LESOTHO LOWLAND WATER SUPPLY SCHEME FEASIBILITY STUDY

WATER RESOURCES ASSESSMENT OF FINAL DEVELOPMENT OPTIONS

May 2004

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This report is to be referred in bibliographies as :

Lesotho Lowlands Water Supply Scheme Feasibility Study (2004). Water resources assessment of final development options. Prepared by WRP Consulting Engineers.

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TABLE OF CONTENTS

1. INTRODUCTION

1.1. BACKGROUND TO THE STUDY 2.1

1.2. APPROACH TO THE STUDY 2.1

1.3. LAYOUT OF THE REPORT 2.2

2. RAINFALL

2.1. OVERVIEW 2.1

2.2. PRELIMINARY SCREENING 2.1

2.3. PATCHING 2.2

2.4. FINAL SELECTION OF RAINFALL GAUGES 2.2

3. STREAMFLOW

3.1. OVERVIEW 3.1

3.2. SCREENING AND EVALUATION 3.1

3.3. PRELIMINARY CALIBRATION AND PATCHING OF RECORDS 3.3

3.4. STREAMFLOW CALIBRATION 3.3

3.5. STREAMFLOW SIMULATION 3.5

3.6. STOCHASTIC STREAMFLOWS 3.8

4. ANALYSIS PROCEDURE

4.1. OVERVIEW OF THE MODEL 4.1

4.2. DESCRIPTION OF PENALTY TYPES 4.2

5. WATER RESOURCES ANALYSES

5.1. OVERVIEW 5.1

5.2. HOLOLO/NGOAJANE SYSTEM 5.3

5.3. HLOTSE SYSTEM 5.6

5.4. MAKHALENG SYSTEM 5.8

6. REFERENCES 6.1

1. INTRODUCTION

1.1. BACKGROUND TO THE STUDY

Numerous hydrological studies have been undertaken in Lesotho, most of which have focused on the Lesotho Highlands Transfer Scheme. However, there are many areas within Lesotho that suffer from water shortages, particularly in the Lowlands area. The Lesotho Lowlands Water Supply Scheme Feasibility Study was commissioned to investigate potential water resource developments to ensure the long-term sustainable water supply to the Lowlands area. The location of the Study Area is shown in **Figure A.1** in **Annexure A**. Parkman Ltd (UK) was appointed to undertake the assignment and WRP Consulting Engineers (SA) was contracted by Parkman Ltd (UK) to undertake the hydrology and water resources assessments.

1.2. APPROACH TO THE STUDY

The overall objective of the project was to determine the most viable and sustainable water supply schemes for the Lesotho Lowlands. This entailed a phased approach to the investigations. The first phase of the study was a broad desktop assessment of all identified schemes. **Table 1.1** provides a list of the schemes assessed and the locations of the catchments are shown in **Figure A.2** in **Annexure A**. The hydrological data published in the WR90 document was used as the basis to assess these various options. WR90 classified the region into hydrological zones for which generic draft-storage relationships have been determined, which were applied to the various dam sites listed in **Table 1.1**. The assessment of the abstraction potential from run-of-river abstraction works was also undertaken using WR90. Regionalised deficient-flow-duration-frequency relationships were used to provide an indication of the cumulative inflow expressed as a percentage of the MAR for various durations. The WR90 analyses are reported on in detail in the Intermediate Report.

Table 1.1 : Schemes identified in Phase 1.

Site name	Infrastructure type	River
Upper Ngoajane Weir	Diversion weir with no upstream storage	Ngoajane
Middle Ngoajane Dam	Dam	Ngoajane
Lower Ngoajane Dam	Dam	Ngoajane
Lower Ngoajane Abstraction	Run-of-river abstraction supported by Lower Ngoajane Dam	Ngoajane / Hololo
Upper Hlotse Dam	Dam	Hlotse
Lower Hlotse Dam	Dam	Hlotse
Lower Hlotse Abstraction A(1)	Run-of-river abstraction supported by Upper Hlotse Dam	Hlotse
Mamafubelu	Dam	Mamafubelu
Mamafubelu Abstraction B(1)	Run-of-river abstraction supported by Mamafubelu Dam	Hlotse
Mapoteng	Dam	Northern Phutiatsana
Metalong	Dam	Southern Phutiatsana
Likhutlong Dam (Upper Makhaleng)	Dam	Makhaleng
Matsapong Dam (Middle Makhaleng)	Dam	Makhaleng

• Site name	• Infrastructure type	• River
• Lower Makhaleng Dam	• Dam	• Makhaleng
• Upper Makhaleng off bank storage	• Off-bank storage dam	• Makhalaneng
• Lower Makhaleng off bank storage	• Off-bank storage dam	• Mamaebana
• Lower Makhaleng abstraction point(2)	• Run-of-river abstraction with no upstream storage	• Makhaleng
• Ha Mahooana	• Dam	• Quoquaane
• Ha Khoeli	• Dam	• Korokoro

Note (1) : Same abstraction points, but supported by different upstream storages (i.e. two different schemes).

Note (2) : 2 possible locations of Lower Makhaleng abstraction point have been provided.

Three schemes were selected for detailed analysis after completion of the intermediate phase of the study, these being :

- A run-of-river abstraction directly from the Hololo River downstream of the confluence with the Ngoajane River, possibly supported with releases from a new Ngoajane Dam or from the existing Muela Dam;
- A run-of-river abstraction directly from the Hlotse River downstream of the confluence with the Mamafubelu River possibly being supported with releases from the proposed Hlotse Dam; and
- A run-of-river abstraction directly from the Makhaleng River at the Mohales Hoek road bridge possibly being supported with releases from the Matsapong Dam.

The locations of these various catchments are shown in **Figure A.3** in **Annexure A**. A more detailed hydrological and water resource analysis was undertaken for these three options, the approach to which was as follows :

- Acquire and compile all available hydrological data (mainly streamflow, rainfall and evaporation) in a database;
- Evaluate the hydrological database and select data for use in the hydrological analyses;
- Calibrate the WRSM2000 streamflow generation model using appropriate catchment rainfall and observed streamflow records;
- Generate synthetic streamflow sequences for development nodes within the identified schemes;
- Compile water resource networks of the identified schemes for the Water Resources Yield Model (WRYM); and
- Undertake stochastic yield analysis of the identified schemes in the WRYM to determine the supply capabilities at the specified level of assurance (1 in 50 years).

1.3. LAYOUT OF THE REPORT

Chapter 2 of the report provides a summary of the acquisition and assessment of the rainfall data used in this assignment while Chapter 3 provides a similar summary for the streamflow data. This is followed by a presentation of the methodology utilised to determine the yields of the various systems. Chapter 5 describes the three systems analysed and presents the results of the analyses. The study references are presented in Chapter 6.

2. RAINFALL

2.1. OVERVIEW

Rainfall data for the study area were acquired from the Ministry of Natural Resources (Department of Metrology) as well as the South African Weather Bureau. There is a significant coverage of rainfall gauges, particularly around the border areas (as is shown in **Figure A.4** in **Annexure A**), however, there is a scarcity of rainfall data in the interior of Lesotho. In particular, the lack of rain gauges in the higher lying areas of the Study Area may lead to an under-estimation of catchment rainfall.

Rainfall data were required for two purposes in this assignment, namely for the simulation of catchment runoff using the WRSM 2000 model and for the simulation of rainfall on the surface of impoundments using the WRYM model. The process of producing such rainfall data was as follows :

1. Preliminary screening and evaluation of rainfall data;
2. Grouping and patching of rain gauges;
3. Final screening and evaluation of rainfall data; and
4. Creation of catchment rainfall files.

The following sections discuss each of these steps in more detail.

2.2. PRELIMINARY SCREENING

A preliminary evaluation of the rainfall data was undertaken and this screening exercise indicated that much of the rainfall data are poor and not fit for use in a hydrological study such as this. Inspection of these data revealed that many of the rainfall records were neither long enough nor reliable enough to simulate streamflow. In addition, the locations of many of the rain gauges are too remote to be representative of the rainfall at the various points of interest in the Study Area. A total of 57 rain gauges were selected for use in the subsequent patching exercise, and 15 rain gauges were used for the streamflow generation.

Listings of the raw observed rainfall records of those gauges finally selected for streamflow simulation purposes are provided in **Annexure B**. Part of the screening exercise was to generate cumulative mass plots of the annual rainfall totals to check for stationarity of the data. The mass plots of the final selected gauges are provided in **Annexure C**.

2.3. PATCHING

The rainfall records selected after preliminary screening were patched and extended to create complete monthly data sets from 1935 to 1999. Ideally, a longer record would have been preferable, however, only a few of the observed records extended back to 1920 and patching with such a dearth of data would have created unreliable results. In addition, the last two years of the records had to be discarded since the streamflow simulation model (WRSM2000) does not accept data after 1999 in the current format. Rather than reformat the entire rainfall database, it was decided to utilise the slightly shorter records. This still provides 65 years of records, which is deemed acceptable for stochastic streamflow modelling.

Table 2.1 presents the various groups of rain gauges that were used for the patching process. The gauges indicated in bold are those that were eventually selected for use in this assignment. Those rainfall records that were used for patching but that were not used in the assignment are fit for use but were considered to be too remote to be representative of the rainfall on the three catchments considered. Listings of the patched rainfall records of those gauges used for streamflow generation are provided in **Annexure D**.

Table 2.1 : Grouping of rain gauges used for patching purposes.

Group 1	Group 2	Group 3	Group 4	Group 5	Group 6	Group 7
297-337	***298-244***	***265-875***	265-039	263-888	235-110	204-392
297-401	298-301	***266-001***	***297-082***	264-022	235-183	204-486
297-436	298-481	266-370	***297-388***	264-039	235-243	204-515
297-519	298-512	266-437		264-042	***264-715***	204-518
297-544	298-545	266-931		264-110	***264-836***	204-640
297-612	298-638	266-646		264-235		204-819
297-721	298-791	267-126		264-291		***233-775***
297-825	298-818	267-107		***264-417***		***234-150***
298-031	298-871			264-459		***234-170***
298-194	299-008			264-473		
298-481	332-834			264-735		

Note : Gauges in bold italics were those selected for streamflow generation.

2.4. FINAL SELECTION OF RAINFALL GAUGES

The patched rainfall records for those gauges considered fit for use were then selected according to their geographical location relative to the catchments and their length of record. **Table 2.2** provides a list of the rain gauges that were eventually selected for the purposes of simulating catchment runoff. The rainfall records were combined to generate the aerial rainfall over the three catchments of interest using the HDYP08 model. Listings of the catchment rainfall files are provided in **Annexure E**.

Table 2.2 : Details of rain gauges used in this assignment.

Gauge number	Gauge name	Start date	End date	Length of record (years)	Elevation (m.a.s.l.)	Latitude (S)	Longitude (E)
Ngoajane/Hololo Catchment :							
297436	Butha-Buthe	1930	2002	72	1768	28º 46'	28º 15'
297612	Hololo	1964	2002	58	1640	28º 43'	28º 21'
297825	St Peters	1964	2002	58	1860	28º 45'	28º 28'
298194	Ox Bow	1957	2002	45	2591	28º 43'	28º 37'
298244	Caledonia	1921	1982	61	1951	28º 34'	28º 39'
Hlotse Catchment :							
265875	Pelaneng	1932	1979	47	2040	29º 05'	28º 30'
266001	Rampai	1970	1995	25	2901	29º 01'	28º 30'
297082	Leribe	1930	2002	72	1666	28º 53'	28º 03'
297388	Pitseng	1937	2002	65	1780	28º 57'	28º 13'
Makhaleng Catchment :							
233775	Thabana Morena	1936	2002	66	1676	29º 57'	27º 25'
234150	Mpharane/Mt Carmel	1925	2002	77	1752	30º00'	27º 35'
234170	Malealea	1954	2002	48	1966	29º 51'	27º 34'
264417	Roma	1935	2001	66	1646	29º 27'	27º 44'
264715	Molimo Nthuse	1962	2002	40	2040	29º 25'	27º 54'
264836	Thaba Putsoa	1962	2002	40	2600	29º 26'	27º 58'

3. STREAMFLOW

3.1. OVERVIEW

Streamflow data for this assignment were acquired from the Ministry of Natural Resources (Department of Water Affairs). The hydrometric network in Lesotho seems to be fairly extensive with there being 45 streamflow gauging stations as is shown in **Figure A.5** in **Annexure A**. However, it was found that there are significant shortcomings in the streamflow gauging, data capture and archiving. These problems are expanded on in the following sections.

Streamflow records were required at the locations of the proposed dams and abstraction points in order to determine the quantity of water that may be available for use on a sustainable basis (the scope of work required an assurance of supply of not less than a 1:50 year reliability). The observed streamflow records were calibrated using the WRSM 2000 model and sequences were then simulated at the requisite locations using the same model. The system yields were determined using the WRYM model. The process of producing the requisite streamflow sequences was as follows :

1. Screening and evaluation of streamflow data for fitness of use;
2. Preliminary calibration and patching of streamflow records;
3. Final calibration of the observed records; and
4. Simulation of streamflow sequences at the proposed development sites.

The following sections discuss each of these steps in more detail.

3.2. SCREENING AND EVALUATION

The first step in determining whether a streamflow gauge would be fit for use in the water resources assessment was to undertake a preliminary screening of the available data. This was undertaken on a manual basis in association with staff from the Department of Water Affairs (Khaba, 2003) and the details of the screening and evaluation of the gauges is provided in **Annexure F**. The first group of problems that arose pertained to the quality and existence of flow data, with typical problems being :

1. Rating curves have not been determined so water levels cannot be converted into flows;
2. Records of water levels are available on charts but have not been digitised;
3. Intermittent gauge plate readings by an observer are only available; and
4. Stations have been closed and little or no data are available during their operational period.

The records exhibiting one or some of the above problems were discarded from further use in the study.

The second step in selecting streamflow data for use in the study was to choose those records that were of a reasonable length. Short streamflow records are of little value since they do not provide an indication of the long term variability of the water resources and therefore may not be representative of conditions over time. All digital records less than 10 years (the minimum period considered adequate for water resources assessments) were discarded from further evaluation.

Streamflow data from gauges that are distant to the Study Area are also of little use since they will not be representative of the local hydrological conditions. To this end, the final selection of streamflow gauges was undertaken based on the relative location of the gauging stations to the Study Area. A summary of the classification of the streamflow data for fitness of use is provided in **Table 3.1**.

Table 3.1 : Classification of streamflow gauges according to fitness for use in the study.

Classification of streamflow gauge data	Number
Gauges considered to have poor or no flow data	24
Gauges considered to be too far from the Study Area	15
Gauges with data considered to be fit for use	6
Total number of gauging stations	**45**

The details of those streamflow gauges that were finally selected for use in the assignment are provided in **Table 3.2** and the locations are shown in **Annexure A.5**. The listings of the observed records at these gauges are provided in **Annexure G**. It is normal to naturalise streamflow records before patching and calibration. Naturalisation involves adding back to the observed streamflow record any abstractions or runoff reductions that occurred historically upstream of the point of observation. There is little development upstream of most of the gauges considered in this assignment so it was assumed that the observed record is the naturalised record. The only important development is Muela Dam, the balancing and power generation storage facility of the Lesotho Highlands Water Scheme, that is located in the catchment of Gauge CG26. This dam was commissioned in 1996 so it only affects the last three years of the observed record at the gauge, and it was assumed that the record prior to 1996 represented natural conditions.

Table 3.2 : Details of the final selected streamflow gauges.

Gauge number	River	Location	Latitude	Longitude
Ngoajane/Hololo catchment area :				
CG 26	Hololo	Khukhune	28°44'01"	28°24'08"
CG 55	Ngoajane	St Charles	28°41'05"	28°24'04"
Hlotse catchment area :				
CG 50	Maoa-mafubelu	Pontmain	28°57'00"	28°14'00"
CG 25	Hlotse	Ha Setene	28°54'07"	28°06'05"
Makhaleng catchment area :				
MG 19	Makhaleng	Molimo-Nthuse	29°25'00"	27°53'00"
MG 23	Makhaleng	Qaba	29°52'00"	27°37'00"

Table 3.2 : (Cont.)

Gauge number	Start date	End date	Quaternary	Catchment area (km2)
Ngoajane/Hololo catchment area :				
CG 26	1965	1999	D21B	212
CG 55	1980	1999	D21A	149
Hlotse catchment area :				
CG 50	1979	1999	D21K	294
CG 25	1965	1999	D21J	728
Makhaleng catchment area :				
MG 19	1964	1999	D15A	95
MG 23	1982	1999	D15A, B, C, D	1554

3.3. PRELIMINARY CALIBRATION AND PATCHING OF RECORDS

It is noted in the listings of the observed streamflow records in **Annexure G** that there are months where data have been flagged as either missing or suspect (data are identified with a "+" or "*" respectively). This process was done through manual inspection of the data. Furthermore, significant numbers of data were found to have been derived from daily observations rather than from continuously logged or charted water level records (demarcated with a "#"). In the latter case, there are no better data available so the records were scanned manually for obvious errors and were accepted as adequate for the purposes of the assignment. On the other hand, the missing and suspect data had to be patched to ensure that an adequate calibration of the final record could be obtained.

The patching process utilised the WRSM2000 model to infill the missing and suspect data in the observed records. The model was run initially using the regional parameters as given in the Surface Water Resources of South Africa (1990) documentation, commonly referred to as WR90. The missing and suspect data were then infilled with the simulated values output from the WRSM2000 model. The parameters were then adjusted to obtain better calibration results and the flagged data infilled again. This process was undertaken several times until there was no significant change in the infilled and simulated values. Listings of the patched records are provided in **Annexure H**, which were used for the final streamflow calibration.

It should be noted that errors will have become entrenched in the streamflow records through both accepting the manual observations as adequate and patching as part of the calibration process. However, this was the best available information for the assignment.

3.4. STREAMFLOW CALIBRATION

The WRSM2000 model was used to calibrate the patched streamflow records. The model is driven by a single rainfall file where the rainfall is represented as a percentage of the mean annual precipitation. The preparation of these catchment rainfall files is discussed in **Section 2.4** and listings are provided in **Annexure E**. The Mean Annual Precipitation (MAP) of each of the gauged catchments is required to determine the monthly rainfall depths from the rainfall file. The estimates of MAP for the gauged catchments were assumed to be the same as the MAP for the quaternary catchment within which the gauge falls. The quaternary MAPs were obtained from the WR90 documentation, the details of which are provided in **Table 3.3**.

Table 3.3 : Hydrological parameters for the gauged catchments.

Gauge	CG 26	CG 55	CG 25	CG 50	MG 19	MG 23
Quaternary	D21B	D21A	D21K	D21J	D15A	D15A, B, C, D
Area (km2)	212	149	728	294	95	1554
MAP (mm)	1021	978	991	960	974	935
MAE (mm)	1275	1275	1300	1300	1450	1450

Another important hydrological parameter required by the model is evapotranspiration, which is derived from estimates of evaporation and a conversion factor. The WR90 documentation provides a monthly distribution of evaporation according to hydrological zones. All of the gauged catchments fall within Hydrological Zone 20B, the monthly distribution of which is provided in **Table 3.4**. This distribution was used with the WR90 estimate of Mean Annual Evaporation (MAE) given in **Table 3.3** to determine the monthly evaporation depths listed in **Table 3.4**. The pan factors listed in **Table 3.5** were used to convert the monthly evaporation depths to vegetation evapotranspiration.

Table 3.4 : Monthly evaporation (mm) for the gauged catchments.

	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Total
Zone 20B Distribution	10.8%	11.7%	13.5%	12.7%	9.9%	8.6%	5.9%	4.6%	3.5%	4.1%	6.0%	8.7%	100%
CG26 & CG27	138	149	172	162	126	109	76	59	45	52	77	111	1275
CG25 & CG50	141	152	175	165	128	111	77	60	46	53	78	113	1300
MG19 & MG23	157	170	195	184	143	124	86	67	51	59	87	126	1450

Table 3.5 : Monthly pan evaporation factors.

Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
0.80	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.80	0.80	0.80

As mentioned in **Section 3.3**, there is very little development in the catchments upstream of the gauging points so there was no need to consider aspects such as reservoir operation, afforestation or irrigation development.

The model then requires eleven parameters to be set in order to simulate a runoff sequence. Each of these parameters represents a process in the rainfall-runoff cycle (or hydrological cycle). The model then compares statistics of the simulated record with those of the observed streamflow to determine the closeness of fit. The various parameters are adjusted until an acceptable closeness of fit between simulated and observed streamflow records is obtained. The functionality of the model is discussed in more detail in the User Guide (Water Research Commission, 2001).

The details of the calibrations of the six gauged records are provided in **Annexure I** and the final calibration parameters are listed in **Table 3.6**. It should be noted that the calibration of gauge CG50 was not good. The observed data were originally based on observer recordings of the gauge plate at this site. On the basis of the poor calibration and the possible inaccuracies in the observed record, gauge CG50 was not considered further.

Table 3.6 : Calibrated model parameters for the gauged catchments.

Para-meter	Description	Units	CG 26	CG 55	CG 25	CG 50	MG 19	MG 23
POW	Power of soil storage runoff curve	-	3	2.5	3	3	3	3
SL	Soil moisture at zero subsurface flow	mm	0	0	0	0	0	0
ST	Soil moisture storage capacity	mm	180	150	110	40	40	50
FT	Subsurface flow at soil moisture capacity	mm/month	12	35	10	40	55	41
GW	Maximum groundwater flow	mm/month	0	0	0	0	0	0
Zmin	Minimum absorption rate	mm/month	999	999	999	999	999	999
Zmax	Maximum absorption rate	mm/month	999	999	999	999	999	999
PI	Interception loss	mm/day	1.5	1.5	1.5	1.5	1.5	1.5
TL	Lag of surface runoff	months	0.25	0.25	0.1	0.25	0.25	0.25
GL	Lag of soil runoff	months	0	0	0	0	0	0
R	Evaporation - storage coefficient	-	0.5	0.5	0.5	0.5	0.5	0.5

3.5. STREAMFLOW SIMULATION

3.5.1. Overview

Having calibrated the observed streamflow records, the next step involved simulating the streamflow at the three different dam and abstraction sites. The calibration parameters from the appropriate gauged catchments were used along with the characteristics of the simulation catchments to generate streamflow sequences that could be used in the water resources assessment. The streamflow simulations for each of the study catchments are described in the following sections.

3.5.2. Ngoajane/Hololo catchment

The Ngoajane/Hololo catchment was divided into three sub-catchments according to the proposed and existing developments as is shown in **Figure A.6** in **Annexure A**. It is noted that Muela Dam is located in this area. Three sets of streamflow records were simulated for this catchment, namely :

1. At the proposed Ngoajane Abstraction site;
2. At the proposed Ngoajane Dam site; and
3. At the existing Muela Dam.

The hydrological parameters used for these simulation catchments are provided in **Table 3.7**. The monthly evaporation depths and pan factors listed in **Tables 3.4** and **3.5** were used for the simulations.

Table 3.7 : Hydrological parameters for the Ngoajane simulation catchments.

Gauge	Ngoajane abstraction	Ngoajane dam	Muela dam
Quaternary	D21A	D21B	D21B
Catchment area (km2)	391.7 (211)(1)	149.8	30.9
MAP (mm)	1021	978	1021
MAE (mm)	1275	1275	1275

Note (1) : The incremental catchment of the proposed Ngojane Abstraction site is the total catchment area less the areas of the two upstream catchments.

Gauges CG26 and CG55 are located within this catchment but on different rivers. They have similar catchment areas and are at similar elevations. Inspection of **Table 3.6** indicates that the only differences occur with parameters POW, ST and FT, and that these are not significant. Therefore, it was assumed that a combination of the calibration parameters would provide reasonable simulated streamflow sequences. The parameters used in the simulation are listed in **Table 3.8**.

Table 3.8 : Simulation parameters for the Ngoajane/Hololo catchment.

POW	SL	ST	FT	GW	Zmin	Zmax	PI	TL	GL	R
3.0	0	165	21	0	999	999	1.5	0.25	0	0.5

The abstraction site simulation catchment contains both the proposed Ngoajane Dam site and the Muela Dam simulation catchments in the upper reaches. Therefore, streamflow sequences were simulated for the total simulation catchment areas of all three sites and the two upper records were subtracted from the abstraction site record to produce an incremental streamflow sequence. Statistical summaries of both the calibrated and the simulated streamflow sequences in the Ngoajane Catchment are provided in **Table 3.9**. Listings of the simulated streamflow sequences are provided in **Annexure J**.

Table 3.9 : Statistics of the streamflow sequences in the Ngoajane catchment.

Statistic	Unit	CG26	CG55	Dam site	Muela Dam	Abstrac -tion site
MAR	million m^3	37.03	32.37	36.7	5.95	86.66
Standard deviation of annual flows	million m^3/yr	20.56	11.89	13.53	3.11	39.46
Coefficient of variability	%	55.51	36.75	36.86	52.34	45.54
Coefficient of skewness	-	0.6638	0.1866	0.5935	0.6297	0.5977
Range	% MAR	315.92	132.85	234.34	151.32	410.82
Autocorrelation coefficient of annual flows	-	0.0807	-0.1567	0.1073	0.1001	0.1027
Mean of logs of annual flows	Million m3	1.4955	1.4794	1.535	0.7083	1.89
Standard deviation of logs of annual flows	-	0.2693	0.1727	0.1643	0.2551	0.2128
Index of seasonal variability	%	29.19	22.01	19.41	25.86	23.74

3.5.3. Hlotse catchment

The locality plan of the Hlotse catchment is shown in **Figure A.7** in **Annexure A**. In this case, only two sets of streamflow records were simulated for this catchment, namely :

4. At the proposed Hlotse Abstraction site; and
5. At the proposed Hlotse Dam site.

The hydrological parameters of the two simulation catchments are provided in **Table 3.10**. As with the Ngoajane simulations, the monthly evaporation depths and pan factors listed in **Tables 3.4 and 3.5** were used also in the simulation of the streamflow sequences for the Hlotse catchment.

Table 3.10 : Hydrological parameters for the Hlotse simulation catchments.

Gauge	Hlotse abstraction	Hlotse dam
Quaternary	D21J, K and L	D21J
Catchment area (km2)	726.4 (367)$^{(1)}$	359.4
MAP (mm)	726	969
MAE (mm)	1300	1300

Note (1) : The incremental catchment of the proposed Hlotse Abstraction site is the total catchment area less the area of the Hlotse Dam site catchment.

The calibration parameters of the streamflow at gauge CG25 listed in **Table 3.6**.were used for these simulation catchments. The proposed abstraction site simulation catchment contains the proposed dam site simulation catchment in the upper reaches. Therefore, streamflow sequences were simulated for the total simulation catchment areas of both sites and the upper record was subtracted from the abstraction site record to produce an incremental streamflow sequence. Statistical summaries of both the calibrated and the simulated streamflow sequences in the Hlotse Catchment are provided in **Table 3.11**. Listings of the simulated streamflow sequences are provided in **Annexure J**.

Table 3.11 : Statistics of the streamflow sequences in the Hlotse catchment.

Statistic	Unit	CG25	Dam site	Abstraction site
MAR	million m^3	130.6	72.39	137.23
Standard deviation of annual flows	million m^3/yr	84.87	43.9	84.48
Coefficient of variability	%	64.98	60.64	61.56
Coefficient of skewness	-	0.9114	0.7954	0.8205
Range	% MAR	395.09	631.29	693
Autocorrelation coefficient of annual flows	-	0.2226	0.1836	0.1765
Mean of logs of annual flows	Million m3	2.0099	1.7665	2.0419
Standard deviation of logs of annual flows	-	0.3379	0.3131	0.3164
Index of seasonal variability	%	28.52	28.91	28.68

3.5.4. Makhaleng catchment

The locality plan of the Makhaleng catchment is shown in **Figure A.8** in **Annexure A**. Again, only two sets of streamflow records were simulated for this catchment, namely :

1. At the proposed Makhaleng Abstraction site; and

2. At the proposed Makhaleng Dam site.

The hydrological parameters of the two simulation catchments are provided in **Table 3.12**. As with the previous simulations, the monthly evaporation depths and pan factors listed in **Tables 3.4 and 3.5** were used also in the simulation of the streamflow sequences for the Makhaleng catchment.

Table 3.12 : Hydrological parameters for the Hlotse simulation catchments.

Gauge	Makhaleng abstraction	Makhaleng dam
Quaternary	D15 A, B, C, D & E	D15A & B
Catchment area (km2)	2163 (1628)(1)	535
MAP (mm)	871	972
MAE (mm)	1450	1450

Note (1) : The incremental catchment of the proposed Hlotse Abstraction site is the total catchment area less the area of the Hlotse Dam site catchment.

The calibration parameters of the streamflow at gauge MG19 (listed in **Table 3.6**) were used to simulate the streamflow at the proposed dam site, and those parameters from gauge MG23 were used for the simulation of the streamflow at the proposed abstraction site. The proposed Makhaleng abstraction site simulation catchment contains the proposed dam site simulation catchment in the upper reaches. In this case streamflow sequences were simulated for the incremental catchment areas of both sites. Statistical summaries of both the calibrated and the simulated streamflow sequences in the Makhaleng Catchment are provided in **Table 3.13**. Listings of the simulated streamflow sequences are provided in **Annexure J**.

Table 3.13 : Statistics of the streamflow sequences in the Makhaleng catchment.

Statistic	Unit	MG19	MG23	Dam site	Abstract-ion site
MAR	million m^3	30.32	388.27	166.85	365.51
Standard deviation of annual flows	million m^3/yr	10.58	161.74	56.99	133.96
Coefficient of variability	%	34.89	41.66	34.16	36.65
Coefficient of skewness	-	0.0989	0.3881	0.3812	0.2759
Range	% MAR	207.81	302.11	341.63	389.59
Autocorrelation coefficient of annual flows	-	0.0542	0.3812	0.0102	0.0798
Mean of logs of annual flows	Million m3	1.4523	2.5504	2.195	2.5307
Standard deviation of logs of annual flows	-	0.1698	0.1951	0.1614	0.1757
Index of seasonal variability	%	23.87	23.61	23.65	22.99

3.6. STOCHASTIC STREAMFLOWS

The WRYM model requires incremental streamflow records to be input at the appropriate simulation points as is discussed in **Section 4**. The six system analysis hydrology input sites were :

1. Proposed Ngoajane Dam site
2. Proposed Ngoajane Abstraction site
3. Proposed Hlotse Dam site
4. Proposed Hlotse Abstraction site
5. Proposed Makhaleng Dam site
6. Proposed Makhaleng Abstraction site

In the case of Muela Dam, the hydrology of this catchment was excluded from the system model and the influence was simulated as a fixed inflow. The details of the WRYM simulations are provided in **Section 5**. Details of the stochastic tests for each of the incremental hydrologies are provided in **Annexure K**.

4. ANALYSIS PROCEDURE

4.1. OVERVIEW OF THE MODEL

The Water Resources Yield Model (WRYM) of the South African Department of Water Affairs (1999) is a network model which uses a sophisticated network solver in order to analyse complex water resource systems under various operating scenarios. The strength of the WRYM lies in the ability to change the operating rules via the external system data files and no changes to the actual program source code are required.

The WRYM is based on the assumption that a water resource system can be represented by a flow network. A water resource system can be configured using nodes and links to represent the various elements of the system being modelled. By careful selection of penalty structures, the network can be analysed for each time period and solved using an efficient network solver which has evolved from network programming techniques. The WRYM can represent any water resource system which incorporates the following physical processes:

- Naturalised inflows;
- Precipitation and evaporation associated with reservoirs;
- Diffuse irrigation and afforestation demands from the various catchments:
- Storage and releases of water from reservoirs;
- Physical discharge controls at the outlets from reservoirs;
- Specified inflows from adjacent subsystems on a monthly basis;
- Specified demands (e.g. agricultural, industrial and municipal),
- Water flow in channels (e.g. natural streams, diversion channels, minimum flow channels, multi-purpose min-max channels, pumping channels etc.); and
- Losses in conveyance channels.

The WRYM is capable of simulating a wide range of operating policies governing the allocation of water in a multi-purpose multi-reservoir system. Water resource problems involving energy production, flood control, water supply, irrigation, low flow augmentation, diversion and navigation requirements can be modelled using WRYM. A major advantage of the WRYM is its flexibility in allowing the user to define operating policies governing the allocation of water by altering penalty structures in the data set rather than modifying the source code of the program. Full details of the background and application of the WRYM are provided in the User Guide (South African Department of Water Affairs, 1999).

The WRYM was designed to assess the long-term yield capabilities of a system for a given operating policy. It is used to analyse systems at constant development levels (i.e. the system and the system demands remain constant throughout the full simulation period). The WRYM can be used to analyse a historical flow sequence - usually in the order of 20 to 80 years in length. Unfortunately results obtained from historical analyses alone can be very misleading and depend to a great extent on the period of record used in the analysis.

To this end, stochastic flow sequences are also included in the analysis process. Clearly it is extremely important to specify not only the yield values but also the corresponding level of assurance or alternatively risk of failure. The reliability associated with a given yield is of the utmost importance and provides an indication of the level of assurance or risk of failure associated with the yield value.

4.2. DESCRIPTION OF PENALTY TYPES

A typical WRYM system schematic is presented in **Figure L.1** in **Annexure L**. Both penalty structures for the dam storage zones and penalty structures for the channel reaches are depicted in this schematic. **Figure 4.1** indicates a typical penalty structure for the storage component of a dam. There are three "columns" in the figure, namely the zone boundary name, the zone penalty and the zone boundary elevation.

10 - Batllava		
FSL	10000	630.5 masl
RCL	5	628.0 masl
DSL	15	625.0 masl
Bottom	10000	622.0 masl

Figure 4.1 : Typical penalty structure for a dam indicating different storage zones.

The elevation defines the levels relative to mean sea level of the boundaries of the various zones used in the penalty structure. In this case there are four such zones, which are described below :

- The uppermost zone represents the flood zone and comprises anything above the full supply level (FSL) of 630.5 m.a.s.l. If water enters this zone it does so at a penalty of 10 000 units and is therefore a very "costly" zone in which to store water.

- The second zone is between the FSL (630.5 m.a.s.l.) and a selected Rule Curve Level (RCL) of 628.0 m.a.s.l. This is one of the working storage zones of the reservoir which has a penalty of 5 units. All zones below the FSL can be thought of as having a value rather than a penalty associated with them. For example, any water in the second zone has a value of 5 units, and it will therefore incur a penalty of 5 units to take water from this zone to meet a demand elsewhere.

- The third zone is between the RCL and the dead storage level (DSL) of 625.0 m.a.s.l. Water in this zone has a value of 15 units and represents the other working storage zone of the reservoir.

- The water between the DSL and the bottom of the dam (622.0 m.a.s.l.) has a value of 10 000 units and the penalty is such that it will be very "costly" to draw water from this zone, so it will not contribute to meeting the yield.

The four penalties used in this scenario have the effect of restricting the working storage of the dam to the second and third zones. Should a second dam be utilised in the system then the penalties of the working storage behind that dam would have to be of appropriate values so as to create an operating rule which prioritises the sequence of abstractions from the various working storage zones. It should be noted that a dam should have at least one working storage zone but it can have a maximum of seven if required by an operating rule.

In most cases, the channel penalties take the forms shown in **Figure 4.2**. The two examples in this figure would be used to represent the following :

- Channel 35 , is a general flow channel that has a single penalty structure for an unlimited flow. The range in flows is between zero and infinity and the associated penalty for this range is 0 units.

- Channel 5 is a demand channel that has a double penalty structure for a specified demand (Dem). Any shortfall in this demand results in a penalty of 250 units. There is a zero penalty if the demand is supplied in full.

These are examples of two of many penalty structures which may be used in an analysis.

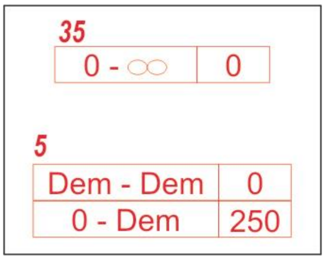

Figure 4.2 : Typical penalty structures for system channels.

5. WATER RESOURCES ANALYSES

5.1. OVERVIEW

The Water Resources Yield Model (WRYM) was used to determine the yield capabilities of each of the systems proposed. The model is used to analyse systems at constant development levels i.e. the system and the system demands remain constant throughout the full simulation period. It is reported in the previous sections that the hydrological database covers the period 1935 to 1999. This period of historical analysis therefore includes the droughts experienced in the early 1980's and 1990's.

One of the most useful tools in the WRYM is the inclusion of stochastic flow sequences in the analysis process (as is discussed in **Section 3.6**). Unfortunately results obtained from historical analysis alone can often be very misleading and depend to a great extent on the period of record used in the analysis. This can be clearly seen in **Table 5.1** which shows the variation in historical firm yield for a particular reservoir for various periods of record for a simple system in KwaZulu-Natal which has a critical period in the order of two to three years.

Table 5.1 : Variability of firm yield with record length

Period of record	Cumulative volume ($10^6 m^3$)	Firm yield ($10^6 m^3/a$)
1930 – 1934	5	96
1930 – 1939	10	84
1930 - 1949	20	84
1930 – 1969	40	80
1930 - 1989	60	51

The figures in **Table 5.1** clearly indicate that the firm yield from a reservoir (or system of reservoirs) can be greatly influenced by the record length available for the analysis. This does not imply that any of the firm yield values given in **Table 5.1** are incorrect. To the contrary, the firm yields are valid, however, one important piece of information is missing without which the values given are misleading. The reliability associated with a given yield is of the utmost importance and provides an indication of the level of assurance or risk of failure associated with the yield value. It is extremely important to specify not only the yield values but also the corresponding level of assurance or alternatively risk of failure. The terms of reference of this assignment required that the 1:50 year yield be used for the design criteria.

The use of stochastically generated flow sequences is now standard practice in Southern Africa and the same techniques have been used successfully in several other parts of the world. One of the problems associated with the use of stochastically generated flow sequences concerns the validity of the sequences, particularly in a system context, where the relationships between flows at different parts of the system are crucially important. For this reason, considerable effort is spent ensuring that the sequences generated are in fact realistic and plausible. Numerous different checks and tests are carried out to verify and validate the stochastically generated sequences. These are documented in **Annexure L**.

The WRYM requires a set of four monthly hydrological data files for each sub-catchment that is simulated, these being :

1. Naturalised runoff (*.INC file);

2. Reduction in runoff due to afforestation (*.AFF file);

3. Diffuse irrigation (*.IRR file); and

4. Point rainfall at reservoir (*.RAN file).

The naturalised runoff files are the simulated streamflow sequences for the sub-catchments discussed in **Section 3.5** and listed in **Annexure J**.

Diffuse demands normally include the uncontrolled demands upstream of dams that are supplied directly from rainfall or runoff, such as afforestation and irrigation. These demands can therefore be deducted directly from the natural flow (as given in the .INC file) before the flow enters the system and is for that reason included as diffuse irrigation demands or afforestation water use. In the case of the three systems analysed, there is no afforestation or diffuse irrigation of any significance in the upstream catchments therefore these were assumed to be zero.

Controlled demands such as irrigation, urban and industrial requirements can be modelled in the WRYM either as a monthly time series of demands or as 12 monthly demand values. For these three areas in Lesotho, no irrigation or afforestation exists and these files are therefore set at zero. A brief description of the most important components regarding the hydrological database is given in the next sections.

Net evaporation losses from open water surfaces can be significant. The effect of this has to be taken into account in the system analysis. In order to calculate the net evaporation losses from impoundments it is necessary to make an assessment of both the rainfall on and the gross evaporation from the exposed water surfaces. To this end, it was assumed that the Mean Annual Precipitation (MAP) at the proposed dam site is the same as that of the closest rain gauge. Representative monthly rainfall records (*.RAN) were then generated for each of the proposed dam sites by multiplying the monthly time series catchment rainfall record listed in **Annexure E** (which is expressed as percentages of the catchment MAP) with the relevant point MAP.

Gross evaporation, or lake evaporation, is modelled in the WRYM as 12 monthly values since there is less variability in potential evaporation from one year to another. Furthermore, evaporation does not vary much spatially within small areas such as the catchments analysed, it was assumed that the catchment Symons pan evaporation values given in **Table 3.4** would be representative of the point evaporation at the proposed dam sites. The factors given in **Table 5.2** were applied to convert the pan evaporation values into lake evaporation values (Chapman, 1996). Lake evaporation is not linked to a specific sub-catchment in the WRYN but to the relevant dam. It is therefore possible to include different lake evaporation losses for dams although they are located in the same sub-catchment.

Table 5.2 : Monthly pan to lake evaporation conversion factors.

Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
0.81	0.82	0.83	0.84	0.88	0.88	0.88	0.87	0.85	0.83	0.81	0.81

It is not acceptable to abstract all of the water out of a system without leaving some to satisfy the needs of other downstream users and to ensure that the integrity of the aquatic environment is not compromised. Determination of the environmental water requirements is a complex and time consuming exercise that is usually undertaken during the design phase of a water resource development. In the case of a feasibility study, such as this assignment, it is essential that any analyses are undertaken making allowances for a first order estimate of the environmental requirements. There is very little information on the environmental water requirements in the Study Area, so it was assumed that a minimum of 5% of the flow will always remain in the rivers and would not be available for abstraction.

5.2. HOLOLO/NGOAJANE SYSTEM

5.2.1. Overview

The various catchments that comprise the proposed Hololo/Ngoajane System are shown in **Figure A.6** in **Annexure A** and schematic diagrams of the proposed systems are presented in **Figures L.2 and L..3** of **Annexure L**. The development options that were considered in this case were :

1. A run-of-river abstraction directly from the Hololo River downstream of the confluence with the Ngoajane River (**Figure L..1**);

2. Abstraction from the same position but being supported with releases from the Ngoajane Dam (**Figure L..2**); and

3. Abstraction from the same position but being supported with releases from the Muela Dam (**Figure L..3**).

Muela Dam, and the associated Lesotho Highlands Transfer Scheme, provides a complex dynamic in terms of simulating the water resources of this catchment. It is understood that the normal operating rule of Muela Dam is a preset pattern of releases and that all surplus runoff from the upstream catchment is transferred along with the Highlands water. As a result it was practical to make a simplifying assumption that the influence of the Muela Dam could be simulated as a fixed transfer into the Ngoajane/Hololo catchment. This is a reasonable assumption since any change in the operating rule can be simulated as a different transfer pattern, whilst spills will only occur during extremely wet periods which are not likely to influence the system yield.

5.2.2. Hydrology

The system has two sub-catchments, nodes 10 and 25, which represent the catchment of the Hololo River Downstream of Muela Dam and the catchment of the proposed Ngoajane Dam. The incremental runoff time series for these impoundments were routed through these nodes. As mentioned in the previous sections, the streamflow sequences were assumed to be natural since very little development that could be construed as water intensive was observed in the Ngoajane/Hololo catchments. No other runoff sequences were considered in the assessment of this system.

The MAP at the proposed Ngoajane Dam site was estimated to be 807 mm. This value was combined with the catchment aerial rainfall file listed in **Annexure E.1** to obtain the monthly rainfall file on the surface of the impoundment (*.SEC). The monthly lake evaporation values modelled in the system are provided in **Table 5.3**.

Table 5.3 : Monthly pan to lake evaporation conversion factors for Ngoajane Dam.

Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Total
112	122	143	136	111	96	67	52	38	43	62	90	**1071**

5.2.3. Reservoir characteristics

The elevation-area-volume relationships of the proposed Ngoajane impoundment are provided in **Table 5.4**. This table was input into the model and the system assessed for various impoundment capacities.

Table 5.4 : Ngoajane dam area and volume characteristics.

Elevation (m.a.s.l.)	Area (ha)	Cumulative volume ($10^6 m^3$)
1624.7	0	0
1630.0	8	0.22
1640.0	23	1.76
1650.0	65	6.13
1660.0	119	15.34
1670.0	189	30.76
1680.0	276	54.03

5.2.4. Environmental requirements

It was assumed that a minimum flow would be prescribed to meet the needs of the environment downstream of the proposed development. In this case, a minimum of 5% of the flow was not available for abstraction by setting Channel 60 (in **Figures L.1, L.2 and L.3**) as a minimum flow channel.

5.2.5. Abstractions and return flows

As with the diffuse water use, the Ngojane/Hololo catchment is considered to have little water intensive development so no direct abstractions and return flows were simulated.

5.2.6. Losses

It is normal that there are conveyance losses when water is released from an impoundment to a downstream abstraction, particularly during periods of low flow. To this end, a loss channel was included in the system (Channel 40 from Node 16) to simulate the effect of the conveyance losses. This was simulated as a fixed proportion abstraction channel set to remove 5% of the flow passing Node 16. It is acknowledged that this may not be the case during higher flows since the conveyance losses would tend to decrease proportionally, however, it is a reasonable assumption for during low flows when the firm yield would be estimated (see discussion in **Section 5.1**).

5.2.7. Analysis results

The WRYM was simulated based on the above-mentioned assumptions and system configurations using 501 stochastically generated streamflow sequences. The first scenario considered no support from Muela Dam and the second scenario assumed a continuous release of 0.15 m^3/sec from Muela Dam. Various sizes of the proposed Ngoajane Dam were considered and the 1:50 year (98% reliability) firm system yields were determined. The resulting yields for the various dam sizes with no support from Muela Dam are listed in **Table 5.5** and the relationship is shown graphically in **Figure 5.1**. The corresponding results for the scenario with support from Muela Dam are shown in **Table 5.6** and **Figure 5.2** respectively.

Table 5.5 : Ngoajane system yield (without support from Muela dam).

Full Supply Level (m.a.s.l.)	Capacity (million m^3)	98% Yield (mill m^3/a)
No dam	No dam	2.50
FSL = 1635	4.47	7.20
FSL = 1640	6.64	8.98
FSL = 1645	8.82	13.20
FSL = 1660	15.34	23.73
FSL = 1680	54.03	39.00

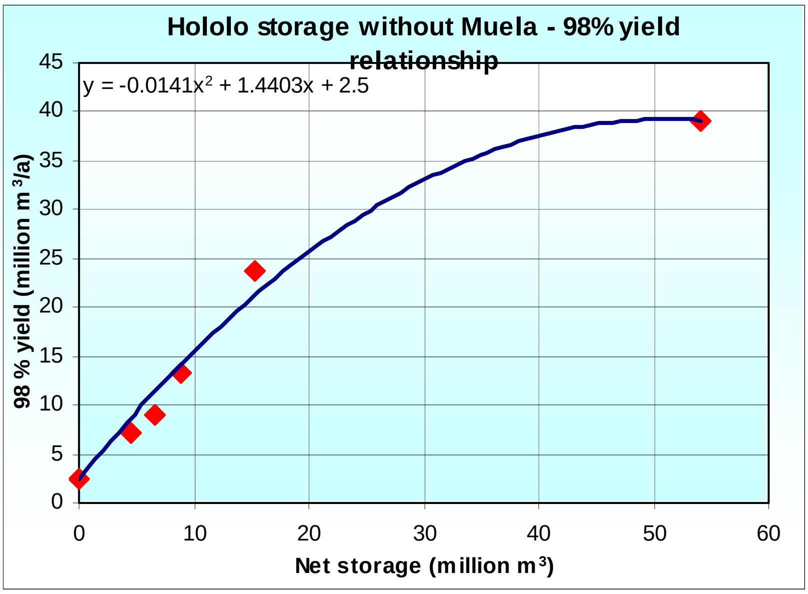

Figure 5.1 : Yield-storage relationship for the Ngoajane system without support from Muela.

Table 5.6 : Ngoajane system yield (with support from Muela dam).

Full Supply Level (m.a.s.l.)	Capacity (million m^3)	98% Yield (mill m^3/a)
No dam	No dam	7.28
1635	4.47	12.03
1640	6.64	14.03
1645	8.82	18.10
1660	15.34	28.47
1680	54.03	43.80

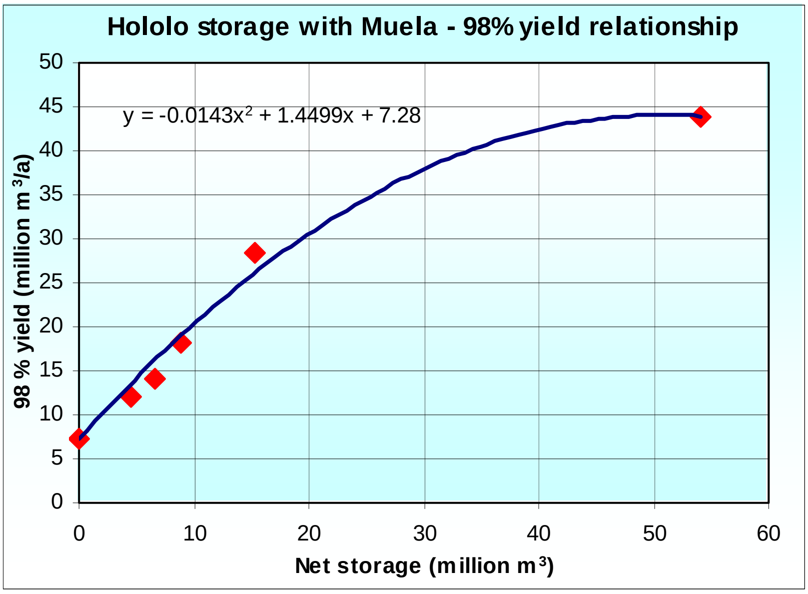

Figure 5.2 : Yield-storage relationship for the Ngoajane system with support from Muela.

5.3. HLOTSE SYSTEM

The various catchments that comprise the proposed Hlotse System are shown in **Figure A.7** in **Annexure A** and schematic diagrams of the proposed systems are presented in **Figures L.4 and L..5** of **Annexure L**. The development options that were considered in this case were :

1. A run-of-river abstraction directly from the Hlotse River downstream of the confluence with the Mamafubelu River (**Figure L.4**); and

2. Abstraction from the same position but being supported with releases from the proposed Hlotse Dam (**Figure L.5**).

5.3.1. Hydrology

The system also has two sub-catchments (nodes 10 and 25) which represent the catchment of the proposed Hlotse Dam and the incremental catchment between the proposed dam and the proposed abstraction works. The incremental runoff time series for these impoundments were routed through these nodes and no diffuse afforestation or irrigation was considered.

The MAP at the proposed Hlotse Dam site was estimated to be 864 mm. This value was combined with the catchment aerial rainfall file listed in **Annexure E.2** to obtain the monthly rainfall file on the surface of the impoundment (*.SEC). The monthly lake evaporation values modelled in the system are provided in **Table 5.7**.

Table 5.7 : Monthly pan to lake evaporation conversion factors for Hlotse Dam.

Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Total
114	125	145	139	113	98	68	52	39	44	63	92	**1092**

5.3.2. Reservoir characteristics

The elevation-area-volume relationships of the proposed Hlotse impoundment are provided in **Table 5.8**. This table was input into the model and the system assessed for various impoundment capacities.

Table 5.8 : Hlotse dam area and volume characteristics.

Elevation (m.a.s.l.)	Area (ha)	Cumulative volume ($10^6 m^3$)
1579.7	0	0
1581.7	7	0.35
1590.0	35	1.80
1591.7	51	3.29
1600.0	115	9.28
1601.7	137	12.68
1610.0	225	26.26
1611.7	270	33.02
1620.0	451	60.06

5.3.3. Environmental requirements

It was assumed that a minimum flow would be prescribed to meet the needs of the environment downstream of the proposed abstraction point. As with the Ngoajane Dam, a minimum of 5% of the flow was not available for abstraction by setting Channel 60 (in **Figure L.5**) as a minimum flow channel.

5.3.4. Abstractions and return flows

The Hlotse catchment is considered to have little water intensive development so no direct abstractions and return flows were simulated.

5.3.5. Losses

The conveyance losses for water released from the proposed Hlotse Dam were simulated as a fixed proportion abstraction channel set to remove 5% of the flow passing Node 16.

5.3.6. Analysis results

The WRYM was simulated based on the above-mentioned assumptions and system configurations using 501 stochastically generated streamflow sequences. Various sizes of the proposed Hlotse Dam were considered and the 1:50 year (98% reliability) firm system yields were determined. The resulting yields are listed in **Table 5.9** and the relationship is shown graphically in **Figure 5.2**.

Table 5.9 : Hlotse system yield.

Full Supply Level (m.a.s.l.)	Capacity (million m^3)	98% Yield (mill m^3/a)
No dam	No dam	0.28
1600	9.28	10.75
1605	17.77	15.15
1610	26.26	18.35
1620	60.06	29.00

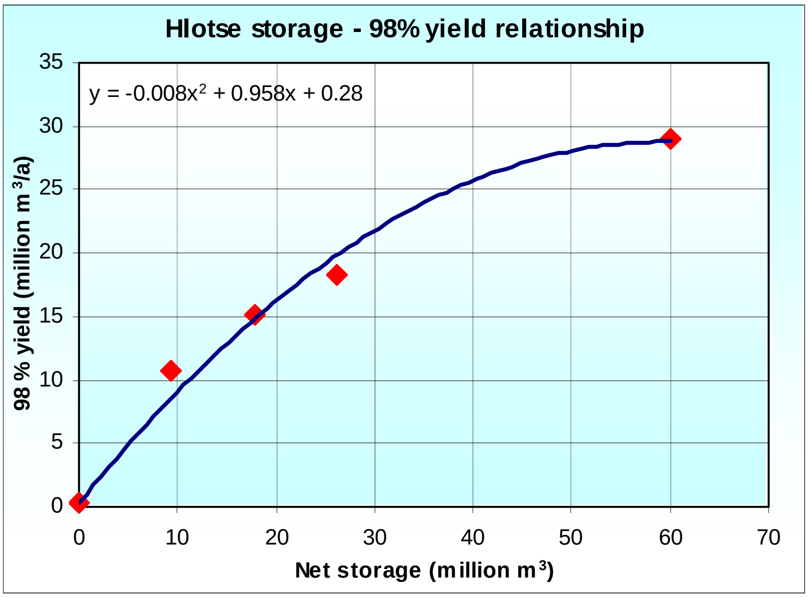

Figure 5.2 : Yield-storage relationship for the Hlotse System.

5.4. MAKHALENG SYSTEM

The various catchments that comprise the proposed Makhaleng System are shown in **Figure A.7** in **Annexure A** and schematic diagram of the proposed system is presented in **Figure L.6** of **Annexure L**. The development options that were considered in this case were :

1. A run-of-river abstraction directly from the Makhaleng River at the Mohales Hoek road bridge; and

2. Abstraction from the same position but being supported with releases from the Matsapong Dam.

5.4.1. Hydrology

The Makhaleng system was also simulated with two sub-catchments (nodes 10 and 25) which represent the catchment of the proposed Matsapong Dam and the incremental catchment between the proposed dam and the proposed abstraction works. No diffuse afforestation or irrigation was considered.

The MAP at the proposed Matsapong Dam site was estimated to be 801 mm. This value was combined with the catchment aerial rainfall file listed in **Annexure E.3** to obtain the monthly rainfall file on the surface of the impoundment (*.SEC). The monthly lake evaporation values modelled in the system are provided in **Table 5.10**.

Table 5.10 : Monthly pan to lake evaporation conversion factors for Matsapong Dam.

Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Total
127	139	162	155	126	109	76	59	43	49	70	102	**1218**

5.4.2. Reservoir characteristics

The elevation-area-volume relationships of the proposed Hlotse impoundment are provided in **Table 5.11**. This table was input into the model and the system assessed for various impoundment capacities.

Table 5.11 : Hlotse dam area and volume characteristics.

Elevation (m.a.s.l.)	Area (ha)	Cumulative volume ($10^6 m^3$)
1656	0	0.00
1671	40	3.78
1675	50	4.79
1680	67	7.72
1690	99	15.99
1696	129	23.41
1700	149	28.36

5.4.3. Environmental requirements

As with the previous systems, a minimum of 5% of the flow was not available for abstraction by setting Channel 60 (in **Figure L.6**) as a minimum flow channel.

5.4.4. Abstractions and return flows

The Makhaleng catchment is considered to have little water intensive development so no direct abstractions and return flows were simulated.

5.4.5. Losses

The conveyance losses for water released from the proposed Matsapong Dam were simulated as a fixed proportion abstraction channel set to remove 5% of the flow passing Node 16.

5.4.6. Analysis results

The WRYM was simulated based on the above-mentioned assumptions and system configurations using 501 stochastically generated streamflow sequences. Various sizes of the proposed Matsapong Dam were considered and the 1:50 year (98% reliability) firm system yields were determined. The resulting yields are listed in **Table 5.11** and the relationship is shown graphically in **Figure 5.3**.

Table 5.11 : Makhaleng system yield.

Full Supply Level (m.a.s.l.)	Capacity (million m^3)	98% Yield (mill m^3/a)
No dam	No dam	8.14
FSL = 1658	0.50	11.96
FSL = 1660	1.01	17.84
FSL = 1665	2.27	29.20
FSL = 1685	12.25	58.84
FSL = 1700	28.36	92.00

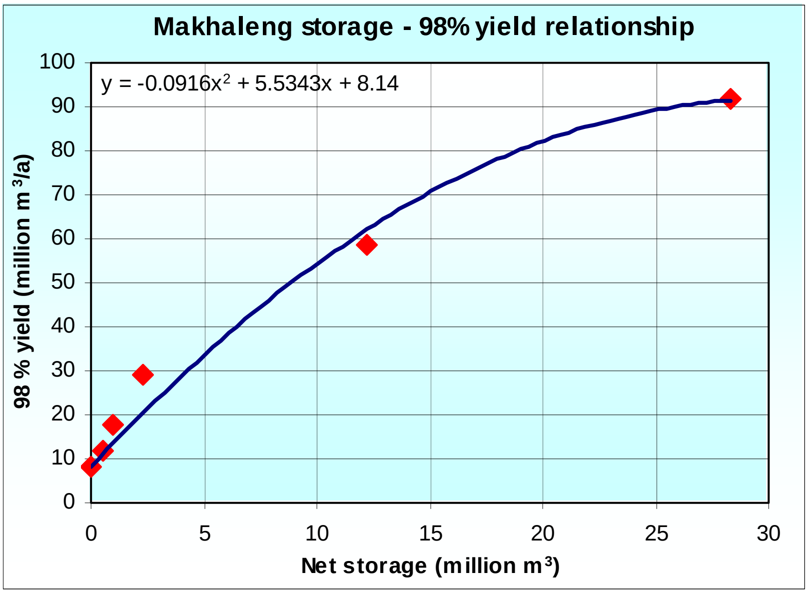

Figure 5.3 : Yield-storage relationship for the Makhaleng system.

6. REFERENCES

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