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 (10^6m^3)	Firm yield (10^6m^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

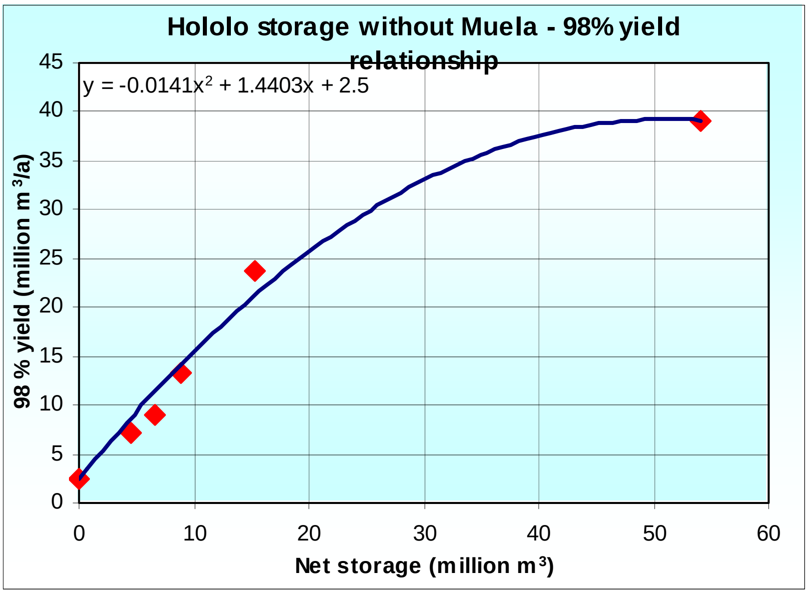

Figure 5.1 : Yield-storage relationship for the Ngoajane system without support from Muela.

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

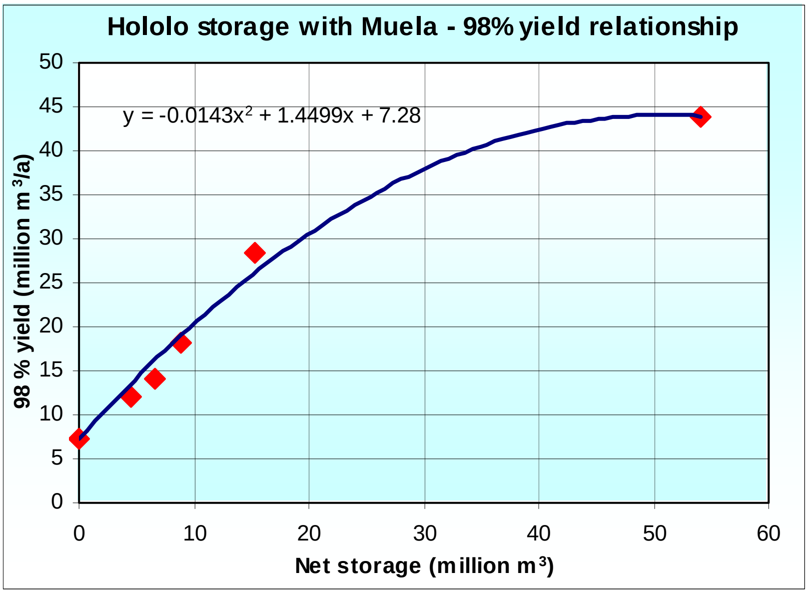

Figure 5.2 : Yield-storage relationship for the Ngoajane system with support from Muela.

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 (10^6m^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

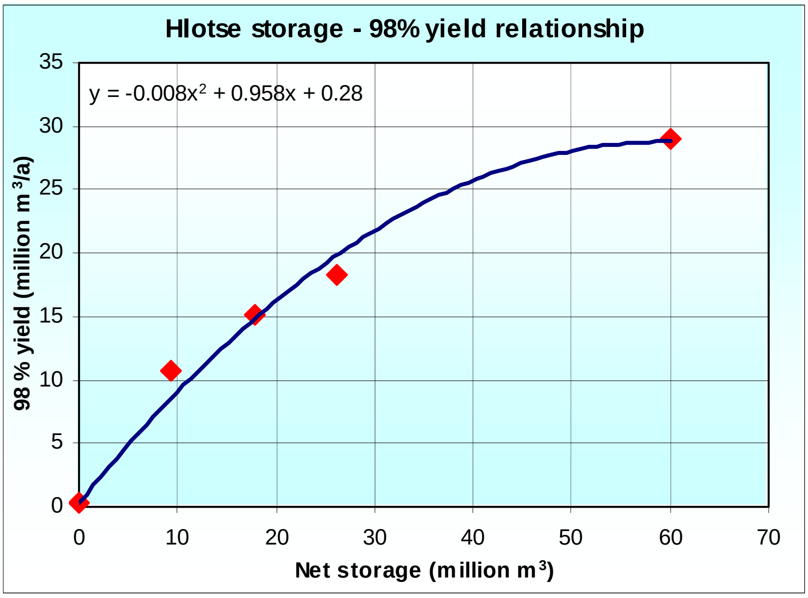

Figure 5.2 : Yield-storage relationship for the Hlotse System.

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

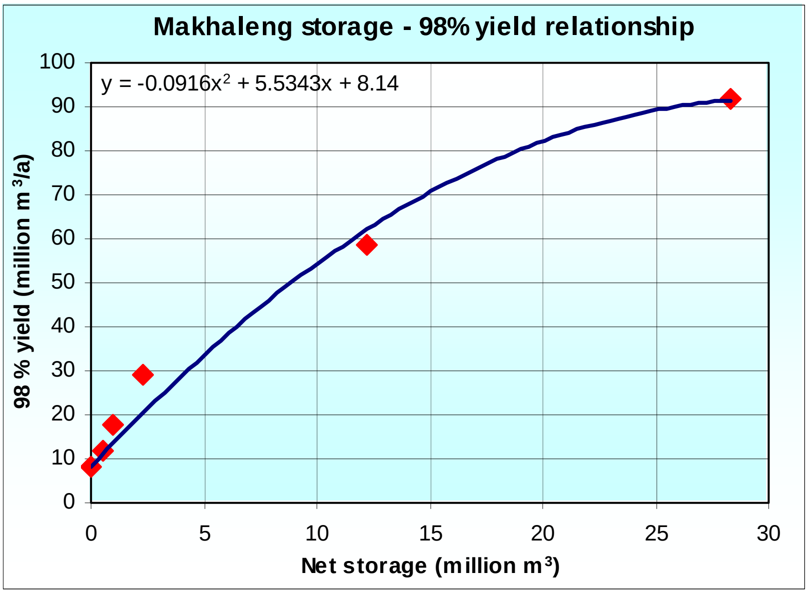

Figure 5.3 : Yield-storage relationship for the Makhaleng system.