the net runoffs contained in the associated sub-catchment hydrology data sets.
- Simulated model results were checked against the known physical characteristics of system components, such as the full supply, dead storage and bottom levels of reservoirs.
- The system network connectivity was checked by undertaking mass balances at selected nodes in the system to ensure that the defined linkages in the system definition are correct.
- Simulated model results were checked to ensure that the behavior of the system does reflect the intended operating rules, including the following situations:
  - When reservoirs / dummy dams are full;
  - When reservoirs / dummy dams are empty;
  - During drawdown events;
  - When supply priorities control the flow of water.

4.1.5 Run control settings

Run control settings in the WRYM are used to define general information on how the system will be analyzed for a particular model run. For the yield analysis of the study area, this includes, most importantly, the following:

- An analysis period of 85 years from the 1920 to the 2004 hydrological year (i.e. October 1920 to September 2005) was used. This corresponds with the selected Study period as well as with the updated and extended hydro-meteorological data sets.

- The long-term stochastic yield analyses were undertaken using the PARAM.DAT-file developed as part of the stochastic stream flow analysis and based on 201 91-year stochastically generated stream flow sequences.
- The short-term stochastic yield analyses were undertaken based on 501 5-year stochastically generated stream flow sequences.

With regard to short-term stochastic yield analyses mentioned above it should be noted that such analyses are undertaken for the purpose of deriving short-term yield-reliability characteristics of defined sub-systems within the system under consideration.

4.1.6 System yield

(a) Definition

The water users supplied directly from the main dams were explicitly modelled in the WRYM at the 2012 constant development level. The surplus yields of the dams (the Orange River Project: Gariep and Vanderkloof Dams) were determined (after supplying water to all users). This was achieved by imposing a single (variable) target draft on the yield node supported by both dams in order to evaluate their behaviour in various supply situations. For this purpose, the special WRYM *Yield channel-type* was used.

(b) Determination

Yield results presented in this report are based on two distinct types of analyses. The first is a *historical yield analysis* which is undertaken by analysing the WRYM system based on the time-series of monthly historical natural incremental runoff volumes contained in the *.INC-files, which cover the period of 85 years from the 1920 to the 2004 hydrological year (i.e. October 1920 to September 2005).

The most important result from such an analysis is the *historical firm yield* (HFY) of the system for the scenario under consideration. The HFY is determined by means of an iterative process and is defined as the highest annual target draft that can be supplied from the system without causing a failure. However, while the HFY provides a reasonable indication of the water resource capability of the system it does not show the likelihood (or probability) that the water volume in question could be supplied without failure, since it is possible that a dry period may still occur that is more severe than any period covered by the historical record.

The second is a *long-term stochastic yield analyses*, which is undertaken by repeatedly analysing the WRYM system based on stochastically generated time-series of monthly historical natural incremental runoff volumes. These time-series, or sequences, are generated by the WRYM at run-time based on the statistical parameters contained in the

PARAM.DAT file, developed as part of the stochastic stream flow analysis of the Study For this purpose 201 85-year stochastically generated stream flow sequences were used.

The results of a long-term stochastic yield analysis include the assurance of supply associated with each of the target drafts analyzed under a particular scenario, which, in turn, may be used to derive the yield-reliability characteristics (YRC) curve. This curve provides a graphical representation of the relationships between yield and reliability of supply and is used as a basis for allocating a system’s water resources to a group of users with varying supply assurance criteria. Generally, the assurance characteristics of a particular target draft are expressed in terms of its recurrence interval (RI), which is defined as the average time period between failures. For example, if the RI is shown as “1:200” years, this implies, on average, one failure every 200 years, or a risk of failure of 1 . 200 = 0.5 % in any given year. This can also be expressed as an annual assurance of supply of 100 % – 0.5 % = 99.5 %.

4.2 Yield Analyses Scenarios

A total of 14 main scenarios were analyzed and are described in the following sections. Following the assessment of the results, it became evident that various sub-scenarios were required, and these were then also carried out. Only the important sub-scenario results are presented under the results section.

While the Vaal tributary flows do not directly impact the Orange system, as they are not used to support any Orange demands, the spills do have a slight impact on the availability of flows at Douglas weir and therefore the resulting irrigation requirement from the Vanderkloof canal. The Vaal is not specifically included in the Orange WRYM configuration used, and only a single inflow sequence is included representing the Vaal spills. This inflow sequence was obtained from a historic analysis using the WRPM configured as described in the scenario descriptions. The WRPM provides a more representative flow sequence as water quality affects some of the operating rule decisions that only the WRPM can mimic. The Vaal flows do affect later scenarios where Vioolsdrift Dam and the downstream EWR are included, as they can be captured in and utilized from Vioolsdrift Dam.

4.2.1 Scenario 1: Present Day (Base Scenario)

This scenario models estimated actual water use regardless of whether this is lawful. Hence, the purpose of this scenario is to model the actual current flow regime as a baseline and to determine the yield available from the Orange River Project under current conditions. Yield to be determined at Gariep and Vanderkloof. The full Phase 1 of the LHWP and urban/industrial/mining demands at 2012 development level are assumed in this Base Scenario.

Conditions for the Integrated Vaal System as simulated with the WRPM.

1. All the urban/industrial and mining demands imposed on the Integrated Vaal system will be at 2012 development level.
2. Irrigation will be based on 2012 allocations where applicable.
3. Irrigation in the Vaal at lawful plus 34%. (In the Vaal reconciliation study (DWAF, 2009) it was identified that there is a significant amount of unlawful irrigation in the upper Vaal, utilizing the transferred water from Lesotho and the Thukela. Currently only 66% of that has been removed.)
4. Curtailments imposed on demands as required to meet the agreed levels of assurance.
5. Transfer from LHWP to Vaal equal to 780 million m^3/a according to the current agreement.
6. EWR releases from Katse and Mohale based on the latest implemented results as used in the Comparative Study (DWA, 2010a).
7. Operational losses from the Lower Vaal will be in line with the latest calibration done for the Vaal Reserve study (DWA, 2010b).
8. Set the additional salt loads and salinity recharge rates to those applicable to 2012 development level.
9. Mine water desalination needs to be in place to prevent Bloemhof Dam from operating too full.

Conditions for the Integrated Orange-Senqu River System as simulated with the WRYM.

1. All the urban/industrial and mining demands imposed on the Orange system will be at 2012 development level.
2. Irrigation will be based on 2012 allocations where applicable.
3. The 12 000 ha allocated for use by resource poor farmers will include only those already developed.
4. Transfer from LHWP to Vaal equal to 780 million m^3/a according to the current agreement.
5. EWR releases from Katse and Mohale based on the latest implemented results as used in the Comparative Study (DWA, 2010a).
6. EWR for Orange as currently released for the river mouth (287.5 million m^3/a) as obtained from the ORRS (referenced as ORRS EWRs) (DWAF, 1996).
7. Transfer to the Eastern Cape through the Orange/Fish tunnel based on the latest data from the Orange Annual Operating Analysis (DWA, 2012b). This is based on the allocation and scheduled irrigation area and current supply to

Port Elizabeth.

8. Current transfer schemes and related operating rules from the Caledon to the Modder River catchment in place (Welbedacht to Bloemfontein and Novo Transfer).
9. Include Metolong Dam with 2012 demands imposed on the sub-system.
10. Orange/Riet transfer. Current demands will be modelled in detail as part of the system.
11. Orange/Vaal (Douglas) transfer. Current demands will be modelled in detail as part of the system.
12. Operational losses from the Lower Vaal will be in line with the latest calibration done for the Vaal Reserve study (DWA, 2010b).
13. Hydro-power at Gariep and Vanderkloof dams will be generated in accordance with downstream demands only.
14. Minimum operating level for Gariep set equal to the minimum operating level for releases through the Orange Fish Tunnel.
15. Minimum operating level for Vanderkloof Dam is equal to the minimum operating level for releases into the Vanderkloof main canal.
16. Spills from Douglas Weir and contributions from the Lower Orange hydrology will not be used to supply Lower Orange demands as there is no storage available in the lower Orange to be able to utilize these flows in practice.

4.2.2 Scenario 2: Present Day including new EWR

This scenario is as Scenario 1 with the only difference the inclusion of the new EWRs available for the Orange River (only Augrabies summer EWR) (ORASECOM, 2012). The purpose of this scenario is to determine the effect of the new EWR on the yield available from the system. Yield to be determined at Gariep and Vanderkloof.

Scenario 2a: Augrabies summer EWR including high flows structure

Scenario 2b: Augrabies summer EWR excluding high flows structure

4.2.3 Scenario 3: Present Day including Knoffelfontein Dam

This scenario is as Scenario 1 with the only difference the inclusion of the possible Knoffelfontein Dam in the Riet River. The purpose of this scenario is to determine the yield available from the Knoffelfontein Dam.

Yield to be determined at Knoffelfontein Dam.

Scenario 3a: EWR 19 on Riet River to be included

Scenario 3b: EWR 19 on Riet River to be excluded.

4.2.4 Scenario 4: 2040 Development Level plus Phase 2 of the LHWP in place

The purpose of this scenario is to determine the yield deficit in the Orange system at the 2040 development level with the fully utilized Phase 2 of the LHWP in place. This scenario includes the full Phase 1 and 2 of the LHWP and urban/industrial/mining demands at 2040 development level and is the same as Scenario 1, but with the following changes:

Conditions for the Integrated Vaal System as simulated with the WRPM.

1. Desalinate water from the mine dewatering and use it to supply to Rand Water. Information obtained from the Vaal AOA 2012/2013 (DWA, 2013b) was used whereby 47.8 million m^3/a could be treated and provided to Rand Water at a TDS concentration of 200 mg/l. In combination with this, 16.44 million m^3/a from the Far Western mining basin was assumed to be discharged into the Vaal River system with an associated TDS concentration of 700 mg/l.
2. Set the additional salt loads and salinity recharge rates to those applicable to 2040 and adjust the initial salt storages of the relevant developed catchments accordingly.
3. All the urban/industrial and mining demands imposed on the Integrated Vaal system will be at 2040 development level.
4. Irrigation will be based on 2040 expected demands/allocations as applicable.
5. Irrigation in the Vaal at lawful plus 15%.
6. EWR releases from Katse, Mohale and Polihali dams based on the latest implemented results as used in the Comparative Study.

Conditions for the Integrated Orange-Senqu River System as simulated with the WRYM.

1. All the urban/industrial and mining demands imposed on the Integrated Orange system will be at 2040 development level.
2. Irrigation will be based on 2040 expected demands/allocations as applicable.
3. 12 000ha allocated to Resource Poor Farmers fully developed.
4. Additional Namibian irrigation developments.
5. With new EWR requirements on the Orange River, still only just Augrabies Summer and present mouth requirement.
6. EWR releases from Katse, Mohale and Polihali dams based on the latest implemented results as used in the Comparative Study (DWA, 2010a).
7. Increased the Novo Transfer capacity (2.4 m^3/s) and Tienfontein pumping capacity (4.0 m^3/s) as applicable for 2040.

8. Include a Vioolsdrift re-regulation Dam.

Scenario 4a: Augrabies summer EWR including high flows structure

Scenario 4b: Augrabies summer EWR excluding high flows structure

4.2.5 Scenario 5: 2040 Development Level plus Phase 2 of the LHWP and Large Vioolsdrift Dam

The purpose of this scenario is to determine the maximum yield increase that can be obtained from a Large Vioolsdrift Dam with the expected 2040 demands in place downstream of the dam.

Assumptions as for Scenario 4, but with the following changes:

1. Include different sizes of Vioolsdrift Dam and determine the yield increase at Gariep and Vanderkloof.
2. Expected demands downstream of Vioolsdrift Dam included as for Scenario 3.
3. Vioolsdrift Dam also used for re-regulation purposes.
4. Include full optimised EWRs from ORASECOM study (Augrabies Summer and EWR site 5) (ORASECOM 2012)

5a: Vioolsdrift size maximum DWA, 2010a with 2040 demands imposed.

5ai: Vioolsdrift size maximum with additional demand imposed to determine the additional demand that could be supplied by a large Vioolsdrift Dam over and above the yield increase at Gariep/Vanderkloof dams.

5di: Vioolsdrift dam size minimum: this is the base scenario that all future results are compared with.

5dii: 5di without Polihali and related transfer to the Vaal to determine the effect of Polihali on the system.

5div: 5di with no EWRs in place in combination with scenario 5dv to determine the impact of the EWR a site 5 on the system yield.

5dv: 5div with only EWR 5 in place to determine impact of EWR 5 on the system yield.

5dvi: 5div without any Vioolsdrift Dam to determine benefit of Vioolsdrift Dam on system without the EWRs influencing the Vioolsdrift Dam yield.

4.2.6 Scenario 6: 2040 Development Level plus Phase 2 of the LHWP and raised Gariep Dam

The purpose of this scenario is to determine the yield increase that can be obtained from raising Gariep Dam.

As Scenario 5di, but with the following additional development:

1. Include raised Gariep Dam.
2. Ensure that the operating rule between Gariep and Vanderkloof is still working well and that both dams are empty during the critical period.

6a: Raise Gariep by 5m

6b: Raise Gariep by 10m

4.2.7 Scenario 7: 2040 Development Level plus Phase 2 of the LHWP and Bosberg Dam

The purpose of this scenario is to determine the yield increase that can be obtained from Bosberg Dam.

As Scenario 5di, but with the following additional development:

1. Include Bosberg Dam. Consider at least two sizes. The smallest dam based on the maximum dam size that will not spill over the water shed to the Kraai. The largest dam that will not inundate Lesotho and requires a saddle dam to prevent water from spilling to the Kraai.
2. Bosberg Dam operating rule must allow support to Gariep and Vanderkloof dams only when they reached their m.o.l.
3. Include Bosberg EWR as used in Comparative study (DWA, 2010a)

7a: small Bosberg Dam – 57m high and do not spill to the Kraai River basin

7b: large Bosberg Dam – 100m high, (Would need a saddle dam)

7c: medium Bosberg Dam – 83.7m high

4.2.8 Scenario 8: 2040 Development Level plus Phase 2 of the LHWP and Boskraai Dam

The purpose of this scenario is to determine the yield increase that can be obtained from Boskraai Dam.

As Scenario 5di, but with the following additional development:

1. Include Boskraai Dam. Consider the largest dam that will not inundate Lesotho.
2. Boskraai Dam operating rule must allow support to Gariep and Vanderkloof dams only when they reached their m.o.l.
3. Include Bosberg EWR as used in Comparative study (DWA, 2010a)

8a: Small Boskraai Dam - 75m high and will not inundate Lesotho.

8b: Large Boskraai Dam – 92m high.

8c: Medium Boskraai Dam – 84.3m high.

4.2.9 Scenario 9: 2040 Development Level plus Phase 2 of the LHWP and Ntoahae Dam

The purpose of this scenario is to determine the yield increase that can be obtained from Ntoahae Dam.

As Scenario 5di, but with the following additional development:

1. Include Ntoahae Dam.
2. Ntoahae Dam operating rule must allow support to Gariep and Vanderkloof dams only when they reached their m.o.l.
3. Ntoahae EWR as used in Comparative study (DWA, 2010a)

9a: Ntoahae Dam including dead storage as used in LHWP studies.

9b: Ntoahae Dam excluding dead storage

4.2.10 Scenario 10: DWA, 2010a 2040 Development Level plus Phase 2 of the LHWP and Malatsi Dam

The purpose of this scenario is to determine the yield increase that can be obtained from Malatsi Dam.

As Scenario 5di, but with the following additional development:

1. Include Malatsi Dam.
2. Malatsi Dam operating rule must allow support to Gariep and Vanderkloof dams only when they reached their m.o.l.
3. Malatsi EWR as used in Comparative Study (DWA, 2010a)

10a: Malatsi Dam including dead storage as used in the LHWP studies

10b: Malatsi Dam excluding dead storage

4.2.11 Scenario 11: 2040 Development Level plus Phase 2 of the LHWP and Vanderkloof Lower Level Storage

The purpose of this scenario is to determine the yield increase that can be obtained by utilizing the lower level storage in Vanderkloof Dam.

As Scenario 5di, but with the following additional development:

1. Set the Vanderkloof m.o.l. to the dead storage level allowing the utilisation of the lower level storage.

4.2.12 Scenario 12: 2040 Development Level plus Phase 2 of the LHWP and Boskraai Dam

The purpose of this scenario is to determine the yield increase that can be obtained from Kraai Dam.

As Scenario 5di, but with the following additional development:

2. Include Kraai Dam.
3. Kraai Dam operating rule must allow support to Gariep and Vanderkloof dams only when they reached their m.o.l.
4. Include Kraai EWR as scaled from Boskraai EWR

12a: Small Kraai Dam - 947.4 million m^3 capacity

12b: Large Kraai Dam - 2989 million m^3 capacity

4.2.13 Scenario 13: 2040 Development Level plus Phase 2 of the LHWP, Vanderkloof Lower Level Storage and raised Gariep Dam

The purpose of this scenario is to determine the yield increase that can be obtained from different combinations of Vioolsdrift dam, raising Gariep Dam and utilizing the lower level storage of Vanderkloof dam.

As Scenario 5di, but with the following additional development:

1. Include raised Gariep Dam (10m).
2. Set the Vanderkloof m.o.l. to the dead storage level allowing the utilisation of the lower level storage.

13a: Vioolsdrift reregulating only

13b: Vioolsdrift yield (510 million m^3 capacity) and reregulating

13c: Vioolsdrift yield (544.8 million m^3 capacity) and reregulating

4.2.14 Scenario 14: 2040 Development Level plus Phase 2 of the LHWP and Verbeeldelingskraal Dam

The purpose of this scenario is to determine the yield increase that can be obtained from Verbeeldingskraal Dam.

As Scenario 5di, but with the following additional development:

1. Include Verbeeldingskraal Dam.
2. Verbeeldingskraal Dam operating rule must allow support to Gariep and Vanderkloof dams only when they reached their m.o.l.
3. Include Verbeeldingskraal EWR as scaled from Bosberg Dam EWR

4.2.15 Scenario 15: 2040 Development Level plus Phase 2 of the LHWP, Vanderkloof Lower Level Storage, Verbeeldingskraal Dam and raised Gariep Dam

The purpose of this scenario is to determine the yield increase that can be obtained from Vioolsdrift yield dam, raising Gariep Dam, utilizing the lower level storage of Vanderkloof dam and Verbeeldelingskraal Dam.

As Scenario 13, but with the following additional development:

1. Include Verbeeldingskraal Dam.
2. Verbeeldingskraal Dam operating rule must allow support to Gariep and Vanderkloof dams only when they reached their m.o.l.
3. Include Verbeeldingskraal EWR as scaled from Bosberg Dam EWR

4.3 Yield Analyses Results

4.3.1 Historic results

Only the important results of the WRYM analyses are presented in **Table 4-1**. For the purpose of the historic firm yield analysis, all the current demands were imposed on the system. The yield channel was the used to draw additional water from Gariep and Vanderkloof dams to determine whether there is still surplus yield available from the system. In many of the cases, as the system was in a deficit, demands then had to be reduced in order to obtain a surplus yield and thereafter calculate the system deficit based on the surplus yield less the size of the demand that was reduced. The total system yield was obtained by adding the existing demands imposed on the system, to the surplus or deficit available from the system. The yield was determined for the option where no EWR is supplied as well as for the option with the EWR supplied resulting in a reduced yield then available to supply the other demands imposed on the system. The column in **Table 4-1** referred to as “With EWR” represents the total system yields after the EWR was supplied. The column referred to as “No EWR” refers to the total system yield when no EWRs were imposed on the system.

Table 4-1: Results of WRYM analyses (values given in million m^3/a)

Scenario	Brief Description	Surplus / Deficit	With EWR	No EWR	Yield increase	Live storage increase	Total evapor-ation	Evapor-ation increase	Spills	Spills difference
1	Current day	212	3,038	3,325			815		4,062	0
2b	Current day + new EWR no High flows	-213	2,613	3,325	-425	0	825	10	4,421	358
4d	Polihali full transfer to Vaal new EWR & Vioolsdrift rereg dam & new EWR	-753	2,299	3,021	120	110	834	19	4,093	31
5di	Polihali full Vaal transfer, Vioolsdrift yield (510) & rereg dam current EWR	-561	2,491	3,213	192	250	836	0	4,055	0
6b	Polihali,full Vaal transfer, Raised Gariep by 10m & Viools yield (510) & rereg	-211	2,841	3,563	350	4,735	1,119	283	3,503	-552
7d	Polihali,full Vaal transfer, Bosberg (3065) & Viools Yield (510) & reregulating	-184	2,868	3,590	377	3,315	890	54	3,683	-372
8d	Polihali,full Vaal transfer, Boskraai (8288) & Viools Yield(510) & reregulating	376	3,428	4,150	937	8,538	978	142	3,134	-921
9c	Polihali,full Vaal transfer, Ntoahae (1720, 20 dead) & Viools Yield(510)&rereg	-329	2,723	3,445	232	1,950	839	3	3,841	-214
10c	Polihali,full Vaal transfer, Malatsi (878, 7.5 dead) & Viools Yield(510) & reregulating	-442	2,610	3,332	119	1,121	842	6	3,943	-112
11	Polihali,full Vaal transfer, VDK low level use & Viools yield (510) & reregulating	-424	2,628	3,350	137	1,100	815	-21	3,939	-116
12a	Polihali,full Vaal transfer, Kraai (929) & Viools Yield(510) & reregulating	-477	2,575	3,297	84	1,179	909	73	3,938	-117
12b	Polihali,full Vaal transfer, Kraai (2971) & Viools Yield(510) & reregulating	-231	2,821	3,543	330	3,221	955	119	3,688	-366
13a	Polihali,full Vaal transfer, Raised Gariep by 10m, VDK low level use & Viools reregulating corrected *	-234	2,818	3,540	327	5,450	1,073	237	3,587	-468
13b	Polihali,full Vaal transfer, Raised Gariep by 10m, VDK low level use & Viools yield (510) & reregulating *	-72	2,980	3,702	489	5,590	1,067	232	3,403	-652
13c	Polihali,full Vaal transfer, Raised Gariep by 10m, VDK low level use & Viools yield (544.8) & reregulating	-67	2,984	3,706	494	5,625	1077	241	3,400	-655
14	Polihali,full Vaal transfer, Verbeeldelingskraal (1 363) & Viools Yield (510) & reregulating	-409	2,642	3,364	152	1,613	895	59	3,883	-172
15	Polihali,full Vaal transfer, Raised Gariep by 10m, VDK low level use & Viools yield (510) & reregulating * (what is the difference between 15 & 13b??)	85	3,136	3.858	646	6,953	1100	264	3,256	-799

Note: * - Gain in yield due to Vioolsdrift yield dam is 162 million m^3/a thus 30 million m^3/a less than 5di"

4.3.2 Long Term Stochastic results

The results of the Long Term Yield analyses are presented as a total system yield, as opposed to the historic results which are surplus/deficit yields and presented as comparisons between scenarios. The Long Term Curve for the ORP system for Scenario 1 is presented in **Figure 4-1**, and the summarized results given in **Table 4-2**.

Table 4-2 : Long-Term Stochastic yield results for the Orange River Project

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)
Gariep and Vanderkloof	3716	3332	3084	2892

4.3.3 Short Term Stochastic results

The short term stochastic results are also quoted as the total system yield at the various starting storages of the dams. The short term stochastic yield characteristics for the ORP system were determined for two scenarios. The first is Scenario 1(same as for Long term stochastic yield) and second scenario is as Scenario 1 but with Polihali Dam included. The results are summarized in **Table 4-3** and **Table 4-4** respectively.

Table 4-3 : Short-Term Stochastic yield results for the Orange River Project Scenario 1

Starting storage (as % of live FSC)	Selected period length (years)	Yield Mill m3/annum at indicated RI			
		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

The Short Term Curves for ORP system applicable to Scenario 1 and related starting storages are presented in **Figure 4-2** to **Figure 4-7.**

Table 4-4 : Short-Term Stochastic yield results for the Orange River Project Scenario 1 with Polihali in place

Starting storage (as % of live FSC)	Selected period length (years)	Yield Mill m3/annum at indicated RI			
		1:200	1:100	1:50	1:20
100%	5	3106	3240	3482	3964
80%	5	2885	3067	3296	3774
60%	5	2542	2707	3023	3437
40%	3	2109	2310	2562	2953
20%	2	1400	1689	1841	2193
10%	1	1023	1084	1231	1370

The Short Term Curves for ORP system applicable to the second scenario (with Polihali in place) and related starting storages are presented in **Figure 4-8** to **Figure 4-13**.

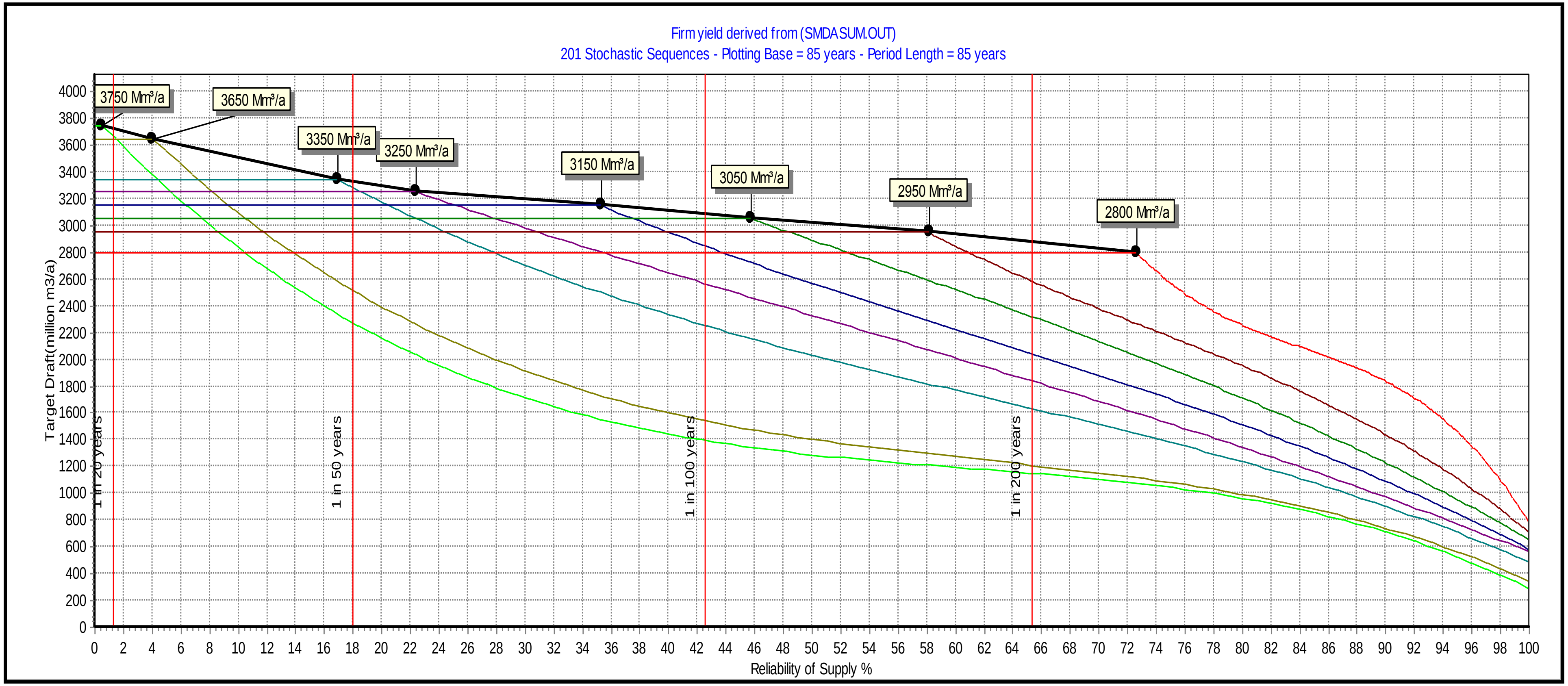

Figure 4-1: Long Term Stochastic yield curve for the Orange River Project

SHORT TERM STOCHASTIC CURVES FOR ORP BEFORE POLIHALI DAM IS IN PLACE

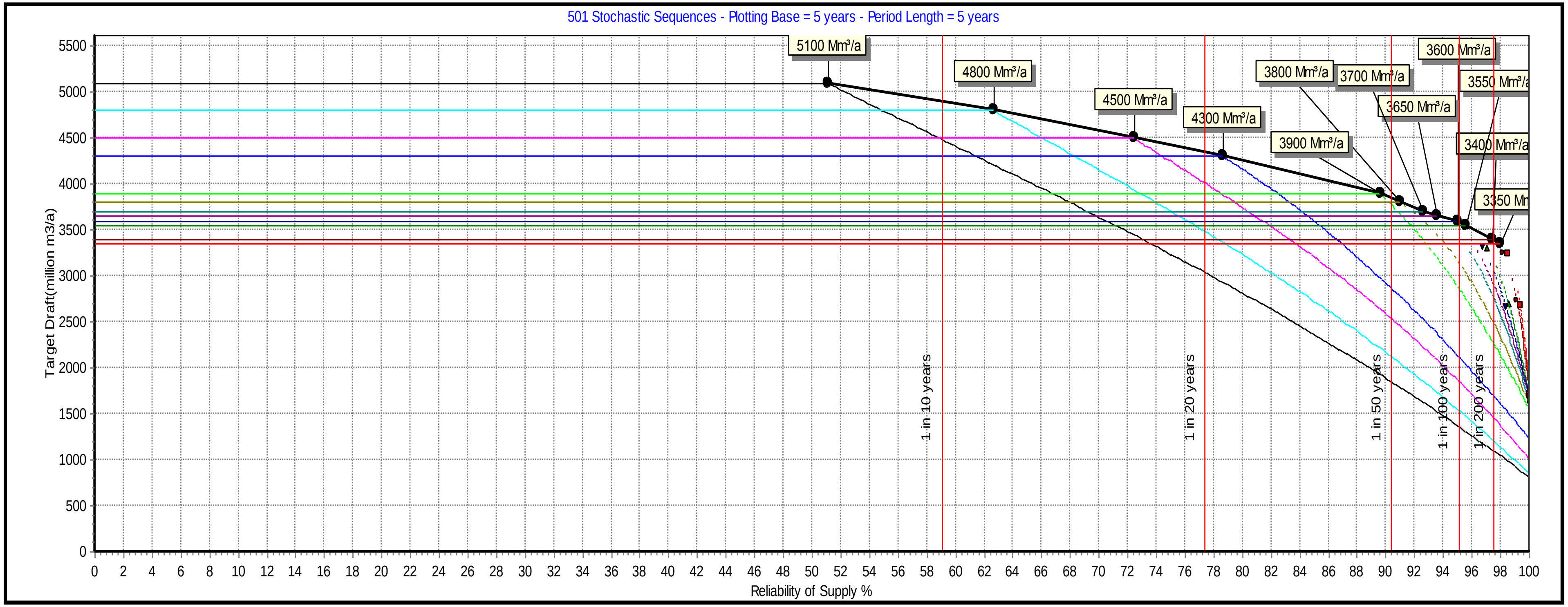

Figure 4-2:Short Term Stochastic yield curve-Orange River Project starting storage 100%

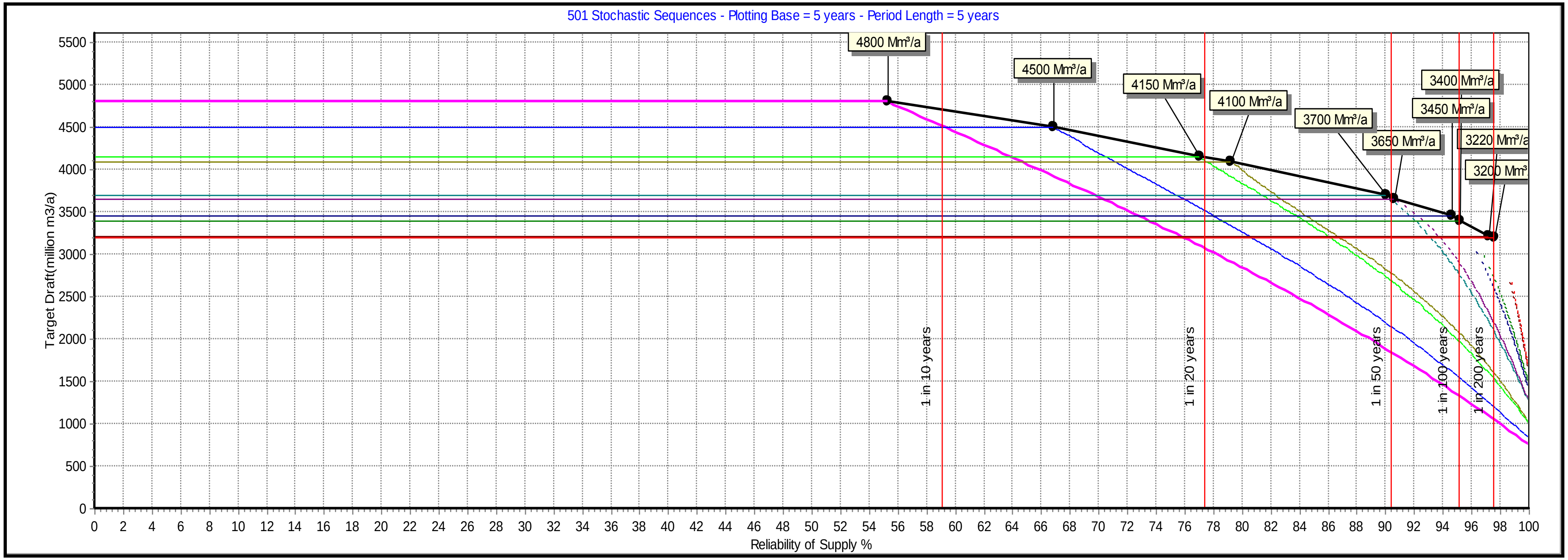

Figure 4-3:Short Term Stochastic yield curve-Orange River Project starting storage 80%

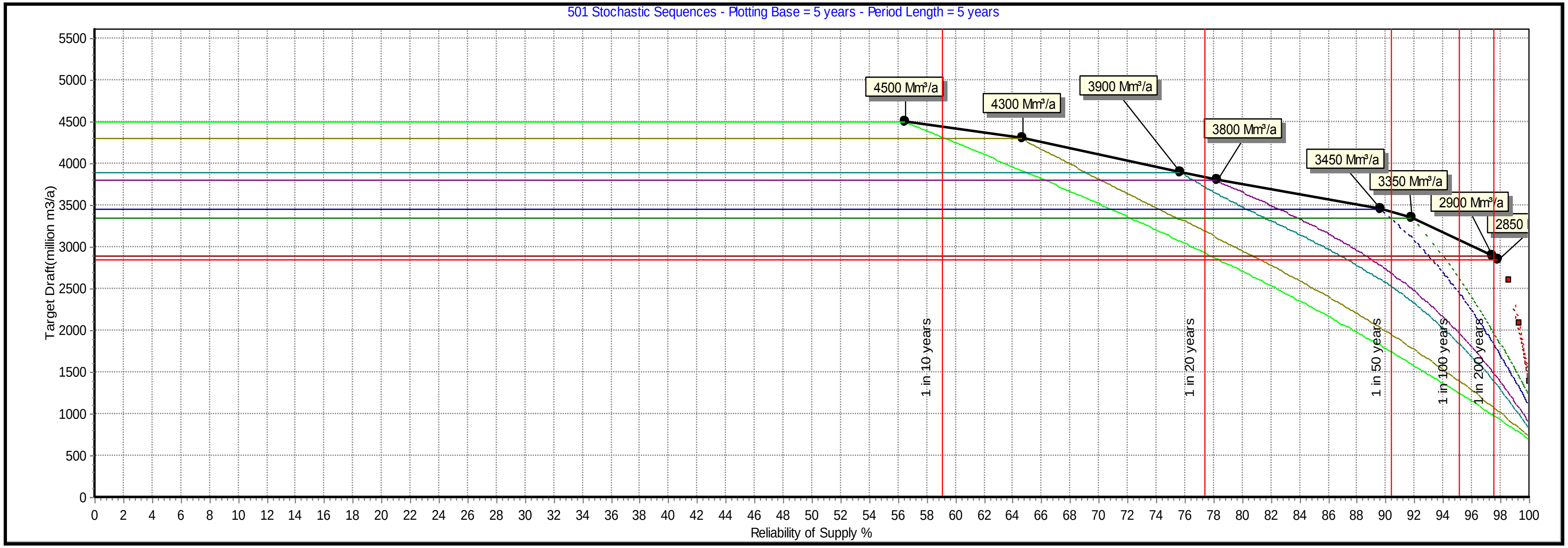

Figure 4-4: Short Term Stochastic yield curve-Orange River Project starting storage 60%

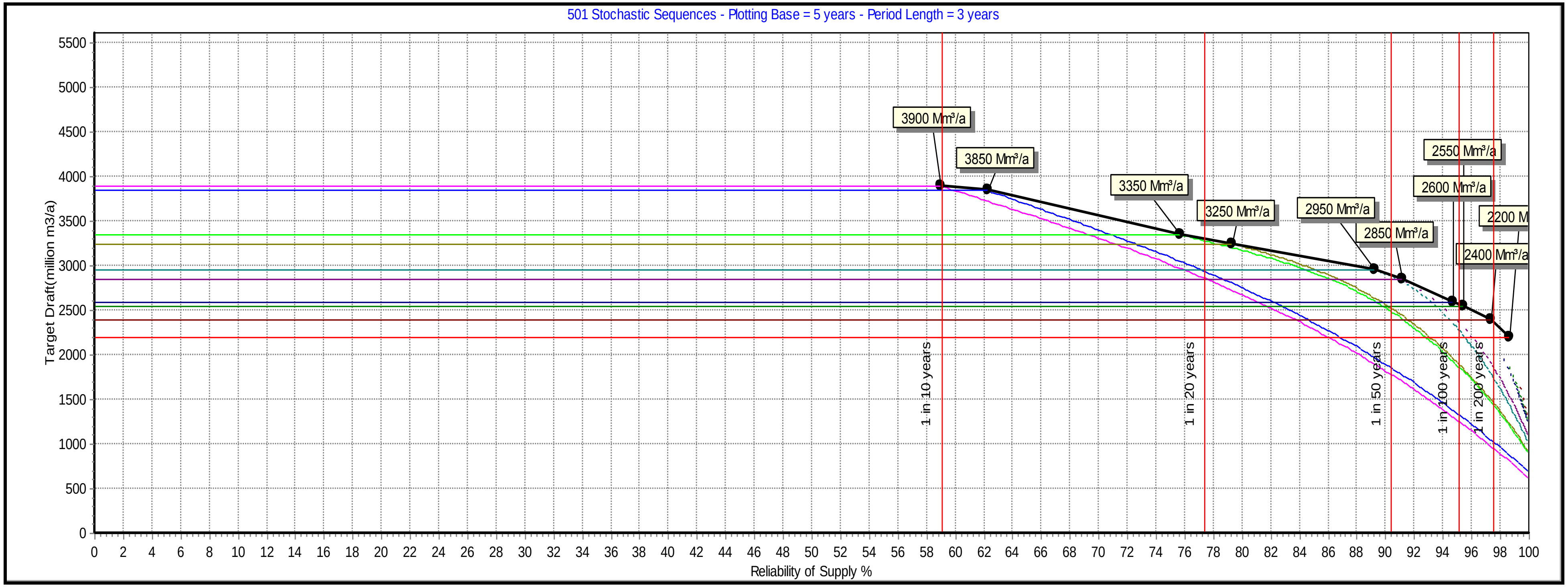

Figure 4-5: Short Term Stochastic yield curve-Orange River Project starting storage 40%

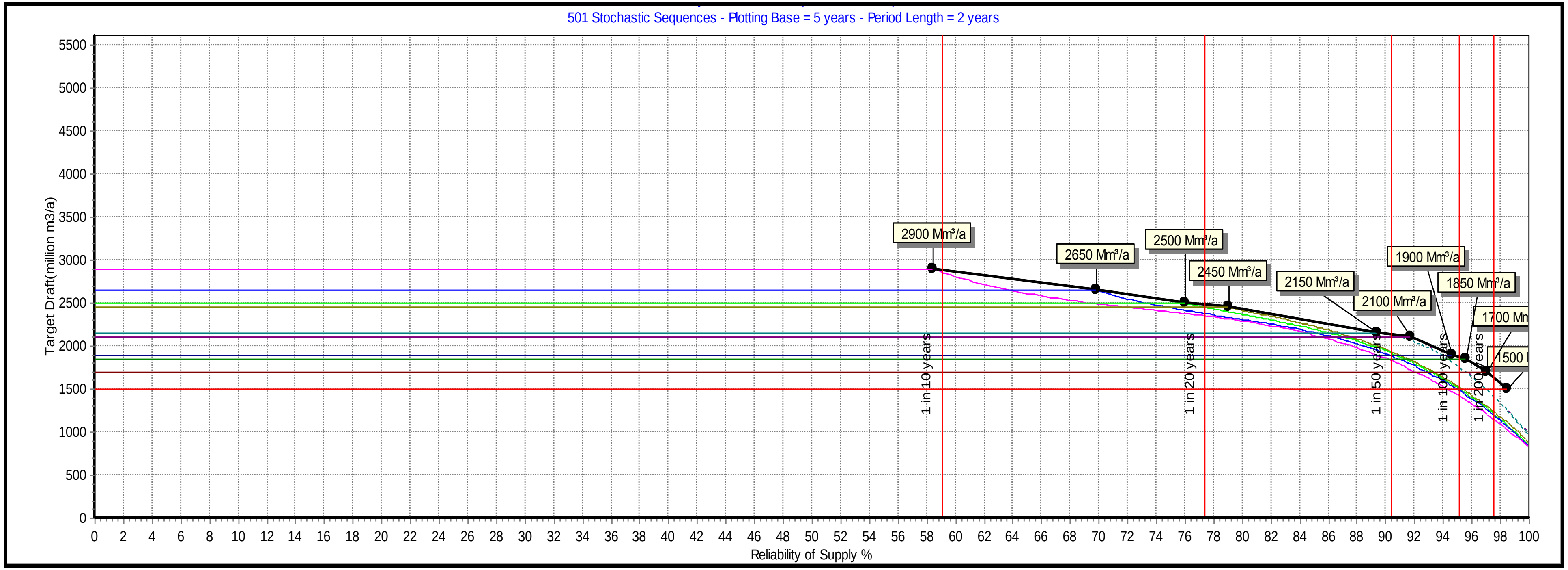

Figure 4-6: Short Term Stochastic yield curve-Orange River Project starting storage 20%

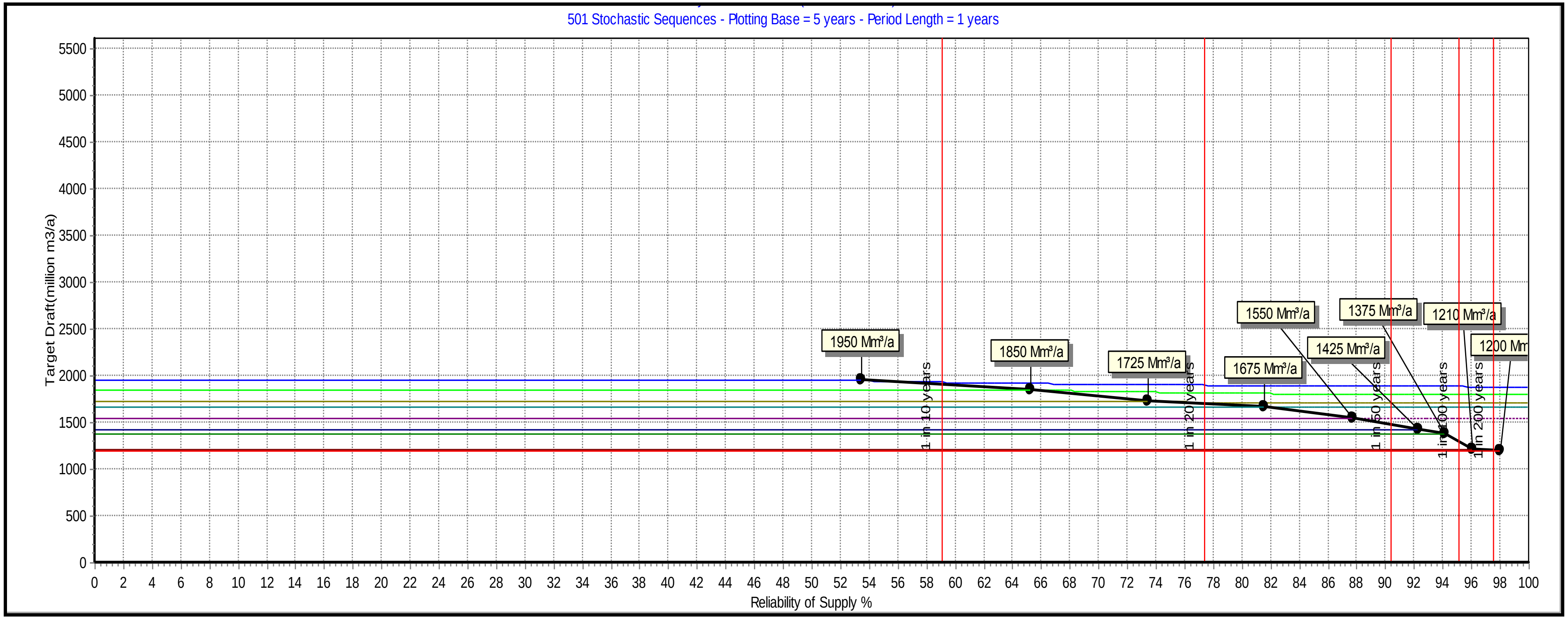

Figure 4-7: Short Term Stochastic yield curve-Orange River Project starting storage 10%

SHORT TERM STOCHASTIC CURVES FOR ORP WHEN POLIHALI DAM IS IN PLACE

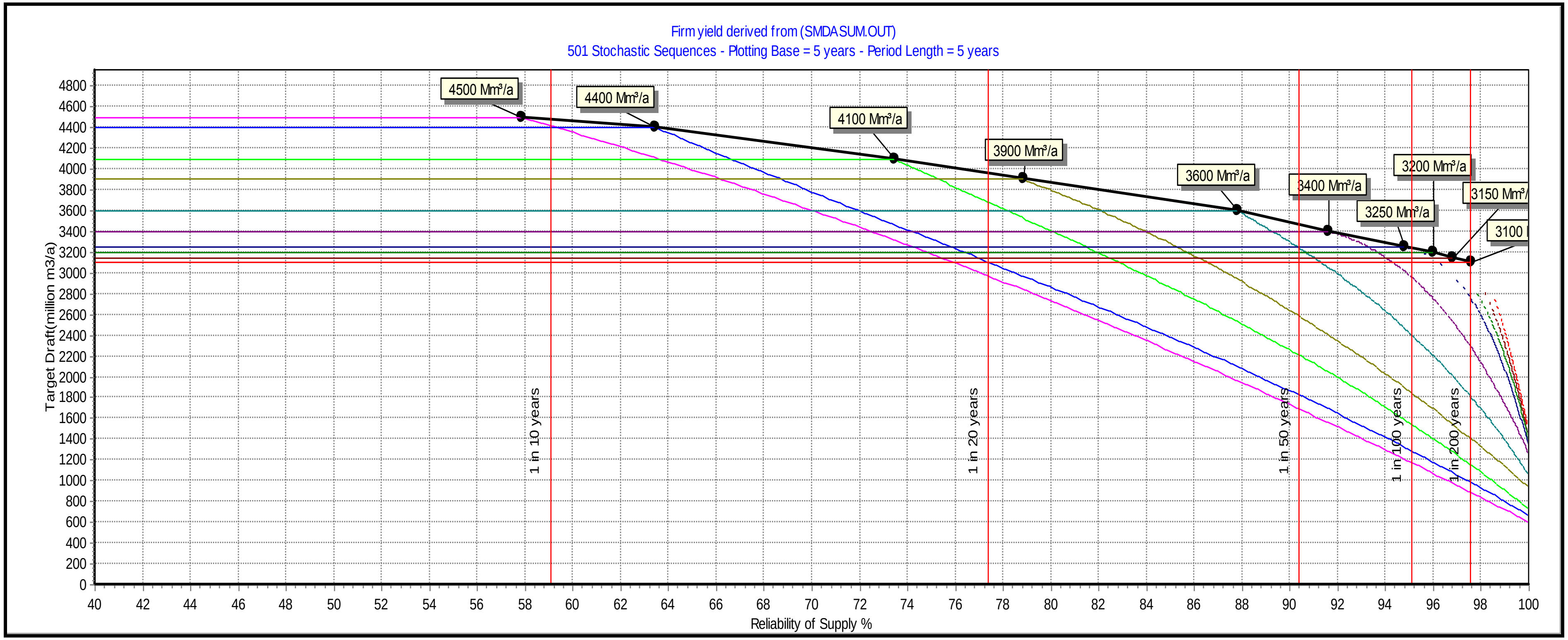

Figure 4-8:Short Term Stochastic yield curve-Orange River Project starting storage 100%

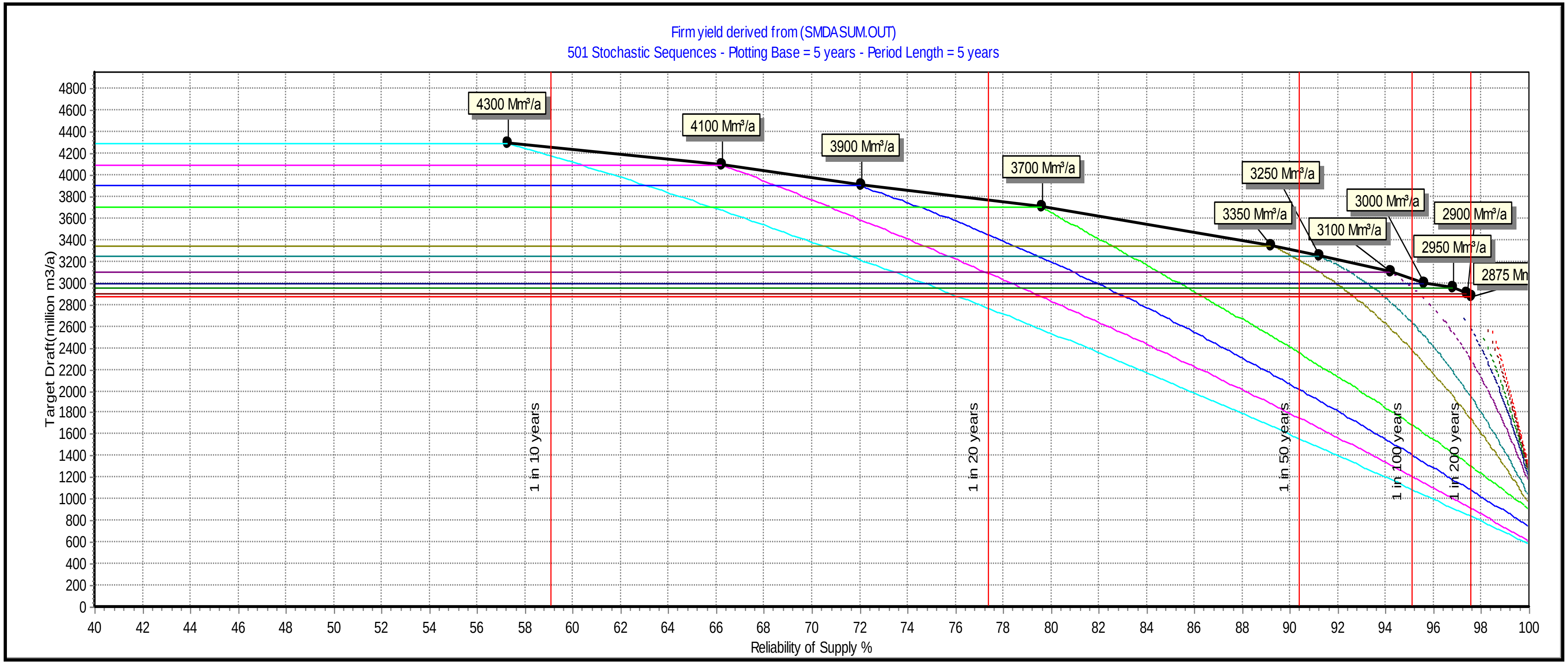

Figure 4-9:Short Term Stochastic yield curve-Orange River Project starting storage 80%

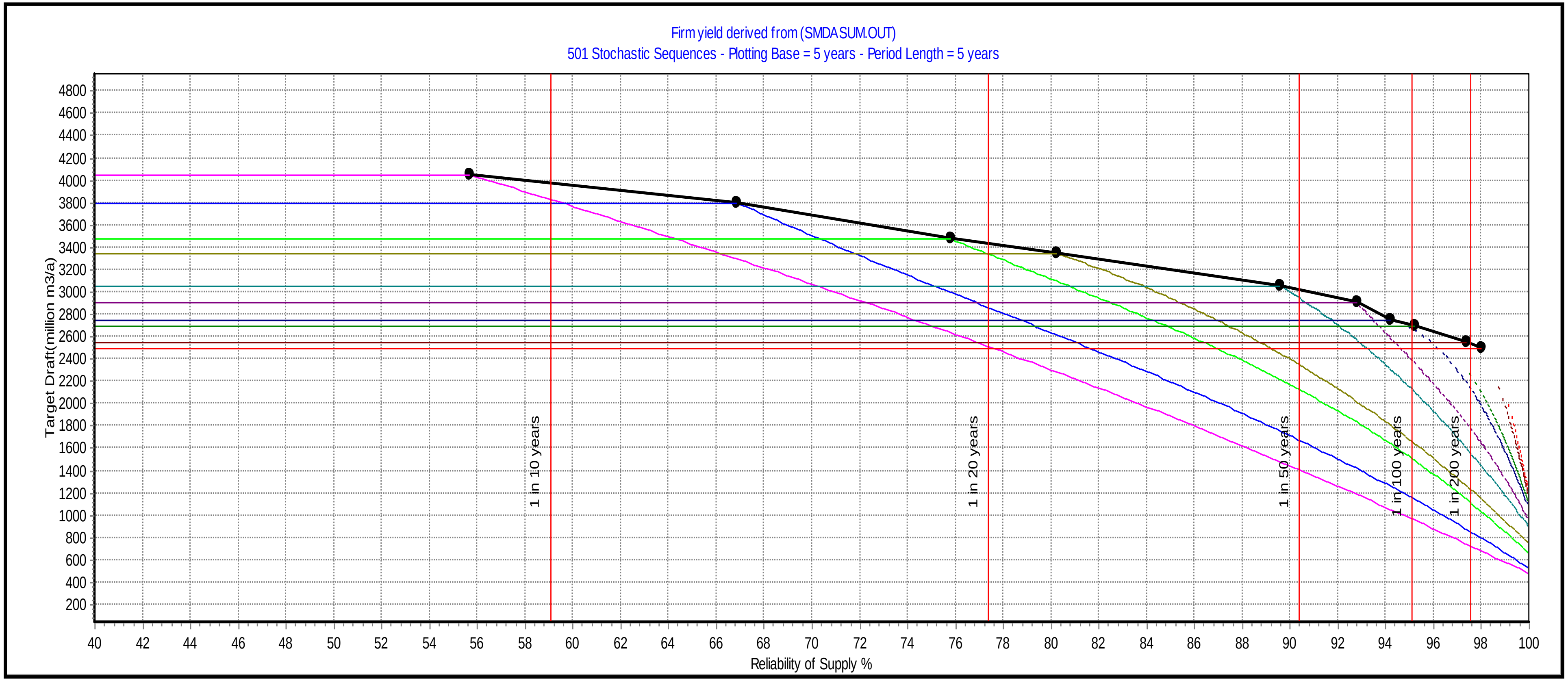

Figure 4-10: Short Term Stochastic yield curve-Orange River Project starting storage 60%

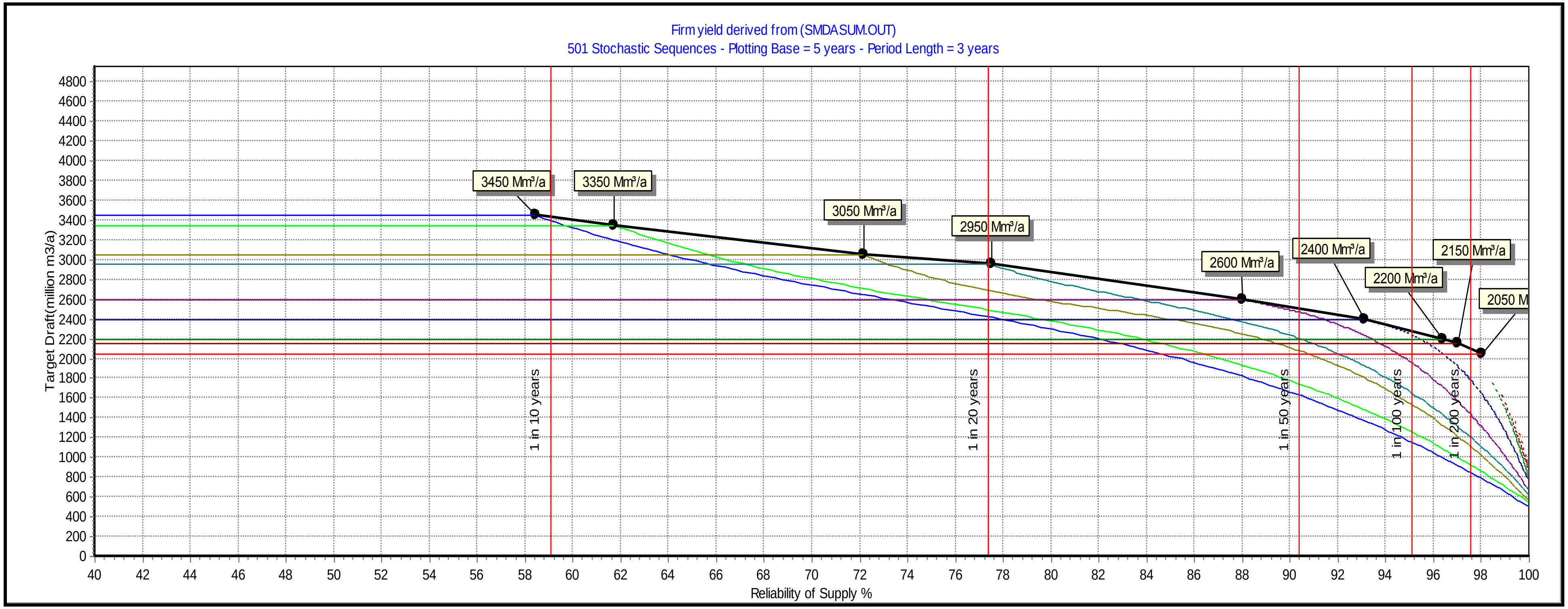

Figure 4-11: Short Term Stochastic yield curve-Orange River Project starting storage 40%

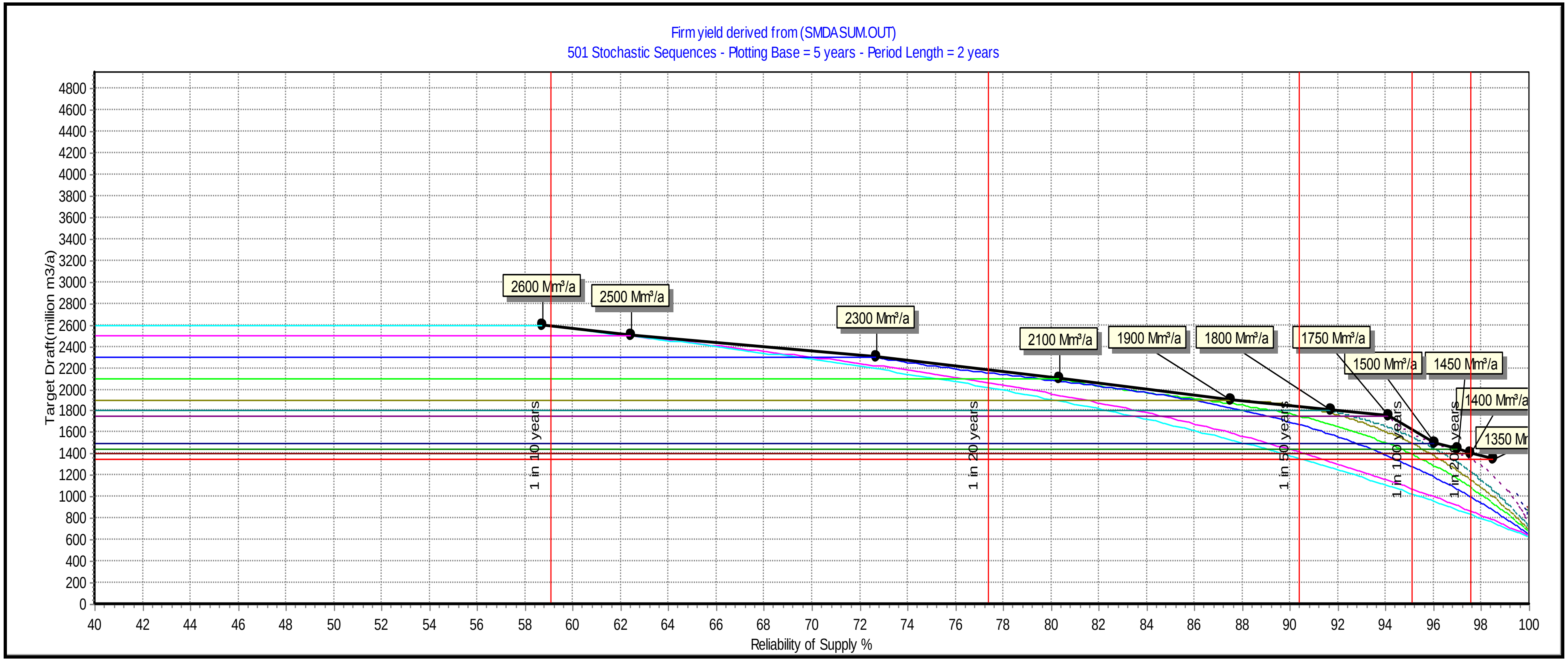

Figure 4-12: Short Term Stochastic yield curve-Orange River Project starting storage 20%

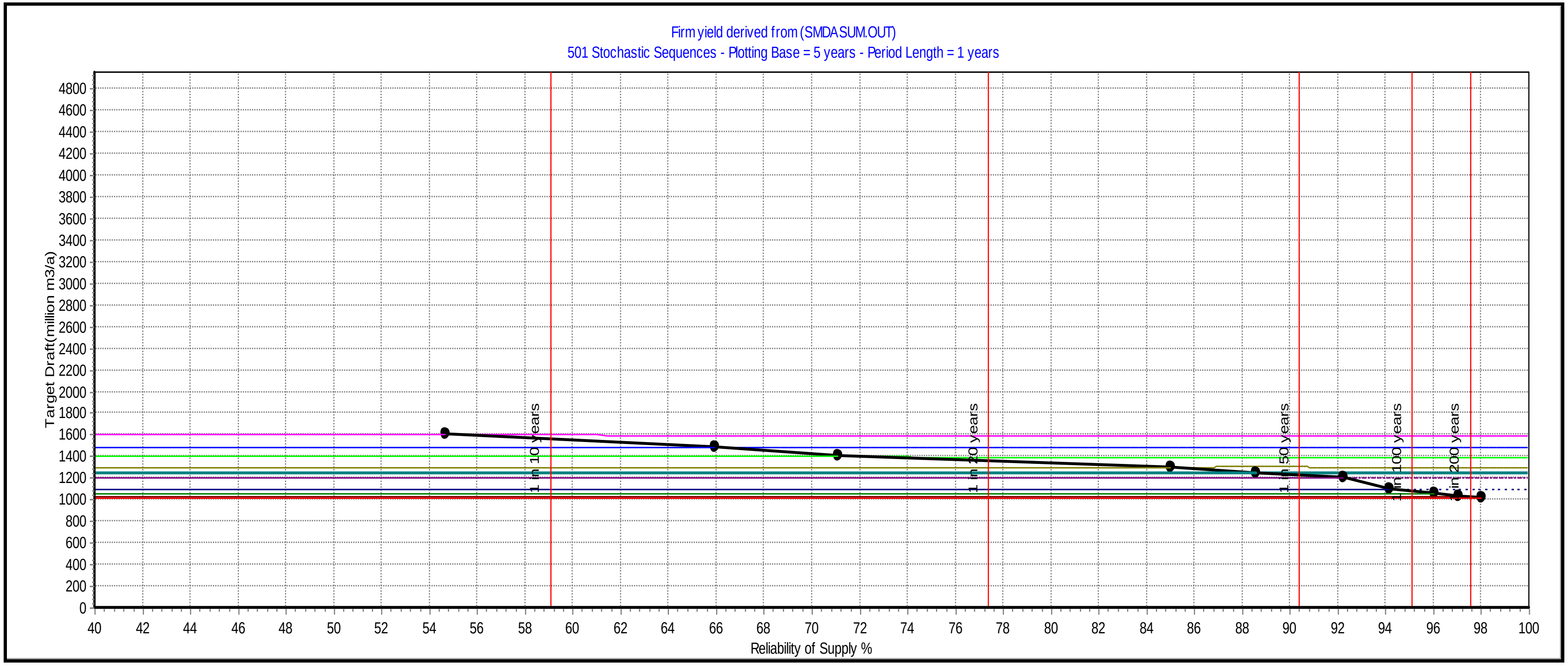

Figure 4-13: Short Term Stochastic yield curve-Orange River Project starting storage 10%

5 WATER RESOURCES PLANNING ANALYSIS

5.1 Configuration of the WRPM

The planning analysis of the study area was undertaken using the Water Resources Planning Model (WRPM) and the data sets representative of the Integrated Vaal River System in combination with the Orange River system covering the total Orange River Basin within the RSA, Namibia, Botswana and Lesotho. The purpose of the WRPM analysis is to determine the timing of intervention options for the different scenarios as identified from the Preliminary Strategy and follow up discussions. The timing of the intervention options as used for the Preliminary Strategy was based on a comparison between the historic firm yield results and the expected growth in demand over time. The WRPM makes use of dynamic stochastic risk of failure analysis over the planning period, taking into account the demand growth, restriction of demands during droughts, phasing in of intervention options over time, the impact of filling times of new storage dams as well as the requirements of water quality related operating rules. The required timing of intervention options can therefore be determined more accurately by the WRPM application, than by simply comparing yield and demand growth over time.

The WRYM network was used as a basis for the WRPM, with the adjustments required to switch the model to planning and projection mode. System schematic diagrams of the WRPM configuration of the study area are presented in **Figures B-1** to **B15** of **Appendix B**. The yield model outputs in the form of the updated short term yield reliability curves were included into (see **Section 4.4.3)** the WRPM where applicable.

Run control settings in the WRPM are used to define general information on how the system will be analyzed for a particular model run. For the planning analysis of the study area, this includes, most importantly, the following:

- For the projection run, 501 sequences were analyzed.
- A 27 year projection run was carried out, starting in May 2014.
- The major dams were set to start the analysis at their actual observed levels on 1 May 2014.
- Demands were set to grow according to their projections till the year 2040
- The priority classifications presented in **Table 5-1** were used for the various types of users included in the system.

Table 5-1: **Priority classification for the ORP system**

User category	Priority Classification			
	High (99.5% assurance) 1 in 200 year	**Medium High (99% assurance) 1 in 100 year**	**Medium Low (98% assurance) 1 in 50 year**	**Low (95% assurance) 1 in 20 year**
Irrigation	10	40	0	50
Urban	50	30	0	20
Losses	100	0	0	0

The operating rules used in the analysis were aligned with the current operating rule as applicable to the system setups used for the annual operating analyses carried out for the Integrated Vaal System, the Orange River System (ORP) and the Greater Bloemfontein System each year. Slight adjustments to the operating rules were made to accommodate future developments such as Phase II of the LHWP, Vioolsdrift Dam, Verbeeldingskraal Dam etc. Details of these changes will be explained as part of the scenario definition descriptions given in **Section 5.2**.

The WRPM uses the short term stochastic yield characteristics as part of the operating rule to impose restrictions on the water use and or activate transfers to support a particular system or sub-system to protect the resource from running empty during severe drought periods. When intervention options are used that directly impact on the yield characteristics of a system or sub-system, it will require the development of new sets of short-term stochastic curves.

As a significant amount if intensive yield analyses are required to develop a set of short term yield characteristic curves, it was not possible to develop new sets of short term yield curves for the possible proposed future intervention options. Two different approaches were thus followed to determine the timing of the intervention options.

- Approach one was to analyze scenario 1 using all the required sets of short term stochastic yield for the IVRS, the Orange ORP System and the Greater Bloemfontein System.
- The second approach was to analyze scenario 1 with the short term stochastic yield sets for the Orange ORP and for the Greater Bloemfontein System excluded from the analysis.

This means that for option 1 restriction will be imposed on the main systems during drought events, to protect the resources from complete failure. To be able to identify the time when a next intervention option need to be added to a system, the assurance of supply will be evaluated by means of a typical curtailment plot. When curtailment are imposed on the system more often than dictated by the agreed assurance of supply for the particular system, it means that the system is no longer able to adhere to the required assurance of supply and intervention will be needed at that time.

For option 2, curtailments (restrictions) will only be imposed on users within the IVRS as short term stochastic yield sets were available for all the intervention options impacting on the IVRS. For the Orange ORP System and the Greater Bloemfontein System several additional sets of short term yield curves will be required to address the proposed future intervention options. This means that no restrictions will be imposed on the Orange ORP and Greater Bloemfontein systems. For this option one can thus not evaluate the assurance of supply to these two systems. The method followed for this option is to evaluate the projected storage levels in the storage dams used to support the specific system, to identify when and at what risk will the storage in the system be depleted, thus reaching the minimum operating level for the system under consideration.

By comparing the results from scenario 1 for both approaches described above, one can obtain an indication of the expected difference in timing due to the two approaches followed. Most of the proposed future intervention options for the Orange ORP system will impact on the yield characteristics of the ORP, in which case the second approach using dam failures need to be followed to determine the timing for the different intervention options. Results obtained from the scenario 1 comparison can thus be used to slightly adjust results from scenario two onwards, if required.

5.2 Planning Analyses Scenarios

5.2.1 Scenario 1: Determine timing of intervention option after Polihali Dam

This scenario includes the following:

- Water Conservation and demand management
- Real time modelling and monitoring to reduce operating requirements
- Shared utilization of Polihali Dam (turned on in May 2022)

This analysis will indicate when Vanderkloof Low level storage utilization option needs to be phased in. The WC/WDM and real time modelling and monitoring intervention options only impact on the demand imposed in the system and do not impact on the yield of the ORP. New short-term yield curves are thus not required for these two intervention options. The inclusion of Polihali Dam will cut of runoff previously available for the ORP and will result in a decrease in the ORP yield as indicated by the yield results. For this development a new set of short term yield curves will be required for the ORP. This set of short term yield curves was prepared and was included in the data sets applicable to Scenario 1. The following sub-scenarios were considered for the WRPM analyses regarding Scenario 1:

Scenario 1a: Include restriction rules

Scenario 1b: Scenario 1a excluding restriction rules

Scenario 1c: Scenario 1a using alternative assurance of supply criteria

For scenarios 1a, 1b and 1c, **Figure 5-1** depicts the transfer from Polihali to the Vaal and the available water for the Orange. The required transfer from the LHWP in support of the IVRS as shown in **Figure 5-1** was obtained from the latest evaluations produced from the Vaal River System Reconciliation Strategy Maintenance Study as produced in April 2013. The remainder of the yield available in Polihali Dam was then made available for use in the Orange ORP System. The operating rule used gave priority to the transfer to the Vaal, and only when satisfied will the remainder of the available water in Polihali Dam be made available to support the Orange System.

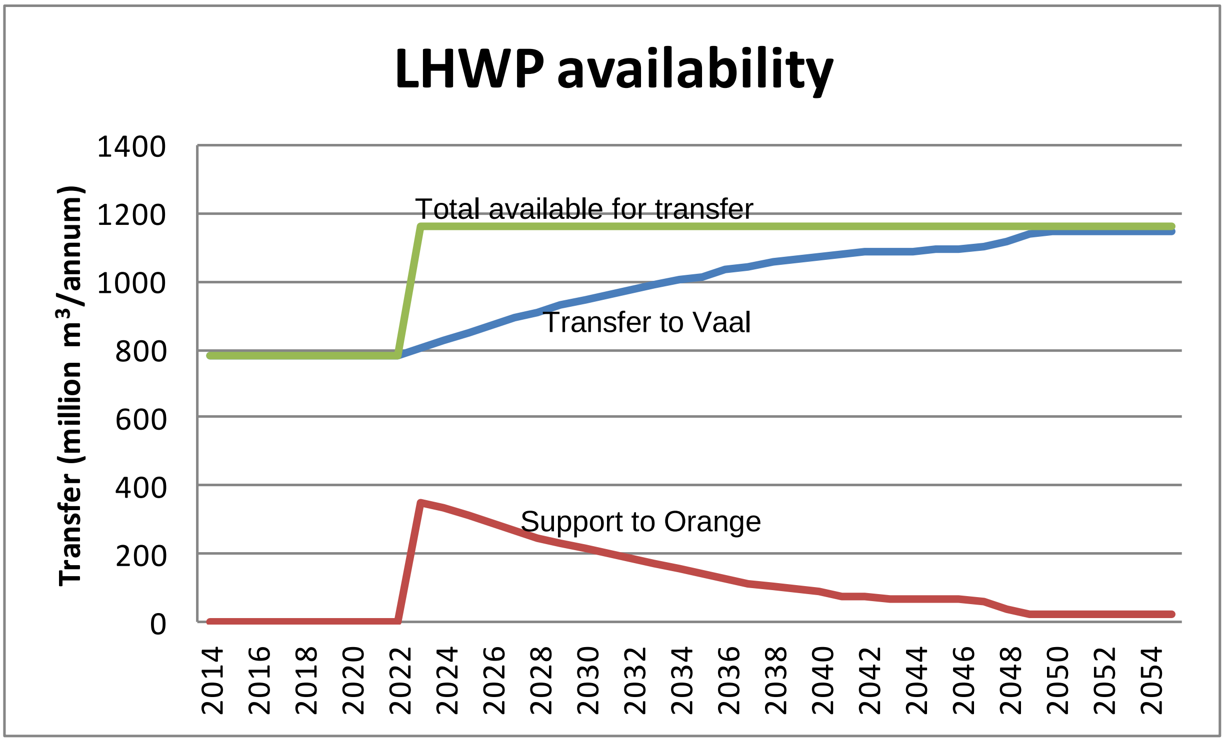

Figure 5-1: LHWP simulated transfers

5.2.2 Scenario 3: Determine the timing for the next intervention option after the implementation of the preferred EWR and inclusion of Vioolsdrift Dam

Based on Scenario 1b with the following added:

- Vanderkloof Low Level Storage utilization included from May 2019

- Include Viooldrift reregulating in combination with Yield Dam from May 2025
- Implement preferred EWR 1 year later than Vioolsdrift Dam

This option will indicate when and if a next intervention option is required after the implementation of the preferred EWR and Vioolsdrift Dam. All three the intervention options listed above for Scenario 3 will impact on the yield available from the ORP. Due to the lack of short term yield characteristics for these intervention options, the second approach was followed to determine the timing of the next intervention option being the raising of Gariep Dam or the building of a Verbeeldingskraal Dam.

5.2.3 Scenario 4: Utilize Raised Gariep Dam as the next intervention option after Vioolsdrift and preferred EWR

Based on Scenario 3 with the following added:

- Raised Gariep (10M) from May 2026

This option will indicate if the raised Gariep option is sufficient to maintain the balance over the planning period and until when. As for Scenario 3, the second approach was followed to determine the time until when the raised Gariep Dam will be able to maintain the positive water balance.

5.2.4 Scenario 5: Utilize Verbeeldelingskraal Dam as the next intervention option after Vioolsdrift and preferred EWR. (Verbeeldingskraal Dam is an alternative for the raised Gariep option)

Based on Scenario 3 with the following added:

- Include Verbeeldelingskraal Dam from May 2026

This option will indicate if the Verbeeldelingskraal Dam option is sufficient to maintain the balance over the planning period and until when. As for Scenario 3, the second approach was followed to determine the time until when the possible future Verbeedingskraal Dam will be able to maintain the positive water balance.

5.3 Planning Analyses Results

5.3.1 Scenario 1: Determine timing of intervention option after Polihali Dam

As described in **Section 5.2.1** four sub-scenarios were considered as part of the Scenario 1 analyses. **Scenario 1a** curtailment plot (**Figure 5-2**) indicated that the curtailment criteria for the Orange ORP System were violated from 2019 onwards (areas in red) on a continuous basis. The violations from 2019 to 2021 was still small but increased significantly from 2022 onwards when Polihali Dam started to impound water.

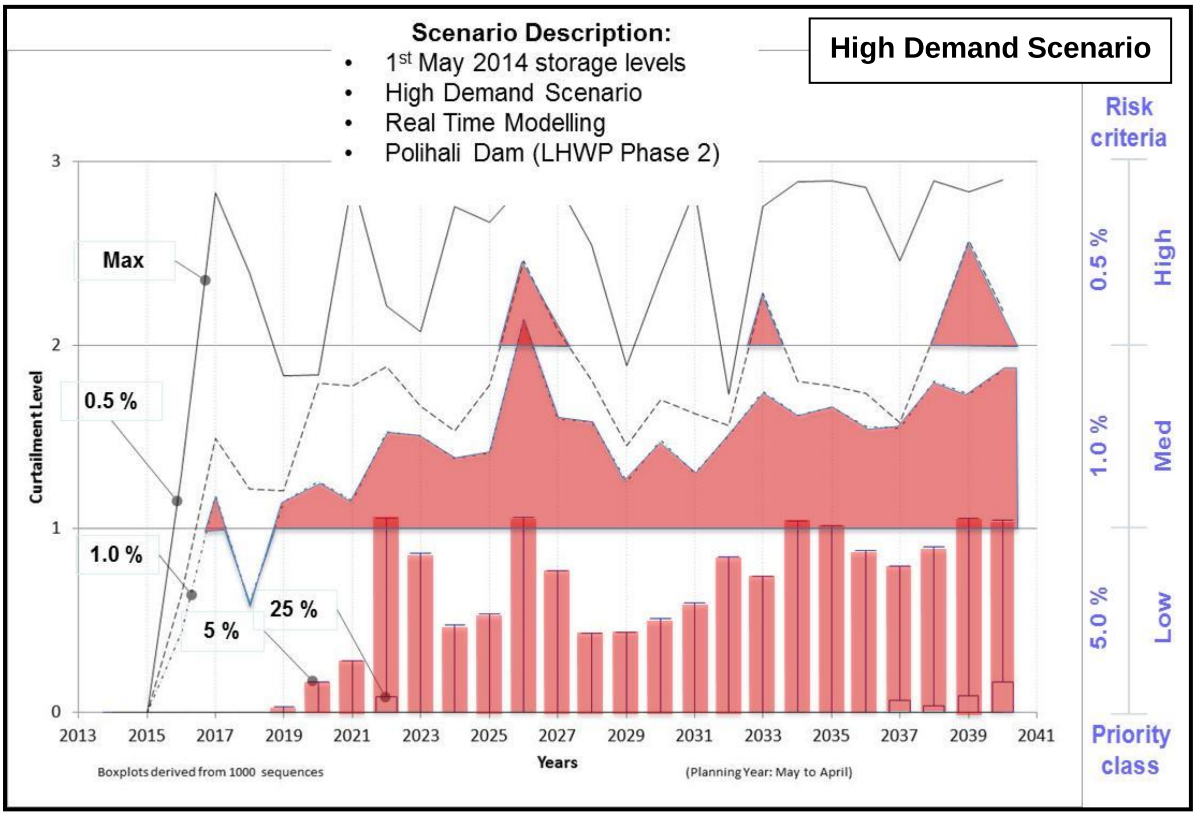

Figure 5-2: Scenario 1a ORP Curtailment plot

Scenario 1b results which exclude the use of the short term stochastic yield curves for the ORP was evaluated by using the second approach based on the risk of no supply. The combined Gariep and Vanderkloof Dam storage projection plot (**Figure 5-3**) indicated a possible failure in supply at the 99.5% risk level (1 in 200 year recurrence interval) by 2020 and for the 99% risk level (1 in 100 year) by 2022. This result is fairly well in line with that obtained from Scenario 1a, although approximately 1 to 2 years earlier, depending on the significance of the shortages experienced.

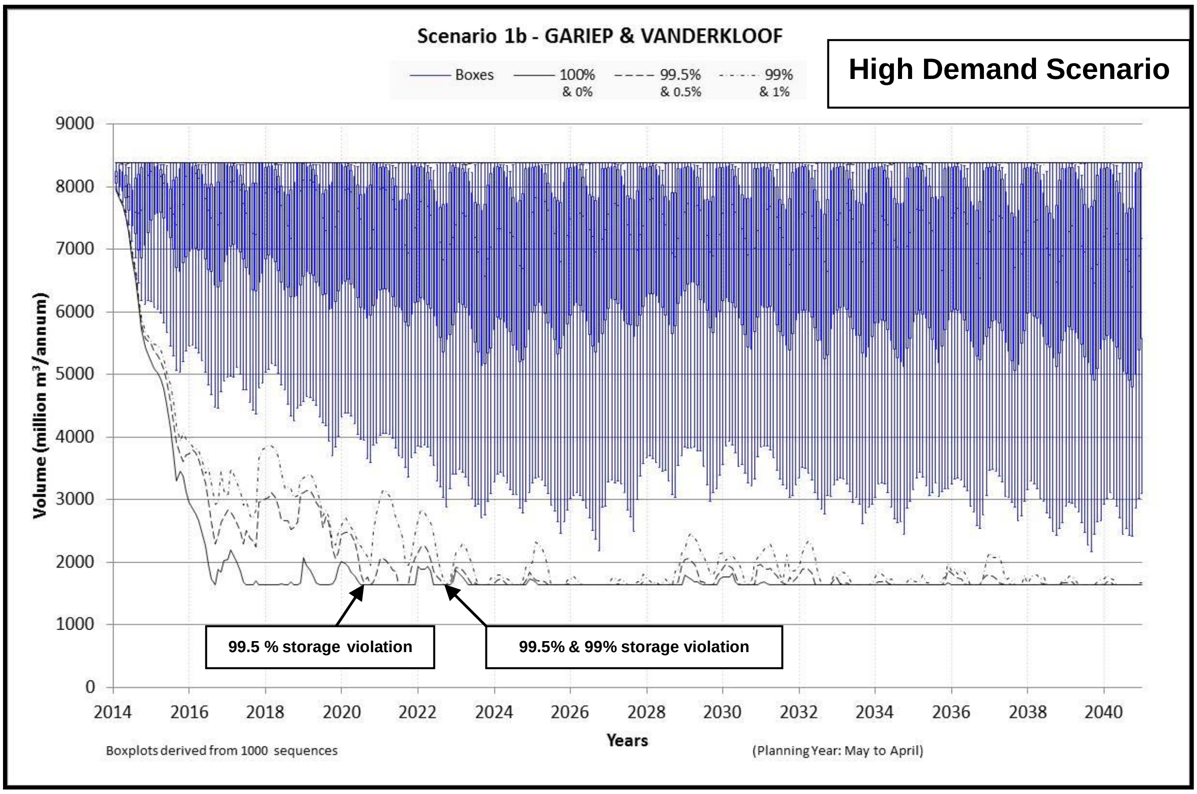

Figure 5-3: Scenario 1b Combined Gariep and Vanderkloof Storage projection plot

Scenario 1c used an alternative assurance of supply criteria. To be able to determine the impact of the reduced assurance of supply to the users from the Orange ORP System it was necessary to use the short term stochastic yield characteristics as part of the operating rule for this scenario. The reduced assurance of supply used for this scenario is shown in **Table 5-2**, with the current assurance of supply allocations indicated by the values given in brackets

Table 5-2 : Adjusted priority classification for the ORP system

Water supply sector	% of the water demand to be supplied at given assurance			
	1 in 200 (99.5%)	1 in 100 (99%)	1 in 20 (95%)	1 in 10 (90%)
Irrigation	0 (10)	30 (40)	(50)	70
Urban/Mining	50	30	(20)	20
Losses River Req	100	0	0	0

Results from this analysis showed a significant reduction in the violation of the curtailment criteria (**Figure 5-4**) to such an extent that curtailment criteria were only violated from 2022 onwards, when the inclusion of Polihali Dam significantly impacts on the ORP yield. The violation of the curtailment criteria from 2022 onwards is significantly less severe than that evident from Scenario 1a.

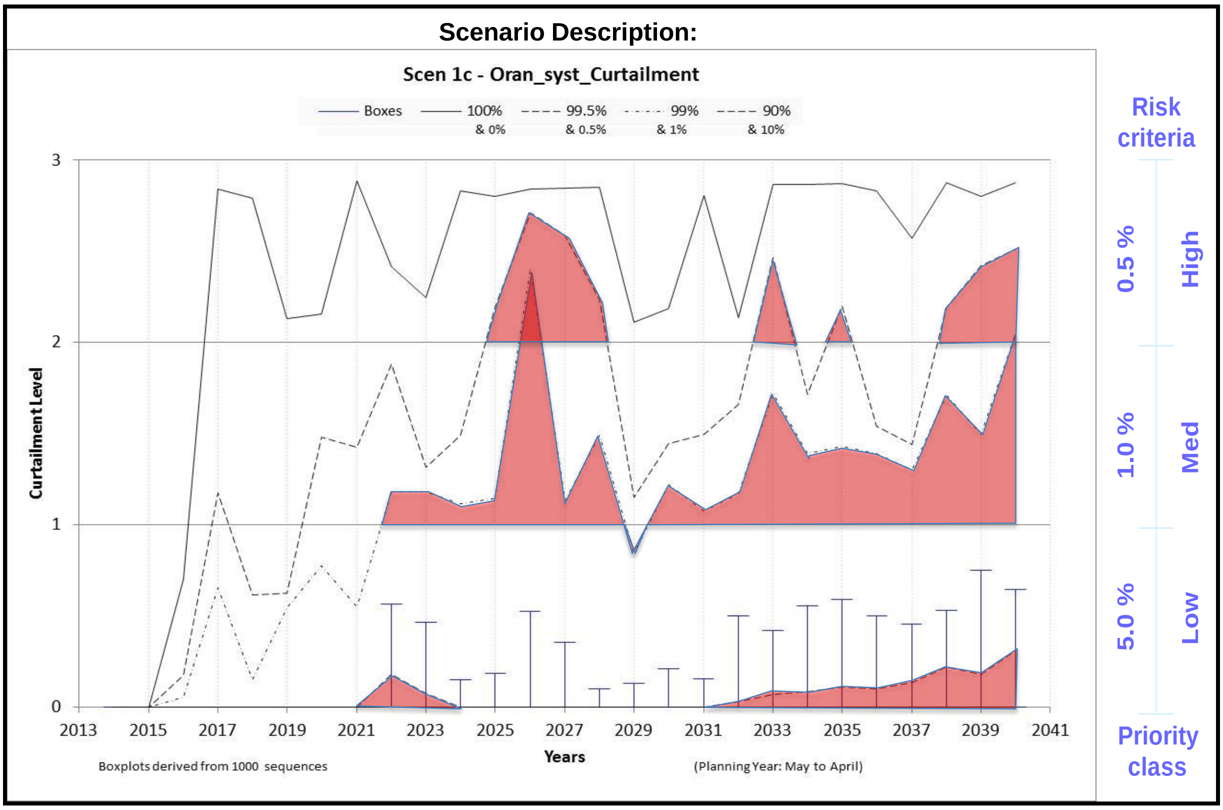

Figure 5-4: Scenario 1c ORP Curtailment plot

Results from all the **Scenario 1 sub-scenarios** indicated that Polihali Dam struggled to fill over the simulation period (see **Figure 5-5**). This is due to two facts; firstly the gross storage capacity of Polihali Dam is in excess of 3 times the MAR into Polihali Dam. Secondly, for Scenario 1 Polihali Dam is used to support both the IVRS as well as the Orange ORP System. This requires that Polihali needed to supply it full yield from 2024 onwards, only allowing a two year warming up period for Polihali Dam, which is clearly not sufficient.

The support to the IVRS and to the Orange system as obtained from the Scenario 1 analysis results are given in **Figure 5-6**. The fact that the operating rule for these two support component provided priority to the Vaal is clearly evident from these two boxplots as the support to the Orange System is over the total analysis period given at a lower assurance. This operating rule was applied to all the other scenarios, although this is not necessarily the optimum operating rule. For the purpose of the reconciliation strategy this rule should be sufficient. It will however be important to optimize this rule so that the maximum benefit of utilizing Polihali Dam as a shared resource can be obtained.

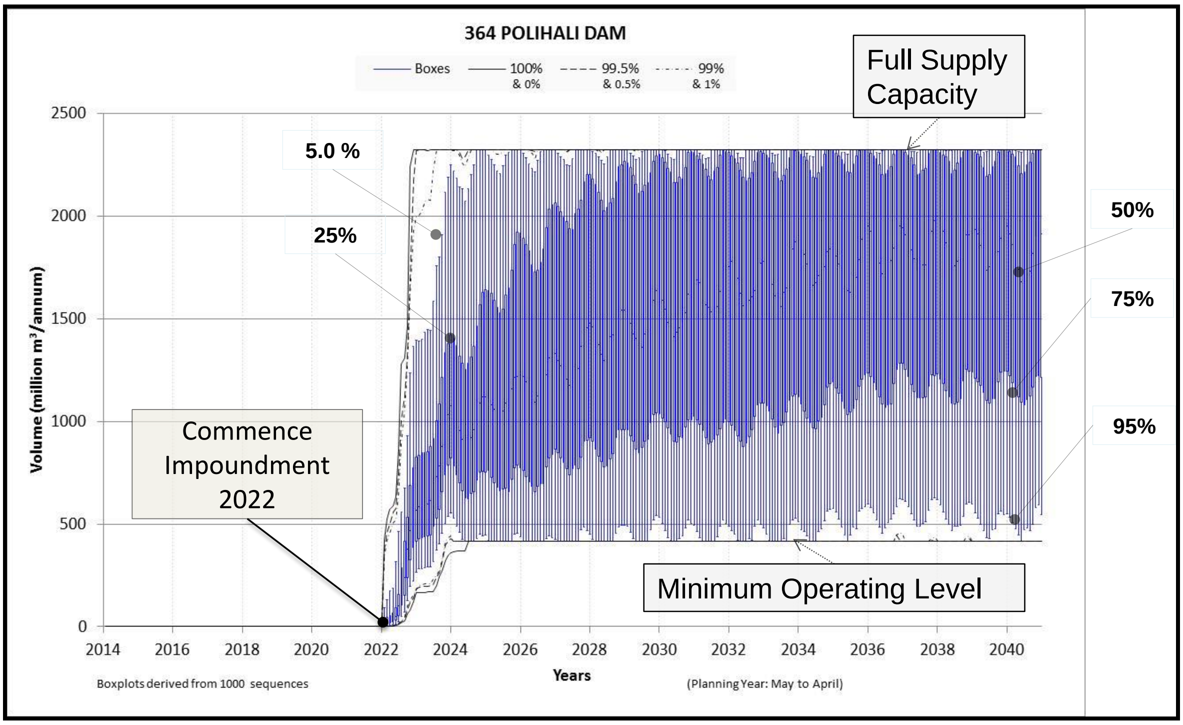

Figure 5-5: Scenario 1 Polihali Dam Storage projection plot

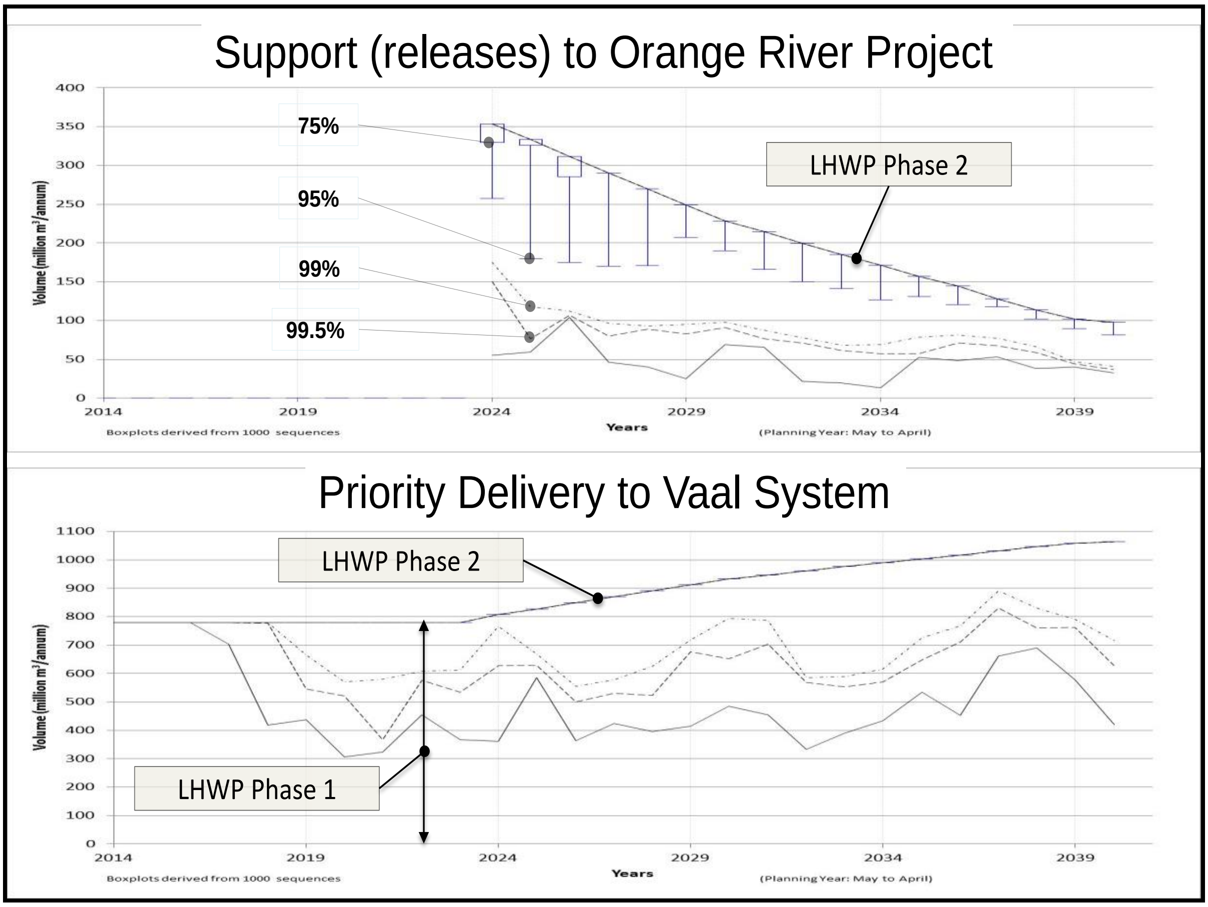

Figure 5-6: Scenario 1 Polihali Dam support to the IVRS and to the Orange system

5.3.2 Scenario 3: Determine the timing for the next intervention option after the implementation of the preferred EWR and inclusion of Vioolsdrift Dam

As described in **Section 5.2.2** the purpose of Scenario 3 is to determine the timing of the next intervention option being the raising of Gariep Dam or the building of a Verbeeldingskraal Dam. The storage projection plot showing the combined Gariep and Vanderkloof Dam storage relevant to Scenario 3 is shown in **Figure 5-7** indicating the first risk of failure violation in 2026.

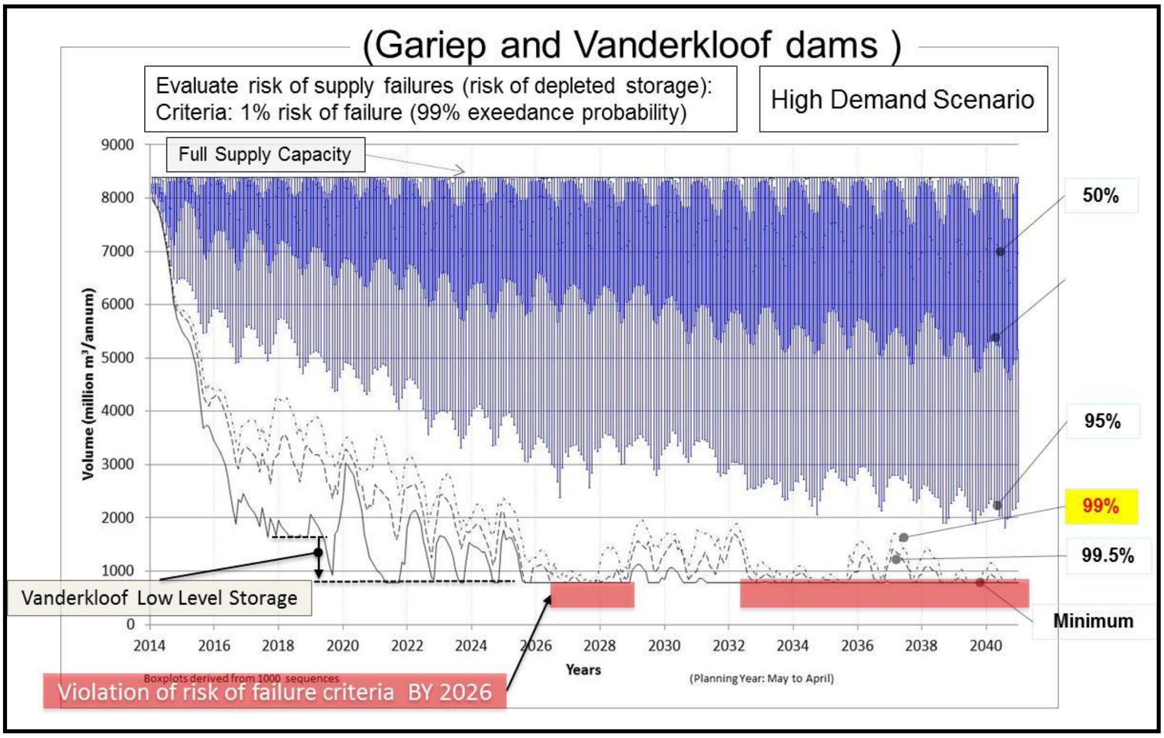

Figure 5-7: Scenario 3 Combined Gariep and Vanderkloof Storage projection plot

The drop in the m.o.l. due to the Vanderkloof low level storage utilization is evident from 2019 onwards as recommended from the scenario 1a analysis. From 2029 to 3032 a short term improvement in the storage levels can be seen, which is as result of an improvement in the Polihali support assurance levels, most probably as result of Polihali starting to reach higher storage levels. This behavior is also evident from the storage projection plot produced for scenario 1b and the Polihali support volumes shown on **Figure 5-6**.

The Vioolsdrift Storage projection plot (**Figure 5-8**) shows that the filling of Viooldrift Dam is very quick due to the small storage in comparison with the available runoff at this site. This storage plot, only shows the live storage used to generate yield as due to the monthly time steps of the WRYM and WRPM the storage impact for reregulation purposes can't be simulated properly, and is regarded as part of the storage below the m.o.l. as shown in **Figure 5-8**.

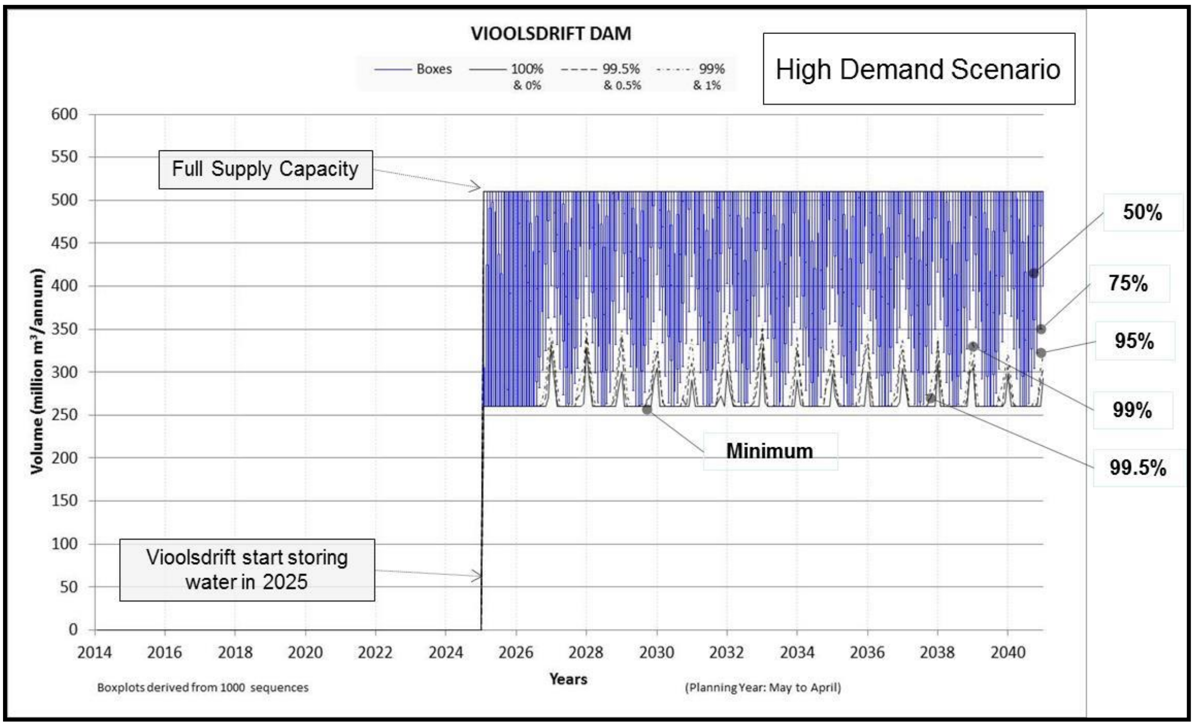

Figure 5-8: Scenario 3 Vioolsdrift Storage projection plot

For scenario 3 it was assumed that the preferred EWR on the Lower Orange will be implemented by 2026. The risk analysis confirms that Vioolsdrift Dam is on its own not sufficient to support the preferred EWR and a next intervention option is required at the time of EWR implementation. This then dictate the timing when the raised Gariep or Verbeeldingskraal Dam options need to be implemented.

5.3.3 Scenario 4: Utilize Raised Gariep Dam as the next intervention option after Vioolsdrift and preferred EWR

Scenario 4 is utilized to determine whether the raising of Gariep Dam will be sufficient to provide a positive balance for the Orange ORP System for the remainder of the planning period. The storage projection plot for the combined Gariep Vanderkloof Dam storage in **Figure 5-9** shows that only temporary failures occurred during 2027 and 2028. For the remainder of the projection period no failures occurred. It is important to note that this projection still excludes the impact of WC/WDM and if included these failures will most probably be eliminated.

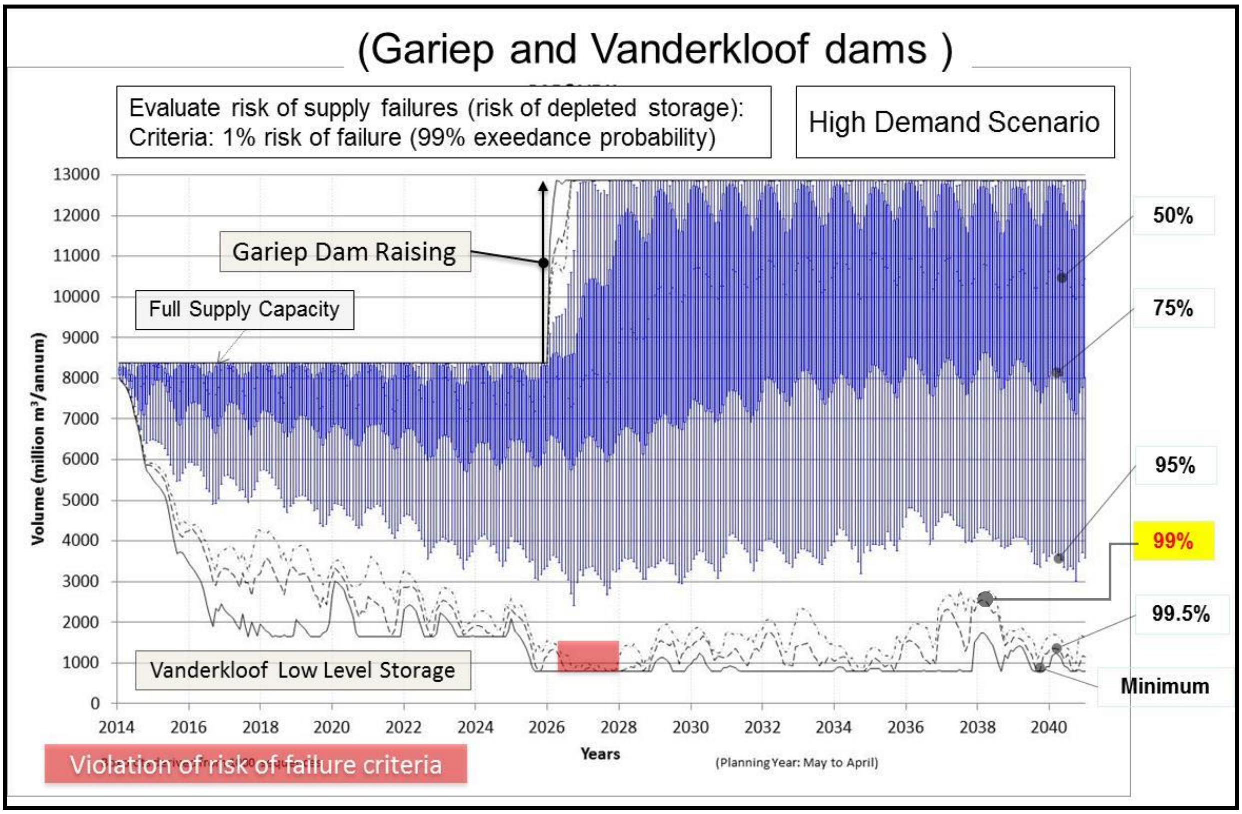

Figure 5-9: Scenario 4 Combined Gariep and Vanderkloof Storage projection plot

Results from this analysis therefore confirm that the raising of Gariep as the last intervention option is sufficient to maintain a positive balance over the entire planning period.

5.3.4 Scenario 5: Utilize Verbeeldelingskraal Dam as the next intervention option after Vioolsdrift and preferred EWR.

In scenario 5 the Verbeeldingskraal Dam intervention option is utilized as an alternative to the raising of Gariep Dam. The storage capacity of Verbeeldingskraal Dam is limited to prevent this dam from inundating part of Lesotho. The storage projection plot for the combined Gariep, Vanderkloof and Verbeeldingskraal dams (**Figure 5-10**) shows, that the increase in the total system storage due to Verbeeldingskraal is much less than the storage added when Gariep Dam is raised.

The performance of Verbeeldingskraal Dam with a much smaller storage capacity is surprising, as it is almost as good as the raised Gariep. The reason for this good performance was already evident from the yield analyses carried out with the WRYM, which showed that the raised Gariep Dam option results in very high evaporation losses due to the significant increase in the water surface area of Gariep Dam.

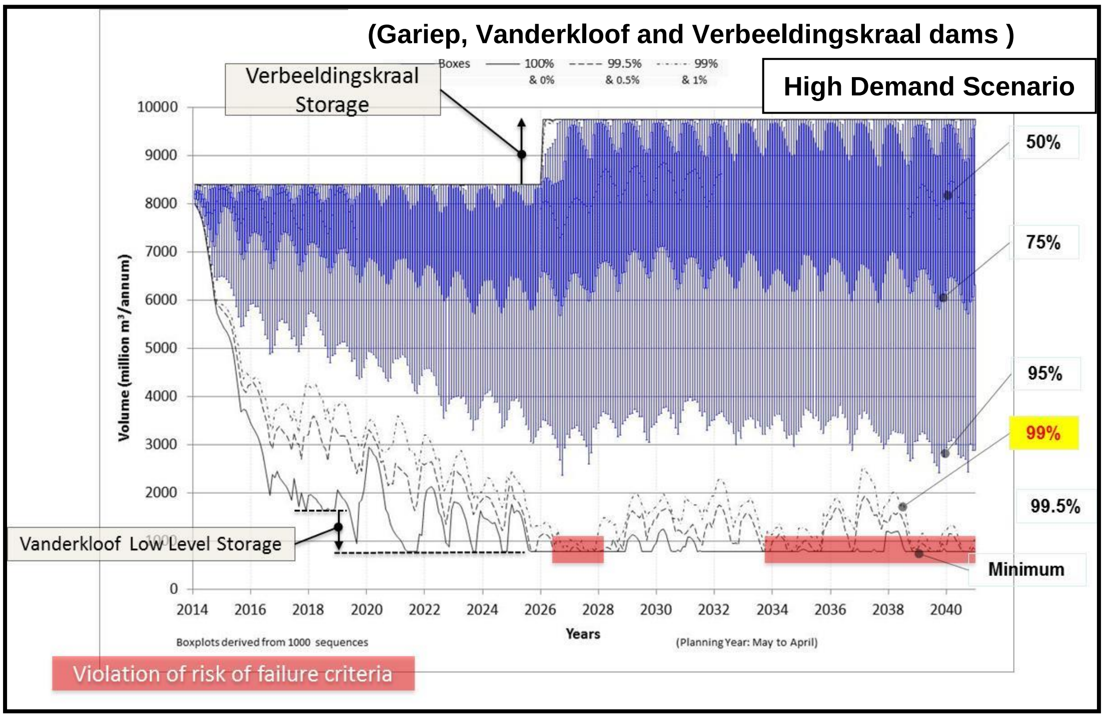

Figure 5-10: Scenario 5 Combined Gariep and Vanderkloof Storage projection plot

The evaporation losses from the Orange ORP system reduced by approximately 180 million m^3/a when the Verbeeldingskraal option is used instead of the raising of Gariep Dam. The Verbeeldingskraal option also result in 480 million m^3/a more spills reaching the river mouth on average, than for the raised Gariep option. The higher spills will be beneficial to the EWR on the Lower Orange as well as for the yield generated at Vioolsdrift Dam.

Similar to the raised Gariep option temporary failures were evident in 2027 and 2028 where after the system recovered again. Small failures however started to occur again from 2035 onwards for scenario 5 where the Verbeeldingskraal option is included as the alternative to the raising of Gariep Dam.

6 CONCLUSIONS AND RECOMMENDATIONS

The following important conclusions can be drawn from the WRYM and WRPM analyses carried out as part of the Orange Reconciliation Strategy.

1. The Orange ORP System is currently for practical purposes just in balance. The small surplus available will be utilized by the further development of the 120 million m^3/a already allocated to the resource poor farmers.
2. Polihali Dam, the phase ll component of the LHWP will significantly impact on the Orange ORP System yield (reduction of 284 million m^3/a), which will result in a deficit in the Orange ORP system. The increased transfer from the LHWP to the Vaal as result of Polihali Dam was determined as 437 million m^3/a.
3. When implementing the recommended EWR on the Lower Orange, a significant reduction in the yield available from the ORP (Gariep and Vanderkloof dams). The reduction in the yield is very sensitive to the EWR used as well as related assumptions. The recommended EWR reduce the yield by as much as1060 million m^3/a, but if only the summer month (no high) flows are requested with no winter flows the yield reduction is 722 million $m^{3/}$a. This impact further reduces to 479 million m3/a when the PES EWR is used.
4. To be able to effectively supply the EWR at the Orange River estuary a control structure on the Lower Orange is required. The possible future Vioolsdrift Dam will be ideal for this purpose.
5. The yield available from Vioolsdrift Dam as well as the sizing of Vioolsdrift dam is very sensitive to the EWR used, the demands downstream of the dam as well as the development of large upstream storage dams. These will typically include the raising of Gariep Dam, Bosberg or Boskraai Dam and Verbeeldingskraal Dam.
6. The IVRS do not require the full yield available from Polihali Dam, which will result in a surplus available in Polihali Dam for quite a long time before the full yield is taken up by the growth in the IVRS requirement.
7. By reducing the assurance of supply in particular to irrigation, which is currently receiving a fairly high supply assurance, can significantly increase the water availability in the system.
8. Operating rules can play a significant role in the yield available in the Orange ORP System. This is in particular important when development of dams upstream of Gariep is considered as an intervention option. Due to very high evaporation losses from Gariep Dam, a rule that keep the water for as long as possible in the upstream

dam should increase the yield available due to the reduction in evaporation losses.

9. The filling periods for the large storage dams such as the raised Gariep and Polihali dam can be quite long as evident from the WRPM analyses results, and will thus impact on the supply capability in the initial years.

10. Utilizing the Lower Level Storage in Vanderkloof Dam impact on the hydro-power generated at the dam. This impact can be reduced significantly by using the correct operating rule when an upstream storage dam is used to support Gariep and Vanderkloof dams.

11. Although Verbeeldingskraal Dam storage is significantly less that that obtained by the raising of Gariep Dam, the performance of Verbeelingskraal Dam in system context is very good and is almost as good as the raised Gariep. This is most probably due to much lower evaporation losses from the entire system, when the Verbeeldingskraal option is used.

12. The identified intervention options as included in the WRPM analyses are sufficient to maintain the water balance over the planning period.

From these conclusions the following recommendations followed:

1. Use Polihali Dam to initially support both the IVRS as well as the Orange ORP System.
2. The operating rule imposed on Polihali Dam to manage the duel support from the dam will be very important and will significantly impact on the water availability in both the IVRS and the Orange ORP System. Further work is recommended to refine this operating rule, which in the end need to be agreed upon by both Lesotho and the RSA.
3. Determine the URV for the different intervention options and select the most appropriate combination to maintain a positive water balance over the planning period.
4. A classification study is required to obtain a decision on the final agreed EWRs to be imposed on the Orange ORP system. This need to be done as soon as possible as it significantly influences decisions on the future developments.
5. Discuss the assurance of water supply requirements with the stakeholders to find agreement on lower assurances of supply in particular to irrigation.
6. The impacts of large upstream developments on the environment, specifically along the Lower Orange and the estuary need to be evaluated in more detail, to prevent further deterioration of the environment.
7. Vanderkloof lower level storage need to be in operation by 2019.
8. Vioolsdrift Dam needs to be in place and able to deliver its yield before the recommended EWRs can be imposed. It was assumed that the final agreed EWRs (Reserve) will be applied by 2026 and Vioolsdrift Dam will start storing water in 2025.
9. The next recommended intervention option can be the raised Gariep Dam or the building of Verbeeldingskraal Dam in the Upper Orange. One of these intervention options need to be in place and be able to deliver water by 2026.

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APPENDIX A

WRYM SCHEMATIC DIAGRAMS

APPENDIX B

WRPM SCHEMATIC DIAGRAMS