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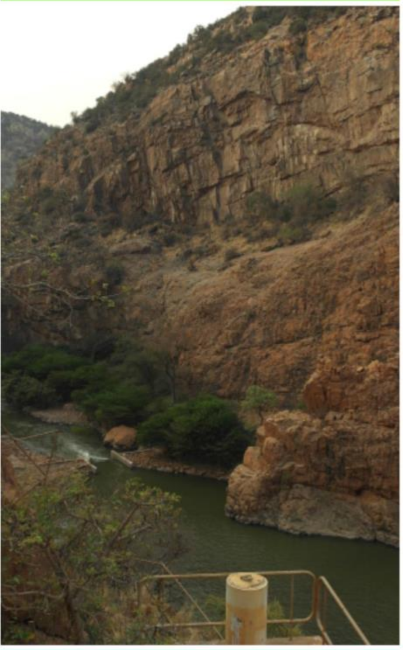

THE DEVELOPMENT OF THE LIMPOPO WATER MANAGEMENT AREA NORTH RECONCILIATION STRATEGY

HYDROLOGICAL ANALYSIS

Volume 1: Main Report

FINAL

DECEMBER 2015

Project Name:	***Limpopo Water Management Area North Reconciliation Strategy***
Report Title:	***Hydrological Analysis: Volume 1 – Main Report***
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Limpopo Water Management Area North Reconciliation Strategy

Date: December 2015

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The *Limpopo Water Management Area North Reconciliation Strategy Hydrological Analysis Report* is divided into two volumes.

The first volume (**Volume 1: Main Report**) contains the main text, dealing with the description of the modelling process, results, conclusions and recommendations of the hydrological analysis.

The second volume (**Volume 2: Appendices**) contains the appendices referenced in *Volume 1* of the Hydrological Analysis Report. The appendices contain tables, figures and information related to the input and results of the hydrological analysis using the *Water Resources Simulation Model 2000* (WRSM2000).

EXECUTIVE SUMMARY

The Study Area, the Limpopo Water Management Area (WMA) North refers to the Limpopo WMA as defined in the first National Water Resources Strategy (NWRS-1).

This report describes the hydrological analysis undertaken on the six main river catchments of the Limpopo WMA North. The six river catchments include the Matlabas (A41), Mokolo (A42), Lephalala (A50), Mogalakwena (A6), Sand (A7) and Nzhelele (A8) river catchments. The key objectives of the hydrological analysis were to:

- *Evaluate, improve, update and extend available stream flow data from previous studies to cover the Study Period of 1920 to 2010 (i.e. October 1920 to September 2011) using updated rainfall and land-use data; and*
- *Generate time-series of natural monthly stream flow for the Study Period at a quaternary or sub-quaternary catchment level, where appropriate.*

The climate over the Study Area is temperate and semi-arid in the south to extremely arid in the north. Mean annual rainfall ranges from 300 mm to 700 mm with the potential evaporation well in excess of the rainfall. Runoff is low due to the prevalence of sandy soils in the most of the Study Area. The water resources, especially surface water resources, are heavily stressed due to the present levels of development. Surface water resources in the Study Area are almost fully developed and future water requirements will need to rely on the extensive groundwater resources within the area. However, in some areas groundwater resources are already over-exploited. It is crucial that water supply is secured and well managed.

A summary of the water use in the Study Area, per water use sector, is illustrated in ***Figure i*** *as percentages of the total water requirement. The total water requirement in the Study Area is estimated at 598 million m³/a, of which 273 million m³/a (46%) is supplied from surface water resources and 325 million m³/a (54%) is supplied from groundwater resources.*

Stream flow reduction (SFR) activities constitute of widespread invasive alien plants (IAP) throughout the Study Area and limited commercial forestry on the slopes of the Soutpansberg mountains in the Sand and Nzhelele river catchments.

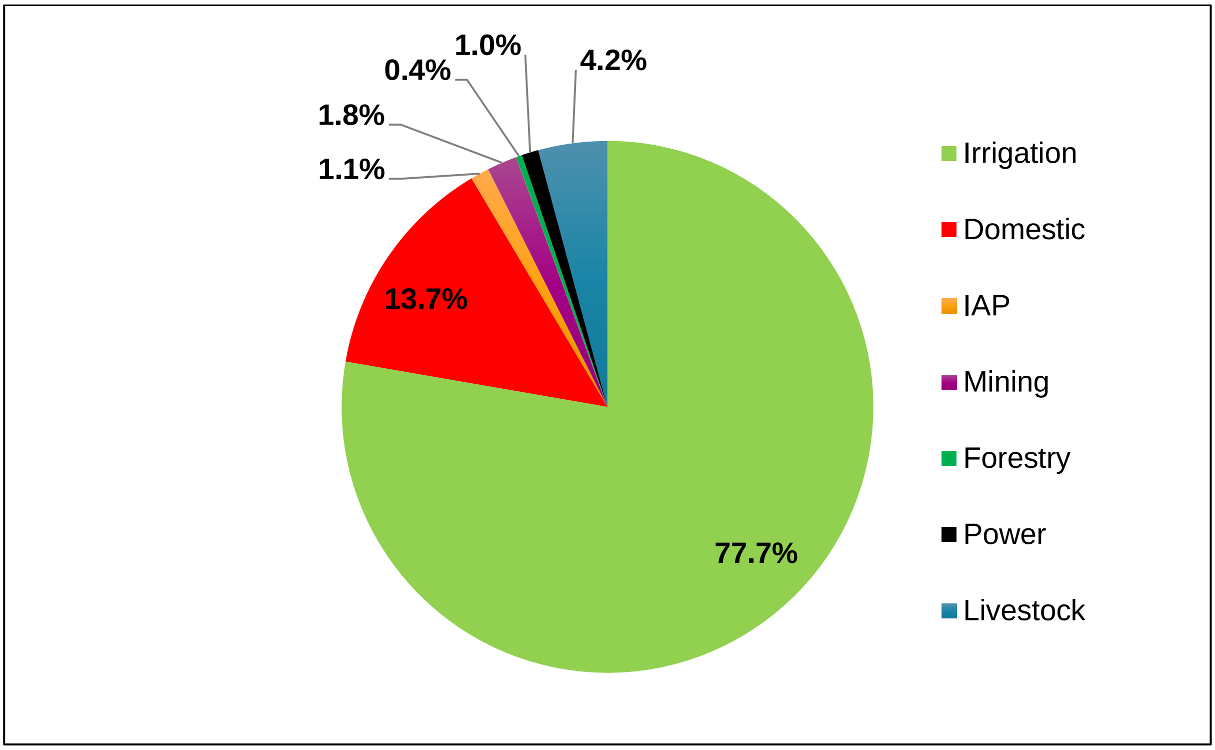

Figure i: Water use per sector as a percentage of the total water requirement

The irrigation sector is the largest water user in the Study Area, accountable for approximately 78% of the total water requirement. The four large dams, the Mokolo, Doorndraai, Glen Alpine and Nzhelele, mainly support large-scale irrigation. Groundwater is also extensively used for irrigation supply, especially in the middle region of the Study Area and along the Limpopo River main stem. Surface water usage for domestic purposes is localised to larger settlements and urban areas. There are many smaller rural supply areas which rely solely on groundwater, sourced from boreholes and alluvial sand aquifers along the tributaries of the Limpopo River.

The IAP covers a total condensed area of 315 km² and results in a reduction of stream flow equal to 7 million m³/a. The considerably low SFR, bearing in mind the extensive area covered by IAP, may be due to their low prevalence in the riparian areas.

In total there are 93 surface water monitoring points in the Study Area, of which 68 are stream flow gauging stations. The geographical location of the stream flow gauging stations covers most of the Study Area, but the quality of data records was found to be generally poor. In the entire Study Area of 56 444 km^2, there are only 11 stream flow gauging stations with adequate data quality and appropriate record length for calibrating the representative catchment rainfall-runoff model systems in the Water Resources Simulation Model (WRSM2000). The scarcity of reliable stream flow records are a concern, especially in the Matlabas and Sand river catchments. There is only one *operational stream flow gauging station in the Matlabas River and none in the Sand River catchment.*

Despite the lack of observed stream flow data, acceptable to good calibration of the stream flow against rainfall were achieved. Particular attention was given to the calibration of the regional groundwater recharge, interflow and base flow estimates in order to account for the groundwater-surface water interaction. This was conducted using the Groundwater-Surface Water Interaction Model (GWSWIM) or SAMI model, incorporated into the WRSM2000.

After acceptable calibration of the representative rainfall-runoff model systems were achieved, time-series of natural stream flow at the outlets of every quaternary or sub-quaternary catchment were generated. Natural stream flow refers to the stream flow that would have occurred if there were no human interference, such as water use, water resources development and SFR activities.

A summary of the hydrological analysis results (natural MAR) is provided in ***Figure ii*** *per river catchment. The following conclusions were made regarding the hydrological analysis results:*

- *The Study Area receives a mean annual precipitation (MAP) of 470 mm with a potential mean annual evaporation (MAE) of 1 456 mm. This implies that on average three times more water is lost through evaporation than what precipitates on the surface of the Study Area.*
- *The simulated natural MAR of the study area is 977 million m^3/a (unit runoff of approximately 17 mm/a). The most runoff is generated in the Mokolo and Mogalakwena river catchments, accounting for approximately 55% of the natural runoff in the Study Area.*
- *On average 4% of the rainfall is converted to runoff in the Study Area.*
- *In the Sand River catchment, approximately 2% of the MAP is converted to runoff. This is attributed to the presence alluvial aquifers along the Sand River, which takes up a large portion of the rainfall/stream flow as recharge.*
- *Compared with the WR2005 Study (WRC, 2008), the overall natural MAR simulated for this Study is 1% higher over the corresponding study period of 1920 to 2004.*
- *About 46% of the simulated natural MAR in the Study Area have a confidence level higher than 70%. A further 41% had a confidence level of between 50% and 70% and 13% had a confidence level of lower than 50%.*

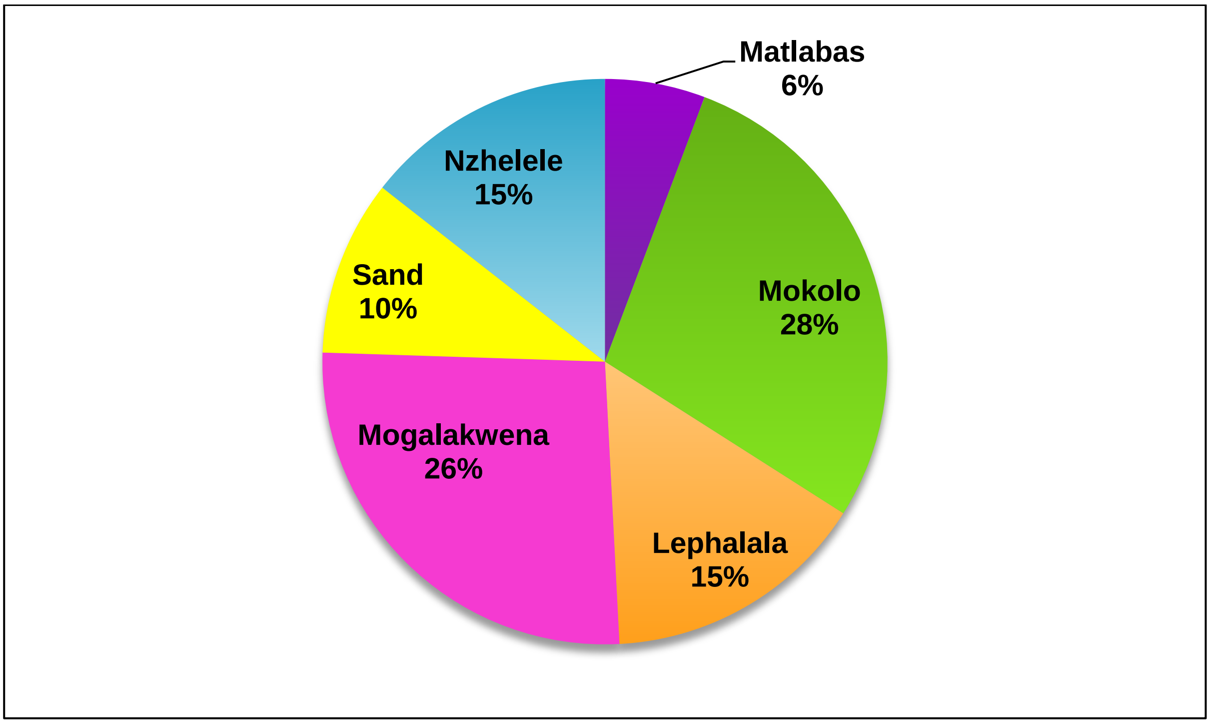

Figure ii: Natural MAR per river catchment as a percentage of the total natural MAR

Stationarity tests were conducted on all 112 simulated natural incremental stream flows. Cusum and single mass plots were produced and assessed. These tests showed that the incremental hydrology simulated was of sufficient stationarity. Stationarity tests are important for the stochastic stream flow analysis and in generating the param.dat files which will be used as input to the subsequent Water Resources Yield Model (WRYM) and the Water Resources Planning Model (WRPM).

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AECOM	AECOM SA (Pty) Ltd
D:NWRP	Directorate: National Water Resource Planning
DM	District Municipality
DWA	Department of Water Affairs
DWS	Department of Water and Sanitation
FSA	Full Supply Area
FSC	Full Supply Capacity
GWS	Groundwater Scheme
GWSWIM	Groundwater-Surface Water Interaction Model
IAP	Invasive Alien Plants
LM	Local Municipality
MAE	Mean Annual Evaporation
MAP	Mean Annual Precipitation
MAR	Mean Annual Runoff
MCWAP	Mokolo and Crocodile River (West) Water Augmentation Project
NMAR	Natural Mean Annual Runoff
RSA	Republic of South Africa
SAWS	South African Weather Services
SFR	Stream Flow Reduction
S-pan	Symons pan
V&V	Validation and Verification
WCWDM	Water Conservation and Water Demand Management
WMA	Water Management Area
WR2005	Water Resources of South Africa - 2005
WR2012	Water Resources of South Africa - 2012
WR90	Water Resources of South Africa - 1990
WRPM	Water Resources Planning Model
WRSM2000	Water Resources Simulation Model 2000
WRYM	Water Resources Yield Model

LIST OF UNITS

a	annum
ha	hectare
kℓ	kilolitre
km	kilometre
km^2	square kilometre
ℓ/c/d	litre per capita per day
ℓ/s	litre per second
m	metre
m^3	cubic meter
m^3/a	cubic meter per annum
Mℓ/d	mega litre per day
mm	millimetre
$m^3/ha/a$	cubic meter per hectare per annum

1 INTRODUCTION

1.1 APPOINTMENT OF PSP

The Department of Water and Sanitation (DWS), then Department of Water Affairs (DWA) appointed **AECOM SA (Pty) Ltd** in association with three sub-consultants **Hydrosol**, **Jones and Wagener** and **VSA Rebotile Metsi Consulting** with effect from 1 March 2014 to undertake the **Limpopo Water Management Area North Reconciliation Strategy**.

1.2 BACKGROUND TO THE PROJECT

The DWS (then DWA) identified the need for the development of the *Limpopo Water Management Area (WMA) North Reconciliation Strategy*. The Limpopo WMA North refers to the Limpopo WMA as defined in the first edition of the *National Water Resource Strategy (NWRS-1)* (DWA, 2004). The original 19 WMAs were consolidated into nine WMAs during 2012 and acknowledged in the second edition of the *National Water Resource Strategy (NWRS-2)* (DWA, 2013).The newly defined Limpopo WMA also includes the original Crocodile (West) and Marico WMA as well as the Luvuvhu River catchment, previously part of the Luvuvhu and Letaba WMA (DWA, 2004). However, these additional areas will not be part of this Reconciliation Strategy.

The Limpopo WMA North comprises of six main river catchments; Matlabas, Mokolo, Lephalala, Mogalakwena, Sand and Nzhelele, as shown in **Figure 1.1**. Most of these river catchments rely on their own water resources and are managed independently from neighbouring catchments. This implies that some river catchments require separate and independent reconciliation strategies whilst others need integrated water resources management reconciliation strategies.

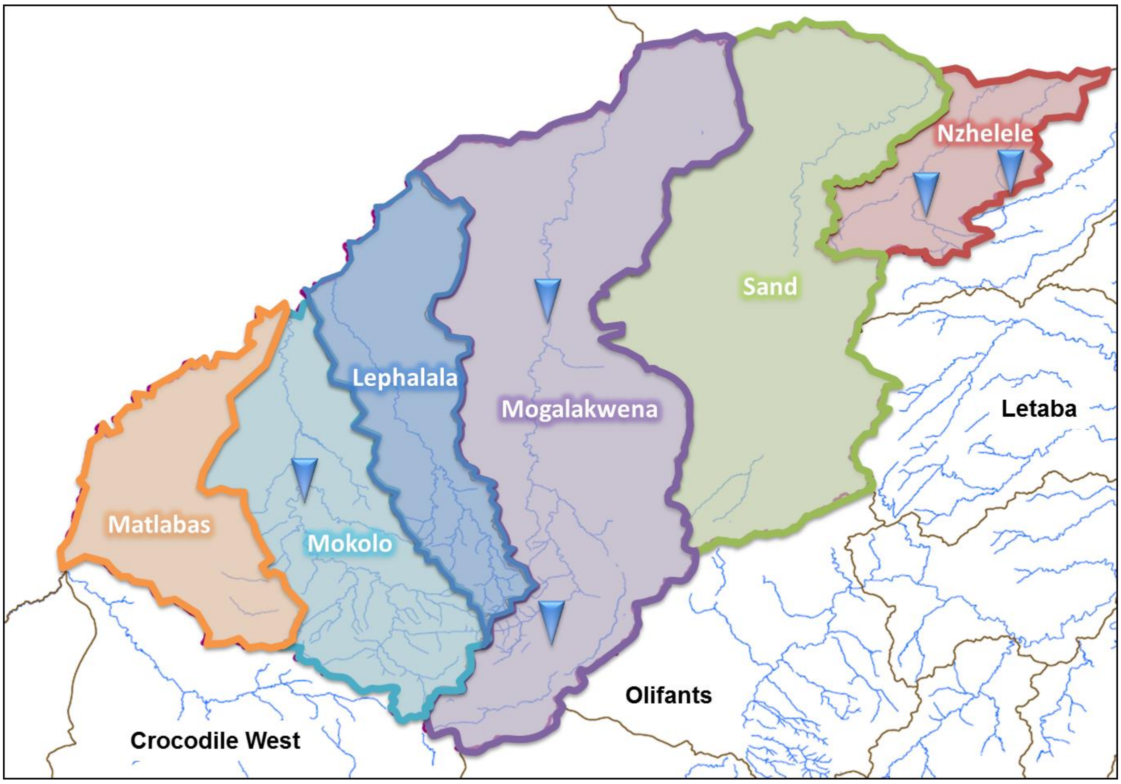

Figure 1.1: Overview of the catchments of the Limpopo WMA North

The main urban areas within the WMA include Mokopane, Polokwane, Mookgophong, Modimolle, Lephalale, Musina and Makhado. Approximately 760 rural communities are scattered throughout the WMA, mostly concentrated in the central region. The main economic activities are irrigation and livestock farming as well as the expanding mining operations due to the vast untapped mineral resources in the area. The water resources, especially surface water resources, are heavily stressed due to the present levels of development. It is crucial that water supply is secured and well managed.

The most western area of the Limpopo WMA North, the Matlabas River catchment, is a dry catchment with no significant dams and low growth potential for land-use development.

The large Mokolo Dam, in the Mokolo River catchment, supplies water to the Matimba Power Station, Medupi Power Station, Grootegeluk Coal Mine, the Lephalale Local Municipality (LM) as well as a number of downstream irrigators. The dam is able to meet the bulk of the current requirements but will in future rely on transfers from other WMAs to provide the water requirements of the aforementioned power stations with a sufficient high assurance of supply.

The middle reaches of the Lephalala River catchment have a high conservation value with irrigation activities dominant in the remainder of the catchment. Irrigation in this area is supplied by surface water and alluvial aquifer abstraction.

The bulk of the water resources in the Mogalakwena River catchment have been fully developed. The Doorndraai Dam is over allocated. Additional water to support the rapid expanding mining activities in the vicinity of Mokopane needs to be augmented by transfers from the Flag Boshielo Dam in the adjacent Olifants River catchment. Glen Alphine Dam presently supplies water to emerging farmers, who has not yet taken up their full allocated quota, and is expected to supply the growing domestic requirements in future.

Groundwater resources in the Mogalakwena and the Sand river catchments have been extensively utilised, and possibly over-exploited by the dominating irrigation sector. The expanding urban and industrial requirements of Polokwane and Makhado LMs, currently supplied by Albasini Dam, rely heavily on water transfers from adjacent WMAs. This includes transfers from the Ebenezer Dam, Dap Naude Dam, Flag Boshielo Dam and Nandoni Dam in the Olifants WMA.

Domestic and irrigation water in the small but highly developed Nzhelele River catchment is supplied through the Mutshedzi Dam Regional Water Supply Scheme and the Nzhelele Dam Regional Water Supply Scheme as well as extensively from groundwater resources. The inflows to the Mutshedzi and Nzhelele dams have been significantly reduced as a result of significant afforestation upstream of these dams. The area is in deficit due to the over-allocation and over development of irrigation.

The Sand and Nzhelele river catchments have high coal mining potential but the availability of local water resources may limit future mining development.

1.3 STUDY AREA

The Limpopo WMA North is the most northern WMA in South Africa and refers to the area described as the Limpopo WMA in NWRS-1. Refer to **Figure 1.2** for the location and general layout of the Study Area. The areas indicated in grey show the additional catchment and WMA areas included in the Limpopo WMA as per NWRS-2 and which do not form part of the Study Area for this reconciliation strategy.

The Limpopo WMA North forms part of the internationally shared Limpopo River Basin which also includes sections of Botswana, Zimbabwe and Mozambique. The Limpopo River forms the entire length of the northern international border between South Africa and Botswana and Zimbabwe before flowing into Mozambique and ultimately draining into the Indian Ocean. The dry Limpopo WMA North is augmented with transfers from the adjacent Letaba, Olifants and Crocodile West river catchments. No transfers are currently made from the Limpopo WMA North to other WMAs.

The main rivers in the Study Area, which form the six major catchment areas, are the Matlabas, Mokolo, Lephalala, Mogalakwena, Sand and Nzhelele rivers. These rivers, together with other smaller tributaries, flow northwards and discharge into the Limpopo River.

The climate over the Study Area is temperate and semi-arid in the south to extremely arid in the north. Mean annual rainfall ranges from 300 mm to 700 mm with the potential evaporation well in excess of the rainfall. Rainfall is seasonal with most rainfall occurring in the summer with thunderstorms. Runoff is low due to the prevalence of sandy soils in the most of the Study Area, however, loam and clay soils are also found.

The topography is generally flat to rolling, with the Waterberg on the south and the Soutpansberg in the north-east as the main topographic features. Grassland and sparse bushveld shrubbery and trees cover most of the terrain.

The southern and western parts of the WMA are mainly underlain by sedimentary rocks, whilst metamorphic and igneous rocks are found in the northern and eastern parts. With the exception of some alluvium deposits and dolomites near Mokopane and Thabazimbi, these formations are mostly not of high water bearing capacity. The mineral rich Bushveld Igneous Complex extends across the south-eastern part of the WMA, and precious metals are mined at various localities throughout the area. Large coal deposits are found in the north-west.

Several wildlife and nature conservation areas have been proclaimed in the WMA, of which the Nylsvley Nature Reserve, Mapungubwe National Park and the Marekele National Park are probably the best known.

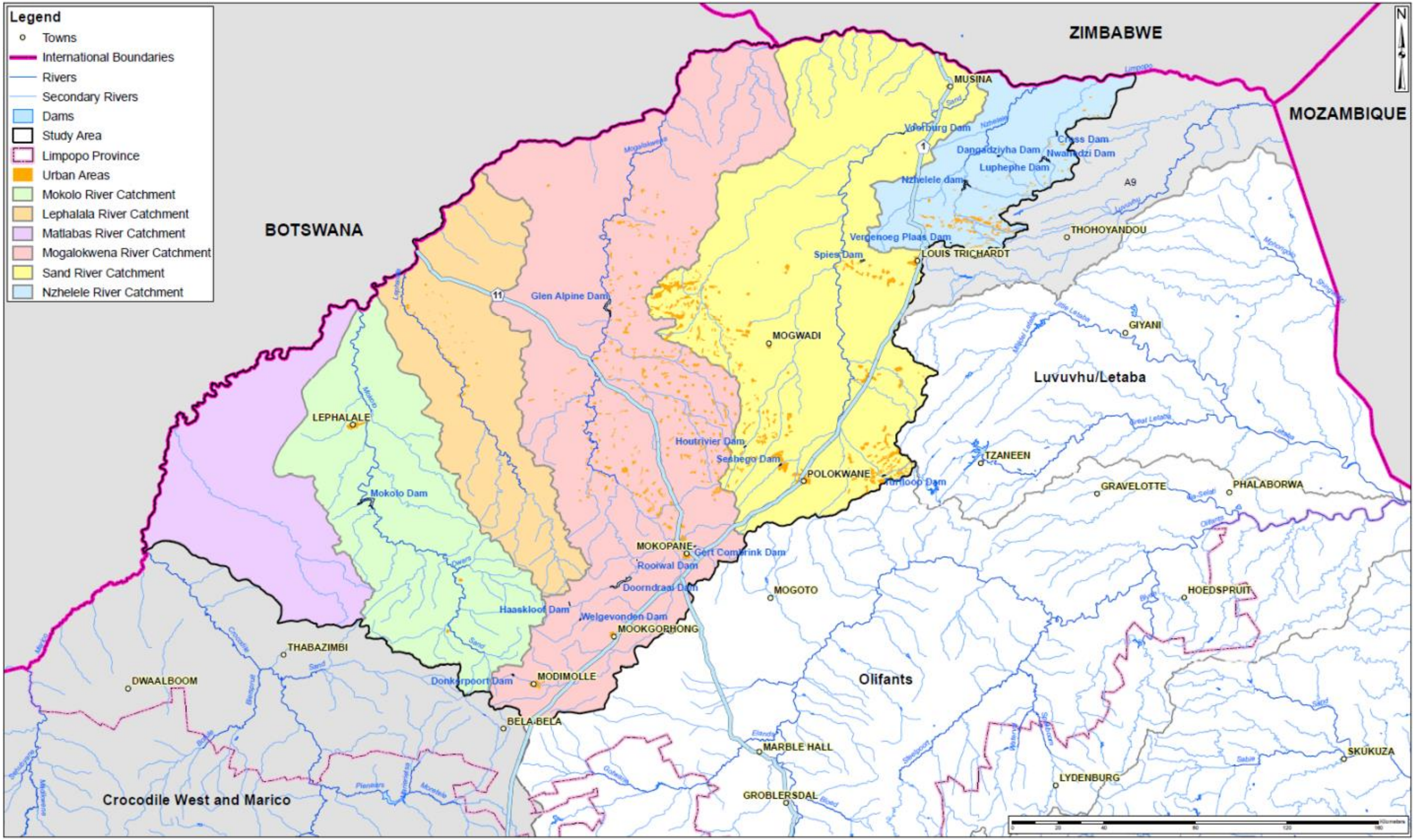

Figure 1.2: Study Area

1.4 MAIN OBJECTIVES OF THE STUDY

The main objective of the study is to formulate a water resource reconciliation strategy for the entire Limpopo WMA North up to 2040. The reconciliation strategy must a) address growing water demands as well as water quality problems experienced in the catchment, b) identify resource development options and c) provide reconciliation interventions, structural and administrative/ regulatory. To achieve these objectives, the following aspects are included in the study:

- Review of all available information regarding current and future water requirements projections as well as options for reconciliation;
- Determine current and future water requirements and return flows and compile projection scenarios;
- Configure the system models (WRSM2000 rainfall-runoff catchment model, also known as the Pitman Model, the *Water Resources Yield Model* (WRYM) and the *Water Resources Yield Model* (WRPM)) in the study area at a quaternary catchment scale, or smaller, where required, in a manner that is suitable for allocable water quantification. This includes updating the hydrological data and accounting for groundwater surface water interaction;
- Assess the water resources and existing infrastructure and incorporate the potential for *Water Conservation and Water Demand Management* (WCWDM) and water reuse as reconciliation options; and
- Develop a preliminary short-term reconciliation strategy followed by a final long-term reconciliation strategy.

1.5 PURPOSE AND STRUCTURE OF REPORT

The purpose of this report is to provide a detailed description of the hydrological analysis of the Limpopo WMA North river catchments. The report includes summaries of:

- The objectives of the hydrological analysis;
- The information of the data sources;
- The water use and return flow, infrastructure and hydro-meteorological data used in the analysis;
- The rainfall-runoff modelling results;
- The evaluation of the results; and
- The conclusions and recommendation from the analysis.

1.6 OBJECTIVES OF HYDROLOGICAL ANALYSIS

The key objectives of the hydrological analysis of the Limpopo WMA North were to:

- Evaluate, improve, update and extend available stream flow data from previous studies to cover the Study Period of 1920 to 2010 (i.e. October 1920 to September 2011) using updated rainfall and land-use data; and
- Generate time-series of natural monthly stream flow for the hydrological years 1920 to 2010 (i.e. October 1920 to September 2011) at a quaternary or sub-quaternary (quinary) catchment level, where appropriate.

The enhanced *Water Resources Simulation Model 2000* (WRSM2000) rainfall-runoff model including the *Groundwater-Surface Water Interaction Model* (GWSWIM) or Sami-model was used for the hydrological analysis.

The catchment rainfall time-series produced as part of the rainfall analysis served as input to the WRSM2000 for the purpose of calibration against the observed stream flow records and generation of long term natural stream flow time-series. The rainfall analyses are discussed in detail in the *Rainfall Data Analysis Report (P WMA 01/000/00/02914/2/1)*. The natural stream flow time-series are a critical input to the water resource system yield and planning analyses using the *Water Resources Yield Model* (WRYM) and *Water Resources Planning Model* (WRPM).

1.7 METHODOLOGY

The following steps were undertaken to meet the objectives of the hydrological analysis:

- Collect and evaluate water use, return flow, infrastructure and hydro-meteorological data from various information sources (described in detail in **Section 2**);
- Develop comprehensive schematic network diagrams representative of the runoff and water use for the six river catchments in the Study Area for the hydrological analysis (See **Appendix B**);
- Evaluate, format and patch the available stream flow data to meet the WRSM2000 requirements;
- Verify the WRSM2000 model configurations;
- Calibrate observed stream flow and groundwater abstractions against catchment rainfall through adjustment of the WRSM2000 parameters;

- Generate natural long term stream flow time-series for the Study Period of 1920 to 2010 (i.e. October 1920 to September 2011); and
- Assign confidence levels to the results obtained from the analysis.

2 INFORMATION SOURCES

2.1 PREVIOUS AND PARALLEL HYDROLOGICAL STUDIES

Details of previous and parallel studies in the Study Area are provided in Table 2.1. A brief overview on the availability and level of detail of the hydrological data of each study are also included.

Table 2.1: Previous and parallel studies in the Limpopo WMA North area

Study name	Reference study name	Relevant Catchment	Date of Study	Level of Study	WRSM2000 Study Period (Hydrological years)
Water Resources of South Africa - 2005	WR2005	Study Area (A4 to A8)	2008	National	1920 – 2004
Updating the Hydrology and Yield Analysis in the Mokolo River catchment	Mokolo	A42	2007	Detailed	1920 – 2003
The Limpopo River Basin Monograph	LIMCOM	Study Area (A4 to A8)	2010	Low	1920 – 2010
Water Resources of South Africa - 2012	WR2012	Study Area (A4 to A8)	2015	National	1920 – 2009
Nyl River Hydrological Modelling	Nylsvlei	A61A to A61E	2014	Detailed	1920 – 2009

A full set of the WRSM2000 system configurations and hydro-meteorological data from the *WR2005 Study* (WRC, 2008) were produced for the entire Limpopo WMA North. However, these results do not provide the necessary spatial resolution and detailed water- and land-use data required by this *Study*. Furthermore, the Limpopo WMA North groundwater resources are regarded as critical to augment the existing water resources, specifically in the remote areas of the Study Area where surface water resources are limited. Being a national study, the WR2005 Study could not give the necessary attention to the detailed calibration of the groundwater (Sami) parameters. It is also particularly important to gain a better understanding of the groundwater surface water interaction in the Study Area to fully utilise and protect this valuable resource.

The *LIMCOM Study* (LIMCOM, 2013) based their WRSM2000 system configurations, and hence their spatial resolution on that of WR2005 Study. The LIMCOM Study did not recalibrate the WRSM2000 but simply extended the natural stream flow of the WR2005 Study up to the 2010 hydrological year (September 2011).

The *Mokolo Study* (DWA, 2007) configured the WRSM2000 system for the Mokolo River catchment to a high spatial resolution and obtained good calibration results. The hydrological analysis of the Mokolo River catchment focused on the impact of irrigation supplied from both groundwater and surface water on the surface runoff. The Mokolo River catchment's WRSM2000 model configuration was accepted without any changes for the hydrological analysis of this Study, i.e. no recalibration was done and the hydro-meteorological data were simply extended with seven years up to the 2010 hydrological year (September 2011).

The *WR2012 Study* (DWA, 2013) was not yet completed at the time of conducting this hydrological analysis and hence only data available at that time, such as the rainfall data, could be used.

The *Nylsvlei Study* (EScience Associates, 2014) used a novice approach to model the Nylsvlei wetland situated in the upper reaches of the Mogalakwena River catchment. Nylsvlei is an instream wetland, unlike most other wetlands which are mostly off-channel wetlands. The methodology applied in the Nyl Study was adopted for the hydrological analysis of this Study. The modelling procedure and the results obtained are discussed in **Section 7.2.2.**

2.2 PARALLEL STUDIES

Results available from parallel studies undertaken in the Limpopo WMA North provided an important source of information for the hydrological analysis undertaken as part of the *Limpopo WMA North Reconciliation Strategy*.

Schoeman & Vennote, who are also part of this study team, recently conducted the *Validation and Verification Study for the Limpopo WMA* (DWA, 2013a), along with other sub-consultants, for the DWS. The study will be referred to as the *V&V Study* in this report. The V&V Study included three main components:

- An assessment which provided a broad overview of the current irrigation water use situation in the Study Area based on information obtained from aerial photography and satellite imagery;
- Validation of the irrigation water use in the Study Area by means of detailed investigations, including sampled field surveys. The results of the validation process show various levels of development, including 2014 and 1998; and
- Verification of the irrigation water use in the Study Area to determine the extent of existing lawful use.

Results from the V&V Study (DWA, 2013a), especially with regard to irrigation requirements from groundwater, provided essential information to the hydrological analysis. The following information was incorporated in this Study:

- The current and historical characteristics of irrigation in the Study Area, which include the extent of irrigated areas, crop types, irrigation systems and associated efficiencies, approach to calculate irrigation volumes, sources of water and associated return flow volumes.
- The current and historical characteristics of water bodies, including the locality, size and volume-surface area relationships for small storage dams;
- The current afforestation developments in the Sand and Nzhelele river catchments in terms of the type of tree species and the associated percentage distribution in each quaternary catchment.

2.3 OTHER SOURCES

Table 2.2 summarises additional sources of information considered for the hydrological analysis. Note that appropriate references were made to these sources in the associated sections of this report.

Table 2.2: Additional sources of information for the hydrological analysis

Data Type	Information Source
Rainfall data	• Reconciliation Strategy *Rainfall Analysis Report (P WMA 01/000/00/02914/2/1).*
Monthly evaporation data	• The WR90 publications (WRC, 1994). • The WR2005 publication (WRC, 2008). • DWS weather stations.
Monthly raw gauged stream flow data and monthly reservoir balance data	• DWS HYDSTRA database. • Operational releases information for the Glen Alpine and Nzhelele dams were obtained from operational managers at these dams. • Research institutions.
Maps of river systems and catchment areas	• The WR90 publications (WRC, 1994) and the WR2005 publication (WRC, 2008). • Satellite imagery. • Google Earth.
Characterisation of groundwater-surface water interaction	• Groundwater specialists and the GWSWIM. • GRAII Study (DWA, 2006) and other studies undertaken by DWS to characterise the groundwater resources of the country. • The V&V Study (DWA, 2013a) to estimate groundwater utilisation. • Publications from research institutions.
Water Use Data	• WARMS registered water use database. • DWS Regional Office. • All Towns Reconciliation Study (DWA, 2011). • The V&V Study (DWA, 2013a) for irrigation related water use.

3 STUDY AREA AND HYDROLOGICAL CHARACTERISTICS

The Study Area for the hydrological analysis as part of the *Limpopo WMA North Reconciliation Strategy* covers the entire Limpopo WMA North as described in **Section 1.3**. The Study Area comprises of six major river catchments which are all tributaries to the Limpopo River, namely the Matlabas, Mokolo, Lephalala, Mogalakwena, Sand and the Nzhelele (including the Nwanedi) river catchments. Furthermore, the river catchments are sub-dived into nine tertiary catchments and 68 quaternary catchments.

As part of the hydrological analysis, quaternary catchments in the Study Area were divided into a number of smaller sub-catchments (*sub-quaternaries* or *quinaries*), for modelling purposes where necessary. The subdivision of quaternaries was based on the physical layout of the catchment in question, taking into account aspects such as the locality of the main tributaries relative to the main-stem river, the location of flow gauging stations, water use abstractions, return flow centres and water bodies.

A brief overview of the hydrological characteristics of each of the six major catchments per tertiary catchment is summarised in **Table 3.1**. A detailed breakdown of the meteorological input data for the hydrological analysis, viz. *Mean Annual Precipitation* (MAP) and *Mean Annual Evaporation* (MAE), is provided in **Table H.2** of **Appendix H** per quaternary and sub-quaternary catchments. Furthermore the rainfall and evaporation characteristics of the Study Area are illustrated in **Figures A.2** and **A.3** of **Appendix A** respectively.

Table 3.1: Summary of the WR2005 hydrological characteristics of the six major river catchments within the Limpopo WMA North

River catchment	Tertiary catchment	River	Gross Area	Net Area	MAR	MAP	MAE
			km^2	km^2	million m^3/a	mm/a	mm/a
Matlabas	A41	Matlabas	6014	3 613	51	516	1 899
Mokolo	A42	Mokolo	8 395	7 610	264	558	1 807
Lephalala	A50	Lephalala	6 725	5 041	143	490	1 880
Mogalakwena	A61	Nyl	5 452	5 227	163	614	1 750
	A62	Mogalakwena	5 795	5 584	69	479	1 883
	A63	Mogalakwena	8 067	6 981	41	391	2 014
Sand	A71	Sand	12 307	11 932	70	392	1 820
	A72	Brak	3 462	2 592	16	406	1 924
Nzhelele	A80	Nzhelele/Nwanedi	4 203	4 064	115	457	1 746
Total-Limpopo WMA North			**60 420**	**52 643**	**931**	**471**	**1 854**

The hydrology of the six major river catchments, as well as the potential water resources to meet current and future water requirements, are described below:

- *The Matlabas River (A41A to A41E)* - The Matlabas River catchment is a dry catchment with non-perennial flow and hence no sustainable yield from surface water. The limited water use in this catchment is mostly from groundwater, which is under-exploited.
- *The Mokolo River (A42A to A42J)* - The Mokolo River catchment is located in the higher rainfall portion of the Study Area and is also the most developed catchment from a water resources perspective. The Mokolo Dam is the largest dam in the Study Area and provides water for a multitude of uses. There is also a significant amount of irrigation from groundwater. Groundwater is under-utilised and could be used to support increased domestic requirements, provided the water quality is acceptable. Water will also be transferred from the Crocodile (West) River catchment to augment the supply to the Lephalale town area to support new strategic power and mining developments by means of the *Mokolo and Crocodile River (West) Water Augmentation Project* (DWA, 2009).
- *The Lephalala River (A50A to A50J)* - The Lephalala River catchment has limited water resources. Irrigation takes place mainly in the higher rainfall upper reaches where there are a large number of farm dams. Irrigators in the lower reaches make use of water from alluvial aquifers. The catchment appears to be stressed and no new allocations should be made for irrigation purposes. The middle reaches of the Lephalala River catchment has a high

conservation value and is sensitive to development. Hence, WCWDM is critical to minimize the deficit in the catchment. Furthermore, additional water for domestic purposes should be sourced from groundwater should WCWDM not suffice.

- *The Mogalakwena River (A61, A62 and A63)* - The Mogalakwena River catchment has limited surface water resources but large groundwater resources, which have already been extensively exploited by the irrigation sector. The towns of Modimolle, Mookgopong and Mokopane are mostly supplied by Doorndraai Dam and transfers from Roodeplaat Dam in the Crocodile (West) River catchment. There is a rapid expansion of mines in the area and the water supply to these mines must be secured as a matter of priority. Additional water resources are groundwater and transfers from the Flag Boshielo Dam in the Olifants River catchment.
- *The Sand River (A71 and A72)* - The Sand River catchment is a dry catchment with very limited surface water resources. However, it has exceptional groundwater reserves which have been fully and possibly over-exploited, mostly by irrigation. The water requirements are large compared to the rest of the Study Area, but again irrigation is the largest water user. Urban requirements are supplied mostly from transfers from other WMAs. Polokwane is mostly supplied from transfers from the Dap Naude and Ebenezer dams located in the Luvuvhu and Letaba WMA (as defined in the NWRS-1 (DWA, 2004) and the Olifantspoort weir in the Olifants River catchment. Louis Trichardt is supplied from transfers from the Albasini and Nandoni dams in the Luvuvhu and Letaba WMA (as defined in the NWRS-1 (DWA, 2004))
- *The Nzhelele River (A80A to A80G) and the Nwanedi River (A80H to A80J)* - The Nzhelele River has a small catchment dominated by irrigation, with a small area of afforestation and domestic use by the rural sector. Nzhelele Dam is the second largest dam in the Study Area and provides most of the water requirements in this catchment while groundwater is also extensively used. The Nwanedi River catchment is a very small catchment in the north-eastern corner of the Study Area characterised by over-allocated and large over-developed areas under irrigation. For the purpose of this report, the Nzhelele River catchment will refer to both the catchment area of the Nzhelele River as well as the catchment area of the Nwanedi River.

4 WATER USE AND RETURN FLOWS

4.1 OVERVIEW

A comprehensive assessment of the current and historical water use and human activities that impacted on stream flow were undertaken as part of this Study. Refer to the *Water Requirements and Return Flows Report (P WMA 01/000/00/02914/4)* for detail information in this regard. These water uses served as input to WRSM2000 for calibration purposes.

Major water and land use development in the Study Area took place towards the late 1940s, following the commissioning of the two large Nzhelele and Doorndraai dams. These dams initiated the development of especially large-scale irrigation, which is currently the largest water user in the Study Area. New power stations and mining developments, as well as the associated secondary developments, will increase the domestic and industrial water use. *Stream flow reduction* (SFR) activities through the high prevalence of *invasive alien plants* (IAP) are widespread in the Study Area. The impact of afforestation on SFR is limited to the areas with high rainfall (> 800 mm/a) such as on the slopes of the Soutpansberg Mountains in the upper reaches of the Nzhelele River catchment.

The water requirements of the seven major urban centres found within the Study Area, namely Modimolle, Mookgophong, Lephalale, Mokopane, Polokwane, Makhado and Musina, are supplied from several of sources. There are also several smaller rural water supply schemes which supply approximately 760 communities mainly from groundwater. Furthermore, a large part of the population within the Study Area is dependent on subsistence agriculture and hence livestock watering also contributes to the water use.

A summary of the water requirements at the 2010-development level, as sourced from the V&V Study (DWA, 2013a) and the *All Towns Studies* (DWA, 2011), is presented in **Table 4.1**. It is important to note that some of the irrigation water requirements are not supplied from water resources within the Study Area (i.e. from water resources not fed by runoff generated in the Study Area), but from the Limpopo River main stem and associated sand aquifers. This is further discussed in **Section 4.3.3**. The irrigation water requirements given in **Table 4.1** are the total requirements, inclusive of the water sourced from the Limpopo River main stem.

Table 4.1: Summary of total water requirements in the Limpopo WMA North at the 2010-development level

Sector	Source	Water requirements (million m^3/a)						
		Matlabas	Mokolo	Lephalala	Mogalakwena	Sand	Nzhelele	Total
Irrigation	Surface water[1]	2.41	36.98	42.91	39.41	53.59	25.16	200.46
	Groundwater	2.32	3.18	26.90	60.00	168.05	3.93	264.36
	Sub-total	**4.73**	**40.16**	**69.81**	**99.41**	**221.64**	**29.08**	**464.82**
Domestic	Surface water	-	5.00	-	7.94	10.66	3.16	26.76
	Groundwater	-	1.01	2.98	14.83	31.96	4.56	55.34
	Sub-total	**0.00**	**6.01**	**2.98**	**22.77**	**42.62**	**7.72**	**82.10**
Mining and power generation	Surface water	-	11.20[2]	-	-	-	-	11.20
	Groundwater	-	-	-	1.59[3]	4.20[4]	-	5.79
	Sub-total	**0.00**	**11.20**	**0.00**	**1.59**	**4.20**	**0.00**	**16.99**
IAP[5]	Surface water	-	-	1.18	2.58	0.99	2.13	6.88
Afforestation[5]	Surface water	-	-	-	-	0.16	2.01	2.17
Livestock	Surface water	2.28	2.11	2.39	11.49	5.15	1.75	25.17
Catchment total	Surface water	4.69	55.29	46.48	61.42	70.55	34.20	272.63
	Groundwater	2.32	4.19	29.88	76.42	204.21	8.49	325.49
	Total	**7.01**	**59.48**	**76.36**	**137.84**	**274.76**	**42.68**	**598.12**

Note: (1) Includes supply from irrigation schemes.

(2) Grootegeluk Coal Mine (5.10 million m^3/a) and Matimba Power Station (6.10 million m^3/a) - both supplied from Mokolo Dam.

(3) AMPLATS Platinum Mine (1.59 million m^3/a).

(4) Venetia Diamond Mine (4.20 million m^3/a).

(5) Reduction in runoff.

4.2 DOMESTIC AND SMALL INDUSTRIAL WATER USE

Domestic and industrial water use (excluding mining and power generation) in the Study Area is supplied by several sources namely; boreholes, springs, rain water, dams, pools, stagnant water, rivers or streams, water vendors and water tankers. The estimated total current domestic and industrial water requirement in the Study Area is 82 million m^3/a.

Domestic and industrial water requirements, sourced from surface water, are mainly supplied by six dams in the Study Area. These dams include the Mokolo Dam, Donkerpoort Dam, Welgevonden Dam, Doorndraai Dam, Houtrivier Dam and Mutshedzi Dam. Groundwater is a significant water resource in the Study Area, supplying approximately 67 % of the domestic and industrial water use. A large number of rural communities rely solely on groundwater abstracted from well fields or alluvial aquifers along the Sand and Limpopo rivers. The largest concentration of groundwater users are found in the following quaternary catchments:

- *A71C*, which includes the Botlokwa Groundwater Scheme (GWS), Ramakgopa GWS and Rietgat GWS; and
- *A72A,* which includes the Avon GWS, Blouberg GWS, Ga-Hlako GWS, Silwermyn/Kirstenspruit GWS, Senwarabarwana GWS, Mogwadi/Wurthsdorp GWS, and Molemole West GWS.

Water transfers from adjacent WMAs as defined in the NWRS-1 (DWA, 2004) augment supply to urban centres such as Polokwane, Louis Trichardt, Modimolle and Mookgopong. Polokwane relies on transfers totalling 25 million m^3/a from Ebenezer Dam and Dap Naude Dam, in the Luvuvhu and Letaba WMA, as well as the Olifantspoort Weir, in the Olifants WMA. Water is transferred from Albasini Dam (Luvuvhu and Letaba WMA) to Louis Trichardt and augmented by transfers from Nandoni Dam (Luvuvhu and Letaba WMA) when required. Modimolle and Mookgopong are supplied by Roodeplaat Dam in the Crocodile (West) and Marico WMA. Future transfers include additional transfers from Nandoni Dam to Louis Trichardt, effluent return flows from the Crocodile River (Crocodile (West) and Marico WMA) to the Lephalala River catchment as part of the *Mokolo and Crocodile River Water Augmentation Project* (MCWAP) and a possible transfer from the Klipvoor Dam in the Crocodile (West) and Marico WMA to Mookgopong.

Table C.1 of Appendix C summarises the total domestic and industrial water requirement in the Study Area at the 2010-development level. Note that only quaternary catchments with a domestic water requirement of more than 0.1 million m^3/a are shown in the table.

4.3 IRRIGATION WATER USE

4.3.1 Overview

Irrigation is the dominant water user in the Study Area, comprising 78% of the total water requirement. The main crops within the Study Area include tobacco and citrus. Dryland cultivation with crops such as grain sorghum and cotton are also practised.

The estimated irrigated area at the 2010-development level is 666 km^2 with an annual water requirement of 465 million m^3. However, 152 km^2, with a water requirement of 146 million m^3, is directly supplied from the Limpopo River main stem and associated sand aquifers. Approximately 57% of the irrigation is supplied from groundwater and 36% from surface water with only 7% from regulated government irrigation schemes. Approximately 48% of the total irrigated area is located in the dry Sand River catchment, supplied mainly by groundwater resources.

No significant irrigation growth is expected in the Study Area due to the limited water resources. Furthermore, a large number of irrigation farmers are converting to game farming. This happens at a greater scale in the Mokolo, Lephalala and Sand river catchments with a consequent reduction in the irrigation water requirement.

Detailed information, both historical and current, obtained from the V&V Study (DWA, 2013a) includes:

- Extent of irrigated area, crop types and source of water for each area under irrigation;
- Representative monthly crop requirements (in mm/a) per quaternary catchment;
- Representative irrigation efficiencies and return flow estimates per quaternary catchment (as a percentage of the supply); and
- Scheme allocation limits.

The irrigation assessment describes the location, the source and volume of water required by the irrigators. The simulation of irrigation water supply to was used to quantify the impact on groundwater and surface water resources and to get a better understanding on their interaction. This information served as one of many inputs to the WRSM2000 to calibrate the model.

4.3.2 Areas under irrigation

The location and extent of irrigated areas in the Study Area are shown in **Figure A.4** of **Appendix A**.

A summary of the irrigated areas at the 2010-development level supplied from surface water, such as dams, rivers and schemes, as well as from groundwater, is provided in **Table 4.2** for each river catchment in the Study Area. Distinction is made between the irrigation water requirements supplied by water resources fed by runoff generated in the Study Area and the irrigation water requirements supplied from the Limpopo River main stem and associated sand aquifers.

The irrigated area for each quaternary catchment is provided in **Table C.2** of **Appendix C**. Distinction is made between the area supplied from surface water, schemes and groundwater. **Table C.2** also shows the historical growth in irrigated area over the period 1920 to 2010 and is graphically represented in **Figure C.1** and **Figure C.2**.

Table 4.2: Summary of irrigated areas in the Limpopo WMA North at the 2010-development level

River catchment	Irrigated area (km^2)									
	Surface water			Groundwater			Scheme	Total		
	Catchments[1]	Limpopo[2]	Total	Catchments[1]	Limpopo[2]	Total	Catchments[1]	Catchments[1]	Limpopo[2]	Total
Matlabas	2.6	2.6	5.2	1.9	0.3	2.2	-	4.5	2.9	7.4
Mokolo[3]	81.1	-	81.1	9.5	-	9.5	-	101.4	-	101.4
Lephalala	52.6	0	52.6	30.4	22.2	52.6	-	63.7	22.2	83.0
Mogalakwena	43.5	4.6	48.1	58.1	16.8	74.9	10.9	112.5	21.4	133.9
Sand	27.5	27.9	55.4	243.5	0	243.5	-	271	27.9	298.9
Nzhelele	2.5	8	10.5	5.6	0.1	5.7	25.2	33.3	8.1	41.5
TOTAL	**209.7**	**43.3**	**253**	**329.8**	**36.4**	**366.2**	**46.9**	**586.3**	**79.7**	**666.1**

Note: (1) Area supplied from sources fed by runoff generated in the Study Area only.
(2) Area supplied by the Limpopo River main stem and associated sand aquifers.
(3) From the "Updating the Hydrology and Yield Analysis in the Mokolo River Catchment" Study (DWA, 2007).

4.3.3 Irrigation requirements and return flows

The irrigation water requirements, supplies and return flows were simulated in WRSM2000 using the WQT-SAPWAT *Irrigation Block (RR) Module* which requires the following information as input:

- *Rainfall time-series* and *average monthly evaporation* representative of the area under irrigation.
- *Area under irrigation* and the *historic irrigation area growth* over the study period. This information is supplied per quaternary catchment in **Table C.2** of **Appendix C**.
- *Representative quaternary catchment crop irrigation requirements*, which are calculated from the field area weighted crop irrigation requirement (in mm per month) for all the fields in a quaternary catchment, obtained from SAPWAT (WRC, 1999). **Table C.3** summarises the monthly representative crop irrigation requirements as obtained from (DWA, 2013a), per quaternary catchment.
- *Weighted irrigation application efficiency* for each quaternary catchment's representative crop, calculated from SAPWAT using the crop and irrigation system combinations in each catchment. Refer to **Table C.4**. Due to the lack of documented information regarding the changes in irrigation systems over the Study Period, application efficiencies, as the calculated SAPWAT values

for present day conditions, for all quaternary catchments were assumed to have remained constant throughout the simulation period of active irrigation.

- *The total return flows* returned to the river system, expressed as a percentage of the supply, was derived from the application efficiency for each quaternary catchment. This information, obtained from the V&V Study (DWA, 2013a), is also given in **Table C.4**.
- *Effective rainfall factors* were automatically calculated by the SAPWAT model based on actual rainfall and the representative crop irrigation requirement for the month in question.
- *The drought reduction* functionality was enabled, which reduced the irrigation requirement in below-average rainfall years to account for reduced irrigation during dry years as well as a delay in the planting time during dry months.

All the aforementioned information was obtained from the V&V Study (DWA, 2013a).

The average annual irrigation water requirement and the return flows at the 2010-development level were determined from the irrigated areas (**Table C.2** of **Appendix C**). A summary of the average annual irrigation water requirements per river catchment is provided in **Table 4.3** and per quaternary catchment in **Table C.5**. **Table 4.4** provides a summary of the average annual return flows per river catchment and **Table C.6** per quaternary catchment, at the 2010-development level. For **Table 4.3**, **4.4**, **C.5** and **C.6** distinction is made between the irrigated areas supplied from surface water, groundwater and irrigation schemes. Distinction is also made in **Table 4.3** and **C.5** between the irrigation water requirements supplied by water resources fed by runoff generated in the Study Area and the irrigation water requirements supplied from the Limpopo River main stem and associated sand aquifers.

Table 4.3: Summary of irrigation water requirements in the Limpopo WMA North at the 2010-development level

River catchment	Irrigation water requirements (million m^3/a)									
	Surface water			Groundwater			Scheme	Total		
	Catchments	Limpopo	Total	Catchments	Limpopo	Total	Catchments	Catchments	Limpopo	Total
Matlabas	0.6	1.8	2.4	2	0.3	2.3	-	2.6	2.1	4.7
Mokolo*	30.9	0	30.9	3.2	0	3.2	6.1	40.2	0	40.2
Lephalala	38.5	4.4	42.9	0.7	26.2	26.9	-	39.2	30.6	69.8
Mogalakwena	25.4	6.1	31.5	43.2	16.8	60	7.9	76.5	22.9	99.4
Sand	9.9	43.7	53.6	126.8	41.3	168.1	-	136.7	85	221.6
Nzhelele	0.8	5.7	6.5	3.8	0.1	3.9	18.7	23.3	5.8	29.1
TOTAL	**106.2**	**61.7**	**167.9**	**179.7**	**84.7**	**264.4**	**32.7**	**318.5**	**146.4**	**464.8**

Note: (1) Area supplied from sources fed by runoff generated in the Study Area only.
(2) Area supplied by the Limpopo River main stem and associated sand aquifers.
(3) From the "Updating the Hydrology and Yield Analysis in the Mokolo River Catchment" Study (DWA, 2007).

Table 4.4: Summary of average annual irrigation return flows in the Limpopo WMA North at the 2010-development level

River catchment	Average annual irrigation return flows (% supply)			
	Surface water	Groundwater	Scheme	Total
Matlabas	0.19	0.19	0.00	0.38
Mokolo*	2.53	0.27	0.53	3.33
Lephalala	3.25	1.90	0.00	5.15
Mogalakwena	2.42	4.17	0.58	7.17
Sand	3.67	13.38	0.00	17.05
Nzhelele	0.69	0.42	1.78	2.89
TOTAL	**12.75**	**20.34**	**2.89**	**35.98**

* *From the "Updating the Hydrology and Yield Analysis in the Mokolo River Catchment" Study, (DWA, 2007).*

Due to the large irrigation areas scattered throughout the river catchments of the Study Area and the impracticality of modelling each area individually, logical irrigation area groups were identified and the individual areas combined to form a single representative model element. Irrigation areas in a quaternary or sub-quaternary catchment that are supplied from a similar source (dams, run-off-river scheme or groundwater) were combined and modelled using a single WRSM Irrigation Block Module.

Preliminary investigations indicated that since most groundwater irrigation areas are far from river courses, the impact of groundwater irrigation supply on surface stream flow is negligible. Consequently, for the purpose of this hydrological analysis, only the return flows from groundwater irrigation into rivers were modelled explicitly in the WRSM2000 – refer to **Section 7.2.2** for more information in this regard. However, irrigation supplied from groundwater was taken into account in the process of determining appropriate GWSWIM parameter values, which were subsequently applied in the calibration of WRSM2000. Furthermore, irrigation supply volumes were used as input for the GWSWIM.

It was also found that return flows are less than 0.01 million m^3/a if the total irrigation area per quaternary catchment, supplied from groundwater, is less than 30 hectares or 0.3 km^2. The sensitivity of the WRSM2000 is 0.01 million m^3/a and hence irrigation areas smaller than 0.3 km^2 were not modelled.

Modelled Irrigation Block return flows in WRSM2000 are controlled by means of a *Return Flow Factor.* The return flow factor was adjusted by the user, in an iterative process, until the average annual return flow volumes (as a percentage of supply) given in the V&V Study were achieved. Furthermore, flows routed through the Irrigation Block return flow channel can be selected to be either *Net Return Flow* or *Total Return Flow*. The Total Return Flow is calculated as the sum of two components:

- The amount of return flow generated as a direct result of the irrigation applied; and
- The runoff that would have been generated under natural conditions by the irrigated catchment area.

For the purpose of this hydrological analysis, the *Total Return Flow* option was selected since the WRYM Irrigation Block sub-model, which will be used in the subsequent yield analyses, models the *Total Return Flow*.

A separate WRSM2000 analysis was undertaken to determine the appropriate values for the Return Flow Factor for each quaternary catchment and hence to ensure that the correct average annual return flow volumes (as a percentage of supply) were achieved. This involved the modelling of a constant imaginary crop area of 20 km^2 in each of the quaternary catchments and based on the characteristics provided in **Tables C.3** and **C.4**. The analysis was undertaken using the *Net Return Flow*-option in WRSM2000. The results are shown in **Table C.7**.

4.4 INVASIVE ALIEN PLANTS

IAP tend to utilise more water compared to indigenous plant species and subsequently reduce the available runoff in a catchment. The IAP distribution and extent were obtained from the latest IAP survey report – the *National Invasive Alien Plant Survey* (ARC, 2010), conducted by the Agricultural Research Council (ARC). The survey provides information on the spatial distribution, the predominant species and the compacted densities of the IAP per quaternary catchment.

With the exception of the Matlabas River catchment, IAPs are widespread throughout most of the river catchments in the Study Area. The highest density of IAP occurs in the Sand River catchment with a total IAP condensed area of 134 km^2 (2% of catchment area).

IAP in the riparian zone have the largest impact on the reduction of runoff due to the greater water availability from rivers. The percentage IAP in the riparian zone was calculated by assuming that the riparian zone extends 100 m on both sides of a river.

Table 4.5 summarises the IAP distribution and the estimated 2010-development level runoff reduction used as input to the WRSM2000. Note that the area of IAP in the Matlabas River catchment is considered to be negligible. More detailed information on the distribution of IAP at the 2010-development level is provided on a quaternary basis in **Table C.8** of **Appendix C**. The table also includes the percentage distribution of the species of IAP in each quaternary catchment. **Figure 4.1** illustrates the relative proportion of the major IAP species in the Study Area.

As mentioned in **Section 2.1**, the WSRM2000 system model configuration for the Mokolo River catchment set up and calibrated as part of the Mokolo Study (DWA, 2007) was used for this Study. The impact of IAP on the runoff within the Mokolo River catchment was considered insignificant.

Table 4.5: Summary of IAP distribution and estimated runoff reduction for 2010-development levels in the Limpopo WMA North

River catchment	Condensed Area (km^2)	Area In Riparian (km^2)	% in Riparian Zone	2010 Development Runoff Reduction (million m^3/a)
Matlabas	-	-	-	-
Mokolo*	26.2	0.1	1.8	-
Lephalala	12.6	0.1	3.7	1.2
Mogalakwena	83.5	0.1	1.3	2.6
Sand	134.3	0.1	0.6	1.0
Nzhelele	59.0	0.0	0.0	2.1
TOTAL	**315.5**	**0.4**	**7.3**	**6.9**

* *As in the "Updating the Hydrology and Yield Analysis in the Mokolo River Catchment" Study (DWA, 2007)*

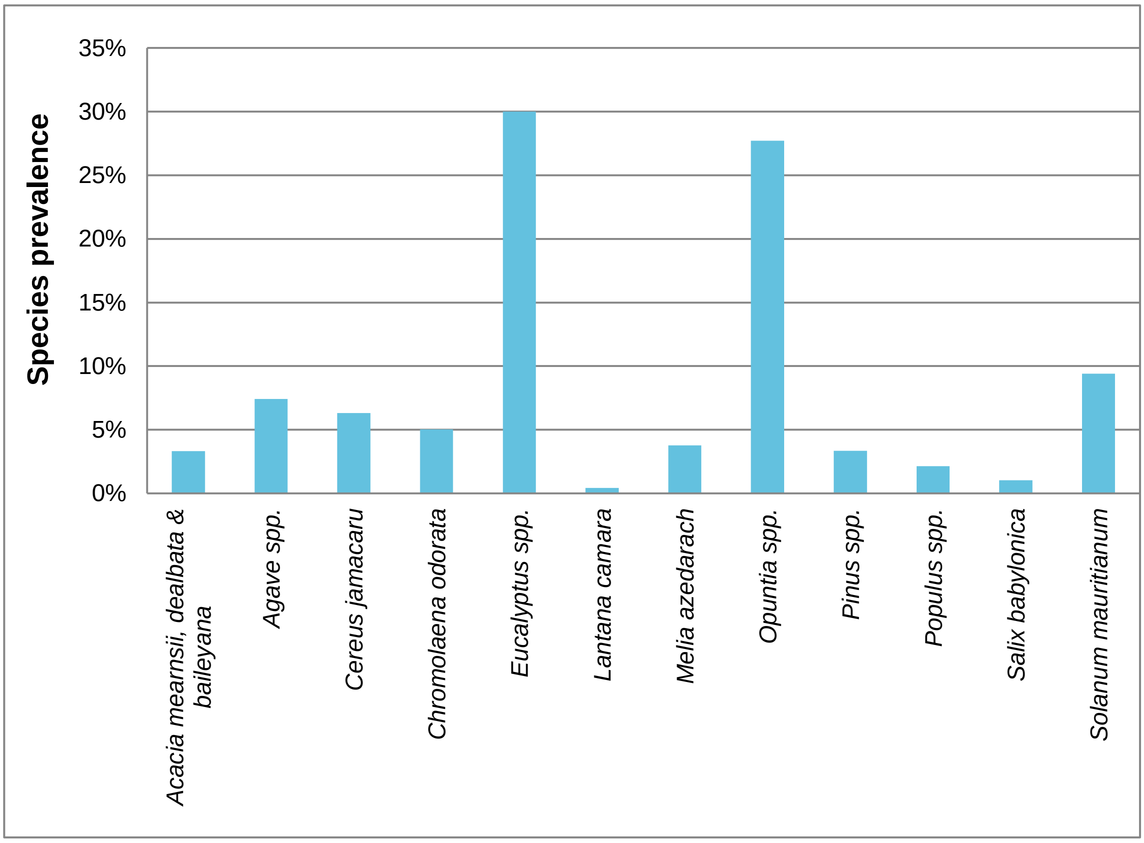

Figure 4.1: IAP species distribution in the Study Area

4.5 OTHER

4.5.1 Water use associated with mining activities and power generation

Current mining and power generation activities in the Study Area include:

- Matimba Power Station and the Grootegeluk Coal Mine which supplies coal to the power station, located in the Mokolo River catchment. The current water allocations from the Mokolo Dam are 5.10 million m^3/a (abstraction point at A42J2) and 6.10 million m^3/a (abstraction point at A42J2) respectively.
- AMPLATS Platinum Mine in the Mogalakwena River catchment with a water requirement of 1.59 million m^3/a is supplied from groundwater.
- Venetia Diamond Mine in the Mogalakwena River catchment, just south of the Limpopo River, abstracts approximately 4.20 million m^3/a form the alluvial sand aquifers along the Limpopo River.

An increase in future mining and power generation developments in the Study Area is expected – more information in this regard is provided in the *Water Requirements and Return Flows Report (P WMA 01/000/00/02914/4)* as part of this Study.

4.5.2 Commercial forestry

Afforestation is confined to the high rainfall regions (> 800 mm/a) on the slopes of the Soutpansberg mountains, in the upper reaches of the Nzhelele River catchment and quaternary catchments A71C and A71H of the Sand River catchment. The area covered by afforestation at the 2010-development level is summarised in **Table 4.6**. The afforestation growth over the study period is shown in **Table 4.7** as sourced from the V&V Study (DWA, 2013a). The impact of afforestation on the water resources in the Study Area is considered negligible, reducing the runoff in the Nzhelele River catchment by approximately 2 million m^3/a, and 0.2 million m^3/a in the Sand River catchment.

Table 4.6: Afforestation in the Limpopo WMA North at 2010-development level

Catchment	Quaternary	Current Afforestation Area (km^2)			
		Eucalyptus	Pine	Wattle	Total
Sand	A71C	0.86	0.00	0.10	1.00
	A71H	3.67	4.48	0.00	8.20
	Total A71	**4.54**	**4.48**	**0.10**	**9.10**
Nzhelele	A80A	6.08	11.53	0.00	17.6
	A80B	0.53	0.89	0.00	1.40
	A80D	0.18	0.00	0.00	0.20
	A80E	0.09	0.00	0.00	0.10
	Total A80	**6.87**	**12.42**	**0.00**	**19.3**
Total Limpopo WMA North		**11.41**	**16.90**	**0.10**	**28.40**

Note: The areas in grey text are considered as negligible.

Table 4.7: Historical growth of afforestation areas in the Limpopo WMA North

Catchment	Quaternary	Growth in Afforestation Areas (km^2)					
		1920	1930	1940	1986	1998	2010
Sand	A71C	0.44	0.59	0.78	0.82	0.97	0.96
	A71H	3.69	4.98	6.63	6.96	8.26	8.15
	Total Sand	**4.13**	**5.57**	**7.41**	**7.78**	**9.23**	**9.11**
Nzhelele	A80A	7.98	10.75	14.33	15.04	17.83	17.61
	A80B	0.64	0.87	1.16	1.21	1.44	1.42
	A80D	0.08	0.11	0.14	0.15	0.18	0.18
	A80E	0.04	0.05	0.07	0.07	0.09	0.09
	Total Nzhelele	**8.74**	**11.78**	**15.7**	**16.47**	**19.54**	**19.3**
Total Limpopo WMA North		**12.87**	**17.35**	**23.11**	**24.25**	**28.77**	**28.41**

Note: The areas in grey text are considered as negligible.

4.5.3 Livestock watering

Livestock watering is primarily supplied from surface water resources. The tendency to convert land-use from irrigation to livestock farming, particularly game farming in the Mokolo, Lephalala and Sand river catchments, has increased the stock watering requirements. Table 4.8 provides a summary of the livestock watering requirements within the Study Area per river catchment.

Table 4.8: Livestock water requirements in the Limpopo WMA North at the 2010-development level

River Catchment	Water Requirement (million m^3/a)
Matlabas	2.28
Mokolo	2.11
Lephalala	2.39
Mogalakwena	11.49
Sand	4.39
Nzhelele	0.75
TOTAL	**25.16**

5 WATER BODIES

5.1 OVERVIEW

The Mokolo Dam is the largest dam in the Study Area and provides water for irrigation, the Matimba Power Station and the town Lephalale. Other large dams in the WMA are the Doorndraai Dam, Glen Alpine Dam, Nzhelele Dam, Mutshedzi Dam and Luphephe Dam. These dams supply irrigation, towns and the surrounding villages. There are no major dams in the Matlabas, Lephalala and Sand river catchments.

A significant number of minor dams are also located within the Study Area, of which the majority are small storage dams used as a source of water for irrigation, stock and game farming, as well as for recreational purposes. The remaining water bodies includes weirs, that are used for diversion of water, storage and flow measuring; gravel pits and slimes dams associated with mining activities, pans and wetlands. Considering the arid climate, unfavourable topography, sandy rivers as well as the important conservation areas further development of surface water resources in the Study Area is limited.

The Nylsvlei floodplain wetland in the upper reaches of the Mogalakwena River catchment is South Africa's largest ephemeral floodplain and has been declared a RAMSAR site due to its international importance and profuse birdlife.

Water bodies, especially the storage capability, is a vital and integral component of the hydrological modelling process as it has an impact on the hydrological behaviour and availability of water resources within the Study Area. Hence, careful consideration should be taken when modelling representative water bodies. Furthermore, evaporation losses occur on the surfaces of water bodies, which is a function of the physical characteristics in terms of the area being exposed to the atmospheric water demand.

For the purpose of the hydrological analysis undertaken as part of this Study, water bodies in the Study Area were divided into five distinct groups, based on the general characteristics that they exhibit within the context of the hydrological cycle and, hence, the way that they are modelled. These are:

- *Major storage dams,* which provide storage capacity and is used as a source of supply for water users. Dams fill up, through the impoundment of surface runoff, to a fixed full supply capacity (FSC), at which point spillage occurs;
- *Small storage dams and weirs*, which provide storage capacity used as a source of supply for water users. These water bodies also act like typical dams;
- *Gravel pits*, which are not generally used for supply purposes, but are also filled by surface runoff and spill at a fixed FSC;
- *Mining slimes dams*, which effectively do not participate in hydrological processes since they are not filled by surface runoff and are managed artificially to avoid spills; and
- *Pans*, which command catchment areas that do not contribute to stream flow in the river system.

5.2 AREA-CAPACITY INPUT FOR THE WRSM2000

The relationship between the area and any given storage of a reservoir in the WRSM2000 model is calculated by the following area-capacity equation:

$$A = a \times C^b \tag{5.1}$$

Where

A	=	Surface area of the dam in km².
C	=	Capacity of the dam in million m³.
a	=	The value of “a” is calculated by setting A = full supply area (FSA) and C= FSC in the above equation.
b	=	The constant “b” is determined from the area-capacity tables of the reservoir considered. If no area-capacity tables are available, a default b-value of 0.6 is assumed, which is the representative average for South African reservoirs.

5.3 MAJOR DAMS

There are several major dams in the Study Area, of which the Mokolo, Nzhelele, Doorndraai and Glen Alpine dams are the largest. The following dams have been modelled as stand-alone dams in the WRSM2000:

- Mokolo Dam in the Mokolo River catchment on the Tambotie River;
- Donkerpoort Dam in the Mogalakwena River catchment on the Klein Nyl River;
- Doorndraai Dam in the Mogalakwena River catchment on the Sterk River;
- Glen Alpine Dam in the Mogalakwena River catchment on the Mogalakwena River;
- Turfloop Dam in the Sand River catchment on the Turfloop River;
- Houtrivier Dam in the Sand River catchment on the Hout River;
- Mutshedzi Dam in the Nzhelele River catchment on the Turfloop River;
- Nzhelele Dam in the Nzhelele River catchment on the Turfloop River; and
- Nwanedi and Luphephe Dams in the Nzhelele River catchment just upstream of the confluence of the Nwanedi and Luphephe rivers.

All major dams are listed in **Table 5.1**. The latest area capacity relationships for the major dams were obtained from detailed dam-survey data from the DWS. The b-values used for each major dam are also provided in the table. Refer to **Section 5.2** for the description of the input for the area-capacity relationship.

Table 5.1: Major dams in the Limpopo WMA North

Reservoir name	Year constructed	Quaternary	DWS number	FSA[1] (km^2)	FSC[2] (million m^3)	Area-capacity relationship (b-value[3])	Major uses and allocations, where available (million m^3/a)
Mokolo	1980	A42F	A4R001	8.29	146.00	0.612	Matimba Power Station (3.0), Grootegeluk Coal Mine (3.4), Lephalale Municipality (3.8), Irrigation (10.4)
Donkerpoort	1970	A61A	A6R003	0.56	2.40	0.600	Modimolle (0.04)
Gert Combrink	1963	A61F	A6R004	2.57	5.14	0.600	Mokopane (3.2)
Doorndraai	1953	A61H	A6R001	5.61	44.20	0.624	Mookgopong and Mokopane (4.4) Irrigation (3.7)
Haaskloof,	1983	A61H	-	0.44	2.02	0.600	N/A
Welgevoden		A61H	-	N/A	N/A	0.600	Mookgopong (0.5)
Rooiwal	1990	A61J	-	2.27	6.81	0.600	N/A
Glen Alpine	1968	A62J	A6R002	4.61	18.89	0.667	Irrigation (13)
Seshego	1968	A71A	-	0.74	2.60	0.600	Seshego (1.3)
Turfloop Dam	1955, Raised in 1984	A71B	-	0.72	3.30	0.600	N/A
Dikgale	1970	A71E	-	2.78	8.25	0.600	N/A
Houtrivier	1984	A71E		1.59	7.49	0.600	Rural villages (0.13)
Voorbrug	1976	A71K	-	0.50	1.32	0.600	N/A
Nzhelele	1948	A80C	-	5.44	51.23	0.653	N/A
Mutshedzi	1990	A80A	-	0.40	2.16	0.600	Domestic supply to 6 villages and Makhado Town (4.35)
Nwanedi	1964	A80H	A8R002	0.57	5.31	0.600	Irrigation (6.8)
Luphephe	1964	A80H	A8R002	1.42	14.80	0.685	
Cross	1975	A80J	-	0.66	2.60	0.600	Balancing dam for Nwandezi and Luphephe

Note: (1) FSA = Full Supply Area
(2) FSC = Full Supply Capacity
(3) "b"-value in the equation $A = a \times C^b$
(4) "N/A" - information not available

5.4 SMALL STORAGE DAMS AND WEIRS

5.4.1 Modelling approach

Small storage dams and weirs were modelled in the WRSM2000 using the model's standard *Reservoir (RV) Module.* The RV-module models the storage behaviour of the reservoir (or impoundment) based on the volume of stored water in the reservoir at the end of every simulation time step (monthly) and a simple mass balance principle. If the storage volume in the reservoir is known at the beginning of the simulation period, then the storage at the end of the first month can be calculated based on the change in storage that has occurred. The change in storage is calculated using the following equation:

$$\Delta S = Inflows - Outflows \tag{5.2}$$

Where:

ΔS	=	Change in storage over the time-step
Inflows	=	Inflows into the reservoir over the time-step
Outflows	=	Outflows into the reservoir over the time-step

Similar to the irrigation areas, small dams in the Study Area were combined into defined groups and modelled in the WRSM2000 using single representative network elements in each quaternary, referred to as *Dummy Dams*. The representative dummy dams were modelled to simulate the combined impact of the individual dams it represents on the hydrological behaviour of each river catchment. Individual dams were combined based on:

- Location within the quaternary;
- Location and nature of water users supplied from the dams; and
- Desired level of complexity of the resulting system model.

For the purpose of this Study, small storage dams and weirs located in a single tributary catchment and supplying water to a discreet set of water users, were combined into a dummy dam. However, consideration was given to the possibility of simulating larger key dams individually.

The location of these small dams and weirs is shown in **Figure A.5** of **Appendix** A.

5.4.2 Methodology for combining individual dams

The V&V Study (DWA, 2013a) provided a detailed dams GIS database, including the FSA and FSC, for small dams and weirs in the Matlabas, Mokolo, Lephalala and Mogalakwena river catchments. The combined dam characteristics (FSA and FSC) of the small dams and weirs in the Sand and Nzhelele river catchments were obtained from the V&V Study (DWA, 2013a) per quaternary catchment and were refined where necessary. Distinction was made between small dams and other water bodies, such as storage weirs, gravel pits, mining slimes dams and pans in order to generate representative dummy dams.

The area-capacity relationships obtained from the detailed GIS database of the V&V Study was used to derive more realistic FSCs based on the water bodies' FSAs. The surveys of larger reservoirs in the Study Area were also used in obtaining some of the FSCs of the dams in close proximity of the large reservoir under consideration.

The physical characteristics (FSA and FSC) of the dummy dams were derived from the characteristics of the individual dams the dummy dam represent. A dummy dam's FSC and FSA were calculated by simply adding up the FSCs and FSAs of each included individual dam. The area-capacity relationship is represented by the equation discussed in **Section 5.2**. The a-value is generated by the FSC and FSA of the dummy dam. The b-value is deterministically calculated if dam survey information is available. However, for dummy dams a default value of 0.6 is usually applied.

In the case of the Matlabas, Mokolo, Lephalala and Mogalakwena river catchments, representative a-values and b-values were determined per quaternary catchment by means of plotting the FSA vs. FSC for all the small storage dams in the quaternary catchment under consideration and fitting a power trend line through the data. As previously mentioned, the characteristics (FSA and FSC) of small dams in the Sand and Nzhelele river catchments were provided per quaternary catchment. Therefore, the national standard average b-value of 0.6 was used as input to WRSM2000 for modelling purposes.

Figure 5.1 shows an example of the area-capacity plot for quaternary catchment A61A from which the a-values and b-values were determined.

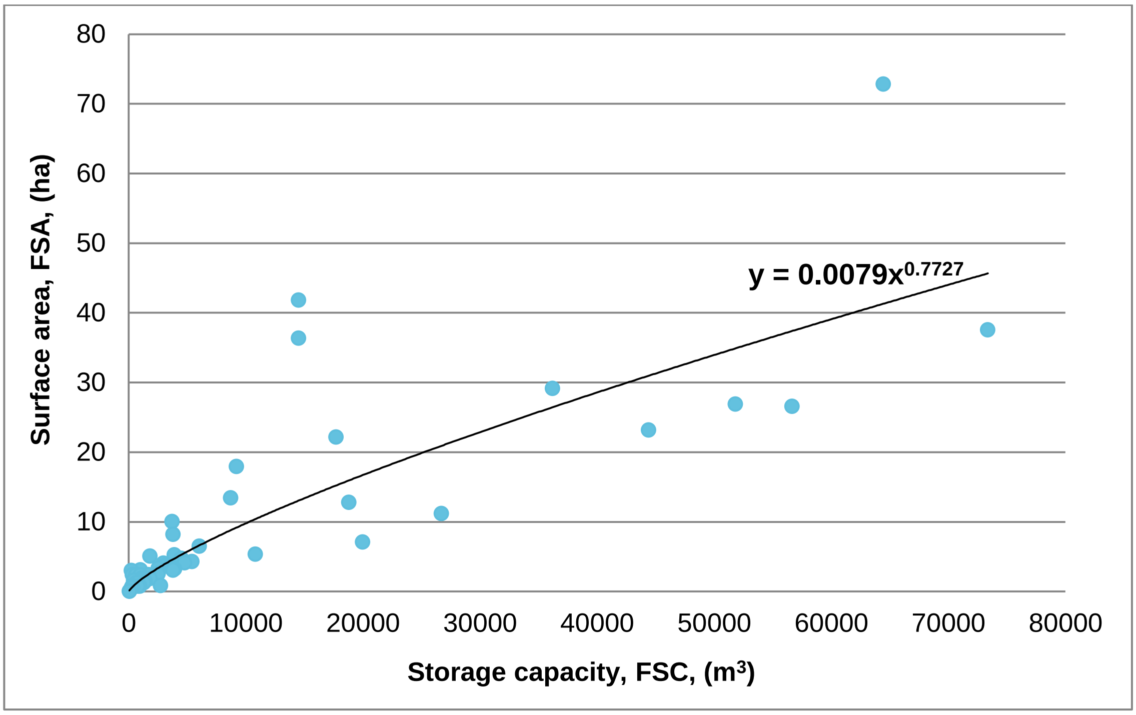

Figure 5.1: A61A area-capacity plot

5.4.3 Dummy dam characteristics

Small dams in the Study Area were combined into dummy dams according to their location relative to the runoff catchments and the water users. Table D.1 in Appendix D provides a summary of the total FSAs and FSCs of the dummy dams per quaternary catchment, as well as the a-value and b-value obtained as discussed in Section 5.4.2.

The historical growth of dummy dams, representing small storage dams and weirs, over the period 1920 to 2010 is presented in Table D.2 of Appendix D and shown graphically in Figure D.1. The representative network element per catchment or modelled river system is also included in the table.

5.5 GRAVEL PITS

Gravel pits behave similar to small storage dams and weirs in that they are also filled by surface runoff and spill at a fixed FSC. Gravel pits are not generally used for supply purposes and therefore it was decided not to model gravel pits in the hydrological analysis. However, the only exception is the gravel pits of the Mokolo River catchment where gravel pits were explicitly modelled as described in the hydrological analysis of the Mokolo Study (DWA, 2007). A total of 91 gravel pits with a total combined FSC of 2.43 million m^3, FSA of 1.61 km^2 and catchment runoff area of 90 km^2 were included in the hydrological analysis.

5.6 MINING SLIMES DAMS

Mining slimes dams effectively do not participate in hydrological processes since they are not filled by surface runoff and are managed artificially to avoid spills. It was therefore decided that slimes dams would not be modelled as part of this hydrological analysis and are not accounted for in the system networks of the WRSM2000.

5.7 PANS AND WETLANDS

Pans are located in the geographically flat catchment areas. Pans impact on the hydrological cycle in that the catchment areas that these pans command do not contribute to surface water flows in the river system. In the case of this Study, pans were not modelled explicitly.

The Nylsvlei wetland in the upper reaches of the Mogalakwena River catchment is declared a RAMSAR site and is South Africa's largest ephemeral floodplain. It is of high importance to model the Nylsvlei area properly as it intercepts and absorbs runoff from the high rainfall Waterberg Mountains resulting in delayed and decreased flows in the Nyl River before reaching the Mogalakwena River downstream.

Care had to be taken to correctly model and calibrate the Nylsvlei wetland in the WRSM2000. The modelling approach is discussed in more detail in **Section 7.2.2**.

6 HYDRO-METEOROLOGICAL DATA

6.1 OVERVIEW

The analysis of hydro-meteorological data involves many processes, depending on the availability and quality of data as well as the type of information under consideration. In general, the level of confidence that can be placed on the results of a water resources study is largely dependent on the quality of the information available, especially hydro-meteorological data in this case. The most important hydro-meteorological data include:

- Rainfall data;
- Evaporation data; and
- Measured stream flow and dam balance data.

An overarching principle was therefore applied whereby all available data of relevance was analysed and considered for possible use in this Study. Details on the analysis of these data sets are provided in the following sections of this report.

6.2 RAINFALL DATA

Monthly rainfall time-series data provide a critical input to hydrological analyses and are used as primary input to the WRSM2000, as well as for the modelling of water use (particularly irrigation) and the behaviour of water bodies.

The rainfall data analysis undertaken as part of the hydrological analysis of the Limpopo WMA North is reported on in a separate supporting document, *Rainfall Data Analysis Report (P WMA 01/000/00/02914/2/1)*. Due to the number of hydro-meteorological studies previously conducted in the Study Area, existing representative catchment rainfall records, which serve as input into WRSMWRSM, were evaluated through visual inspection and basic statistical analyses. Individual point rainfall data time-series were analysed only in isolated cases with critical problems in the catchment rainfall records.

Figure A.2 in **Appendix A** illustrates the spatial distribution of the rainfall regime, as well as the rainfall gauging stations available and used in the rainfall data analysis and subsequent hydrological analysis. The final MAPs used in this Study are provided per quaternary or sub-quaternary catchments in **Table H.2** of **Appendix H**.

6.3 EVAPORATION DATA

Evaporation data are required as an input to the WRSM2000 to estimate:

- Catchment evapo-transpiration as part of the rainfall-runoff simulation process;
- Evapo-transpiration from irrigated crops;
- Evaporation losses from the surface area of water bodies; and
- The amount of evaporation from the groundwater zone, through application of the GWSWIM.

Evaporation data is more consistent on an annual basis compared to rainfall and stream flow data, e.g. evaporation in one October-month is similar to evaporation in the next October-month. Therefore, it is generally considered to be acceptable to model evaporation data simply by applying 12 average monthly evaporation values over the standard hydrological year for the particular area in question.

For the purpose of the hydrological analysis undertaken as part of this Study, evaporation data used were primarily based on the WR2005 evaporation data (WRC, 2008). The average monthly A-pan evaporation values for each of the quaternary catchments are provided in **Table E.1** of **Appendix E**. The WRSM2000, however, uses the Symons pan (S-pan) evaporation data which can be converted from the average monthly A-pan evaporation by applying the following formula:

$$(S - pan) = -16.2354 + 0.8793 \text{ x } (A - pan) \quad (6.1)$$

Where:

S-pan = Calculated S-pan evaporation value for the month in question (mm);

A-pan = A-pan evaporation value for the month in question (mm).

The resulting S-pan evaporation data for each quaternary catchment are provided in **Table E.2** of **Appendix E**. S-Pan evaporation data is used for the calculation of irrigation water requirements. However, for the WQT-SAPWAT method, the S-pan evaporation data is only used for return flow calculations in the Irrigation Block module. The MAE spatial distribution is illustrated in **Figure A.3** in **Appendix A**.

Catchment evapo-transpiration is calculated in the WRSM2000 by applying 12 monthly S-pan-to-catchment evapo-transpiration conversion factors (refer to

Table 6.1). Evaporation losses from the surface area of water bodies are calculated similar to the evapo-transpiration, using S-pan-to-lake evaporation conversion factors (refer to Table 6.2). Both the S-pan-to-catchment evapo-transpiration conversion factors and S-pan-to-lake evaporation conversion factors is common to all catchment areas in South Africa and was obtained from the WR90 publications (WRC, 1994).

Table 6.1: S-pan-to-catchment evapo-transpiration 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

Table 6.2: S-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	0.81	0.87	0.85	0.83	0.81	0.81

Finally, the amount of evaporation from the groundwater zone is estimated in the WRSM2000 through application of the GWSWIM, based on A-pan evaporation. Evaporation from the groundwater zone is calculated by applying monthly S-pan-to-A-pan conversion factors. These factors are determined by dividing A-pan evaporation values by S-pan values for the corresponding months as included in Table E.3 of Appendix E.

6.4 MEASURED STREAM FLOW AND DAM BALANCE DATA

6.4.1 Overview

Observed stream flow data provide a critical input to water resources studies and are used in the process of calibrating the WRSM2000 systems. Stream flow data are also the basis for generating natural stream flow data time-series which are a direct input to the subsequent stochastic hydrology analysis and water resources yield analysis. The methodologies and results of the stochastic hydrology analysis, as well as the water resource yield and planning analyses will be provided in the *WRYM Report (P WMA 01/000/00/02914/7)* and the *WRPM Report (P WMA 01/000/00/02914/9)* as part of this Study.

The process of analysing observed stream flow data involved various aspects as listed below and discussed in the following sections:

- Assessment of available stream flow gauge data;
- Selection of stream flow gauges for calibration based on length of record, quality of data, geographical location, etc.; and
- Patching of raw monthly stream flow data.

6.4.2 Assessment of available stream flow gauge and dam balance data

The DWS has 93 registered monitoring points on the online HYDSTRA database in the Study Area. The monitoring points include 68 river gauging stations, 12 reservoir monitoring points, ten canal and three pipeline measurements. These monitoring points are listed in **Table E.4** of **Appendix E**, along with their location and record period.

Canal and pipeline measurement data are abstraction data. This data is used in dam balances and to determine bulk water abstractions, but are not used directly in the WRSM2000 calibration process. The initial evaluation of the stream flow gauge and dam monitoring data involved the following:

- An initial visual inspection of each stream flow and dam inflow record to determine the completeness of the data and to identify periods with complete data acceptable for calibration;
- Inspecting of the DWS Station Catalogue to determine the abstraction and release components associated with a particular reservoir;
- Evaluation of the credibility of gauging stations and dam balance information based on DWS Gauge Inspection Reports (DWA, 2009) (DWA, 2011); and
- Comments from previous studies on the accuracy and usefulness of the individual stations.

6.4.3 Selection of stream flow gauges and dam balance data

Stream flow records and dam inflow records for the calibration of the WRSM2000 systems, were selected based on the following criteria:

- Record length – gauges with more than 15 years of data was given preference for further evaluation;
- Completeness of the data; and
- Geographical location within the Study Area.

Of the available 80 stream flow gauging stations on the HYDSTRA database, which include 12 reservoir inflow records, 16 records were found to be reliable and suitable. This includes the four stream flow gauges used in the earlier Mokolo Study (DWA, 2007). Some of the stream flows gauging stations were only used to visually compare the simulated stream flow with the observed stream flow record, especially in areas where monitoring data is scarce. This process is referred to as *verification*. Five of the original 12 reservoir monitoring points or reservoir inflow records were rejected due to poor data quality. The remaining seven were used for calibration of the WRSM2000 systems and verification of stream flows.

The final selection of surface water monitoring points to be used in the calibration of the WRSM2000 system and the verification of flows is provided in **Table 6.3**. The table shows the available record period as well as the record period used. In some cases the first hydrological year is excluded from the used record period due to the number of missing monthly data in that year. Also, only data up to the 2010 hydrological year (i.e. September 2011) were used to coincide with the Study Period.

Figure A.6 in **Appendix A** indicates the stream flow gauging stations and reservoir monitoring points available and used for the purpose of calibrating the WRSM2000 and verifying flows. Stream flow gauges used for calibration is indicated by means of red dots and stream flow gauges used for verification by orange dots.

Table 6.3: Stream flow gauges used for the hydrological analysis of the Limpopo WMA North

Station no.	Quaternary	Available record period			Used record period (Hydrological years)		
		Start	End	Years	Start	End	Years
River							
A4H002*	A42C	1948/03	2014/08	66	1948/10	2010/09	62
A4H004	A41C	1962/08	2014/08	52	1962/10	2010/09	48
A4H005*	A42F	1962/08	2014/09	52	1962/10	2010/09	48
A4H007*	A42H	1962/09	2014/05	52	1962/10	2010/09	48
A4H008*	A42D	1964/08	2014/08	50	1964/10	2010/09	46
A5H004	A50B	1955/12	2015/08	60	1961/10	2010/09	49
A6H009**	A63D	1960/06	1997/02	37	1960/10	1996/09	36
A6H010	A61C1	1964/08	2014/08	50	1963/10	2010/09	47
A6H011	A61A3	1966/11	2014/07	48	1966/10	2010/09	44
A6H012	A61B1	1966/11	2014/08	48	1966/10	2010/09	44
A6H027**	A61J	1953/03	2014/09	61	1952/10	2010/09	58
A6H029**	A63A	1970/04	2014/08	44	1969/10	2010/09	42
A6H033**	A61F	1990/11	2014/08	24	2005/10	2010/09	5
A6H036**	A61J	1995/02	2014/04	19	1995/10	2010/09	15
A7H001**	A71H	1957/07	2000/01	43	1965/10	1999/09	34
A7H003	A71G	1947/10	1995/11	48	1947/10	1994/09	47
Reservoirs							
A5R001**	A50E	1968/02	2015/02	47	1968/10	2010/09	42
A5R002**	A50G	1968/02	2014/01	46	1968/10	2010/09	42
A6R001**	A61H	1953/03	2015/02	62	1955/10	2010/09	55
A6R002	A62J	1967/10	2014/07	47	1970/10	2010/09	40
A8R001	A80F	1948/02	2015/02	67	1970/10	2010/09	40
A8R002	A80H1	1946/01	2015/02	69	1971/10	2010/09	39
A8R003	A80H2	1963/12	2015/02	52	1971/10	2010/09	39

* *Stream flow gauges used in the "Updating the Hydrology and yield analysis in the Mokolo River Catchment" Study (DWA, 2007) with record period extended to 2010.*

** *Stream flow gauges used only to verify the calibration results at certain points on the relevant modelled river system.*

A general discussion on the current status of the hydro-meteorological monitoring network and the relevant stream flow monitoring points is provided for each of the six river catchments in **Section 6.5.2**.

6.4.4 Patching of stream flow data

Raw monthly stream flow data obtained from the HYDSTRA database generally contain missing data values and values considered unreliable, which are highlighted by means of flags. These missing and unreliable values must be filled in or estimated through a "patching" process before it can be used to calibrate the WRSM2000 system and generate natural stream flow time-series.

Various approaches may be adopted for patching raw monthly stream flow data. In the case of this Study, simulated values (using the WRSM2000) were used to patch missing or unreliable data values in the observed stream flow records.

a) Patching using simulated values

Missing or unreliable data values in the observed flow record were patched, using simulated values from the WRSM2000 rainfall-runoff analysis. However, to obtain reliable flows from the WRSM2000, the model first had to be calibrated to some extent. A preliminary simulation using regional calibration parameters was obtained from the WRSM2000 as a first estimate to patch missing data. The WRSM2000 was then calibrated using the preliminary patched values. The final calibration of the WRSM2000, against the observed stream flow data, is only possible once reasonable patching of the stream flow record is achieved.

b) Final adopted patched value

The statistics for the final patched observed stream flow data, at the respective flow gauging stations, are provided in **Table 6.4**.

Table 6.4: Final statistics for patched stream flow gauges and reservoir monitoring points

Station no.	Quaternary	Calibration period		MAR (million m^3/a)		% Patched
		Start	End	Raw	Final	
River						
A4H002*	A42C	1948/10	2010/09	45.02	71.57	20.09
A4H004	A41C	1962/10	2010/09	32.45	32.73	6.08
A4H005*	A42F	1962/10	2010/09	175.66	176.33	6.75
A4H007*	A42H	1962/10	2010/09	7.28	10.70	15.87
A4H008*	A42D	1964/10	2010/09	34.83	45.83	24.17
A5H004	A50B	1961/10	2010/09	53.00	53.04	3.23
A6H009**	A63D	1960/10	1996/09	82.89	-	-
A6H010	A61C	1963/10	2010/09	2.44	2.48	5.95
A6H011	A61A	1966/10	2010/09	4.72	4.77	3.41
A6H012	A61B	1966/10	2010/09	7.07	7.23	3.08
A6H027	A61J	1952/10	2010/09	9.53	12.64	5.60
A6H029**	A63A	1968/10	2010/09	97.00	-	-
A6H033**	A61F	2005/10	2010/09	7.33	-	-
A6H036**	A61J	1995/10	2010/09	39.67	-	-
A7H001**	A71H	1965/10	1999/09	17.61	-	-
A7H003	A71G	1947/10	1994/09	14.49	21.40	14.18
Reservoir						
A5R001**	A50E	1968/10	2010/09	164.76	-	-
A5R002**	A50G	1968/10	2010/09	139.86	-	-
A6R001**	A61H	1955/10	2010/09	21.56	-	-
A6R002	A62J	1970/10	2010/09	87.39	112.12	2.33
A8R001	A80F	1970/10	2010/09	61.68	68.89	3.13
A8R002	A80H	1971/10	2010/09	19.27	19.50	3.75
A8R003	A80H	1971/10	2010/09	8.65	8.75	14.13

* *Gauges used in the "Updating the Hydrology and yield analysis in the Mokolo River Catchment" (DWA, 2007) with record period extended to 2010.*

** *Gauges used to verify the calibration results at certain points on the relevant modelled river system.*

6.5 ASSESSMENT OF THE HYDRO-METEOROLOGICAL MONITORING NETWORK

Once the hydrological analysis of the Study Area was completed, an assessment was made of the availability of hydro-meteorological data in the catchment. The assessment included aspects related to the inadequacy of existing monitoring networks, the possible expansion or improvement of monitoring networks and comments on the quality of the observed records. The findings of the assessment are discussed in the following sub-sections.

6.5.1 Rainfall data

While sufficient rainfall gauges were available for analysis purposes there is a concern that only nine of the 33 gauges used have remained open up to the end of the Study Period (2003 hydrological year). While these nine gauges are fairly well spread over the entire catchment area, serious consideration should be given to re-opening some of the closed gauges.

6.5.2 Stream flow data

It was found that of the 68 stream flow gauging stations and 12 reservoir monitoring points located within the Study Area, only 23, as listed in **Table 6.3**, could be used to calibrate the WRSM2000 setups or to verify upstream calibrations. These 23 surface water monitoring points are adequately spread and provided an overall calibration which reflects the historic flow regime of the Study Area. However, there are some great concerns regarding the monitoring network, especially in the lower lying areas of the catchments and the general quality of the available records. In the Matlabas and Lephalala river catchments there is only one stream flow gauge per catchment with adequate quantity and quality data for calibration purposes. Regional parameters from the WR2005 Study (WRC, 2008) were applied in quaternary catchments where no acceptable stream flow data were available for calibration purposes.

Comments on each of the stream flow gauges and reservoir monitoring points used for the calibration of the WRSM2000 systems, as well as to verify upstream calibrations, are discussed per river catchment below:

a) Matlabas River catchment

The stream flow gauge, **A4H004** (Matlabas River @ Haarlem East), has been recording stream flow data from 1962 to date. The overall record is considered to be good, although it has a number of years with flagged data (6%). A4H004 is the only flow gauging station in the Matlabas River catchment and it is thus vital that it remains open and well managed.

b) Mokolo River catchment

As previously mentioned, the Mokolo River catchment WRSM2000 system was not recalibrated, but based on system model configuration of the Mokolo Study (DWA, 2007). The Mokolo Study concluded that acceptable calibration of the WRSM2000 was achieved while explicitly modelling the impacts of groundwater-surface water interactions using GWSWIM.

Stream flow gauges used as part of the Mokolo Study (DWA, 2007) and which was extended to the 2010 hydrological year for the purposes of this Study included **A4H002**, **A4H005**, **A4H007** and **A4H008**.

c) Lephalala River catchment

The stream flow gauge, **A5H004** (Palala River @ Muisvogelkraal), has a long good record and accurate for low flows. It has been recommended in the flow gauging station assessments (DWA, 2011) that the calibration of the gauging station be investigated and that the discharge table (DT) be checked for validity.

The reservoir monitoring point, **A5R001** (Palala River @ Vischgat Dam) located downstream of **A5H004**, has no dam balance and the dam is used for irrigation. Only spills are measured and not abstractions as well.

Reservoir monitoring point, **A5R002** (Palala River @ Susandale Dam) also does not accurately reflect on low flows but has a relatively long record that is important for flood studies. It is in close proximity to **A5R001**. Flow gauging station assessments (DWA, 2011) recommended that a correlation between the spills at **A5R001** and the inflows at **A5R002** be done. The gauge was not used for calibrating the WRSM2000 but only to verify flow.

d) Mogalakwena River catchment

The stream flow gauge, **A6H009** (Mogalakwena River @ Leniesrus), has recorded data from 1960 to 1996. This gauge should be reopened as it is the most downstream gauge in the Mogalakwena River before the confluence with the Limpopo River.

The stream flow gauge, **A6H010** (Badseloop River @ Vischgat), has a good long record from the early 1960s and is still in operation. The gauge is important for the monitoring of the Nylsvlei wetland area. Flow gauging station assessments (DWA, 2011) recommended that the DWS Regional Office maintain the stream flow gauge to the then current maintenance level.

The stream flow gauge, **A6H011** (Great-Nyl River @ Modderpoort) has a long record with only eight years of the record with flagged or missing monthly values. The gauge monitors flows entering the Nylsvlei wetland and is thus of high importance. Issues regarding dumping of waste near the site of the stream flow gauge have been raised and should be resolved.

The stream flow gauge, **A6H012** (Olifant Spruit @ Olifantspoort), has a long reliable record with very few flagged values. The gauge is located at the confluence of the Olifantsspruit and Nyl rivers and measures localised inflows from a small catchment area. The gauge is important for monitoring the Nylsvlei wetland.

The stream flow gauge, **A6H027** (Sterk River @ Doorndraai), is located downstream of Doorndraai Dam and is the downstream component of the dam. The gauge is important for verifying outflows from the dam, in the form of spills and releases, and hence it should be maintained.

The stream flow gauge, **A6H029** (Mogalakwena River @ Glen Alpine) is located downstream of Glen Alpine Dam, and provides information for verification of flows. However, the data quality is poor.

The stream flow gauge, **A6H033** (Nyl River @ Moorddrift), is the most downstream monitoring point on the Nyl River before its name changes to the Mogalakwena River. The gauge measures the outflow from Nylsvlei wetland. The gauge has reliable data from 2005 which does not contain missing or flagged data.

The stream flow gauge, **A6H033** (Nyl River @ Moorddrift), is only regarded as important for flood studies.

The stream flow gauge, **A6H036** (Sterk River @ Appingen Dam), has extended periods of missing data. However, the importance of the gauge was to verify the upstream calibrated stream flow.

Reservoir monitoring point, **A6R001** (Sterk River @ Doorndraai), provides the inflow for Doorndraai Dam. The information, however, is unreliable as some of the abstractions were not measured and the record has many gaps.

Reservoir monitoring point, **A6R002** (Mogalakwena River @ Glen Alpine Dam), provides the inflow for Glen Alpine Dam. The calculated inflow record into Glen Alpine Dam is long with only few short periods of missing data. The overall quality of the data is good.

e) Sand River catchment

The stream flow gauge, **A7H001** (Sand River @ Waterpoort), is a reliable flow gauge with a long good observed stream flow record from 1966 to 1998. The flow gauging station assessments (DWA, 2011) suggested that this gauge be reopened. Although not constructed to measure high flows, the DWS has determined the high flood peaks at this site by other calculations. This gauge, however, was damaged by floods.

A7H003 (Sand River @ Zamenkomst) has many gaps and no DWS evaluation was available to confirm the reliability of the observed data.

f) Nzhelele River catchment

The floods of 2000 spilled over the non-overspill crest of the Nzhelele Dam and caused damage to the reservoir monitoring point, **A8R001** (Nzhelele River @ Nzhelele Dam). The dam was raised in 1968. Nonetheless, the available data record is long and reliable.

The reservoir monitoring point, **A8R002** (Luphephe River @ Luphephe Dam), was built primarily to increase the assurance of supply to irrigation. The 2000 floods caused only minor damage to the reservoir that might have an influence on the data quality.

Reservoir monitoring point, **A8R003** (Nwanedi River @ Nwanedi Dam), provides the dam balance information for the Nwanedi Dam, primarily supplying irrigation. This gauge is important for high flow measurements. The record is long with little periods of missing or flagged data.

7 RAINFALL-RUNOFF MODELLING

7.1 OVERVIEW

Rainfall-runoff modelling is the primary activity of the hydrological assessment and involves a process whereby the runoff response of a particular quaternary or sub-quaternary catchment is simulated based on a monthly time-series of representative catchment rainfall data as discussed in the earlier sections. Rainfall-runoff modelling was undertaken in the hydrological analysis of the Limpopo WMA North using the WRSM2000 Version 2.4.

For the purpose of this Study, the rainfall-runoff modelling comprised of two components; (i) the configuration and (ii) the calibration of the WRSM2000 as discussed in **Sections 7.2** and **7.3** respectively.

7.2 CONFIGURATION OF ENHANCED WRSM2000

7.2.1 General

The WRSM2000 is a modular water resources simulation program and features five different Module-types as listed below:

- Runoff Module;
- Channel Reach Module;
- Irrigation Block Module;
- Reservoir Module; and
- Mining Module.

Each of these modules simulates a certain hydrological feature within the catchment or river system and contains one hydrological model, or a choice between more than one. The modules are connected by means of *Flow Routes* to form a network which represents the simulated river system. More information regarding the WRSM2000 configuration can be obtained from the WRSM2000 (Enhanced) User's Guide (SSI, 2006).

The GWSWIM is used in the WRSM2000 for explicitly modelling the interaction between groundwater and surface water in the hydrological analysis.

7.2.2 Development of representative system network model

A representative system network model for a water resource system is developed in the form a schematic diagram which indicates the connectivity between and the nature of the various components that make up the system. However, the complexity of the modelled setup is governed by the need to simulate the behaviour of individual system components at a sufficient level of detail and the practical modelling limitations.

The process of developing a representative system network model includes three main aspects:

- Identification of physical system features;
- Assessing the appropriate spatial resolution; and
- Combining and aggregation of system components until the appropriate spatial resolution is achieved.

a) Identification of physical system features

Physical features in each of the quaternary catchments were identified by means of Google Earth. The location and extent of the main land use activities in the Study Area, such as irrigation, were plotted on Google Earth images, together with water bodies and other relevant infrastructure or developments, as polygons. Where necessary, sub-quaternary catchments were delineated based on the location of stream flow measuring infrastructure, water use and return flow centres as well as the location of water bodies relative to the area it supplies.

b) Spatial resolution

The spatial resolution of the network focussed on simulating local catchments and tributaries to reflect the impacts of localised water users, or water user groups, on one another and on the system as a whole. Within this context, the following aspects were considered in the definition of the WRSM2000 system networks:

- The resolution was dictated by the system layout and not by pre-defined modelling units;
- Every quaternary catchment was represented by one or more Runoff Modules in the network;

- Users receiving water from tributaries and from the main stream of the particular river system were modelled separately in order to evaluate local availability;
- Hydrological and climatic conditions; and
- The locations of farm dams and water use abstractions.

c) Aggregation of system components

Due to the large number of similar system elements in each of the six river catchments and the impracticality associated with modelling every element individually, elements with similar characteristics were combined and simulated as single representative network elements. This was particularly the case with irrigation and small water bodies as discussed in **Sections 4.3** and **5.4**. The following principles were taken into account:

- Water abstractions of the same type that have the same supply source should be grouped and be represented by a single system component;
- Farm dams located in tributary catchment should be combined to form a single dummy dam in the network model; and
- The process of combining individual system elements must be undertaken in such a way that the impacts of the resulting element mimics the combined impact of the individual elements it represents.

The resulting system schematic diagrams for this Study, describing the representative system networks for the WRSM2000 are presented in **Figures B.1** to **B.8** of **Appendix B**.

Irrigation Blocks supplied from groundwater is modelled in the WRSM2000 by means of a specific configuration of *Channel Reaches* and *Flow Routes*, as shown in **Figure 7.1**.

Furthermore, small rivers that flow directly into the Limpopo River, and hence which is not a tributary to the main stem of one of the six major rivers, were modelled independently. The associated quaternary catchments include A50J, A63C, A63E, A71L and A80H and A80J.

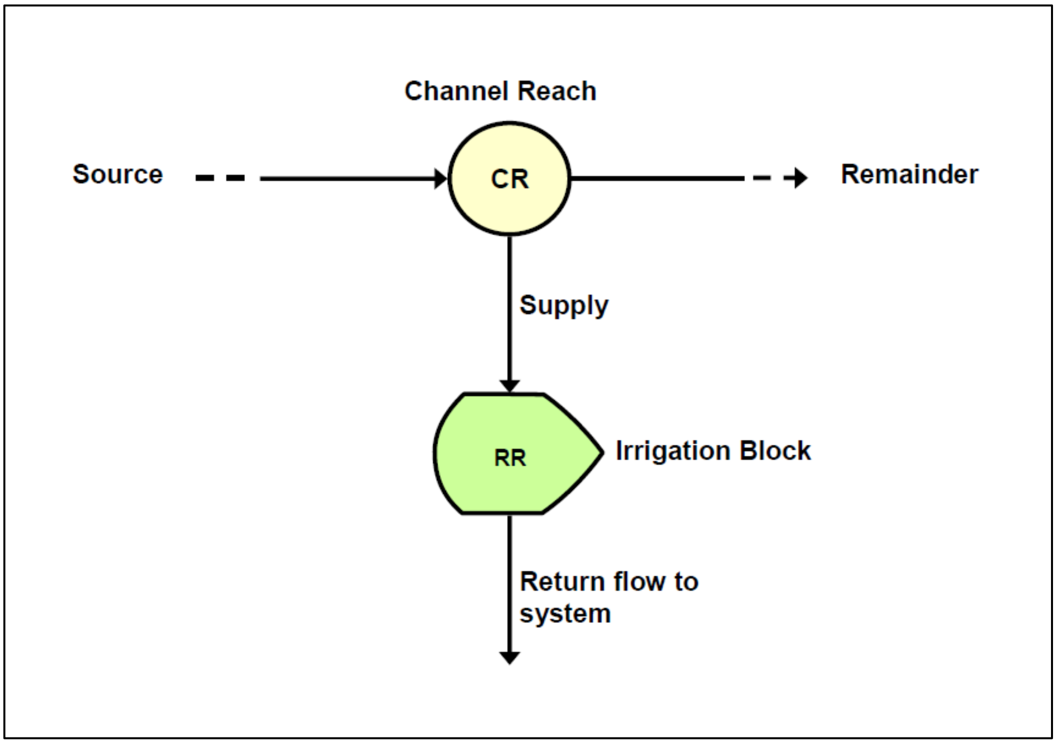

Figure 7.1: Typical WRSM configuration for modelling the supply of water to groundwater Irrigation Blocks

Modelling of the Nylsvlei wetland

Care had to be taken to model the Nylsvlei wetland correctly as it absorbs and gradually releases runoff that is generated in a catchment. The Nylsvlei is located in the head waters of the Mogalakwena River catchment - where more than half of the runoff of the Mogalakwena River is generated. This wetland is located in quaternary catchments A61A to A61E and follows the main stem of the Nyl River. The Nyl River gradually decreases in size and eventually disappears to form an extensive, flat floodplain at the lower end. From here its name changes to the Mogalakwena River.

There is one stream flow gauging station (A6H033) located in quaternary catchment A61F and at the outlet of the Nylsvlei wetland. The gauge measures the flow exiting the wetland and thus provides valuable information regarding the flow regime as a result of the wetland upstream. Due to the short record period of A6H033 (2005 to 2010), the stream flow gauge was not used for calibration but only to verify upstream calibrations from stream flow gauges A6H010, A6H011 and A6H012.

A study done by Royal Haskoning DHV on the hydrological modelling of the Nyl River (EScience Associates, 2014), incorporated a novel methodology for modelling the Nylsvlei wetland. Unlike most wetlands which are mostly off-channel wetlands, Nylsvlei is an instream wetland. Generally, the comprehensive wetland sub-module, allocated to Channel Reach Module in the WRSM2000, is used for off-channel wetlands. However, for the purpose of the hydrological modelling of the *Nyl Study*, Nylsvlei was simulated using the Reservoir Module. The Nylsvlei wetland and Nyl River were therefore considered as one entity. The flow regime at the outlet of the Nylsvlei wetland was modelled to a high degree of accuracy. Hence, this methodology was adopted for hydrological modelling of the Nylsvlei wetland and associated Nyl River for the purpose of this Study.

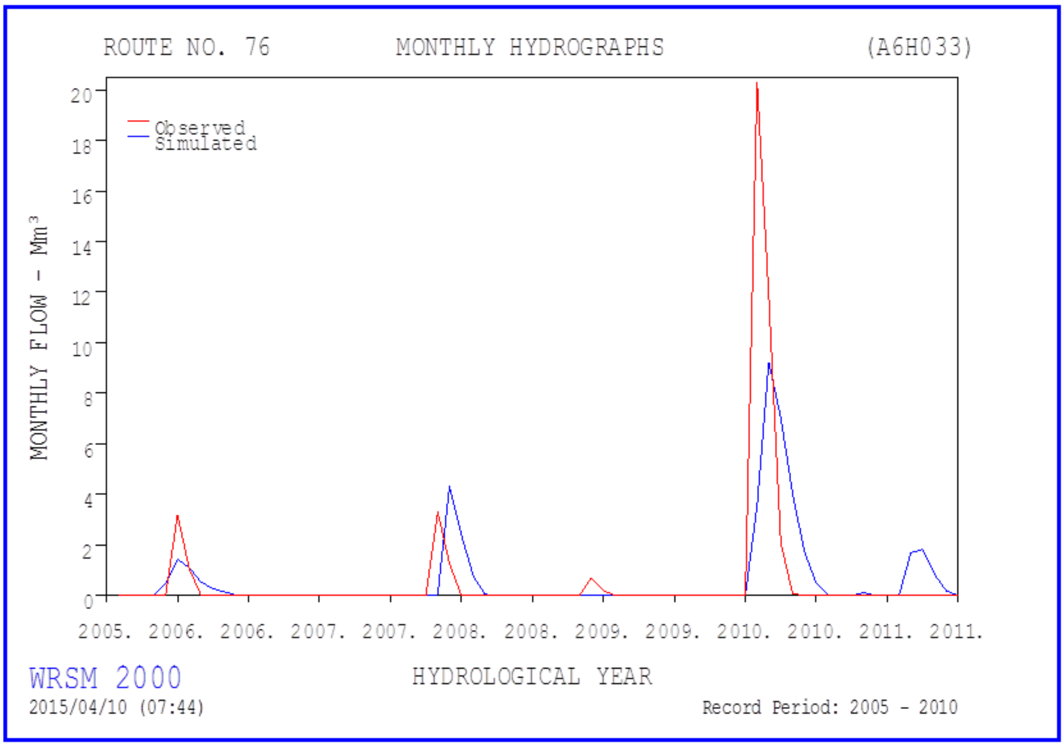

Figure 7.2 shows the initial comparison of observed versus simulated stream flows at stream flow gauge A6H033 using the comprehensive wetland module. The figure clearly illustrates the lag stream flow experienced when using this methodology. Furthermore, it can also be observed that only large flood events result in a hydrograph response. Small to average events are absorbed by the wetland and cannot be seen at the outlet as the stream flow are largely attenuated and lagged.

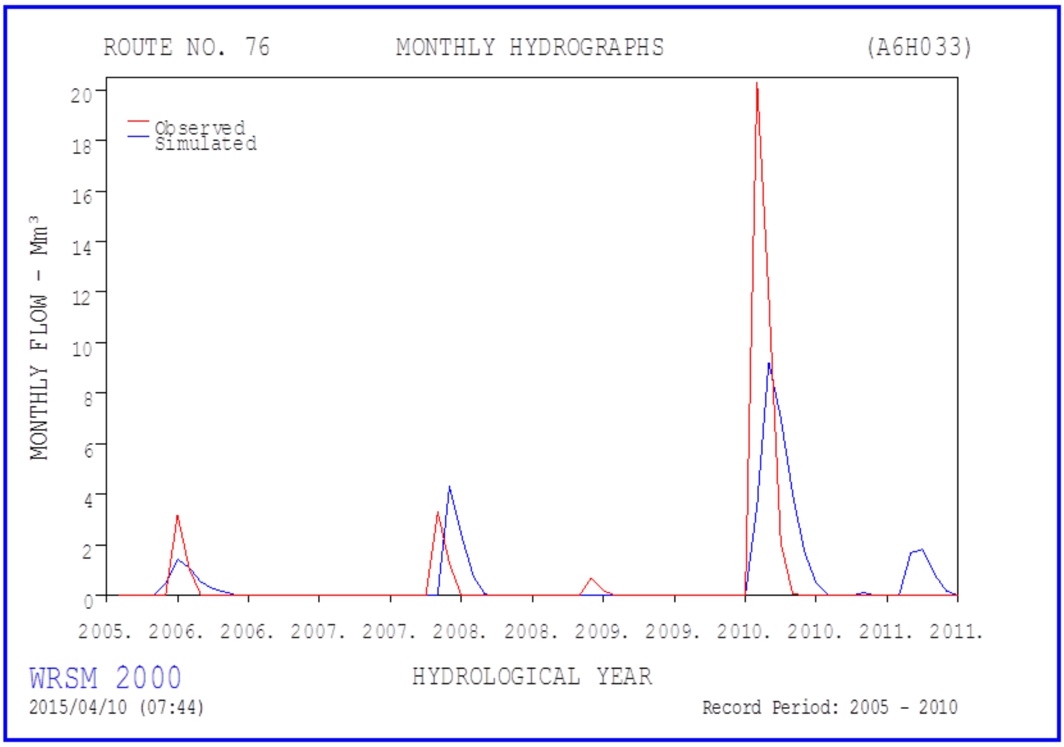

Figure 7.2: Monthly hydrograph of flows at the outlet of Nylsvlei wetland (A6H033) modelled using the Comprehensive Wetland sub-module

Figure 7.3 shows the improved comparison of the observed versus simulated stream flows at gauge A6H033 when modelling Nylsvlei using the Reservoir Module. The remainder of the graphs of observed versus simulated steam flows can be located in **Appendix G**.

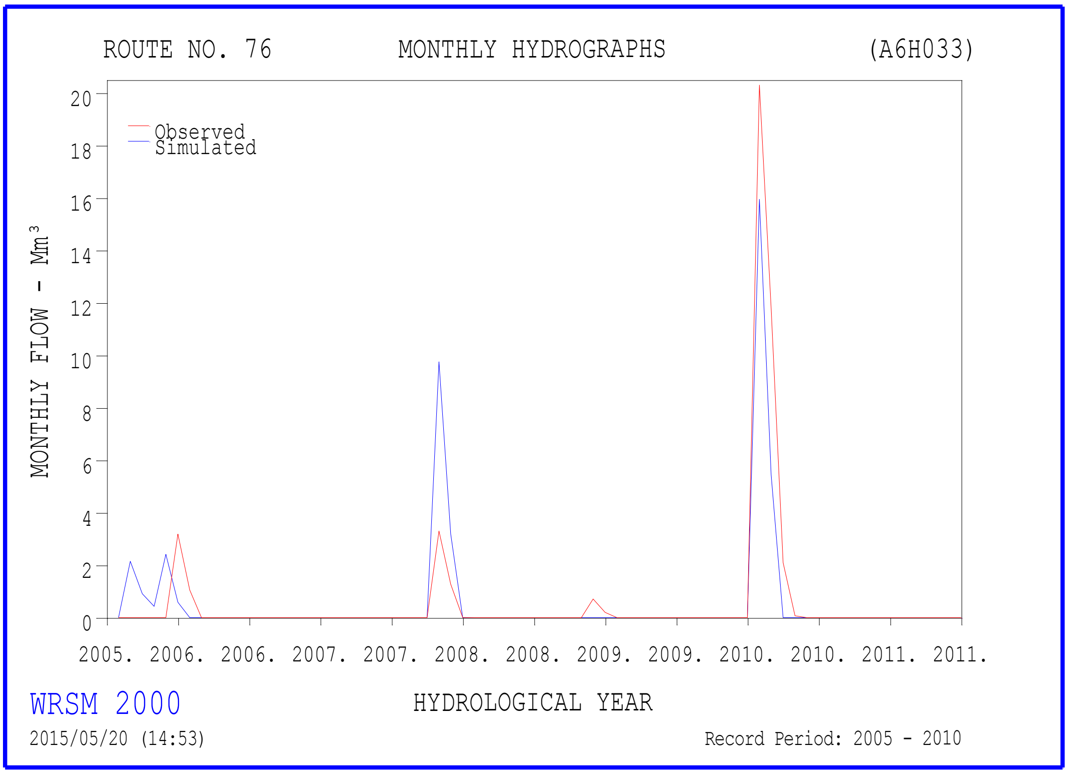

Figure 7.3: Monthly hydrograph of flows at the outlet of Nylsvlei wetland (A6H033) modelled using the Reservoir Module

7.2.3 Testing of network configuration definition

After considering all of the aforementioned principles, a system diagram was developed and data were aggregated at appropriate levels of detail to adequately represent the particular water resource system. This information was then arranged in the WRSM2000 to ensure that the configuration definition input into the model was correct and accurately represented the actual river and water-use system.

The WRSM2000 does not have a user interface capable of graphically illustrating system network diagrams, but provides users with a feature of viewing the configuration definitions in a printable text file format. Hence, this feature was used extensively to manually reconcile aggregated data with data configured in the model.

Furthermore, extensive inspection was undertaken to verify the system integrity as defined in the WRSM2000 system model. This process involved the undertaking of mass balances at each node in the system to ensure that the defined linkages in the system network are correct.

7.3 CALIBRATION OF THE ENHANCED WRSM2000

7.3.1 General

The WRSM2000 is calibrated through an iterative process of adjusting the calibration parameters of the appropriate Runoff Module. These calibration parameters are adjusted until the simulated flows within a considered Flow Route closely, statistically and graphically, mimic the historically observed flows measured at a stream flow gauging station, over the time period for which reliable data are available. To obtain realistic and reliable results, all the changes in historical upstream developments within the catchment which may have an impact on the observed stream flow record, must be accounted for in the WRSM2000. Regional calibration parameters from the WR2005 publications (WRC, 2008) generally serve as a starting point. Table 7.1 provides a list of the twelve WRSM2000 calibration parameters as well as a description and the respective units.

Table 7.1: Description of WRSM calibration parameters

Acronym	Description	Units
POW	Power in the soil moisture / subsurface flow equation	-
GPOW	Power in the soil moisture recharge equation	-
HGSL	Storage below which no recharge occurs	mm
ST	Soil moisture storage capacity	mm
FT	Subsurface flow at full soil moisture capacity	mm/month
HGGW	Maximum soil moisture recharge	mm/month
ZMIN	Minimum catchment absorption rate	mm/month
ZMAX	Maximum catchment absorption rate	mm/month
PI	Interception storage	mm/day
TL	Lag of flow, excluding groundwater	months
R	Coefficient on the evaporation / soil moisture equation	-

Table 7.2 provides a summary of the stream flow gauging stations used, as well as the quaternary or sub-quaternary catchments calibrated with the available of stream flow record period.

Table 7.2: Summary of the stream flow gauges used and the associated quaternary catchments calibrated

Station no.	Quaternary	Representative system model	Quaternaries/ quinaries calibrated	Used record period	
				Start	End
River					
A4H002*	A42C	A42A, A42B and A42C	A42A, A42B and A42C	1948/10	2010/09
A4H004	A41C	A41	A41A and A41B	1962/10	2010/09
A4H005*	A42F	A42E, A42F2 and A42F4	A42F2 and A42F4	1962/10	2010/09
A4H007*	A42H	A42H3	A42H3	1962/10	2010/09
A4H008*	A42D	A42D	A42D	1964/10	2010/09
A5H004	A50B	A50	A50A and A50B	1961/10	2010/09
A6H009	A63D	A63	A63A and A63B	1960/10	1996/09
A6H010	A61C_1	A61	A61C_1	1963/10	2010/09
A6H011	A61A	A61	A61A_3	1966/10	2010/09
A6H012	A61B_1	A61	A61B_1	1966/10	2010/09
A6H027**	A61J	A61	A61H	1952/10	2010/09
A6H029**	A63A	A63	A63A, A63B	1968/10	2010/09
A6H033**	A61F	A61	A61A, A61B, A61C, A61D and A61E	2005/10	2010/09
A6H036**	A61J	A61	A61H and A61J	1995/10	2010/09
A7H001	A71H	A71	A71A, A71B, A71C, A71D, A71E, A71F, A71G and A71H	1965/10	1999/09
A7H003	A71G	A71	A71A, A71B, A71C, A71D, A71E, A71F and A71G	1947/10	1994/09
Reservoir					
A5R001**	A50E	A50	A50C, A50D and A50E	1968/10	2010/09
A5R002**	A50G	A50	A50F, A50G	1968/10	2010/09
A6R001	A61H	A61	A61H	1955/10	2010/09
A6R002	A62J	A62	A62A, A62B, A62C, A62D, A62E, A62F, A62G, A62H and A62J	1970/10	2010/09
A8R001	A80F	A80	A80A and A80B	1970/10	2010/09
A8R002	A80H	A80H&J	A80H_1	1971/10	2010/09
A8R003	A80H	A80H&J	A80H_2	1971/10	2010/09

* *Gauges used in the "Updating the Hydrology and yield analysis in the Mokolo River Catchment" (DWA, 2007) with record period extended to 2010.*

** *Gauges used only to verify the calibration results at certain points on the relevant modelled river system.*

There are a number of ungauged quaternary catchments in the Study Area for which the WRSM2000 system could not be calibrated. In some previous studies calibrated parameters from neighbouring catchments were applied to ungauged quaternary catchments. For the purpose of this Study, regional parameters, from the WR2005 Study (WRC, 2008) were applied. This method provided more realistic and acceptable runoff results. Many of the ungauged catchments, however, fall in the drier low laying areas which do not significantly contribute to catchment runoff.

The following is of note with regard to the availability of stream flow data and the WRSM2000 calibration process for the six river catchments within the Study Area:

a) Matlabas

With regard to the Matlabas River catchment, there are no stream flow gauges downstream of **A4H004**, located at the outflow of quaternary catchment A41B. Hence, the system model could not be calibrated for quaternary catchments A41C, A41D and A41E. However, considering the limited current and anticipated future development within the Matlabas River catchment, this is currently not of great concern.

b) Mokolo

The WRSM2000 system configuration from the Mokolo Study (DWA, 2007) was used for the hydrological modelling of the Mokolo River catchment for this Study. As previously mentioned, the Mokolo Study WRSM2000 system was not recalibrated, but the hydro-meteorological data were simply extended with seven years up to the 2010 hydrological year (September 2011).

c) Lephalala

Only the stream flow record of **A5H004** at the outlet of A50B is suitable for calibration in the Lephalala River catchment. Regional parameters were used for the simulation of A51C to A51J.

d) Mogalakwena

The Mogalakwena River catchment is a complex system and hence the three tertiary catchments (A61, A62 and A63) were modelled as three separate systems. The process of calibrating the Mogalakwena River catchment had to be conducted in series, starting with the calibration and simulation of stream flow in tertiary catchment A61 (Nylsvlei), followed by A62 and ending with

A63. The simulated stream flow at the outlet of quaternary catchments A61G and A61J were defined as inflows into quaternary catchment A62B. Similarly, the outflow from quaternary catchment A62J, through releases from Glen Alpine Dam, served as the inflow to tertiary catchment A63.

In tertiary catchment A61 calibration was achieved at **A6H010**, **A6H011**, **A6H012** which cover the Nyl River and Nylsvlei. The patched and extended data record of **A6H027** served as inflow into quaternary catchment A61J, downstream of Doorndraai Dam (**A6R001**). There were no suitable gauges to calibrate the stream flow in the remainder of A61. The only useful flow gauging station for calibration in tertiary catchment A62 was the Glen Alpine Dam (**A6R002**).

The stream flow gauge, **A6H029**, just downstream of Glen Alpine Dam was patched, extended with simulated stream flow and used as input to A63. There were no stations suitable for calibration in A63. Quaternary catchments A63C and A63E were modelled as separate independent systems as the rivers in these quaternary catchments discharge directly into the Limpopo River.

e) Sand

The Sand River catchment has the highest water requirement in the Study Area with a complex system model configuration. The flow gauging station **A7H003** was used for calibration down to A71G and covers the portion where the bulk of the surface water is generated and used. There are no stream flow gauges for calibration purposes in tertiary catchment A72. Quaternary catchments A72A and A72B make up the Brak River, which joins the Sand River upstream of quaternary catchment A71K. The Sand River discharges into the Limpopo River at A71K. A71L constitutes of a number of small rivers discharging directly into the Limpopo River. Hence, A71L was modelled separately and regional parameters were applied.

f) Nzhelele

The Nzhelele River catchment comprises of the Nzhelele River and the Nwanedi River catchments, both which flow directly into the Limpopo River. Two independent system models were configured for the aforementioned catchment areas. The Nzhelele River system model was calibrated against the inflow record of Nzhelele Dam (**A8R001**) which is representative of the stream flow in quaternary catchments A80A and A80B. However, most of the irrigation in the catchment occur downstream of the dam, i.e. in quaternary catchments A80F and A80G. The Nzhelele River discharges into the Limpopo River at A80G.

The Nwanedi River catchment area comprises of quaternary catchments A80H and A80J. Calibration of A80H was achieved by means of combining the inflow of Luphephe and Nwanedi dams. A80J was simulated using regional parameters and the extended simulated stream flow together with the observed releases from the two dams.

7.3.2 Groundwater surface water interaction

The calibration of the WRSM2000 is directly influenced by the groundwater-surface water interaction within the catchment under consideration and is modelled using the GWSWIM, or SAMI model, incorporated into the WRSM2000. To configure the GWSWIM a set of parameters are required that describe the groundwater and aquifer characteristics.

The standard procedure for modelling groundwater-surface water interaction has two stages. The first stage includes an initial calibration of the WRSM2000 with the GWSWIM de-activated. The preliminary calibration parameters, such as the MAP, rainfall, simulated natural runoff and simulated catchment soil moisture storage time-series (Pitman S), as well as the historical groundwater irrigation requirements, are then provided to a groundwater specialist. Based on the received data sets of the initial calibration, the GWSWIM is set up externally to the WRSM2000 (in a spreadsheet version of the model) to define the regional parameters on a quaternary catchment basis.

As part of the second stage, the resulting GWSWIM parameters are then used for the preliminary configuration of the GWSWIM in the WRSM2000. Subsequently, further WRSM2000 calibrations are then undertaken. The effect of the WRSM2000 parameter changes on the GWSWIM results should be continually monitored to ensure that the modelled groundwater-surface water interaction remains reasonable compared to expected recharge, interflow and base-flow. The monitoring involved mainly two basic checks:

- Assess the validity of the generated base-flow time-series, in comparison to stream flow; and
- Check whether modelled recharge remained lower than the harvest potential.

For the purpose of this Study, regional groundwater parameters, as defined in the WR2005 (WRC, 2008) for each quaternary catchment, were used for the preliminary configuration of the GWSWIM in the WRSM2000. Hence, the first stage described above was omitted. Further calibrations of the WRSM2000 were conducted. The effect of the WRSM2000 parameter changes on the GWSWIM results were continually monitored to ensure the groundwater-surface water interaction modelled is acceptable.

7.3.3 Calibration results

The main objective of the WRSM2000 calibration was to obtain a set of calibration parameters for which the simulated flow, within a considered Flow Route, closely mimics the historically observed stream flows over the time period for which reliable observed data are available.

To determine the reliability of the calibration results, a standard set of simulated and observed flow statistics and graphs were analysed and compared. Relevant statistics include:

- MAR;
- Standard deviation (SD); and
- Seasonal index (SI).

Graphs of the simulated and observed stream flows that were compared include:

- Monthly and annual hydrographs;
- Mean monthly flows plots;
- Gross yield curves;
- Scatter diagrams;
- Histogram of monthly flows; and
- Cumulative frequency plots.

The final calibration parameter values are given in **Table F.1** of **Appendix F** per quaternary catchment or sub-quaternary catchment where applicable. **Tables F.2** to **F.7** of **Appendix F** summarise the comparison of the calibration statistics between the simulated and the observed stream flow records over the calibration period.

The final calibration graphs, including monthly hydrographs, annual hydrographs, mean monthly flow graphs, gross yield curves, scatter diagrams, histograms of monthly flows and cumulative frequency plots are provided in **Appendix G**.

7.4 DEVELOPMENT OF NATURAL STREAM FLOW DATA

The primary purpose of the hydrological analysis as part of this Study was to develop *time-series of natural monthly stream flow data* for defined incremental quaternary and sub-quaternary catchments. These sequences represent the natural stream flow that would have occurred if there was no development or human interference in the considered catchment. This also provides stationary data which contain no intrinsic trends and may be used as direct input to the subsequent stochastic yield analysis and water resource system analyses (WRYM and WRPM).

For the purpose of this Study, time-series of monthly incremental natural stream flow, that covers the Study Period of 1920 to 2010 (hydrological years), were developed for all quaternary and sub-quaternary catchments in the Study Area. Time-series of monthly SFR, caused by IAP (*.IRR-file) and commercial forestry (*.AFF-file), were also generated.

7.4.1 Methodology applied to develop natural stream flow data

Time-series of natural stream flow data were generated by applying the calibrated WRSM2000 system setups as follows:

- Exclude all water volumes that exit the catchment under consideration, including exports, consumptive urban, industrial and irrigation water use, as well as SFR caused by commercial forestry, dry-land agriculture and IAP, groundwater abstractions, etc.;
- Subtract water volumes that enter the catchment under consideration, including imports, as well as urban, industrial and irrigation return flows, etc.;
- Account for the impact of water bodies located upstream of the quaternary catchment in question, including evaporative losses and the impact on runoff caused by the impoundment of stream flow.

In instances where no calibration was plausible, regional parameters, defined in the WR2005 Study (WRC, 2008), were used to generate the natural stream flow data. It was found that the regional parameters generated more realistic and acceptable runoff values in terms of unit runoff than an attempt to apply calibration parameters from neighbouring catchments. Many of the ungauged catchments fall in the low lying, drier areas which do not contribute significantly to the catchment runoff.

Time-series of natural stream flow data were generated for altogether 112 incremental quaternary and sub-quaternary catchments in the Study Area.

7.4.2 Methodology applied to develop time-series of monthly SFR activities

In addition to the time-series of natural monthly stream flow data, time-series of monthly SFR activities for defined incremental quaternary and sub-quaternary catchments, is required as input in the subsequent yield and planning analyses. The time-series of monthly SFR activities should be representative of the current development level and hence, the current reduction in stream flow. The relevant SFR activities in the Study Area are IAPs and commercial forestry.

The process of creating SFR monthly time-series for IAPs and commercial forestry, respectively, involves applying the calibrated WRSM2000 system setups as follows:

- The applicable (IAP or forestry) SFR *"child"* modules, connected to the *"parent"* Runoff Modules, were included in the "natural" WRSM2000 setups. The resulting stream flow time-series for each quaternary and sub-quaternary catchment are representative of the "natural" stream flow data, impacted only by the relevant SFR;
- This monthly time-series of reduced stream flow were compared to the monthly simulated natural stream flow to produce a monthly time-series of the SFR (i.e. water use) caused by either IAP or commercial forestry.

This process was repeated, separately for IAP and commercial forestry to generate the respective *.IRR and *.AFF files. These data files are used as input to the subsequent WRYM and WRPM analyses.

7.4.3 Development of "natural" stream flow data with the impact of groundwater abstractions

The WRYM and WRPM cannot explicitly simulate the groundwater balance process. Hence, the GWSWIM, as part of the WRSM2000, was used to simulate the groundwater mass balance of recharge, aquifer storage and depletion through evaporation and abstraction. A process similar to the generation of time-series of natural stream flow data per quaternary and sub-quaternary catchment (**Section 7.4.1**) was followed. However, in this instance groundwater abstraction was activated to include the impact thereof on the natural stream flow.

7.4.4 Natural stream flow data results

The statistics of the incremental natural stream flow data simulated for each of the 112 defined quaternary and sub-quaternary catchments in the Study Area are given in **Table H.1** of **Appendix H**. The 112 incremental monthly natural stream flow time-series (*.INC-files) are available electronically in Microsoft Excel format on the attached CD (included as **Appendix I**). The names of the .INC-files are consistent with the quaternary or sub-quaternary catchment names as listed in **Table H.1**.

The results of the hydrological analysis, including the rainfall-runoff response for all quaternary and sub-quaternary catchments are provided in **Table H.2** of **Appendix H**. A summary of the results are given in **Table 7.3** per river catchment. **Figure A.6** of **Appendix A** shows the spatial distribution of the natural unit runoff in the Study Area.

Table 7.3: Summary of the hydrological analysis results for the Limpopo WMA North

River catchment	Net Area	MAE	MAP	Natural MAR	Unit runoff
	km^2	mm/a	mm/a	million m^3/a	mm
Matlabas	3 613	1 894	513	55.7	15
Mokolo	7 610	1859	569	276.2	36
Lephalala	5 060	1 565	489	142.3	28
Mogalakwena	17 883	1 894	483	246.2	12
Sand	14 621	1 488	394	88.6	6
Nzhelele	4 112	1 468	455	140.0	34
Limpopo WMA North	**52 900**	**1 711**	**471**	**949**	**18**

8 EVALUATION OF RESULTS

8.1 ASSESSMENT OF RESULTS AND COMPARISON WITH OTHER STUDIES

As described in **Section 7.4**, the main objective of the hydrological analysis was to develop time-series of natural monthly stream flow data for the defined quaternary and sub-quaternary catchments in the Study Area, over the Study Period of 1920 to 2010 (hydrological years). The natural monthly stream flow time-series serve as direct input to the subsequent stochastic hydrological analysis and water resource system analyses.

After the acceptable calibration of the WRSM2000 system configurations, representing the six river catchments in the Study Area, natural stream flow data for the entire Limpopo WMA North could be generated. Natural stream flow data was obtained by simulating the runoff in the respective calibrated WRSM2000 systems with all human interference, such as water resources development, land use and SFR, excluded.

As mentioned, the results of the hydrological analysis, including the rainfall-runoff response for the various quaternary and sub-quaternary catchments are provided in **Table H.2** (**Appendix H**) and **Figure A.6** (**Appendix A**) shows the natural unit runoff distribution, in mm, throughout the Study Area.

Various assessments were made to determine if the results were reliable and acceptable for use in the subsequent stochastic and water resource system analyses. Standard validation tests, by means of *single mass plots* and *cusum plots*, were generated to evaluate the stationarity of the monthly natural stream flow data of each quaternary catchment. These mass plots and cusum plots are presented electronically in Microsoft Excel format on the attached CD (included as **Appendix I**). Based on these validation tests, the time-series of incremental natural stream flow data were considered to be of sufficient stationarity.

Results of this hydrological analysis were also compared to the WR2005 Study (WRC, 2008), to further evaluate the reliability and acceptability of thereof. The comparative results, over the corresponding study period of 1920 to 2004 (hydrological years), are provided in **Table H.3** of **Appendix H**.

Compared with the WR2005 Study, the overall *natural MAR* (NMAR) generated for this Study is approximately 1% higher over the corresponding study period of 1920 to 2004. However, it was noted that the lower runoff areas resulted in a larger percentage difference in the NMARs, e.g. the NMAR generated in the Matlabas River catchment for this Study is 55 million m^3/a compared to the 51 million m^3/a of the WR2005 Study - thus a difference of 10%.

The different hydro-meteorological data also influence the discrepancies between the simulated NMARs of the two studies. This Study identified problems in some of the catchment rainfall records. In some quaternary catchments, different combinations of point rainfall records were used to develop representative catchment rainfall data. Care was taken to discard all non-stationary rainfall data that induced trends in the catchment rainfall data. Refer to the *Rainfall Data Analysis Report (P WMA 01/000/00/02914/2/1)* for more information in this regard.

8.2 MODELLING CONFIDENCE

Modelling of water resource systems involves mathematically representing a real world system as a computer model. The model is a simplification of the real world system and therefore the confidence that can be placed on how well the model represents reality can differ significantly for different situations. Several factors influence the level of confidence, ranging from the data availability to the interpretation of the analyst as to which data should be incorporated.

In effort to quantify the accuracy of this Study's hydrological analysis results, the following aspects of the modelling process have been used to define the level of confidence:

- *Rainfall* – the number of point rainfall stations inside a rainfall zone and the overall stationarity of the rainfall zone time-series record;
- *Observed flow data for calibration* – how well the downstream stream flow gauge represents the quaternary or sub-quaternary catchment as well as the quality of the observed stream flow data;
- *Water use and infrastructure* - Farm and major dam, infrastructure data, confidence of point demands and irrigation data.

Some of these aspects can be compared quantitatively, however, others rely on a more qualitative assessment. Guidelines for evaluating data according to the confidence criteria that have been used in this assessment are explained in **Table 8.1**. The matrix summarising the outcome of the confidence evaluation is given in **Table H.4** of **Appendix H**.

Table 8.1: Guidelines for evaluation of confidence criteria (DWA, 2014)

Criteria	Indicator	Numerical score		
		5	3	0
Rainfall data	Number of point rainfall stations inside rainfall zone	Many with a good spatial distribution	Few	None
	Overall stationarity	No trend and good temporal variability	Some trend and reasonable temporal variability	Large but still acceptable long-term trend
Observed calibration data	The degree the downstream calibration gauge represents the quaternary catchment	At outlet of quaternary	Relatively far downstream	No downstream gauge
	Quality of downstream calibration gauge	Excellent dam balance or stream flow gauge	Only dam balance or good verification site	No downstream gauge
Water use and infrastructure	Farm and major dam, infrastructure data	Excellent survey and canal infra-structure data. Good farm dam area-capacity relationship data. Or no significant dams and other infrastructure	Some survey and canal infrastructure data. Farm dam sized determined from Google Earth area and capacities derived from information of dams in the vicinity.	No survey data for large dams, canal capacities unknown. Farm dam capacities determined from Google Earth areas and using standard capacity formulas.
	Confidence of point demands	All point requirements such as urban and industrial measured, as well as reservoir releases. Or no known point sources	Limited measured requirements, only estimated requirements from sources	Known point sources but no measured point demand data or any other estimates.
	Confidence in irrigation data	Measured or allocation controlled irrigation. Detailed V&V areas, crops and system information. Or no irrigation	Estimated requirements based on observed irrigation, no V&V data and extrapolation of other irrigation data	No accurate irrigation data but irrigation practises observed

The confidence ranges, associated with the NMAR and derived from Table H.4, are summarised in Table 8.2. Furthermore, from the results in Table H.4 (Appendix H), it can be concluded that the reliability of the results decrease towards the drier low laying areas, close to the Limpopo River. This may be due to the few adequate hydro-meteorological monitoring data, especially rainfall and stream flow data, in this area.

Table 8.2: Confidence ranges and associated NMAR

Confidence range (%)	NMAR (million m^3/a)	% of NMAR
>70 (High)	446.5	47%
70-50 (Medium)	382.6	40%
<50 (Low)	119.8	13%

Table 8.2 shows that the confidence in approximately 47% of the simulated incremental natural stream flows are regarded as high. A further 40% is regarded as having a medium confidence and 13% showed a low confidence.

9 INFORMATION REPOSITORY

All the relevant information utilised and generated as part of the hydrological analysis of the *Limpopo WMA North* study is provided electronically with this report for future use (included in **Appendix I**). The electronic data directory structure used for this purpose is as follows:

- [**1.** Documentation]:
  - [**1.1** Volume 1]: This Document in pdf
  - [**1.2** Volume 2] Appendices in pdf:

- [**2.** Hydro-meteorological Data]:
  - [**2.1** Rainfall]:Catchment Rainfall files
  - [**2.2** Stream flow]:
    - [**2.2.1** Patched]: Final patched observed data
    - [**2.2.2** Natural]: Natural simulated time-series for each quaternary catchment, as used in the WRYM model

- [**3.** WRSM2000 System Configuration]
  - [**3.1** Natural Systems]
  - [**3.2** Calibration Systems]

10 CONCLUSIONS

The following conclusions were made regarding the hydrological analysis:

- The overall water use distribution shows that the irrigation sector is the largest water consumer in the Study Area. Irrigation has a total water requirement of 465 million m^3/a, inclusive of the irrigation supplied from the Limpopo River and associated sand aquifers. Approximately 146 million m^3/a of the irrigation water requirement is supplied directly from the Limpopo River main stem and associated sand aquifers. Of the annual irrigation water requirement, 57% is sourced from groundwater, 36% from surface water and 8% from regulated government irrigation schemes.

- The total domestic water requirement in the study area is estimated at 82 million m^3/a of which 67% is supplied from groundwater.

- The total water requirement for large mining and power generation industries in the Study Area is 17 million m^3/a. This includes the Matimba Power Station, Grootegeluk Coal Mine, AMPLATS Platinum Mine and Venetia Diamond Mine.

- The annual reduction in stream flow due to IAP is estimated at 6.9 million m^3. The highest SFR occurs in the Mogalakwena River catchment followed by the Sand River catchment. Of note is that the Sand River catchment has a greater area covered by IAP compared to the Mogalakwena River catchment, however, a lower percentage falls within the riparian zone which results in significantly less SFR.

- There is limited commercial forestry in the Study Area which contributes to SFR. Forestry is confined to the upper reaches and high rainfall regions of the Nzhelele and Sand river catchments. The total SFR due to commercial forestry is estimated at 2.2 million m^3/a.

- Livestock watering is also a significant water user in the Study Area, with an annual water requirement of 25 million m^3/a.

- Throughout the Study Area stream flow gauges have been damaged or destroyed by large floods, of which the 1996 and 2000 floods were the most prominent. Rehabilitation of the stream flow gauges are timeous and in some cases too expensive to fix, resulting in long periods of missing record data.

- Very few of the stream flow gauging records have data satisfactory to calibrate the WRSM2000 system setups. Of the 80 surface water monitoring points, excluding canal and pipeline measurements, only 14 could be used to calibrate the WRSM2000 system setups. This includes ten stream flow gauges and four reservoir monitoring points. Additionally, data records of six stream flow gauges and three reservoir monitoring points were good for visual inspection and verification of calibrated flows.

- It is of great concern that in a gross area covering approximately 60 800 km^2, only 23 surface water monitoring points contain records useable for calibration and verification of stream flow.

- Three gauging stations (A5H004, A5R001 and A5R002) in the Lehalala River catchment were considered for the calibration of the WRSM2000 system setup. The WR2012 stream flow evaluations raised concern regarding the reliability of two gauges, A5R001 and A5R002. These findings were confirmed by this Study. The unit runoff at these gauges is high and seems to overestimate the flow to a great extent. Hence, only A5H004 was used for calibration of the WRSM2000 and regional parameters were applied to downstream quaternary catchments.

- In the Mogalakwena River catchment the inflow records of the major dams, especially Doorndraai Dam and Glen Alpine Dam to a lesser degree, contained long periods of missing and unreliable data. This had an impact on the modelling approach adopted. For Doorndraai Dam the calibration was not based on the inflow record (A6R001), but on the downstream stream flow gauge, A6H027, which measures dam spills and releases. The patched and extended stream flow record of A6H027 served as the incremental outflow for quaternary catchment A61H.

- Only two stream flow gauging stations in the Sand River catchment, A7H001 and A7H003, could be used for calibrating the representative WRSM2000 system. Both these stations are closed and there are no other operational stream flow gauges in the Sand River.

- The dam inflows in the Mogalakwena and Nzhelele river catchments are not accurate for low flow calibrations of the WRSM2000.

- Releases are made from Glen Alpine Dam approximately four times per year. The timing and size of the releases are based on the water levels of about 30 downstream storage weirs as interpreted by downstream farmers. However, the dam is sensitive to releases – if too little water is released, additional releases have to be made and if too much water is released, some is lost in the Limpopo River, reducing the dam to lower levels than necessary.

- The NMAR of the Study Area was found to be 949 million m^3/a, over the Study Period 1920 to 2010 (hydrological years). The majority of the NMAR is generated in the Mokolo and Mogalakwena river catchments and accounts for 55% of the runoff generated in the Study Area.

- Compared with the WR2005 Study, the overall NMAR generated for this Study is only 1% higher over the corresponding study period of 1920 to 2004. However, it was noted that the lower runoff areas resulted in a larger percentage difference in the NMARs, e.g. the NMAR generated in the Matlabas River catchment for this Study is 55 million m^3/a compared to the 51 million m^3/a of the WR2005 Study - thus a difference of 10%.

- Confidence in the simulation results for each quaternary or sub-quaternary catchment was based on criteria such as the spatial distribution of rainfall, water- and land-use data as well as quality of observed stream flow data used for calibration of the WRSM2000 system setups. About 47% of the generated NMAR in the Study Area have a confidence level higher than 70%. A further 40% had a confidence level of between 50% and 70% and 13% had a confidence level of lower than 50%.

- The confidence level of the WRSM2000 simulation results seems to decrease towards the drier low laying areas of the Study Area. The main reasons for the low confidence levels in some areas are due to the poor distribution of rainfall and stream flow gauging stations across the Study Area as well as unreliable stream flow data.

11 RECOMMENDATIONS

Based on the hydrological analysis undertaken as part of the *Limpopo WMA North Reconciliation Strategy* and the conclusions discussed in **Section 10**, the following is recommended:

- The quantity and quality of flow gauging stations in the Study Area should be improved as only 14 of the 93 registered surface water monitoring points located in the Study Area were of reasonable quality to calibrate the representative WRSM2000 system setups.

- Currently only one stream flow gauge, A5H004, in the upper reaches of the Lephalala River catchment contain data adequate for calibration of the representative WRSM2000 system setup. However, this stream flow gauge only monitors flow from quaternary catchments A50A and A50B in the upper reaches of the river. It is thus recommended that the monitoring of releases from the two dams in the Lephalala River catchment, A5R001 (Susandale Dam) and A5R002 (Vischgat Dam), be improved as this would aid in increasing the accuracy of hydrological analysis results. The abstractions for irrigation in the vicinity of A5R001 should also be monitored.

- Monitoring of the inflows of major dams, such as Doorndraai Dam (A6R001) and Glen Alpine (A6R002), must be upgraded and improved as some components contain long periods of missing and unreliable data.

- The abstractions component for *Industry and Town* in the Doorndraai Dam balance record stops in February 2004 and must be updated.

- The releases from Glen Alpine Dam should be monitored by means of appropriate infrastructure such as gauge plates or near real-time monitoring system. Furthermore, a Water User Committee should be established to manage the system effectively and to more accurately determine the timing and volume of releases.

- The establishment of additional streamflow gauges is proposed at the following locations:
  - On the Mogalakwena River before the confluence with the Limpopo River to measure the water discharged from the Mogalakwena River system; and
  - Upstream of the 30 irrigation storage weirs, located up to 70 km downstream of Glen Alpine Dam, in the Mogalakwena River, to quantify losses incurred through releases from the Glen Alpine Dam.

- An operating rule for the Nzhelele Dam (A8R001) should be implemented to both protect the resource and also to optimise the dam utilisation. The historical trajectory of Nzhelele Dam shows that the dam experienced times of large drawdowns.

- Cross Dam, which serves as a balancing dam downstream of the Nwanedi (A8R003) and Luphephe (A8R002) dams, should be gauged and all abstractions monitored.

- Opening of closed stream flow gauging stations should be prioritised, especially in the Sand River catchment where stream flow data records only extend to the late 1990’s. Stream flow gauges, which are critical for water resources planning and which should be reopened, include A7H001 and A7H003.

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Appendix A

Maps

Appendix B

WRSM2000 system schematic diagrams

Appendix C

Water use and return flows

Appendix D

Water bodies

Appendix E

Hydro-meteorological data

Appendix F

WRSM2000 calibration results

Appendix G

WRSM2000 calibration graphs

Appendix H

Simulation results and comparison with other studies

Appendix I

Natural monthly stream flow data