TITLE	Specialist Report Yield analysis
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EXECUTIVE SUMMARY

This report concerns the hydrological yield analysis required for Task 4: The Impact and Risk Assessment, of LHDA Contract 648: The Establishment and Monitoring of Instream Flow Requirements (IFRs) for River Courses Downstream of LHWP Dams.

- The hydrological yield analysis was carried out to determine the impact of supplying IFRs on reservoir yields for Phase 1 and 2 dams.

- The relationship between yield and IFR is one of the important variables LHDA needs to decide on a preferred IFR Scenario.

INPUT PARAMETERS

The yield analysis was performed using the following data in the simulation process:

- inflow sequences based on reviewed hydrological data by LHDA/DWAF Joint Study (1996) for the period 1930 to 1994,
- design data including the Katse and Mohale outlet works and the Mohale and Matsoku diversion tunnels provided by LHDA,
- reservoir area-capacity curves for Katse, Mohale and Mashai Dams, provided by LHDA,
- Mashai off-take pumping capacity of 50 $m^3 s^{-1}$, given in the GSJV 1989, and
- IFRs for Treaty, Design Limitation, Minimum Degradation and Fourth scenarios.

The summary of input parameters used in the modeling of the Phase 1 and 2 are shown in Table 2.4 Further details of these input parameters are given in Section 4.

METHODOLOGY AND RESULTS

The reservoir system was simulated using the LHDA/DWAF Joint Study (1996) hydrology data covering the 1930-1994 period. Historical simulation was performed using a sequence of 65 years of monthly streamflow data. The annual reliability of the system was determined by computing the number of non-recoverable failures during the simulation period.

RESULTS

- A combined system yield of 27.3 m^3s^{-1} and 50.8 m^3s^{-1} was achieved for the historical simulation of the Phase 1 and 2 dams, respectively, for the Treaty releases scenario. Table E.2 summarises the effects of IFR releases on the combined system yield for each of the four scenarios.

Table E.2 System yield associated with each of the four IFR scenarios.

IFR Scenario	Phase 1	Phase 1&2
	System Yield ($m^3 s^{-1}$)	System Yield ($m^3 s^{-1}$)
Treaty	27.3	50.8
Fourth	25.2	47.8
Design Limitation	22.8	43.6
Minimum Degradation	18.3	38.0

- The system yield is sensitive to releases from Katse, Mohale and Mashai Dams and Matsoku Weir to meet IFRs at the IFR sites situated immediately downstream of the dams.

TABLE OF CONTENTS

FIGURES

LIST OF TABLES AND FIGURES

TABLES

FIGURES

LIST OF ABBREVIATIONS

ASV:	Active Storage Volume
BKS:	BKS Incorporated
DWAF:	Department of Water Affairs and Forestry (RSA)
EDNET:	A module of WATHNET Model
EL:	Elevation
FSL:	Full Supply Level
GSVJ:	Gibbs Sogreah Joint Venture
HEC5:	Hydrological Engineering Centre Reservoir Simulation Model
IoH:	Institute of Hydrology
JPTC:	Joint Permanent Technical Commission
LHDA:	Lesotho Highlands Development Authority
LHWP:	Lesotho Highlands Water Project
LHTP:	Lesotho Highlands Tunnel Partnership
LMC:	Lahmeyer MacDonald Consortium
MDP:	Matsoku Diversion Partnership
MOL:	Minimum Operating Level
MCG:	Mohale Consultants Group
MCM:	Million Cubic Meter
NLP:	Network Programming Technique
OSC:	Oliver Shand Consortium
OVTS:	Orange-Vaal Transfer Scheme
RSA:	Republic of South Africa
SIMNET:	A module of WATHNET Model
TSV:	Total Storage Volume
WATHNET:	Water Supply Simulation Package on Network Linear Programming
WATOUT:	A module of WATHNET Model
WATSTRM:	A module of WATHNET Model
WRYM:	Water Resources Yield Model

1 INTRODUCTION

This report concerns the hydrological yield analysis required for Task 4: The Impact and Risk Assessment, of Contract LHDA 648: The Establishment and Monitoring of Instream Flow Requirements (IFRs) for River Courses Downstream of LHWP Dams.

The hydrological yield analysis was carried out to determine the impact of supplying IFRs on reservoir yields for Phase 1 and 2 dams. The simulations of the reservoir systems were undertaken using the historical data available for the period 1930 to 1994, inclusive.

The hydrological yield analysis provides the impacts of various release scenarios on system yield. These impacts are one of the important factors that will be taken into consideration when deciding on which IFR scenario will be implemented.

2 BACKGROUND

2.1 REVIEW OF PREVIOUS STUDIES

Several studies on the Hydrological Yield Analysis of the dams in the Lesotho Highlands Water Project (LHWP) have been done to date. These studies focused mainly on water supply to the Republic of South Africa (RSA) and hydropower development in Lesotho.

The most recent hydrological yield analysis study was done by Mohale Consultants Group (MCG) in 1996, during the design stage of Mohale Dam. The purpose of the study was to determine the optimal height for Mohale Dam. The results indicated that an EL of 2075 masl would result in optimal FSL. The conclusion of MCG (1996) study was that the combined Katse, Matsoku and Mohale Dams (i.e., LHWP Phase 1 dams; with Mohale Dam FSL at 2075 masl) would yield an estimated 28.6 m^3s^{-1}, with an annual reliability of 98%.

Table 2.1 shows the yield analysis results for Phase 1 of LHWP by MCG (1996).

Table 2.1 Summary of overall yield analyses – For Mohale FSL at 2075 masl.

Reservoir System	**Total System Yield (m^3 s^{-1})**	**Incremental Yield (m^3 s^{-1})**
Katse	16.8	16.8
Katse + Matsoku Diversion	19.0	2.2
Katse + Matsoku Diversion + Mohale	28.6	9.6

The second important study was the yield analysis of Phase 1A Dams carried out as a part of the Feasibility Study of the LHWP by Gibb Sogreah Joint Venture (GSJV) from 1986 to 1989. A simulation model was specifically developed for assessment of reservoir yield of this project. The characteristics of tunnels and conveyance facilities and reliability rules were incorporated in the computer model. The study utilised monthly inflows to system reservoirs using 1930 to 1982 records. Two sets of hydrological inflow data were used in the yield analysis namely:

- Stage 1/2A hydrology;
- Stage 1/2B hydrology.

Summaries of these two sets of hydrological data and the results of yield analysis using these data are shown in Table 2.2.

Table 2.2 Summary of Feasibility Study yield analysis.

	MAR (MCM/yr)	D-stream Releases (m^3 s^{-1})	FSL (masl)	Active Storage (MCM)	Yield (m^3 s^{-1})	Rainfal1 (mm/yr)	Initial Storage	Evap (mm/yr)
Phase 1/2A Hydrology								
Katse	649.9	0.5	2045	1245	18.2	1393	Full	574
Mohale	326.4	0.3	2088-2093	1016	9.7	1393	Full	574
Phase 1/2B Hydrology								
Katse	655.6	0.5	2045	1245	16.9	1393	Full	574
Mohale	367.3	0.3	2088-2093	1016	10.1	1393	Full	574

The results of the yield analysis were presented in Technical Note B (GSJV, 1987) to reoptimise the various phases of LHWP. Several development scenarios were considered in Technical Note B (GSJV, 1987). The yield of Katse Dam was estimated at 14.3 - 18.6 $m^3 s^{-1}$. Matsoku Weir and Mohale Dam incremental yields were assessed to be in the range of 1.7 - 2. $m^3 s^{-1}$ and 7.2 - 8.3 $m^3 s^{-1}$, respectively.

Following the GSJV assessment, LHDA performed a reoptimisation of the components of the LHWP (*viz*. Phases 1-4), the results of which were reported in Technical Note J (GSJV, 1988a). During the course of the reoptimisation study, the simulation model used in Technical Note B (GSJV, 1987) was modified and expanded to four models. Two of these were used for yield assessment as follows:

- The System Yield Model was used to determine the nominal yield of the system based on steady state monthly simulation;
- The Dynamic System Model was used to simulate phased introduction of each reservoir from initial impounding with progressive build-up of target yield to the full output, for all phases, of 70 $m^3 s^{-1}$ in year 2020.

Several scenarios were considered and the optimal arrangement in terms of reservoir location and capacity was recommended. The main design parameters of the selected arrangement for Phase 1 and 2 dams are summarised in Table 2.3.

Table 2.3 Summary of Technical Note J (GSJV, 1988a) yield analysis.

	MAR (MCM)	D-stream Releases ($m^3 s^{-1}$))	FSL (masl)	Active Storage (MCM)	Yield ($m^3 s^{-1}$)	Rainfall (mm/yr)	Initial Storage	Evap (mm/yr)
Katse	622.6	0.5	2053	1120	18.2	957	81%	1162
Mohale	310.1	0.3	2069	1016	9.5	944	70%	1151
Matsoku	95.5	0.05	-	-	1.9	-	-	-
Mashai	992.2	1.5	1887	2499.6	25.4	500	66%	1193

2.2 OBJECTIVES OF PRESENT STUDY

The aim of the yield analysis performed for this study was to determine the impact of supplying the IFR described in four scenarios on the system yield for Phase 1 and Phase 2 of LHWP, as required by the Treaty between the Government of Lesotho and the Government of the Republic of South Africa. The yield analysis was performed using the following hydrological data in the simulation process:

- inflow sequences based on reviewed hydrological data by LHDA/DWAF Joint Study (1996) for the period 1930 to 1994,
- design data including the Katse and Mohale outlet works and the Mohale and Matsoku diversion tunnels provided by LHDA, and
- IFRs described in the four scenarios produced in this project.

2.3 INPUT PARAMETERS

The summary of input parameters used in the modeling of the Phase 1 and 2 are shown in Table 2.4. Further details of these input parameters are given in Section 4.

Table 2.4 Summary of input parameters for reservoir system modeling.

Item	**Unit**	**Value**
Annual Reliability of Supply	%	98.0
KATSE DAM:		
Full Supply Level (FSL)	masl	2053
Storage at FSL	MCM	1950
Minimum Operating Level (MOL)	masl	1989
Storage at MOL	MCM	431.4
Active Storage Volume @ 2053 masl	MCM	1518.6
Initial Storage	% of ASV	60
Inflow Sequences	MCM	1930 – 1995
Mean Annual Inflow	MCM/yr	554.8
Releases (Treaty)	$m^3 s^{-1}$	0.50
Adopted Outlet Capacity for low flows (1.2 – 1.9 $m^3 s^{-1}$)	$m^3 s^{-1}$	1.55
Adopted Outlet Capacity for Floods (100 – 260 $m^3 s^{-1}$)	$m^3 s^{-1}$	180
MOHALE DAM:		
Full Supply Level (FSL)	masl	2075
Storage at FSL	MCM	946.93
Minimum Operating Level (MOL)	masl	2005
Storage at MOL	MCM	89.81
Active Storage Volume @ 2075 masl	MCM	857.12
Initial Storage	% of ASV	60
Inflow Sequences	MCM	1930 – 1995
Mean Annual Inflow	MCM/yr	308.8
Downstream Releases (Treaty)	$m^3 s^{-1}$	0.30
Adopted Outlet Capacity for low flows (2.5 – 4.25 $m^3 s^{-1}$)	$m^3 s^{-1}$	3.4
Adopted Outlet Capacity for Floods (57 $m^3 s^{-1}$)	$m^3 s^{-1}$	57
MASHAI DAM:		
Full Supply Level (FSL)	masl	1887
Storage at FSL	MCM	3438.4
Minimum Operating Level (MOL)	masl	1835
Storage at MOL	MCM	1005
Active Storage Volume @ 1887 masl	MCM	2433.4
Initial Storage	% of ASV	60
Inflow Sequences	MCM	1930 – 1995
Incremental Mean Annual Inflow	MCM/yr	819.3
Downstream Releases	$m^3 s^{-1}$	1.5
Pumping Capacity from Mashai to Katse (30 – 50 $m^3 s^{-1}$)	$m^3 s^{-1}$	50
MATSOKU DIVERSION WEIR:		
Full Supply Level	masl	2088.0
Ratio of downstream versus natural annual inflows	%	36%
Downstream Releases	$m^3 s^{-1}$	0.05
MOHALE TUNNEL:		
Length	Km	32
Diameter	m	4
Flow Diversion computed based on storage levels at Katse and Mohale Dams	-	-
****** Matsoku and Mashai have no outlet design limitations***		

3 MODEL SELECTION

3.1 WATER-RESOURCE MODELS

Water-resource modeling has become an essential tool for planning and operation of water resources systems. Research in the area of water-resource modeling indicates that substantial benefit could be gained from optimisation of multi-purpose reservoir systems. An overall review of simulation and optimisation techniques currently used for modeling complex multi-purpose reservoir systems is given in Appendix 1 of the MCG 1996 report. When possible, summaries of examples of actual applications of these techniques are given. The reader may refer to the list of references given for the details of the examples provided at the end of Appendix 1 (MCG, 1996).

3.2 MULTI-RESERVOIR SIMULATION MODELS

A multi-reservoir simulation model capable of simulating multi-reservoir systems was deemed suitable for this study. Several simulation models, many of which are capable of simulating multi-reservoir systems, have been developed by various organisations over the last decade. These generalised models include:

- HEC-5 Simulation of Flood Control and Conservation Systems;
- South-western Division Reservoir Regulation Simulation Model;
- Streamflow Synthesis and Reservoir Regulation (SSARR) Model;
- Texas Department of Water Resources models;
- Water Resources Yield Model.

Brief descriptions of these models are given in Appendix 5.

The simulation models listed above use explicit rules to make water assignments such as reservoir releases and link allocations, and many water supply systems are operated using such rules.

A suite of generalised multi-reservoir simulation models has also been developed by various agencies using Network Linear Programming Technique (NLP), including the models developed for operation of the California State Water Project (Sabet *et al*, 1985, 1986, 1991a,b), ACRES (1990), WRYM (BKS, 1994), WATHNET (1998). These types of models have proved to be more flexible, robust and reliable than the generalised simulation models mentioned above.

Of these, WRYM and WATHNET were extensively assessed for their suitability for performing the Phase 1 yield analysis (see Section 2.1; MGC 1996) and, on the basis of that assessment, the WATHNET model was eventually adopted to perform the Phase 1 yield analysis.

Thus, on the basis of the assessment done by MGC, and in order to facilitate uniformity between the various LHWP studies, it was decided to use the WATNET model to perform the IFR-related yield analysis.

3.3 WATHNET

WATHNET model is a set of four FORTRAN 77 computer programs capable of simulating the operation of a wide range of water supply headworks and transfer systems serving urban, industrial, irrigation and instream demands. The programs are fully interactive and operate in a Windows-based graphics environment.

WATHNET is an example of a generalised simulation model that departs from the traditional approach to system operation. The simulation algorithm is based on a network linear program, which operates the system according to a hierarchy of five objectives and maintains a mass balance at every node in the system but does not explicitly model transfer hydraulics or water quality processes. The operator does not use explicit rules to make assignments. Rather he loads information about the current state of the system as well as forecasts of streamflow and demand, and then runs a network linear programme, which assigns water according to the following hierarchy of objectives:

- satisfy demand (which may be restricted according to predefined restriction rules) at all demand zones;
- satisfy all instream flow requirements;
- ensure that reservoirs are at their end-of-season (month) target volumes;
- minimise delivery costs;
- avoid unnecessary spill from the system.

The four programs in WATHNET are:

EDNET, which is used to define the water supply network, whose elements can have different commission years.

WATSTRM, which is a streamflow utility that simplifies handling of streamflow, demand and evaporation data. WATSTRM also provides a monthly multi-site stochastic streamflow generator.

SIMNET, a program which performs simulations using one of three algorithms. SIMNET creates unformatted output files.

WATOUT, which is an interactive reporting facility used to study the contents of the SIMNET output files. WATOUT uses an interactive graphical interface, which allows rapid comprehension of the simulation results and, for stochastically generated data, provides comprehensive probabilistic performance summaries. For example the user may look at the inflow series and its statistics, reservoir storage levels and their statistics, flow to various tunnels and streams, and system failure statistics for a replicate or multiple replicates. WATOUT enables the user to display the model simulation results on a month by month basis. However, it does not produce tabular outputs, which are often very useful for reporting purposes.

3.4 SIMULATION PROCESS USING WATHNET

The yields of the reservoir system are evaluated using the hydrologic and system data as described in Section 4. The EDNET module of WATHNET was used to prepare the network model representing the system facilities. WATSTRM was used to prepare the input data file in the format acceptable to WATHNET. SIMNET was then used to simulate the reservoir system and, finally, the WATOUT module was used to access the results of reservoir simulation. Annual failures were identified by looking at model output using WATOUT, which has an extensive interactive reporting facility.

4 INPUT DATA

4.1 HYDROLOGICAL DATA

The following hydrological data were used in the yield analysis:

- monthly inflow sequences to Katse, Mohale, Matsoku and Mashai Dams;
- rainfall, and;
- net evaporation losses from the reservoirs.

These are described in the following sections.

4.1.1 Monthly Inflow Sequences to Katse, Mohale and Mashai Dams and Matsoku Weir

Several hydrological studies have been done for the LHWP to date, the most recent of these is the Joint Study of Lesotho Highlands Hydrology (1996) carried out by LHDA and the Department of Water Affairs and Forestry (DWAF) of RSA. The methodology used in this study to estimate the streamflow series for the 1926-1995 period was similar to that used in the earlier feasibility studies for LHWP and subsequent studies undertaken on behalf of DWAF by BKS and other consultants. The overall procedure was as follows:

- The monthly rainfall records were updated and checked for inconsistencies using mass plots.
- The entire set of rainfall records was consolidated and extended to cover the 1920 to 1995 hydrological years (unless otherwise stated, all years refer to the standard hydrological/water year covering October through September inclusive, the water year commencing in October of the year specified).
- Monthly historical streamflow records, as established by the Institute of Hydrology of Wallingford (IoH) using the updated rating curves at gauging stations, were accepted as base data and were initially patched by regression to cover at least October 1967 to May 1996.
- A modified Pitman Rainfall/runoff model (Pitman, 1973), with a monthly time step was used to extend consolidated flow records to cover the period from 1930.
- Extended flow records were transposed to the dam sites to give the required inflow series using the incremental catchment area relationship.

Detailed hydrological data analyses for this study (Contract LHDA 648) are given in the Specialist Hydrology Report No 648-F-13. The monthly streamflow sequences for the 1930-1994 period used for Katse, Mohale and Mashai Dams and Matsoku Weir are given in Appendix 1 and summarised in Table 4.1.

4.1.2 Evaporation from Reservoirs

The monthly open-water evaporations for Katse, Mohale and Mashai Dams were adopted from Technical Note A (GSJV, 1988b) and are given in Appendix 2.

Net evaporation from reservoirs is computed by WATHNET using the average reservoir surface area and net evaporation from reservoirs. The following equation applies:

$$Et_{nt} = Et_{g} - (1-C_{r})\,P_{t} \qquad [1]$$

where;

Et_{nt} = Net Evaporation in mm/ month

Et_{g} = Gross Evaporation or Open-water Evaporation in mm/month

C_{r} = Coefficient of runoff

P_{t} = Mean monthly precipitation on reservoir surface in mm/month.

The estimation of mean monthly precipitation from runoff is described below.

4.1.3 Reservoir Rainfall

It is a normal practice to use the monthly open-water evaporation and monthly rainfall data in estimating the net evaporation data from the reservoir. However, this method does not ensure the correlation between inflow sequences and the rainfall. This means the rainfall over the reservoir surface area is assumed to be the same in wet and dry periods. An improvement was made to this approach by computing reservoir monthly rainfall from historical inflows, using an average runoff coefficient for each catchment. The monthly rainfall values computed were then used as a substitute for the second term of the equation [1] in computation of net evaporation. The runoff coefficient used in this analysis was 35%, which was derived from Technical Note E (GSJV, 1988e) and was evaluated by the Consultant to be appropriate.

Table 4.1 Summary of inflow data to Katse, Mohale, Matsoku and Mashai Dams (Source: LHDA/DWAF Joint Study of Lesotho Highland Hydrology for the period 1930-1994).

Month	**Katse Inflows (MCM)**		**Matsoku Inflows (MCM)**		**Mohale Inflows (MCM)**		**Incremental Mashai Inflows * (MCM)**	
	Mean	**SDEV**	**Mean**	**SDEV**	**Mean**	**SDEV**	**Mean**	**SDEV**
Oct	56.73	62.37	10.05	12.39	27.16	30.31	76.77	140.11
Nov	74.75	63.94	10.83	10.69	38.18	34.30	93.41	97.55
Dec	61.13	49.20	8.26	7.94	29.11	23.11	89.27	85.77
Jan	79.08	65.68	11.05	11.41	40.26	42.76	131.43	113.27
Feb	84.59	57.66	12.39	10.18	45.10	34.81	150.16	134.82
Mar	70.50	60.94	10.49	10.45	40.54	36.13	113.33	130.54
Apr	48.88	41.22	8.02	8.14	34.05	32.71	55.92	50.63
May	23.18	29.00	4.07	6.13	15.69	15.08	33.15	57.97
Jun	11.67	16.96	1.90	2.53	8.12	12.32	16.75	22.66
Jul	9.85	20.46	1.83	3.07	7.24	9.77	12.88	23.83
Aug	13.18	25.25	2.68	5.30	9.60	17.22	16.10	35.88
Sep	20.84	46.67	3.85	8.39	11.11	21.72	26.37	62.01
Annual	**554.38**	**234.08**	**85.42**	**41.91**	**306.16**	**134.67**	**815.53**	**477.42**

**** Incremental Mashai Inflows refers to the inflows from the Mashai incremental catchment area; i.e. excluding the area upstream of Matsoku Weir and Katse Dam..***

4.2 INSTREAM FLOW REQUIREMENTS

The main objective of the hydrological yield analysis for LHDA 648 was to assess the impact on yield of four IFR scenarios, each describing a different modified flow regime. The four scenarios are:

- the Treaty Scenario;
- the Minimum Degradation Scenario;
- the Design Limitation Scenario; and
- the “Fourth” Scenario.

The hydrological requirements for each of these scenarios are described in detail in Report 648-F-13, and summarised below. The biophysical and sociological implications of each scenario are described in Reports 648-F-04 to 07 and Report 648-F-22, respectively.

The first stage of the simulation process was based on the Treaty Scenario, thereafter the other three scenarios were addressed.

The IFRs used in the Treaty Scenario were based on the initial release volumes, design features and other relevant statistics stipulated in the Treaty on the Lesotho Highlands Water Project between the Government of Lesotho and the Government of the Republic of South Africa. These are as follows:

- Minimum releases at Katse and Mohale Dams are defined as a constant flow of 0.5 $m^3 s^{-1}$ and 0.3 $m^3 s^{-1}$, respectively.
- For Matsoku Weir no values are provided for downstream releases in the Treaty or specified in the Feasibility Report (LHWP, 1986a,b). Mohale Consultant Group (MCG, 1996), in agreement with LHDA and the Matsoku Diversion Partnership, used monthly values averaging 0.05 $m^3 s^{-1}$ as being equivalent to the Treaty values for Katse and Mohale Dams (LHDA/MDP, 1996). The actual monthly values used by MCG are October 0.05 $m^3 s^{-1}$, November-March 0.08 $m^3 s^{-1}$, April-May 0.05 $m^3 s^{-1}$ and June-September 0.03 $m^3 s^{-1}$. As the differences are so small, it was proposed to use the average value of 0.05 $m^3 s^{-1}$ as a representative release from Matsoku Weir for this scenario.
- For Mashai Dam also, no values are provided in the Treaty. The values adopted here were from the

Feasibility Report (LMC/OSC, 1986) and in the Re-optimisation Study of LHWP (GSJV, 1988c) for downstream releases was used. This value is 1.5 m^3 s^{-1}.

The second stage of the reservoir simulation process was to incorporate the described IFRs for the three other scenarios. These IFRs detail the flow regime required to maintain the river in a given condition. Table 4.2 shows the required instream flow requirements for each scenario at various IFR Sites. The single figure provided for each of the wet and dry seasons includes both lowflows and floods required during that time. Figure 4.1 shows the location of the IFR Sites in the study area. The details of the computation of these flows are given in the Biophysical Scenario Reports No 648-F-03 to 07.

With the exception of the Treaty Scenario, the above values are the discharges required at each of the IFR sites and not the amount of water that is required as a release from the reservoirs. The WATHNET model was set-up in such a way that the IFR demands were met by first utilising the incremental inflows between the dams and the IFR sites and then releasing the difference from the reservoirs. When natural flow was less than the specified IFRs, the releases made were reduced to the natural flow at the IFR Sites.

Table 4.2 Seasonal IFRs at IFR Sites in the study area in m^3 s^{-1} with Phase 1 and 2 dams in place.

Season	IFR Sites							
	1-Below Matsoku	2-Below Katse	3-Below Katse & Matsoku	4-Below Mashai	5-Below Mashai	6-Below Mashai & Mohale	7-Below Mohale	8-Below Mohale
Treaty Scenario (T)								
Wet*	0.05	0.50		1.50			0.30	
Dry*	0.05	0.50		1.50			0.30	
Minimum Degradation Scenario (MD)								
Wet	2.41	17.60	19.47	38.09	54.91	98.97	10.86	18.50
Dry	0.50	3.16	5.79	12.37	16.60	26.21	2.34	4.20
Design Limitation Scenario (DL)								
Wet	1.59	8.83	14.72	26.11	37.68	77.84	5.53	11.47
Dry	0.41	1.63	3.26	4.58	10.18	26.21	1.81	3.23
4th Scenario (F)								
Wet	1.40	4.49	10.62	12.33	33.61	70.89	3.18	8.28
Dry	0.41	1.06	2.32	4.58	7.60	23.67	1.41	3.23
**Wet = the wet season from October to April. Dry = the dry season from May to September.*								

4.3 SYSTEM DATA

4.2.1 Reliability Requirement

The following interpretation of the required reliability as stipulated in the Treaty (LHDA/DWAF, 1986) and as used in the Mohale Development Yield Assessment Study (MCG, 1996), was applied in assessing the reliability of the system yield in the simulation of the system of reservoirs:

- The reliability should be maintained at ninety-eight percent as required by paragraph 5 Article 7 of the Treaty on the Lesotho Highlands Water Project.
- The required reliability should be met on an annual basis, which means a failure event of two in 100 years could be allowed, irrespective of whether the length of a failure was one or up to twelve months.
- The nominal yield is to be delivered within a calendar year, i.e., January to December. This means, if a deficit in any month of the year is made up within the same calendar year, it is not considered as a failure.

In the simulation of reservoir systems for this project, 65 years of reservoir inflow data (1930-1994) were used. One failure was allowed in 65 years (equivalent to a reliability of 98.5%). It was noted however from a sensitivity analysis on the length of the record that the use of the last 50 years of data also resulted in one failure, a reliability of 98%, and identical yield results to that obtained from the use of 65 years of data. This similarity is due to the occurrence of a major drought in the early 1970s which caused the only failure common to both the 65 year and the 50 year records. Use of the full 65 years of data thus covered one failure while achieving the required reliability of 98%.

4.2.2 Characteristics of Katse, Mohale and Mashai Dams

The location and the schematic representation of the facilities included in Phase 1A, Phase 1B and Phase 2 of the project are given in Figures 4.1 and 4.2. The variables relating to the system of reservoirs used in the yield analysis include Reservoir Stage-Area-Capacity relationship, Minimum Operating Level (MOL) and Full Supply Level (FSL).

The relationship between stage, storage, and reservoir area for Katse Dam are based on values used in Technical Memorandum CEF-05 (GSJV, 1988c) and are given in Figure 4.3. The updated storage capacity curve for Mohale Dam is given in Figure 4.4 and the storage capacity curve for Mashai Dam is given in Figure 4.5.

The MOL for Katse Dam was assumed to be at 1989 masl, which corresponds to a reservoir volume of 431.4 MCM. The MOL for Mohale Dam was assumed to be at 2005 masl, which corresponds to a reservoir volume of 89.8 MCM, and the MOL for Mashai Dam was assumed to be 1835 masl, which correspond to a reservoir volume of 1005 MCM.

The FSL for Katse Dam was assumed to be at 2053 masl, which corresponds to a storage volume of 1950 MCM. The FSL for Mohale Dam was a assumed to be at 2075 masl, which corresponds to a storage volume of 946.9 MCM, and the FSL for Mashai Dam was assumed to be at 1887 masl, which corresponds to a storage volume of 3438.4 MCM.

4.2.3 Mohale Tunnel

The Mohale-Katse connecting tunnel was first recommended in Stage 2A of the Feasibility Study, which was undertaken from 1983 to 1985 (LMC/OSC, 1986a,b). The tunnel was planned to be 32 km in length with a final diameter of 3.4 m. The tunnel was designed to transfer the nominal yield of 9.7 $m^3 s^{-1}$ from the Mohale Dam to Katse Dam.

The selected intake was located as far down the Senqunyane River valley as was possible without incurring an unreasonable penalty on length. The intake invert level was set at 2005 masl, which provided for the minimum submergence level with the reservoir at MOL while still allowing for a 30 m clearance to river-bed level for silt accumulation.

The detailed design (LHDA/LHWP, 1996) was performed by the Lesotho Highland Tunnel Partnership (LHTP). During the design process various design diameters for the tunnel between 2 and 5 m were considered. The selected design has the diameter of 4 m. The governing equation of flow through the Mohale-Katse connecting tunnel may be expressed as follows:

$$Q = K_q H^{½} \qquad [2]$$

Q = discharge through the Tunnel in $m^3 s^{-1}$;
H = head which is the difference between the water level in Katse and Mohale Dams, in m;
K_q = Tunnel discharge coefficient, the value of which varies between 5.047 to 4.16 during the design life of 1 to 56 years.

For the purpose of this yield analysis an average discharge coefficient of 4.5 was used. The head (H in Equation [2]) is computed by WATHNET for every period of simulation (month) based on the reservoir levels at Katse and Mohale Dams.

4.2.4 Matsoku Tunnel

The Matsoku River has its source near Khalong-la-Lithunya in the North Eastern Highlands of Lesotho. It flows south-eastwards towards the Malibamatso River, and turns southwards near Ha Seshote to join the Malibamatso River about 12 km south of the Katse Dam.

At the stream gauge G42 near Ha Seshote, the catchment area of the Matsoku River is about 680 km^2 with a MAR of about 86 MCM/yr. The Liseleng River flows into the Matsoku about 3 km upstream of G42 and contributes about 10% of the MAR at G42.

The Lesotho Highlands Water Feasibility Study (LMC/OSC, 1986a,b) proposed a weir on the Matsoku River about 800 m upstream of the streamflow gauge G42 to divert water through a tunnel into Katse Dam. It was established that the average annual increase in the yield of the Katse Dam that would result from this proposal would be between 50 - 65 MCM/yr - the larger figure being derived from a subsequent study by the Gibb-Sogreah Joint Venture (GSJV, 1988a).

The Feasibility Study proposed a weir with a full supply level of 2063 masl with a 6.4 km long tunnel to an outlet at the then proposed full supply level of Katse Dam at 2040 masl. Subsequent to the Feasibility Study, the optimisation studies (GSJV, 1988a,e) proposed that the Katse FSL be increased to 2053 masl.

During the Matsoku design studies (LHDA/MDP, 1996a and LHDA/MDP, 1996b), six potential sites for the weir, corresponding tunnel routes to seven outlet sites were considered. The potential weir sites were situated both upstream and downstream of the Liseleng tributary and thus had varying MARs and river bed elevations. The report concluded that the sites downstream of the Liseleng needed relatively high FSLs to allow transfer of water into Katse Dam and to prevent backwater flow when Katse Dam was at or above its FSL. Therefore, option 4C5 located at Site 4 was recommended, and Matsoku Weir is now under construction at that site. The catchment area for this site was computed by MDP to be 579.9 km^2. Option 4C5 includes a tunnel diameter of 3.88 m with weir FSL being at 2088 masl.

4.2.5 Mashai Dam

During the Feasibility Study (LMC/OSC, 1986a,b) it was found that Mashai Dam sites upstream and downstream of the confluence of the Mashai River with the Senqu River were feasible. Both an embankment and an arch dam were considered. During the GSJV Study (1989), an embankment dam was chosen to be constructed on the Senqu River at Mashai, about 21 km downstream of the confluence with the Malibamatso River, where a deeply incised meander has formed in the Senqu River.

The dam was designed to be approximately 170 m high with a FSL of 1887 masl. A MOL of 1835 masl was preliminary selected, giving a total active storage of 2433 MCM, while the dead storage below MOL would be about 1005 MCM.

The incremental catchment area to Mashai Dam, excluding the catchment areas of Katse Dam and Matsoku Diversion, is 5530 km^2 and the incremental MAR is 819.3 MCM per year.

4.2.6 Mashai to Katse Pumping Station

For the purpose of reoptimisation of the overall project (GSJV, 1988a), it has been assumed that the water from Mashai Dam will be transferred northwards by pumping into Katse Dam. The pumping system from Mashai Dam to Katse Dam will comprise an intake structure, a suction tunnel and an underground pumping station on the right bank of Mashai Dam with a nominal capacity of about 50 m^3 s^{-1}, and a pumping tunnel of 19 km long and 5.45 m in diameter. The average pumping head will be about 190 m.

4.2.7 Initial Storage Levels

In the yield analysis of reservoir systems for the purpose of planning studies, it is considered acceptable practice to assume the initial reservoir storage as full. There is, however, no universally accepted method of determining the most appropriate initial storage level for reservoir simulations. With the advent of stochastic reservoir simulation the importance of initial storage on system reliability could be minimised by simulating longer sequences of inflow data. In some cases the first few years of simulation can be ignored. However, in this particular case, as the system reliability is assessed using the historical data it was deemed necessary to determine an initial storage that would not have an effect on the long-term behaviour of reservoir system.

During the Mohale Development Project Study (MCG, 1996) a detailed analysis was carried out to establish the appropriate initial storage by plotting the behaviour of the combined storage for Katse and Mohale Dams for the 1930-1995 period. Results indicated that the storage was in the range of 60-70% for half of the time. It was therefore decided to adopt a conservative initial storage of 60% of the Active Storage Volume (ASV).

4.3 THE “DESIGN LIMITATION” CRITERIA

The limitations imposed on possible IFRs by the design of Katse and Mohale Dams, and Matsoku Diversion, outlet capacities were based on the design information provided by LHDA for those facilities. In addition, to ensure that the dams are not excessively drained resulting in redundancy of structures, the releases from the dams to meet the IFRs were not allowed to exceed 30-40% of MAR.

4.3.1 Katse Dam Outlets

Construction of Katse Dam is complete.

The Katse Dam intake on the dam wall is at 1935 masl (119 m below full supply level). Varying the size of an opening in a sleeve valve can regulate releases. Maximum release capacity (valve 100% open) depends on the height of water in the reservoir, and ranges from 1.2 $m^3 s^{-1}$ when the water surface is at 1990 masl (MOL) to 1.9 $m^3 s^{-1}$ at 2060 masl (FSL).

There is an emergency low-level outlet, which was designed for emergency drawdown of the reservoir. Maximum release through the emergency outlet at FSL ranges from 150 to 400 $m^3 s^{-1}$, depending on the extent to which the release gates are opened. At MOL, the discharge ranges from 100 to 260 $m^3 s^{-1}$. The intake for the emergency outlet is at 1900 masl near the bottom of the reservoir. It is possible that anoxic water is released from the bottom of the reservoir but some re-oxygenation will occur during high-pressure releases. Low-level releases are made each month for testing and maintenance purposes (each release lasts a few minutes).

4.3.2 Mohale Dam Outlets

Outflows from Mohale Dam was based on an updated design, which is understood to be 2.5 $m^3 s^{-1}$ when the reservoir is at MOL and 4.25 $m^3 s^{-1}$ at FSL. There is also a low-level outlet that could be used for releasing floods. The Consultant has been advised by LHDA that the present design capacity of the low-level outlet is 47 $m^3 s^{-1}$ at MOL and 57 $m^3 s^{-1}$ at FSL.

4.3.3 Matsoku Diversion Release Capacity

Outflows from Matsoku were geared for the best seasonal distribution of low-flow releases, together with short-duration flushes, taking into consideration the following design parameters:

- Downstream releases will be made through a 600-mm diaphragm valve in the weir outlet block at 2078 masl. The valve can be set to allow a constant release independent of the upstream reservoir water level. The maximum discharge will be 0.65 $m^3 s^{-1}$. The design permits downstream releases to take precedence over tunnel diversions.
- The 18-m weir will be provided with a gated structure located at the downstream end of the forebay, which will release water from bed level. It will be equipped with a buoyancy tank, which will cause the gate to open automatically when the tunnel intake is submerged and the reservoir level is approaching FSL. Under normal operation all flows up to 47 $m^3 s^{-1}$ (less the environmental releases) will divert through the tunnel to Katse Dam, whilst flows higher than 47 $m^3 s^{-1}$ will pass through the scour gate and/or over the spillway. The frequency and magnitude of spills will depend on the sequence of inflows, the capacity of the reservoir, and the way in which the isolating gate in the tunnel inlet is operated. The reservoir will have a small volume and released water quality is expected to be similar to that of the upper Matsoku River.

It is noted here that it will be possible to release any proportion of the inflow from the weir if the outlet tunnel gates from Matsoku Weir to Katse Dam are kept closed.

4.3.4 Mashai Dam Outlets

No design limitations were applied to Mashai Dam as the design has not been finalised. However, to assess the IFR releases with Mashai Dam in place (Phase 2) and based on the design outlet capacity of the Katse and Mohale Dams, the IFR release were limited to a maximum of 36% of the Mashai Dam MAR.

5 IMPACT OF IFR ON THE SYSTEM YIELD

5.1 SYSTEM CONFIGURATION

The following system configurations were investigated in order to determine the impacts of various release scenarios on system yield. For any one scenario, the following configurations were used:

- Configuration I: Existing System (Katse Dam) + IFR,
- Configuration II: Existing System + Matsoku Diversion + Mohale Dam + IFR,
- Configuration III: Existing System + Matsoku Diversion + Mohale Dam + Mashai Dam + IFR.

Brief description of the system configuration follows:

Configuration I:

Present System (Katse Dam) + IFR. Configuration I evaluated the impact of supplying the IFRs on the present system yield. The present system comprises the Katse Dam on the Malibamatso River, and an off-take for water supply to RSA.

Configuration II:

Present System + Matsoku Diversion + Mohale Dam + IFR. This configuration is the Configuration I plus Matsoku run-of-the-river diversion to Katse Dam and the Mohale Dam on the Senqunyane River, which will divert the flows by gravity to Katse Dam.

Configuration III:

Present System + Matsoku diversion + Mohale Dam + Mashai + IFR. This configuration is II, plus Mashai Dam, which will pump the water to Katse Dam.

5.2 CONFIGURATION I - YIELD OF KATSE DAM

The impact of supplying the IFRs on the yield of Katse Dam was assessed by using the input data described in Sections 4.1 and 4.2. A brief description of how the input data were incorporated in the WATHNET model is provided below.

5.2.1 Model Input Data

The inputs required by WATHNET are either provided in input files in ASCII format or interactively input through various menus of the model. The following data were provide through input files:

- monthly inflow sequence to Katse Dam;
- monthly net evaporation from reservoir surface;
- IFR from Katse Dam at IFR Sites 2 and 3 for Treaty, Minimum Degradation, Design Limitation and Fourth scenarios;
- expected system yield, which is the quantity of water that could be exported to RSA.

The following information was provided through WATHNET input menus:

- Katse Dam initial storage conditions;
- equation describing Katse Dam volume versus reservoir area;
- Katse Dam active reservoir storage;
- priority in meeting system demand;
- Katse Dam monthly target storages;
- reservoir failure criterion.

With the exception of the last three, the input data are described in Section 4.2. The last three items may be classified as reservoir operating rules and are described below.

5.2.2 Operation Rules

Two categories of system operating rules were used for the simulation of Katse Dam as follows:

a. Priority in Meeting Demands

The model has the capability to assign demands based on the user-input priorities. In this particular case there are two types of system demands namely: the Katse IFR, and the system yield (demand). Meeting the Katse IFR was given priority over system yield. This means during drought periods IFR will be met before any other delivery is made from Katse Dam. In building the model structure, the IFR was treated as demand and assigned a higher priority than yield. This overcame the inherent assumption in WATHNET that demands on the dam should have priority over IFR releases.

b. Reservoir End-of-Month-Target Volumes

Reservoir end-of-month-target volumes are basically reservoir rule curves. WATHNET is designed in such a way that once a target storage is specified the model will try to meet it. In other words there are penalty-cost functions for deviating from target storage. The more the deviation, the higher the penalty. In the hierarchy of priorities used for this yield analysis, meeting reservoir target volumes was ranked third after satisfying the IFRs (first) and other demands on the dam (second). The end-of-month-target volumes for Katse Dam were specified as the FSL.

c. Reservoir Failure Criterion

In simulation of reservoir systems using WATHNET, any time the reservoir levels drop below MOL the system is deemed to have failed. In the actual analysis only the active storage of Katse Dam was used to meet both system yield and IFRs.

5.2.3 Results of Historical Simulation

Operation of Katse Dam was simulated for yields ranging from 10-17 $m^3\ s^{-1}$ using the input data presented in Sections 4.1 and 4.2. The reliability of the system was evaluated by using the results of simulation. Two types of system failures were encountered; the recoverable and unrecoverable. A recoverable failure is a failure that can be compensated for during the remaining months of the calendar year. These types of failures were not counted as per the interpretation of reliability as stated in Section 4.3.1. Unrecoverable failures could not be recovered during the calendar year. For example if a failure resulting in a deficit of 3 m^3s^{-1} occurs in the month of October and this deficit is met in November this failure is deemed as recoverable. If the deficit cannot be met either in the following November or December of the same year it is deemed as unrecoverable. These were counted as effective failures and used in the computation of annual reliability.

Table 5.1 indicates that the yield of Katse Dam would range between 10.6 $m^3\ s^{-1}$ and 16.5 $m^3\ s^{-1}$ at the required reliability, for the four IFR scenario releases. As an example the simulated reservoir levels of Katse Dam for the period 1930-1994 for the Scenario 4 are given in Appendix 2, Figure A2.1 and Table A2.1.

Table 5.1 Configuration I: Summary of yield analysis results - Katse Dam.

	System Yield ($m^3\ s^{-1}$)
Treaty	16.5
Fourth	15.3
Design Limitation	13.7
Minimum Degradation	10.6

5.3 CONFIGURATION II – COMBINED YIELD OF KATSE AND MOHALE DAMS AND MATSOKU DIVERSION WEIR

Having assessed the yield of Katse Dam as described in Section 5.2, Mohale Dam and Matsoku Diversion were included in the reservoir system. The yield was then assessed by repeating the simulation procedure described in Section 5.2.

The yield analysis was performed using the input data described in Sections 4.1 and 4.2. The following is a brief description of how the input data were incorporated in the WATHNET model.

5.3.1 Model Input Data

The following data were provide through input files:

- monthly inflow sequence to Katse Dam;
- monthly inflow sequence to Mohale Dam;
- monthly inflow sequence to Matsoku Diversion;
- monthly net evaporation from reservoir surfaces (Katse and Mohale Dams);
- IFR from Katse Dam for IFR Sites 2 and 3 for Treaty, Minimum Degradation, Design Limitation and Fourth scenarios;
- IFR from Mohale Dam for IFR Sites 7 and 8 Treaty, Minimum Degradation, Design Limitation and Fourth scenarios;
- IFR from Matsoku Diversion for IFR Site 1 for Treaty, Minimum Degradation, Design Limitation and Fourth scenarios;
- expected yield of the combined system, which is the quantity of water that could be exported to RSA.

The following information was provided through WATHNET input menus:

- reservoir initial storage conditions for Mohale and Katse Dams;

- equation describing reservoir volume versus reservoir area for both reservoirs (Katse and Mohale Dams);
- equation describing flow through Mohale Tunnel based on storage at Katse and Mohale Dams;
- active reservoir storage at Katse and Mohale Dams;
- priority of meeting system demand;
- reservoir monthly target storages for Katse and Mohale Dams;
- priority of reservoir filling;
- reservoir failure criterion.

With the exception of the last four items the remaining input data are described in Section 4.1 and 4.2. The last four items may be classified as reservoir operating rules and are described below.

5.3.2 Operation Rules

Three categories of system-operating rules were used for simulation of the Mohale-Katse-Matsoku system. These are:

a. Priority of Meeting Demands

Two priority levels were assigned in meeting system demands. Meeting the IFR requirements at Katse and Mohale Dam and Matsoku Weir was given the first priority, while system yield (demand) was given the second priority. This means during drought periods the IFRs would be met before any delivery is made from Katse Dam to RSA.

b. Reservoir End-of-Month-Target Volumes

The target end-of-month-target volumes for Katse and Mohale Dams were specified as full. This means after meeting demands and the IFRs, the model will attempt to keep the reservoirs full while minimising spills.

c. Priority of Reservoir Filling

Both Mohale and Katse Dams were assigned priority 1 which means reservoirs will be filled based on hydrological inflows. This is because the transfer between Katse and Mohale will be based on prevailing hydraulic conditions, which requires a certain head to be maintained. This is ensured through lowering and raising water levels at both reservoirs simultaneously.

d. Reservoir Failure Criterion

In simulations of the reservoir system using WATHNET the active storage volume was used as available storage. Therefore, any time the reservoir storage of the combined Katse and Mohale Dams dropped below MOL, the system was deemed to have failed.

5.3.3 Historical Simulation Results

The summary of the results for Configuration II are given in Table 5.2 and Figure 5.1 shows the storage levels of combined system for Scenario 4.

Table 5.2 Configuration II - Summary of yield analysis results – Phase 1 Dams (Katse and Mohale Dams and Matsoku Weir)

Scenario	System Yield ($m^3 s^{-1}$)
Treaty	27.3
Fourth	25.2
Design Limitation	22.8
Minimum Degradation	18.3

The yield of the Katse-Mohale-Matsoku combined system for the required reliability ranges between 18.3 $m^3 s^{-1}$ and 27.3 $m^3 s^{-1}$. As an example the simulated reservoir levels of the combined system for the period 1930-1994 for Scenario 4 are given in Appendix 3, Figure A3.1 and Table A3.1.

5.4 CONFIGURATION III – COMBINED YIELD OF KATSE, MOHALE AND MASHAI DAMS, AND MATSOKU DIVERSION WEIR

Having assessed the combined yield of Katse and Mohale Dams, and Matsoku Weir as described in Section 5.3, Mashai Dam was included in the reservoir system. The yield was then assessed by repeating the simulation procedure described in Section 5.3.

The following is a brief description of how the input data was incorporated in the WATHNET model for this configuration.

5.4.1 Model Input Data

The input data for the reservoir system including Katse Dam, Mohale Dam, Matsoku Diversion, Mohale Tunnel, Mashai Dam and Mashai Pumping Station are provided below.

The following data were provide through input files:

- monthly inflow sequence to Katse, Mohale and Mashai Dams;
- monthly inflow sequence to Matsoku Diversion;
- monthly net evaporation from reservoir surfaces (Katse, Mohale and Mashai Dams);
- IFR from Katse Dam for IFR Sites 2 and 3 for Treaty, Minimum Degradation, Design Limitation and Fourth scenarios;
- IFR from Mohale Dam for IFR Sites 7 and 8 for Treaty, Minimum Degradation, Design Limitation and Fourth scenarios;
- IFR from Matsoku Diversion for IFR Site 1 for Treaty, Minimum Degradation, Design Limitation and Fourth scenarios;
- IFR from Mashai Dam for IFR Sites 4, and 5 for Treaty, Minimum Degradation, Design Limitation and Fourth scenarios;
- expected yield of the combined system which is the quantity of water that could be exported to RSA.

The following information was provided through the WATHNET input menus:

- reservoir initial storage conditions for Katse, Mohale, and Mashai Dams;
- equation describing reservoir volume versus reservoir area for all reservoirs;
- equation describing flow through Mohale Tunnel based on storage at Katse and Mohale Dams;
- active reservoir storage at Katse, Mohale and Mashai Dams;
- Mashai pumping station capacity (50 $m^3 s^{-1}$);
- priority of meeting system demand;
- reservoir monthly target storages for Katse, Mohale and Mashai Dams;
- priority of reservoir filling;
- reservoir failure criterion.

With the exception of the last four items the remaining input data are described in Section 4.1 and 4.2. The last four items may be classified as reservoir operating rules and are described below.

5.4.2 Operation Rules

Three categories of system operating rules were used for simulation of the Mohale-Katse-Matsoku-Mashai system. These are:

a. Priority of Meeting Demands

Two priority levels were assigned in meeting system demands. Meeting the IFRs was given the first priority, while system yield (demand) was given second priority. This means during drought periods the IFRs will be met before any delivery is made from Katse Dam to RSA.

b. Reservoir end of Month Target Volumes

The end-of-month-target volumes for Katse, Mohale and Mashai Dams were specified as full. This means after meeting demands and IFRs the model will attempt to keep the reservoirs full while minimising spills.

c. Priority of Reservoir Filling

Katse, Mohale and Mashai Dams were assigned priority 1, which means reservoirs will be filled based on hydrological inflows. The transfers between Katse and Mohale and between Katse and Mashai were based on prevailing hydraulic conditions, which requires a certain head to be maintained. This is ensured through lowering and raising water levels at all reservoirs simultaneously.

d. Reservoir Failure Criterion

In simulations of the reservoir system, the active storage volume was used as available storage. Therefore, if at any time the reservoir storage of the combined Katse, Mohale and Mashai Dams dropped below MOL, the system was deemed to have failed.

5.4.3 Results of Historical Simulation

Table 5.3 shows the results of the analysis for Configuration III. This table indicates that the combined system yield at the required reliability for the four IFR release scenarios ranges from 38 $m^3 s^{-1}$ to 50.8 $m^3 s^{-1}$.

Table 5.3 Summary of yield analysis results – Phase 1 & 2 Dams (Katse, Mohale and Mashai Dams, and Matsoku Weir).

Scenario	System Yield ($m^3 s^{-1}$)
Treaty	50.8
Fourth	47.8
Design Limitation	43.6
Minimum Degradation	38.0

As an example, the storage behaviour for the combined Katse-Mohale-Matsoku-Mashai system for the Fourth Scenario is given in Figure 5.2 and the summary outputs of the simulation are given in Appendix 4, Figure A4.1 and Table A4.1.

5.5 EFFECTS OF IFR SCENARIOS ON SYSTEM YIELD

To assess the effect of the change in yield as a function of the IFR scenarios, the yield of the combined system for Phase 1 and Phase 2 dams was assessed. Figures 5.3 and 5.4 shows the effect of each of the IFR scenarios on the combined yield for Phase 1 and 2, respectively. These figures clearly indicate the reductions in system yield as a consequence of each of the four IFR release scenarios. For instance, for the Treaty Scenario the yield of the system is 50.8 $m^3 s^{-1}$ since the volume of water required for the IFR is very low. For the Minimum Degradation Scenario, on the other hand, the yield is 38 $m^3 s^{-1}$ since the volume of water required for the IFR is high compared to that required for the Treaty Scenario.

5.6 RELEASES FROM LHWP DAMS FOR FOUR SCENARIOS

Average annual releases corresponding to system yield was calculated for all the LHWP dams and for the four scenarios. These values are summarised in Table 5. 4.

Table 5.4 Summary of average annual releases he LHWPs dams for four scenarios.

Discharge and Yield in m^3s -1					
	Total System Yield	Katse	Mohale	Matsoku	Mashai
Phase 1					
Treaty	27.3	0.50	0.30	0.05	
Fourth	25.2	1.71	0.83	0.66	
Design Limitation	22.8	3.39	1.55	0.72	
Minimum Degradation	18.3	6.40	2.99	0.96	
Phase 2					
Treaty	50.8	0.50	0.30	0.05	1.50
Fourth	47.8	1.71	0.83	0.66	3.78
Design Limitation	43.6	3.39	1.55	0.72	7.43
Minimum Degradation	38.0	6.40	2.99	0.96	11.57

6 SUMMARY

- The purpose of the yield analysis in LHDA 648 was to assess the effects of each of four IFR release scenarios on Phase 1 and 2 dams, using an annual reliability of 98%.

- The hydrological data used for the simulation of the system was from the Joint Study of Lesotho Highlands Hydrology (LHDA/DWAF, 1996) for the period 1930-1994.

- The input parameters for the system modeling for the LHWP Phase 1 and 2 were extracted from previous studies under the approval of LHDA.

- The annual reliability of the system was determined by counting the number of non-recoverable failures during the simulation period.

- A combined system yield of 27.3 $m^3 s^{-1}$ and 50.8 $m^3 s^{-1}$ was achieved for the historical simulation of the Phase 1 and 2 dams, respectively, for the Treaty releases scenario. Table 6.1 summarises the effects of IFR releases on the combined system yield for each of the four scenarios.

Table 6.1 System yield associated with each of the four IFR scenarios.

IFR Scenario	Phase 1	Phase 1 and 2
	System Yield $m^3 s^{-1}$	System Yield $m^3 s^{-1}$
Treaty	27.3	50.8
Fourth	25.2	47.8
Design Limitation	22.8	43.6
Minimum Degradation	18.3	38.0

- The system yield is sensitive to releases from Katse, Mohale and Mashai Dams and Matsoku Weir to meet IFR requirements at the IFR sites situated immediately downstream of the dams
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