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**.