Sharing the Water Resources
Of the Orange-Senqu River Basin

Report No: 002/2008

Feasibility Study of the Potential for Sustainable Water Resources Development in the Molopo-Nossob Watercourse

HYDROLOGY REPORT
FINAL

Submitted by:

PO Box 68735
Highveld
0169
Tel: (012) 665 6302
Fax: (012) 665 1886
Contact: Dr M van Veelen

April 2009

Feasibility Study of the Potential for Sustainable Water Resources Development in the Molopo-Nossob Watercourse

Surface Water Hydrology

Prepared by

Ninham Shand (Pty) Ltd

April 2009

Title:	***Hydrology Report***
Authors:	***Ninham Shand***
Project Name:	***Feasibility Study of the Potential for Sustainable Water Resources Development in the Molopo-Nossob Watercourse***
Status of report:	***Final***
ILISO Project No:	***700192***
Date:	*April 2009*
Keywords:	*Molopo River, Nossob River, Water Resources*

ILISO Consulting (PTY) LTD

Approved for and on behalf of ILISO Consulting (Pty) Ltd, Ninham Shand Incorporated, Schoeman and Partners and Conningarth Economists by

Dr M van Veelen
Director: ILISO Consulting (Pty) Ltd

2009/05/12
Date

ORANGE SENQU RIVER COMMISSION

Approved on behalf of ORESECOM by

Mr Lenka Thamae
Executive Secretary - ORASECOM

2009/05/12
Date

LIST OF STUDY REPORTS IN FEASIBILITY STUDY OF THE POTENTIAL FOR SUSTAINABLE WATER RESOURCES DEVELOPMENT IN MOLOPO-NOSSOB WATERCOURSE PROJECT:

This report forms part of a series of reports done for the Molopo-Nossob Feasibility Study, all reports are listed below:

Report Number	Name of Report
002/2009	Hydrology Report
003/2008	Catchment Status Inventory Report
006/2009	Groundwater Study
007/2009	Main Report

TABLE OF CONTENTS

Page No

LIST OF TABLES

LIST OF FIGURES

ANNEXURES

LIST OF ACRONYMS

CR	Channel Reach Module
DWA	Department of Water Affairs (Botswana)
DWAF	Department of Water Affairs (South Africa)
MAE	Mean Annual Evaporation
MAR	Mean Annual Runoff
MM	Mine Module
ORASECOM	Orange-Senqu River Commission
RR	Irrigation Block Module
RSA	Republic of South Africa
RU	Run-off Module
RV	Reservoir Module
WARMS	Water Allocation and Registration Management System
WRSM2000	Water Resource Simulation Model

1. INTRODUCTION

The Molopo River is an ephemeral tributary of the Orange–Senqu system, which is an international river basin shared by The Kingdom of Lesotho, the Republic of Namibia, the Republic of Botswana and the Republic of South Africa. The Orange-Senqu River Agreement, signed by the governments of the four countries, established the Orange-Senqu River Commission (ORASECOM) to advise the parties on water related issues.

The Molopo River, and its main tributary the Kuruman River, receive most of its flow from tributaries in the Republic of South Africa, most of which have now been dammed for urban and agricultural purposes. As a result, inflow to the main stem of the Molopo River, which forms the boundary between Botswana and South Africa, has become heavily reduced and even non-existent in some years.

The Nossob River, and its main tributary the Aoub River, originate in Namibia and later forms the south-western boundary between Botswana and South Africa down to its confluence with the Molopo River. Dams have been constructed in the upper reaches of the Nossob River.

The reduction in the already limited flows in these sub-basins, due to the exploitation of surface water in the upper reaches, has placed a tremendous strain on the sustainability of rural activities in the south-western corner of Botswana and some parts of South Africa along the Molopo and Nossob Rivers. As an attempt to remedy the situation, the ORASECOM countries has appointed ILISO Consulting, in association with Ninham Shand Consulting Engineers, Schoeman and Partners and Conningarth Economists, to study the feasibility of the potential for the sustainable water resources development in the Molopo-Nossob Sub River Basin.

The aim of this report, which describes the outcome of the hydrological modelling task, is to provide first order estimates of typical surface water runoff volumes in the main rivers in the study catchments. For this purpose, the Pitman rainfall-runoff model was configured for the main subcatchments in the study area. For the South African catchments, the Pitman model parameters were based on regionalised catchment parameters which are readily available from “Surface Water Resources of South Africa 1990” (WR90) (Midgley *et al.*, 1994). These parameters were then transferred to the subcatchments that are located within Botswana and Namibia and used to simulate long-term streamflow sequences based on local observed rainfall records and current land use information. Estimates of surface water runoff have been calibrated based on observed flow records where available as well as on historical records of floods in the Molopo-Nossob catchment.

2. CATCHMENT DESCRIPTION

2.1 LOCATION

The Molopo-Nossob system forms part of the Orange-Senqu system and is shared by the countries of Namibia, the Republic of Botswana and the Republic of South Africa (RSA). A significant portion of the catchment falls within the Kalahari Desert. The system is an ephemeral system and consists of four main subcatchments viz. the Molopo, Kuruman, Nossob and Aoub catchments. The locations of these catchments are shown in, **Figure 2-1** while the catchment areas per country are presented in **Table 2-1.**

Table 2-1: Main Subcatchments within the Molopo-Nossob System

	Catchment Area (km^2)			
	RSA	**Namibia**	**Botswana**	**Total**
Molopo	61 882	18 120	112 583	**192 585**
Kuruman	41 194	0	0	**41 194**
Nossob	4 704	46 928	17 426	**69 058**
Aoub	5 589	34 601	0	**40 190**
Total	**113 369**	**99 649**	**130 009**	**343 027**

2.2 TOPOGRAPHY

There are no distinct topographic features in the study area, with the majority of the area being relatively flat with no climatic barriers. The upper tributaries of the Nossob and Aoub rivers, in the mountainous areas surrounding Windhoek, are characterised by higher elevations (1 700 to 2 000 masl), while high-lying areas to the east and south of Mafikeng (1 500 masl) and Kuruman (1 336 masl) forms the watershed divide between the Molopo / Kuruman system to the north and the Vaal / Orange system to the south.

The Nossob and Aoub catchments gradually fall towards the south, while the Molopo and Kuruman catchments display a gradual decline in elevation towards the west. After the confluence of these rivers, to the south of the Kgalagadi Transfrontier Park, the Molopo River continues southwards until its confluence with the Orange River in the vicinity of the Augrabies Falls in the RSA. **Figure 2-2** displays the topography of the study area.

2.3 DRAINAGE

As a result of the low rainfall, flat topography and the occurrence of pans, dunes and sandy soils over much of the study area, specifically where the rivers flow through the Kalahari Desert, little usable surface runoff is generated. Although occasional runoff occurs in the upper parts of the various subcatchments, evaporation and seepage losses, in conjunction with relatively large storage dams, specifically in the upper Molopo and Nossob catchments, prevent this runoff from reaching the lower reaches except during extreme events. Although there is anecdotal evidence of occasional flow along the lower Kuruman, Molopo, Nossob and Aoub rivers, linked to specific flood events, there is no record of flows in the Molopo River ever having reached the Orange River and the Molopo-Nossob catchment is therefore classified as an endoreic area. Previous recordings of flow in the lower reaches of the Molopo and/or Kuruman rivers were in 1933, 1974/5 and 1975/76. Flow along the lower reaches of the Nossob and Aoub rivers has been recorded in 1934, 1963, 1974 and 1999/2000.

The occurrence of pans in the study area, which are common in the Botswana and Namibian parts of the catchment, also has a significant impact on local drainage patterns and further reduces runoff. Schoeman and Partners, as part of the landuse task of this study, calculated that the water retaining capacity of all 2 607 the pans in the study area equaled some 1 900 million m^3. The number, area and volume of pans in the study area are summarised in **Table 2-2**.

Table 2-2: Details of Pans in the study catchment

Subcatchment	No. Pans	Volume (Mm^3)	Area (km^2)
Molopo	1 179	1 406	972
Kuruman	226	71	54
Nossob	676	279	167
Aoub	526	230	141

2.3.1 Nossob River

The Nossob River originates in the mountainous area to the north-east of Windhoek and its upper reaches are characterised by two main tributaries viz. the Black Nossob and the White Nossob. These tributaries originally drain in an easterly direction towards Gobabis, where they turn south until their confluence at the town of Hoaseb, approximately 70 km south of Gobabis. From Hoaseb, the Nossob River flows in a south-easterly direction and eventually constitutes the border between the Republic of Botswana and the Republic of South Africa. The Nossob River has its confluence with the Aoub River at Twee Rivieren in the Kgalagadi Transfrontier Park and with the Molopo River at the town of Bokspits, 60 km south of the Aoub confluence.

2.3.2 Aoub River

The Aoub River has its origin in the Karubeam Mountains in Namibia north east of Mariental, from where it flows in a south-easterly direction towards the Republic of South Africa. Approximately 80 km upstream of the Namibian/South African border, the Aoub River is joined, from the north, by its main tributary, the Olifants River. The Olifants River originates in the mountainous areas surrounding Windhoek and flows parallel to the Aoub River until their point of confluence. The Aoub River joins the Nossob River at Twee Rivieren in the Kgalagadi Transfrontier Park.

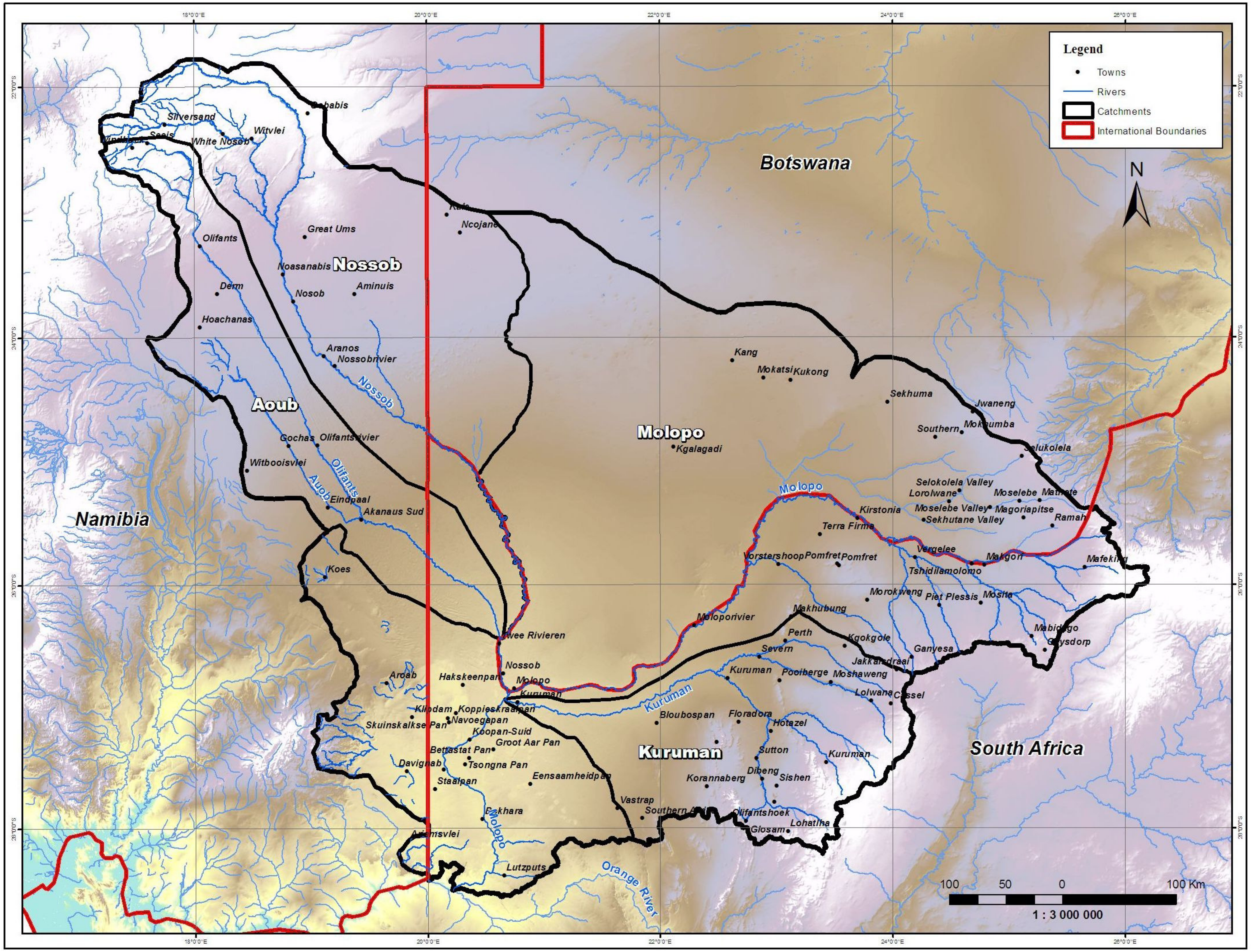

Figure 2-1: Study Catchment

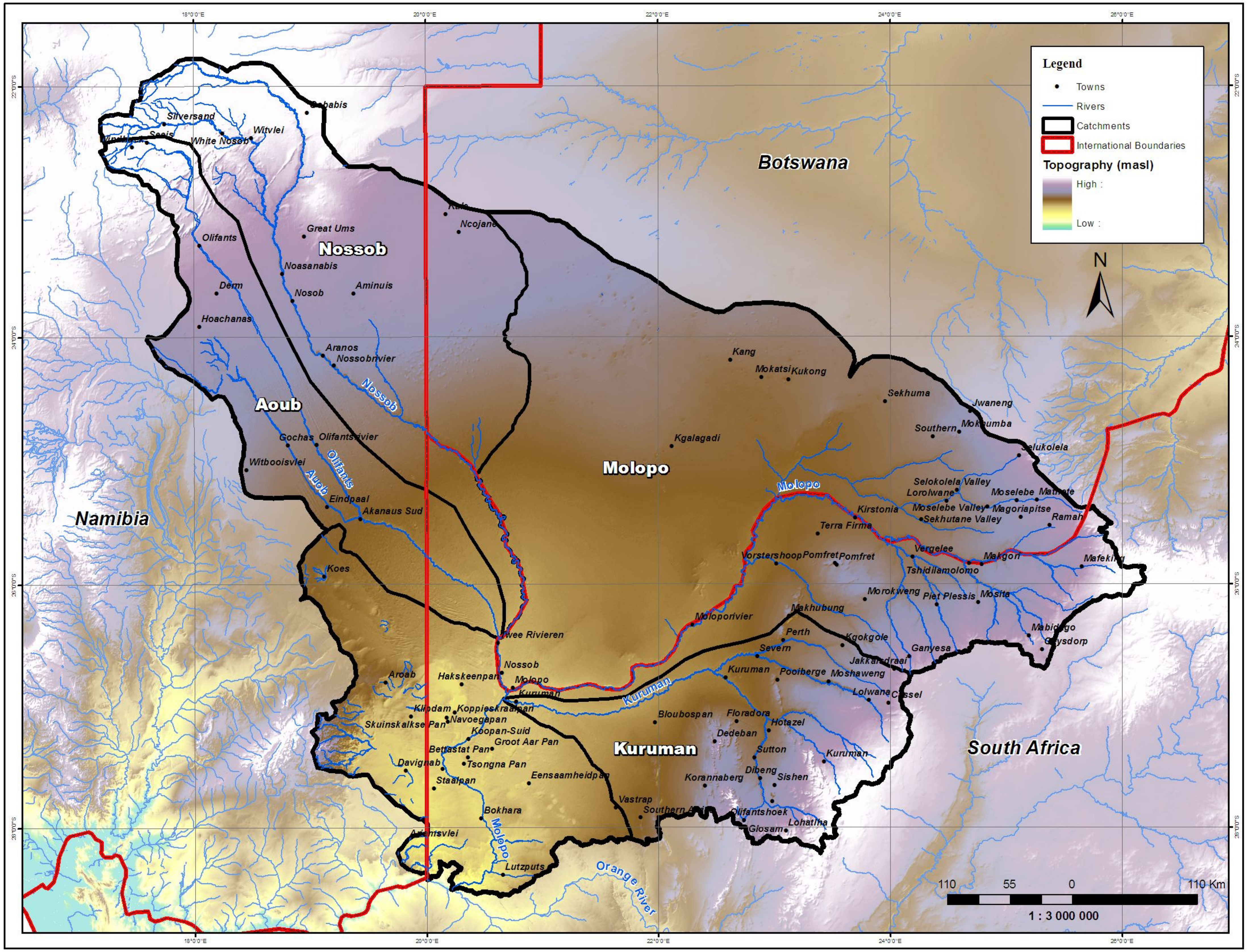

Figure 2-2: Catchment Topography

2.3.3 Kuruman River

The Kuruman River originates south east of Kuruman, where it is fed by various springs, most notably the Great Koning Eye, Little Koning Eye and the Kuruman Eye. Originally, the river flows in a north-westerly direction over a distance of approximately 140 km, after which it turns west and flows parallel to the Molopo River, until it has its confluence with the Molopo River at Andriesvale, in close proximity to the Nossob/Molopo confluence. Various tributaries join the Kuruman River along its upper reaches, including the Ga-Mogara, Moshaweng, Mathlawareng and Kgokgole rivers. The Kuruman catchment is the only subcatchment within the Molopo-Nossob system which falls completely within the Republic of South Africa.

2.3.4 Molopo River

The Molopo River emanates from the area to the east of Mafikeng, where it is fed by various springs, most notably the Molopo Eye and the Grootfontein Eye. From here it flows in a westerly direction and essentially constitutes the border between South Africa and Botswana until its confluence with the Nossob. Several dry-bed, ephemeral streams join the Molopo stem along its upper reaches. These include localised tributaries from the south (South Africa) e.g. Setklagole, Phepane and Disipi rivers, which drain north-westwards towards the Molopo River, and tributaries from Botswana e.g. Ramatlabama and Melatswane, which drain westwards before joining the main stem of the Molopo River. The Molopo River is joined by the Nossob River at Bokspits and the Kuruman River at Andriesvale, immediately south of the Kgalagadi Transfrontier Park, from where it flows southwards before joining the Orange River about 300 km downstream.

2.4 LANDUSE

Most of the land in the study catchment is under natural vegetation and a large portion of the catchment falls within the Kalahari Desert. Areas of cultivation are found in the Upper Nossob and Olifants catchments, where irrigation is predominantly from ground water sources, and the south-eastern parts of the Molopo catchment near Mafikeng where the demand is satisfied from farm dams. No afforestation or large-scale infestations of invasive alien vegetation occur in the study area, although land-invasion by *Prosopis* species is on the increase in Namibia. There is large-scale mining activity in the vicinity of Sishen and Hotazel in the upper Kuruman catchment where manganese ore, iron ore, tiger's eye and crocidolite (blue asbestos) are mined. The towns of Mafikeng, Kuruman, Gobabis and part of Windhoek represent the only significant urban areas in the study catchment, while scattered rural settlements and small towns supporting mining activities abound.

2.5 SOILS AND VEGETATION

The central part of the Molopo-Nossob catchment is covered by moderate to deep Aeolian Kalahari sand, known as *sandveld*. The major soil group of the *sandveld* is the Arenosols, while the upper portions of the Nossob and Aoub catchments, in the vicinity of Windhoek, are characterised by Regosoils. The upper catchment of the Molopo River displays moderate to deep clayey loam. The major soil types in the catchment are shown in **Figure 2-4.**

As a result of the generally arid climate, the Molopo-Nossob catchment is dominated by open tree and shrub savanna (*Tropical Bush* and *Savanna* according to the Acocks veld type classification), with extensive areas covered by grass after rains. Small areas of *Grassveld* (Acocks) occur towards the east of the catchment. Over the majority of the study area, vegetation is sparse.

2.6 CLIMATE

2.6.1 Rainfall

Rainfall within the study area is highly seasonal with most rain occurring during the summer period (October to April). The peak rainfall months are February and March. Rainfall generally occurs as convective thunderstorms and is sometimes accompanied by hail. The mean annual rainfall over the Molopo and Kuruman catchments decreases fairly uniformly from more than 500 mm in the east (upper Molopo catchment) to approximately 150 mm in the vicinity of the Orange River confluence. In the Nossob and Aoub catchments, mean annual rainfall decreases in a southerly direction and varies from about 400 mm in the upper Nossob catchment to less than 200 mm at the confluence with the Molopo River.

Figure 2-3 shows the typical seasonal distribution of rainfall within the study area, while **Figure 2-4** depicts the variation in mean annual precipitation over the study area.

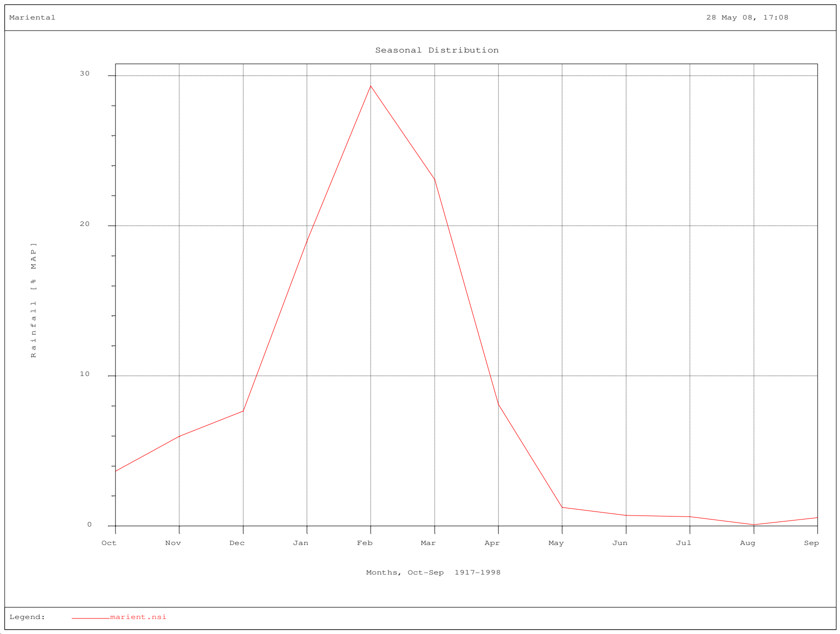

Figure 2-3: Typical Seasonal Rainfall Distribution in Study Catchment

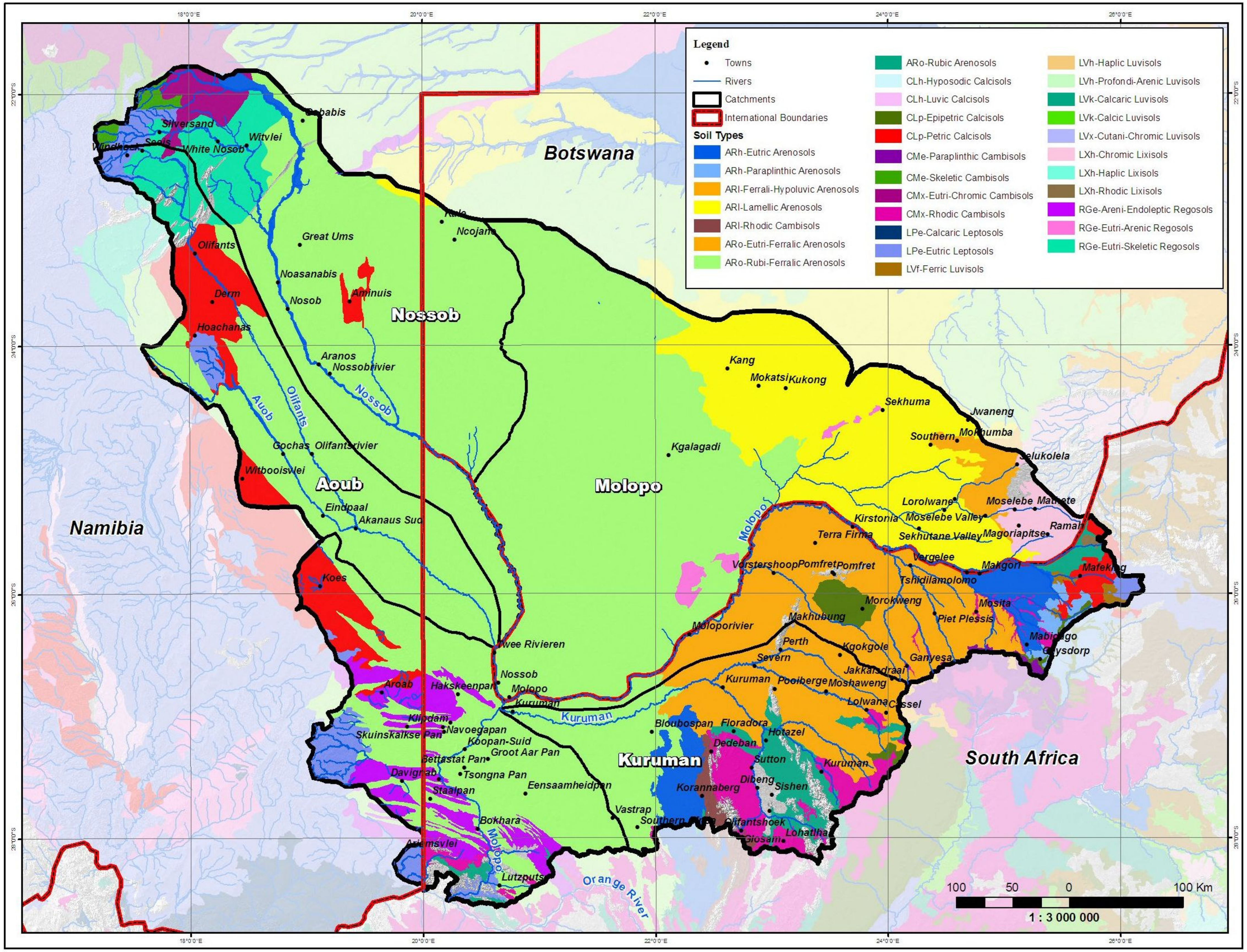

Figure 2-4: Major Soil Types

2.6.2 Evaporation

Evaporation in the Molopo-Nossob catchment is significant with Mean Annual Evaporation (MAE) generally increasing in a north-westerly direction. MAE (S-Pan) varies from about 1 900 mm in the upper Molopo catchment to more than 2 600 mm in the Kalahari Desert. Similar to rainfall, evaporation in the study area is highly seasonal, with evaporation in the summer months more than twice as high as during the winter

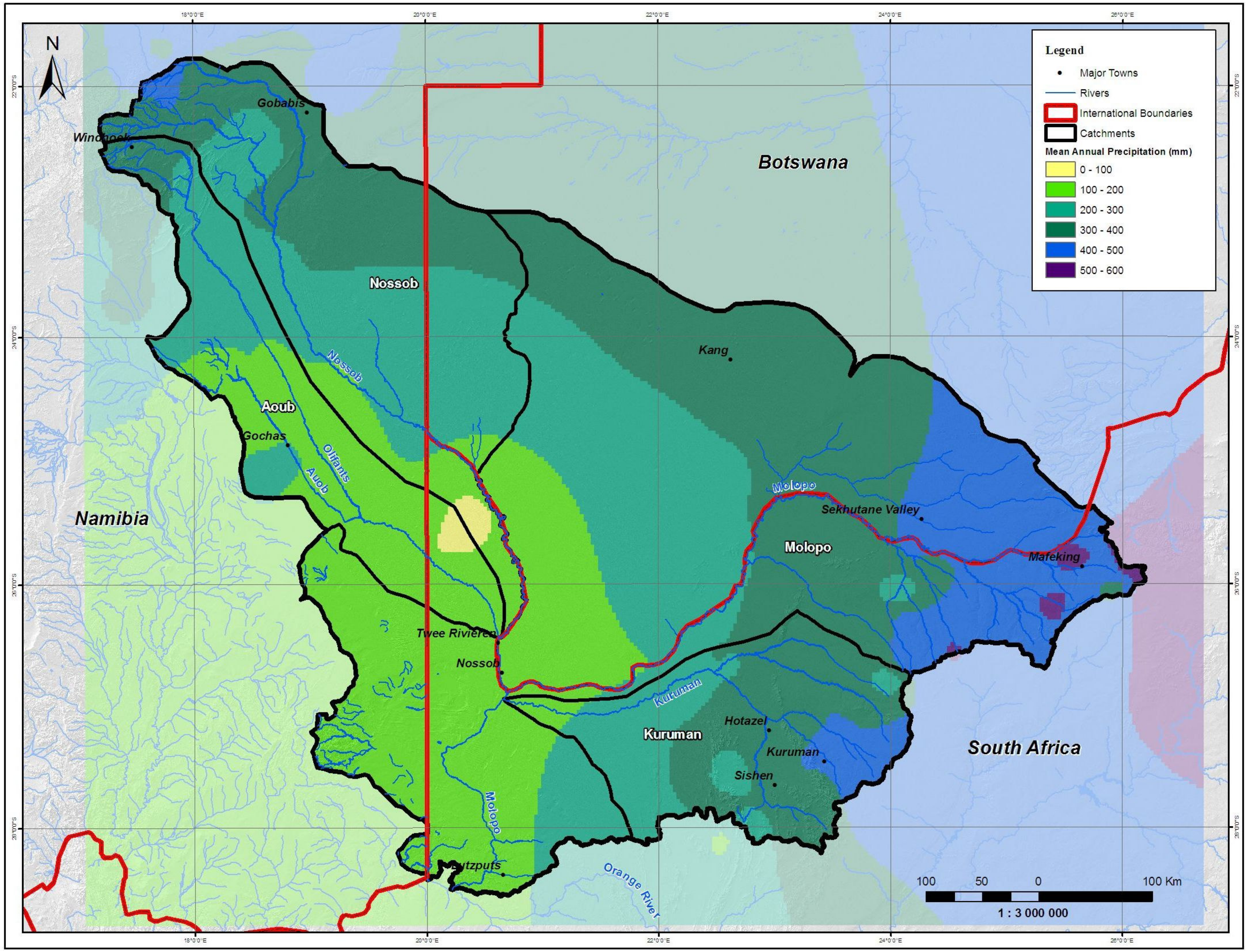

Figure 2-5: Mean Annual Precipitation

3. CATCHMENT MODELLING

3.1 MODELLING STRATEGY

The approach towards modelling streamflow in the Molopo-Nossob study area entailed the use of the monthly rainfall-runoff Pitman model for preparing long term flow sequences for the present day as well as the unimpacted natural state, based on the main hydrological elements of the system.

To ensure realistic simulation of streamflow within a catchment, several development-related aspects have to be quantified beforehand. These typically include:

- the volume of rainfall which could potentially be intercepted;
- the volume of soil water which is directly evaporated or which is lost through transpiration by natural or cultivated vegetation;
- the volume of water abstracted from the river or reservoirs to meet irrigation, industrial, mining or urban demands;
- the volume of water captured by storage structures such as farm dams or large reservoirs; and
- the volume of water transferred during inter basin-transfers.

For this study the recently-updated Water Resource Simulation Model (WRSM2000) (Pitman *et al*, 2006) was used. WRSM2000 operates on the network principle which allows water to be transferred from one module to the next depending on the user-specified configuration of the system. The modules available in WRSM2000 include:

- Runoff module (RU) (for surface water and groundwater routines)
- Channel reach module (CR)
- Reservoir module (RV)
- Irrigation block module (RR)
- Mine module (MM)

3.2 MODELLING PROCEDURE

3.2.1 Evaluation of flow records

The majority of flow gauging stations in the study catchment are situated in the upper tributaries of the various subcatchments (see **Figure 3-1**).

Monthly flow records for 11 flow gauging stations along the Nossob, Olifants and Auob Rivers in Namibia, were obtained from the Namibia Department of Water Affairs, while monthly and daily flow records for 20 flow gauging stations along the Molopo and Kuruman Rivers (and their tributaries) in South Africa were obtained from the South African Department of Water Affairs and Forestry (DWAF) website (www.dwaf.gov.za/hydrology). These records include abstractions and return flows, where these are monitored. In general, the quality of data at the above stations is not good, with records characterised by significant periods of missing or exceeded data. No attempt at patching of the streamflow records was made.

Table 3-1 summarises the flow gauging stations at which data was obtained, while the monthly observed flow records are presented in **Annexure A**.

Table 3-1: Flow Gauging Stations at which data was obtained

Country	River	Station Name	Id.	Period
South Africa	Mareetsane River	Neverset	D4H002	1905-1964
South Africa	Swartbas River	Rietfontein	D4H003	1941-1948
South Africa	Pipeline From Grootfontein-Eye	Valleifontein	D4H004	1958-1974
South Africa	Kuruman-Eye B	Kuruman	D4H006	1959-2004
South Africa	Manyeding-Eye	Manyeding Loc.	D4H007	1959-2005
South Africa	Little Koning Eye	Kono Loc	D4H008	1959-2004
South Africa	Great-Koning-Eye	Kono Loc.	D4H009	1959-2005
South Africa	Bothetheletsa-Eye	Botheletsa Loc.	D4H010	1960-1993
South Africa	Tsineng-Eye	Lower Kuruman 83	D4H011	1960-1994
South Africa	Sewage Works	Mmabatho	D4H012	1997-2008
South Africa	Molopo River	Rietvallei	D4H013	1905-2007
South Africa	Molopo-Eye	Mallepoos-Eye	D4H014	1981-2008
South Africa	Polfontein	Matlabes Loc.	D4H019	1980-1985
South Africa	Compensation Water From Pipeline	Mallepoos-Eye	D4H030	1974-2007
South Africa	Leakage Water	Mallepoos-Eye	D4H031	1980-1981
South Africa	Mareetsane River	Neverset	D4H032	1927-1964
South Africa	Molopo River	Disaneng	D4H033	1996-2007
South Africa	Pipeline To Fisheries	Disaneng	D4H034	1995-1999
South Africa	Irrigation Pipeline	Disaneng	D4H035	1998-2001
South Africa	Canal From Modimola Dam	Molopo (Ratshidi)	D4H036	1996-2007
South Africa	Molopo River	Lotlamoreng Dam	D4H037	1995-2007
South Africa	Mafikeng Treatment Works	Molopo (Ratshidi)	D4H039	1999-2007

Country	River	Station Name	Id.	Period
Namibia	Black Nossob	Mentz	3111M02	1973-2006
Namibia	Black Nossob	Daan Viljoen Dam.	3111R01	1969-2005
Namibia	White Nossob	Otjivero Main Dam	3112R02	1982-2005
Namibia	White Nossob	Amasib	3112M02	1973-2007
Namibia	Black Nossob	Tilda Viljoen Dam	3111R02	1998-2007
Namibia	Aoub	Gochas	3124M01	1973-2007
Namibia	Aoub	Stampriet	3124M02	1977-2007
Namibia	Seeis	Ondekaremba	3125M01	1977-2006
Namibia	Olifants	De Duine	3126M01	1976-1997
Namibia	Usib	Nauaspoort Dam	3122R02	1987-2006
Namibia	Swartmodder	Swartmodder	3121M11	1990-2007
Namibia	Black Nossob	Henopsrus	3111M01	1969-2005

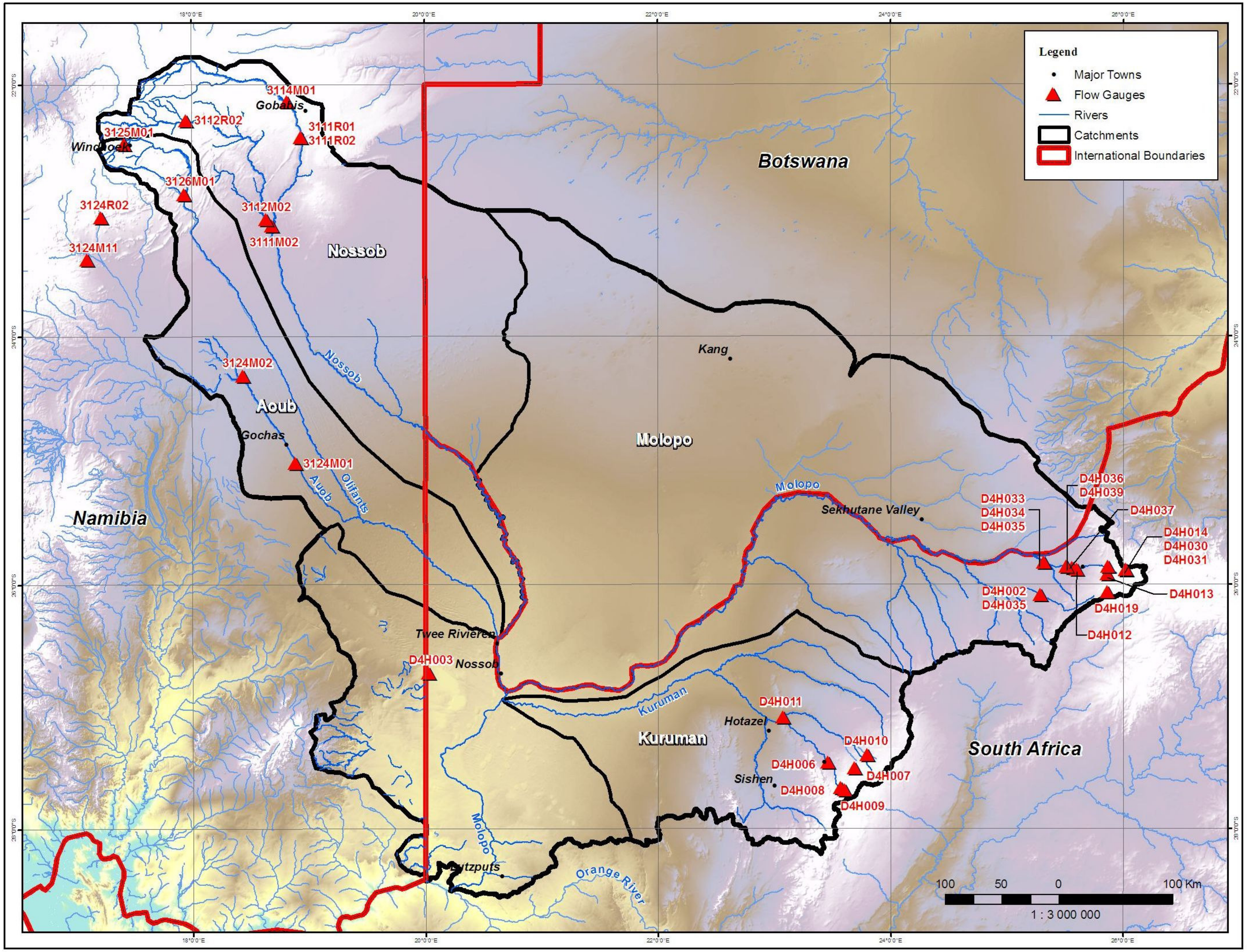

Figure 3-1: Location of Flow Gauging Stations in the study catchment

3.2.2 Evaluation of rainfall records

The generation of representative streamflow data requires reliable monthly rainfall records.

For this study, representative catchment rainfall data, up to 1989, for the South African part of the catchment, were obtained from WR90. This data was then extended to the 2004 hydrological year, based on patched rainfall station data contained in the WR-IMS database (DWAF, 2007).

Rainfall records for stations in the Namibian and Botswana parts of the study catchment were obtained from the Namibia and Botswana Meteorological Services and these were patched using the ClassR and PatchR utilities. These utilities allow for the identification of outliers and appropriate groupings of source rainfall gauges in order to patch the missing records of selected rainfall gauges. ClassR is a utility used to group hydro-meteorologically similar rainfall stations together. Given a number of rainfall station records, the ClassR program performs an outlier analysis which enables the user to make a selection of well-correlated rainfall stations to be used in the patching process. This is achieved in the following way:

- Simple outlier detection by means of scaled absolute difference
- Biplot graphical method employing the Mahalanobis distance measure, and
- Cluster analysis which associates objects by their Euclidian distance.

The grouping of rainfall stations, the number of seasons and associated months are then used as input to PatchR. PatchR performs a multiple patch on all rainfall stations contained within a group, based on a linear regression in combination with expectation maximization to infill missing or suspect values which have been flagged in the input rainfall record. Within each group, the rainfall sequence is lengthened to the earliest and latest date that occurs in the input rainfall records. This process of infilling and extension of rainfall sequences is done as an iterative procedure. Using the above methodology, 48 rainfall station records in Namibia and Botswana were patched and used to generate representative catchment rainfall files.

The common period covered by all of the catchment rainfall files in the study area extended from 1920 to 2004. **Figure 3-2** shows the location of rainfall stations across the study area, while the rainfall station groupings, along with the catchment rainfall files are presented in **Annexure B**.

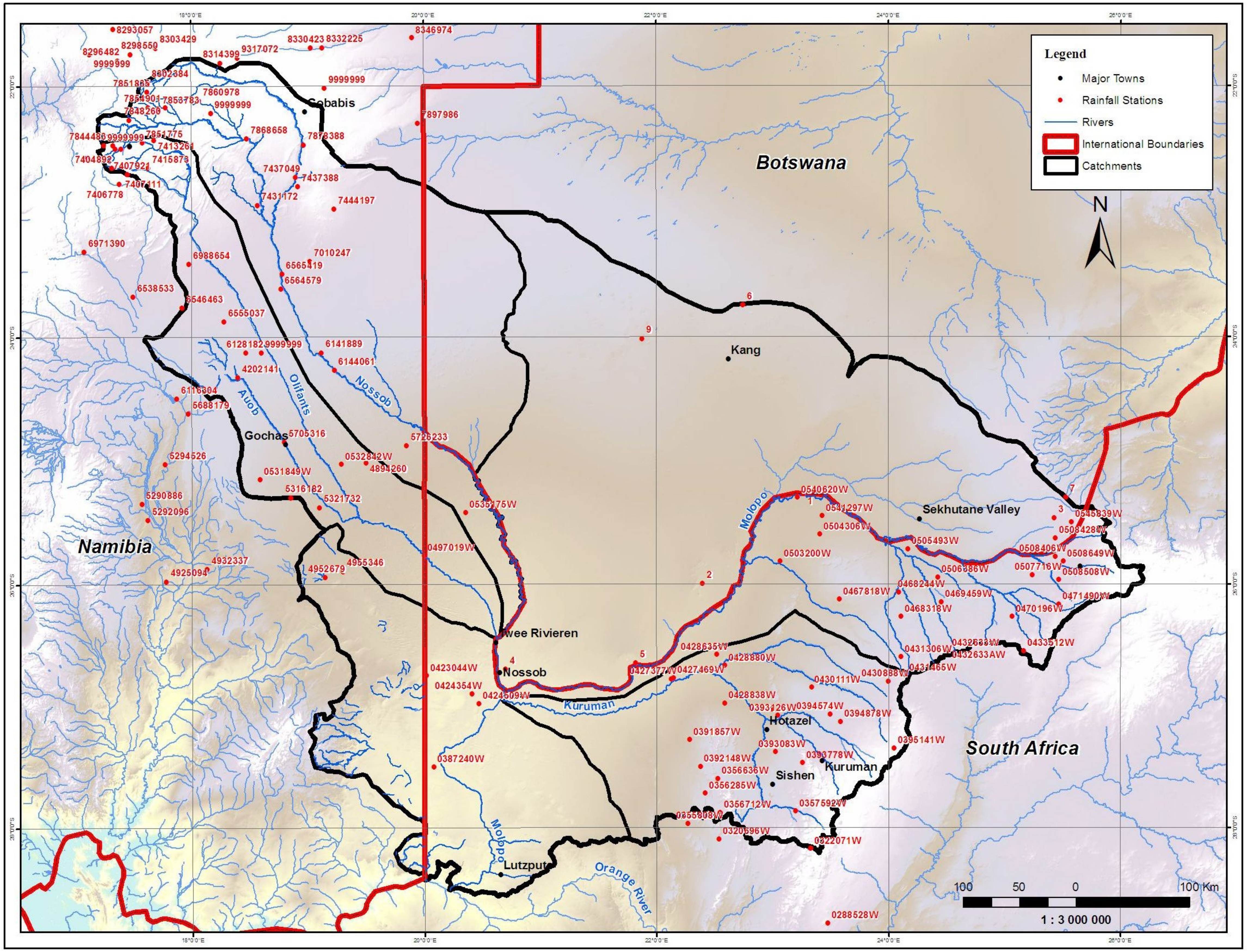

Figure 3-2: Location of Rainfall stations in the Molopo-Nossob study area

3.2.3 Evaporation

Average monthly and mean annual evaporation data for the study area were based on WR90 for the South African part of the catchment, while, for Namibia and Botswana, evaporation data were obtained from previous studies and other relevant publications.

3.2.4 Irrigation

Detailed information about irrigation in the study area was sourced during the landuse task of the Molopo-Nossob study, which was undertaken by Schoeman and Partners, who also provides estimates of irrigation water requirements. Irrigation information for the South African part of the catchments was primarily based on the Water Allocation and Registration Management System (WARMS) database (maintained by the Department of Water Affairs and Forestry). In the absence of registration information, topo-cadastral maps and visual inspection of Landsat satellite images were used to identify irrigated crop areas. To distinguish between irrigation areas supplied from ground water and surface water sources, a 2 km buffer zone was superimposed on all major rivers in the study area. Any irrigation, partly or totally enclosed in this zone, were classified as surface water irrigation, while all irrigation outside the zone were classified as ground water (borehole) irrigation.

The total irrigated crop area for the Molopo-Nossob catchment areas amounted to some 20 692 ha during the year 2000. Irrigation with groundwater (boreholes) totaled 16 651 ha or 81 % of the total irrigated area while irrigation from surface water resources amounted to 4 041 ha or 19 % of the total irrigation area (crop area). The extent of irrigation areas in the study area from both groundwater and surface water sources is shown in **Figure 3-3**.

For the purposes of hydrological modelling, irrigation water demands were modelled based on the WQT method (Allen, 1998), which has been incorporated into the WRSM2000 software, with only areas that are irrigated from surface water sources being modelled. It was assumed that all irrigation demands would be met from farm dams. However, in catchments with surface water irrigation but no farm dams, irrigation demand was supplied from rivers.

During the hydrological modelling, irrigation demands were calculated by means of the WQT. Crop factors as proposed by Schoeman and Vennote were used.

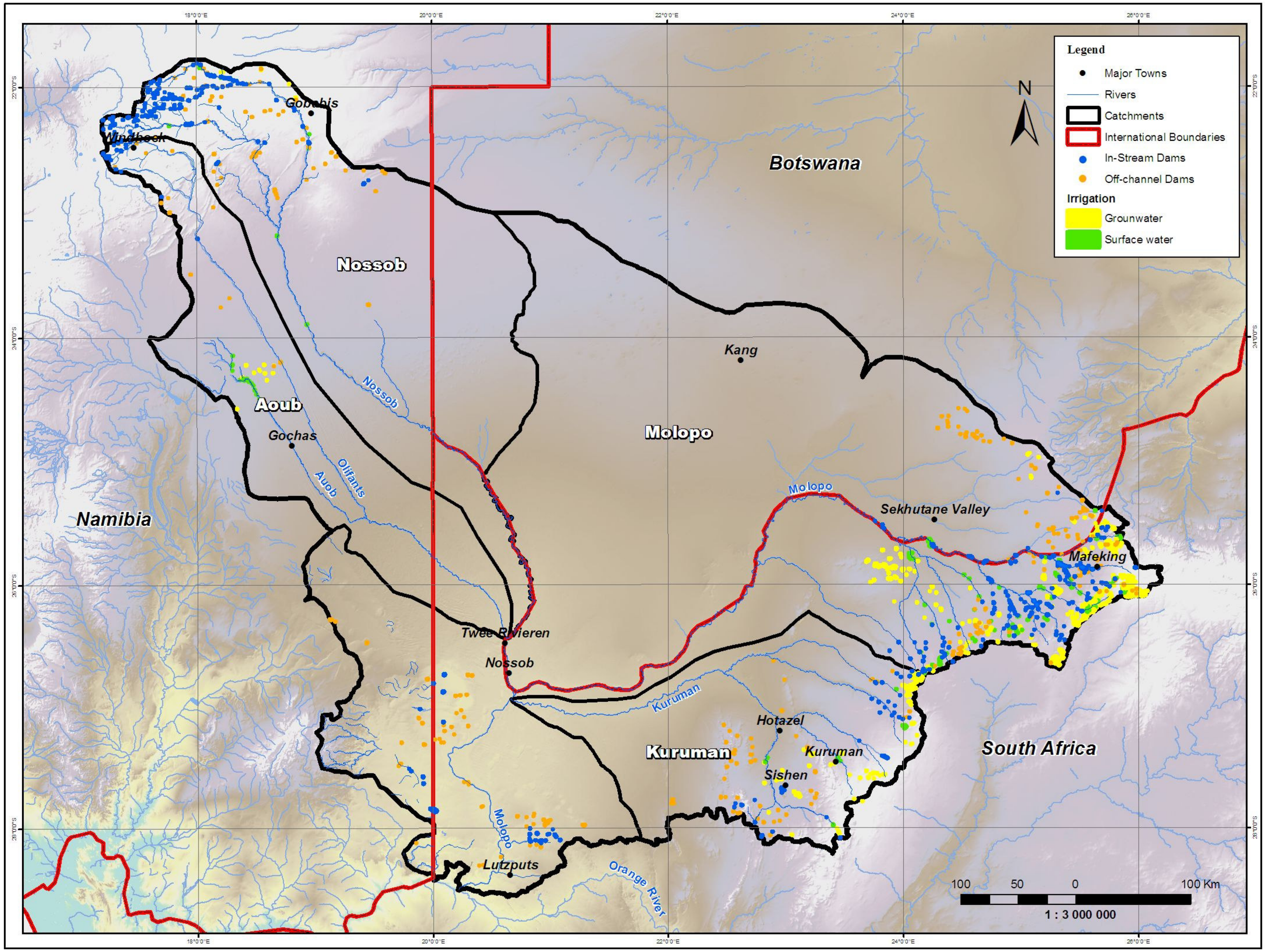

Figure 3-3: The Present Day Extent of Irrigation within the study catchment

3.2.5 Alien Vegetation

Although there are localised scattered infestations of invasive alien vegetation in the study area, little detailed information regarding the age, density, type and extent thereof, as required for modelling purposes, is available. Much of the infested areas is in the riparian zone, where the degree of infestation is largely independent of rainfall. In Namibia, it is known that land-invasion by *Prosopis* species is on the increase, yet no information regarding the extent thereof was readily available.

Due to the limited information on alien vegetation within the study area, coupled with the fact that the impact of alien species on streamflow reduction would probably be insignificant, it was not feasible to include invasive alien vegetation in the hydrological model.

3.2.6 Farm Dams

Information on farm dams in the study area was sourced by Schoeman and Partners, based on an evaluation of 1:50 000 topo-cadastral maps. A total of 687 farm dams were identified (in year 2000) with a total storage capacity of some 125 million m^3. These comprise of in-stream dams (369) with a total storage capacity of 120 million m^3 (95.9 %) and off-channel dams (318) with a total storage of 5 million m^3 (4.1 %). The extent of farm dams in the study area is shown in **Figure 3-4**.

For the purposes of hydrological modelling, individual farm dam areas and volumes within each modelling subcatchment were summed to yield one "dummy" dam with an equivalent capacity representing all farm dams within that subcatchment. All in-channel dams were included in the model, while off-channel dams were not modelled based on the assumption that these dams store water abstracted from boreholes (ground water sources).

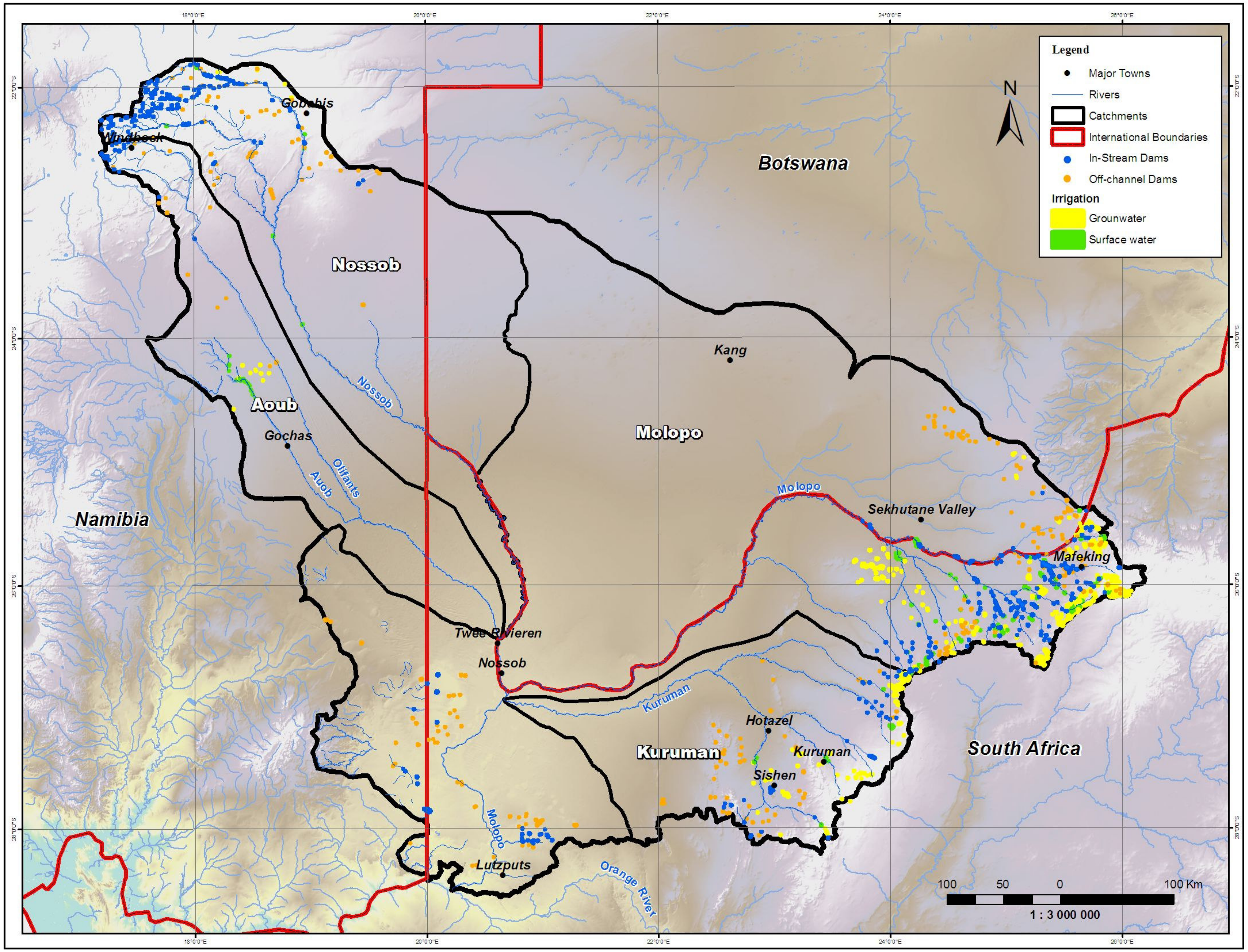

Figure 3-4: The Present Day Extent of Farm Dams within the study catchment

3.2.7 Urban and Rural Water Requirements

The largest urban areas within the study catchment are Mafikeng and Kuruman in South Africa and Gobabis and part of Windhoek in Namibia. The Botswana part of the catchment includes no major urban areas. Data on urban water requirements within the study area were obtained from DWAF in South Africa and DWA and NamWater in Namibia.

The urban demands for Mafikeng are approximately 11 million m^3/a (A.Dube, Pers.com). Approximately 65 % of this demand is sourced from the Molopo and Grootfontein Eyes and the remaining 35 % from the Modimolo Dam. Kuruman supplies almost all of its municipal demand of approximately 9 Mm^3/a from the Kuruman Eye which is abstracted directly at the source, which is equivalent to 94 % of its total demand. Only approximately 6 % of the total supply is contributed by surface water. Some of the rural demands in the lower Molopo-Nossob catchment is supplied via the Kalahari Water Supply Transfer Schemes (refer to **Section 3.2.10**). Gobabis' municipal supply of about 1 million m^3/a is provided from the Otjivero Dam with the shortfall being supplemented by ground water during periods of drought.

Most rural water requirements are met from localised ground water abstractions.

3.2.8 Mining Water Requirements

In the upper Molopo catchment, mining and industrial water requirements are approximately 5 million m^3/a and in the upper Kuruman catchment, approximately 6 million m^3/a (DWAF, 2003). As water requirements for mining are satisfied by ground water sources in conjunction with transfers from outside the study catchment (refer to **Section 3.2.10**), water use for mining has not been taken into consideration in the hydrological model.

3.2.9 Return Flows

Urban and mining return flows from the upper Molopo (larger Mafikeng area) are approximately 7 million m^3/a, contributing to the total available water for use in Mafikeng (Crocodile West WMA, DWAF, 2003). Information on these return flows were obtained from DWAF and have been accounted for in the hydrological model. Urban and mining return flows in the upper Kuruman catchment equal less than 2 million m^3/a and these were not included in the model due to lack of reliable data. Irrigation return flows were accounted for in the model based on information provided by Schoeman and Partners who estimated this to be 10 % of the irrigation supply.

3.2.10 Water Transfers

Due to the scarcity of water within most of the Molopo-Nossob catchment, no water is transferred out of the catchment. However, schemes transferring water into the Molopo-Nossob catchment include the Vaal-Gamagara Regional Water Supply Scheme and the Kalahari Rural Water Supply Schemes:

Vaal-Gamagara Scheme

The Vaal-Gamagara Regional Water Supply Scheme was initiated in 1964 to mainly supply water to the mines in the Gamagara Valley in the vicinity of Postmasburg and further north. The scheme abstracts water from the Vaal River near Delportshoop, immediately downstream of its confluence with the Harts River, from where the water is pumped to a water purification works next to the river. From the purification works, water is pumped via a 99 km double rising main to reservoirs in the Vaal/Molopo watershed near Clifton, from where water is gravity fed over a distance of 182 km along a route which serves Postmasburg, Sishen, Hotazel and Black Rock. Branch pipelines of 24 km and 5 km respectively supply water to the town of Olifansthoek and a reservoir at Beesthoek. The design capacity of the scheme is 36.4 Mℓ/d (13.3 million m^3/a), with allowance having been made to increase this capacity by means of additional booster pumps and reservoirs. In 1995, the actual abstraction by this scheme was 8.4 million m^3/a (this include the water use by the Kalahari East Rural Water Supply Scheme – see next paragaraph).

Kalahari West Rural Water Supply Scheme

The Kalahari West Rural water Supply Scheme was constructed in 1982 to supply farmers north of Upington with water for stock watering and domestic use. The scheme serves a total of 74 farms covering an area of 633 000 ha, which extends into the Molopo catchment. The scheme was implemented as an emergency scheme during a period when groundwater sources in the region started to fail and was designed to serve that part of the Kalahari experiencing the worst water shortages. The scheme sources water from

Upington's municipal system, from where it is pumped via a number of balancing reservoirs and small booster pumpstations. The scheme's peak design capacity is 1.99 Mℓ/d. In 1995, the actual water abstraction via the scheme was estimated to be 0.42 million m^3/a, which, taking peak factor requirements into account, implies that the scheme is being operated at or near capacity.

Kalahari East Rural Water Supply Scheme

The Kalahari East Rural Water Supply Scheme was constructed in the early nineties to supply water to farmers in the Kalahari north of Upington (including parts of the Molopo catchment) with water for stock watering and domestic use. The scheme sources its water from the Vaal-Gamagara pipeline, which is currently underutilised. Water is abstracted from the Vaal-Gamagara pipeline at Kathu, north-east of Olifantshoek, from where water is distributed via a 32 km long rising main, a 4.3 Mℓ reservoir and an extensive gravity pipe network to serve an area of approximately 14 000 km^2. The scheme was designed to deliver a peak flow of 6.18 Mℓ/d, with provision having been made to increase this to 8.52 Mℓ/d. The actual water that was supplied by the scheme in 1995 equalled 1.3 million m^3/a.

Based on the assumption that return flows from the above transfer schemes are negligible, the above transfers have not been included in the hydrological model.

3.2.11 Ecological Reserve Requirements

The ecological Reserve in the Upper Molopo River is estimated to be 5 million m^3/a (Crocodile West & Marico WMA) (DWAF, 2003) and in the lower Molopo River is estimated to be 29 Mm^3/a (Lower Vaal WMA) (DWAF, 2003).

3.2.12 Major Dams

There are a total of nine main dams within the Study Area, none of which are located in Botswana. **Table 3-2** lists their main characteristics, while a brief description of each is provided below. **Figure 3-5** shows their approximate locations.

DAM NAME	RIVER	NEAREST TOWN	COUNTRY	LOCATION Lat	LOCATION Long	DATE COMPLETED	FULL SUPPLY CAPACITY (million m^3)	YIELD (million m3/a)	WALL HEIGHT (m)	DAM TYPE
Otjivero Main	White	Windhoek	Namibia	22°17	17°58'	1984	9,808	1,65	16	Concrete
Otjivero Silt	White	Windhoek	Namibia	22°17	17°57'	1984	7,795	(95%	17	Embankment
Daan Viljoen	Black	Gobabis	Namibia	22°13	18°50'	1958	0,429	0,36	6,6	Concrete Arch
Tilda Viljoen	Off-channel	Gobabis	Namibia	'		1958	1,224	(95%	12.5	Embankment
Lotlamoreng	Molopo	Mafikeng	RSA	25°52	25°36'	1958	0,5		7	Embankment
Modimola	Molopo	Mafikeng	RSA	25°51	25°31'	1995	21,5	13,2	-	Embankment
Disaneng	Molopo	Mafikeng	RSA	25°46	25°16'	1980	17,4	1,0	17	Embankment
Koedoesrand	Koedoe	Mafikeng	RSA	26°14	25°13'	1989	0,75	Unknow	9	Embankment
Blackheath	Molopo	Vryburg	RSA	25°41	24°15'	1971	0,124	Unknow	5	Embankment
Leeubos	Swartbas	Twee	RSA	26°	20°06'	1948	1,071		4	Embankment
Abiekwasputspa	Molopo	Twee	RSA	27°18	20°06	1963	-	Unknow	5	Pan

Table 3-2: Major dams within the Molopo-Nossob Catchment

The Otjivero Dams (Namibia)

These two dams (Otjivero Main Dam and Otjivero Silt Dam) are located on the upper reaches of the White Nossob River in Namibia, approximately 100 km to the to the east of Windhoek. They form the main sources of the bulk water supply scheme known as the *Gobabis Regional State Water Scheme*. This scheme provides water to the town of Gobabis and to some surrounding smaller settlements in the area. The two dams have a combined full supply capacity of 17.8 million m^3. The Silt Dam located about 2,5 km upstream of the Main Dam and is used to reduce sedimentation accumulation in the Main Dam.

The Daan Viljoen Dam and Tilda Viljoen Dam (Namibia)

These two dams are located at Gobabis and also form part of the *Gobabis Regional State Water Scheme*. The Daan Viljoen Dam is an in-channel dam on the Black Nossob River, which impounds flood waters. The water is then pumped into the larger Tilda Viljoen Dam (off-channel), located nearby. Water is also transferred from the Otjivero Main Dam into the Tilda Vijoen Dam via a 110 km pumped pipeline.

Lotlamoreng Dam (RSA)

This small dam is located in the Lotlamoreng Dam Cultural Reserve on the Molopo River and is used for recreational purposes only. It has a capacity of 0.5 million m^3.

Setumo (Modimolo) Dam (RSA)

This dam is located on the Molopo River near Mafikeng and has a capacity 21.5 million m^3. It supplies bulk water for treatment at the Setumo Waterworks (formally Mmbatho Waterworks). The treated water from the works is blended with treated water from the Mafikeng Waterworks (supplied from ground water), and supplied to the urban and peri-urban areas of Mafikeng.

Disaneng Dam (RSA)

This dam is also located on the Molopo River, approximately 35 km downstream of Mafikeng. It provides water for irrigation of about 100 ha at the Disaneng Water User Association (former Disaneng Irrigation Board).

Koedoesrand and Blackheath Dams (RSA)

According to the South African Department of Water Affairs and Forestry, these small dams are used for irrigation purposes.

In addition to the above dams, **Figure 3-5** shows that there are two dams in the Kgalagadi Transfrontier Park viz. Leeubos Dam and Abiekwasputs Pan. However, these dams serve no purpose in terms of water resource management.

3.3 MODEL CONFIGURATION

Model subcatchments were originally based on existing quaternary catchment boundaries (shown in **Figure 3-6**). However, to facilitate the analysis of scheme development options at a finer resolution (to be undertaken during subsequent phases of the study), the quaternary catchments were further delineated based on major tributaries, the location of existing major dams and international boundaries. The final model subcatchments are indicated in **Figure 3-7**.

The endoreic character of the catchment implies that, due to pans, local topography and high infiltration rates, only runoff from a small portion of the catchment reaches the river channel. Net subcatchment areas, which are smaller than the gross catchment areas, were therefore used to calculate surface water runoff from each modelling subcatchment. In the case of the South African quaternary catchments, net catchment areas were defined based on information provided in WR90. In the Namibian and Botswana parts of the catchment, net catchment areas were derived based on typical net to gross area ratios in the South African part of the catchment, in conjunction with information on the location and extent of pans.

The existing, regionalised WR90 Pitman parameters, as specified for the South African quaternary catchments, were used as initial parameters and these were transferred to similar catchments in the rest of the study area.

Network diagrams and relevant subcatchment data including area, MAP, MAE, irrigation area, farm dam areas and volumes for each of the modelling subcatchments are presented in **Annexure C.**

Figure 3-5: Major dams in the Study Catchment

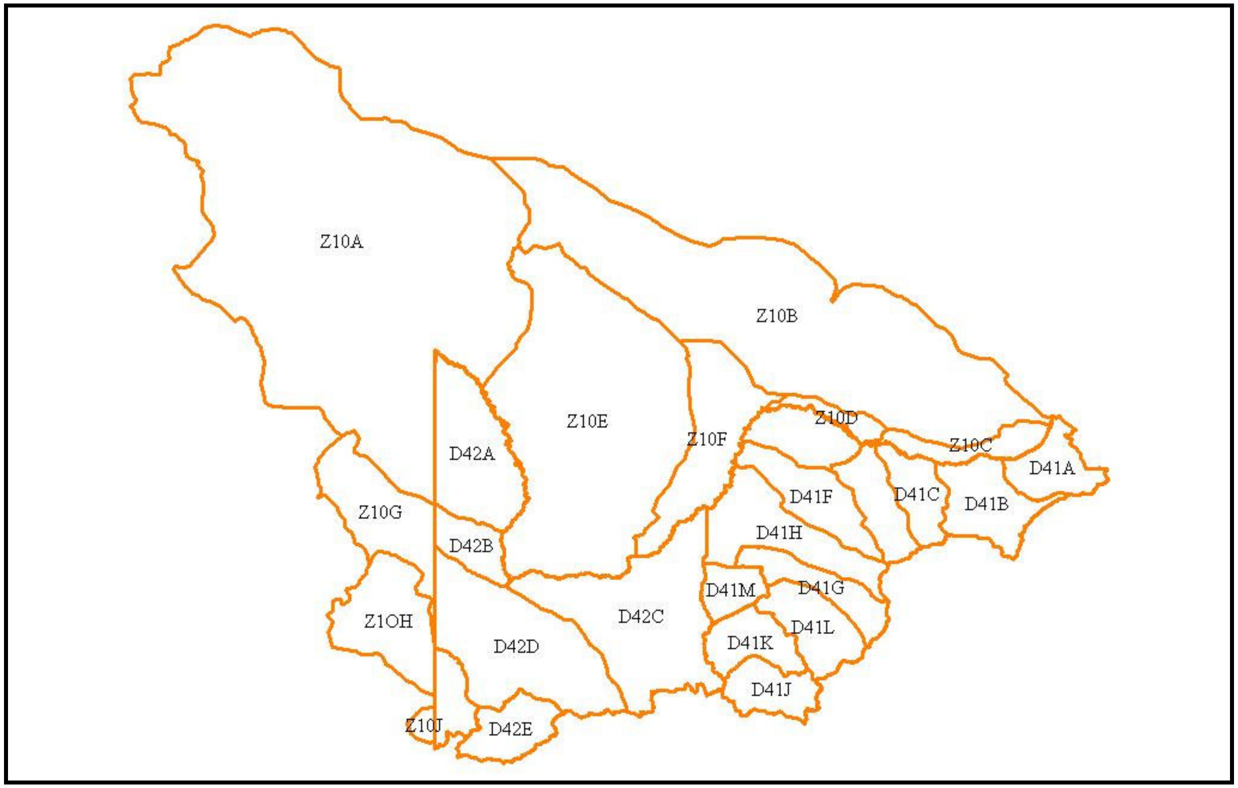

Figure 3-6: Quaternary catchments in study area

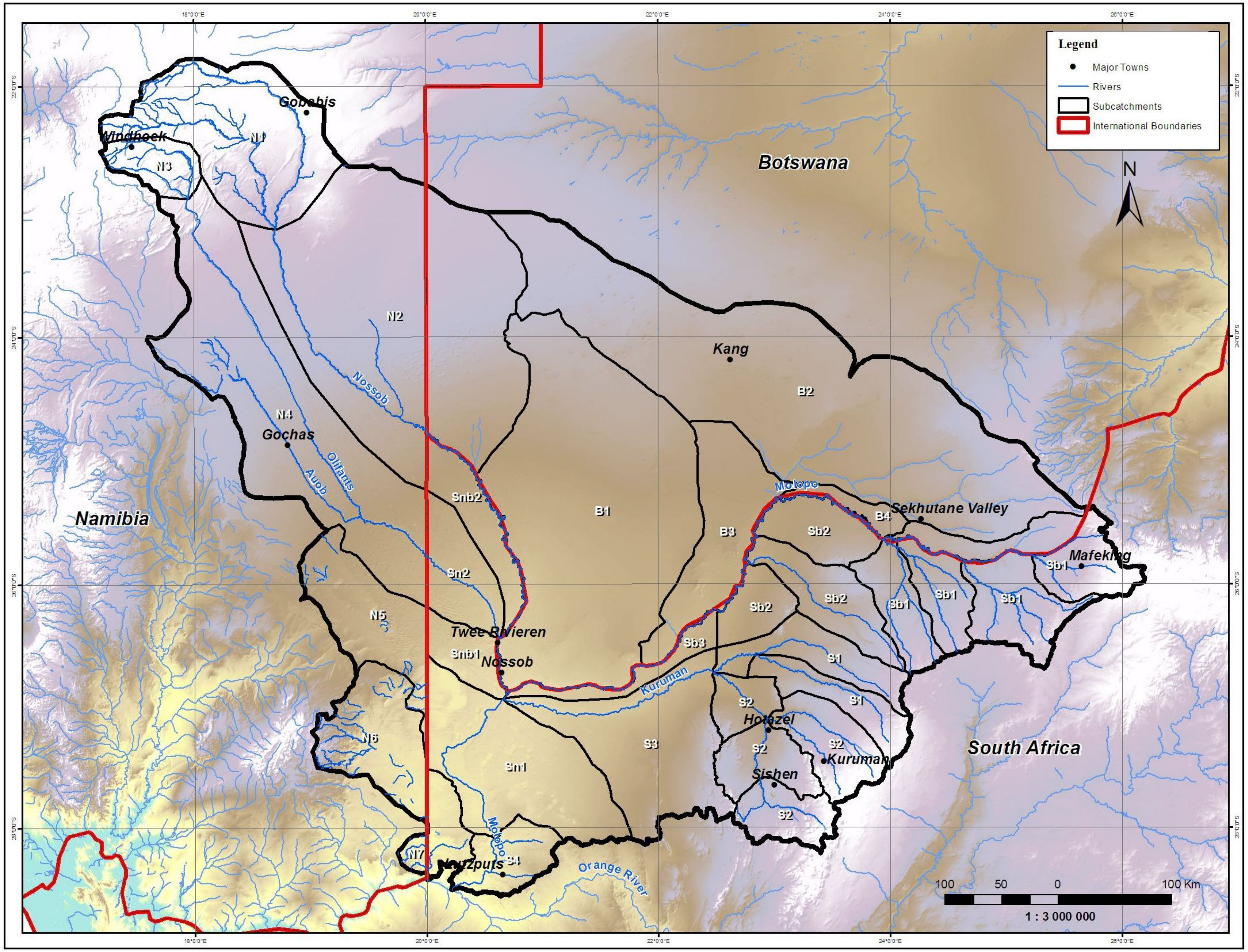

Figure 3-7: Subcatchment Delineation

3.4 MODEL CALIBRATION AND VERIFICATION

The configured Molopo-Nossob catchment model was calibrated wherever possible on observed flow records. However, due to the paucity of accurate and reliable streamflow records within the study catchment, a conventional calibration approach was only possible in the upper Nossob and Olifants rivers as well as on the upper Molopo River and some of its tributaries. This included channel losses as a calibration parameter. The results of these calibrations are displayed graphically in **Annexure D**. Once the Pitman model has been calibrated, the calibrated Pitman parameters were transferred to similar subcatchments in the remainder of the study catchment.

A further, large-scale calibration of the Pitman model for the main subcatchments was then undertaken, based on historical extreme events and anecdotal evidence of flows along certain parts of the lower river reaches. This was mainly achieved by means of adjustments to the Pitman *ST* (maximum soil moisture capacity) parameter and the channel loss function in the WRSM2000 model. In addition to the localised channel losses as determined during the first calibration exercise, this approach therefore allowed for additional ("cumulative") channel losses to be introduced along the system. The historical flood events in the 1970s are simulated, as well as two small events in the mid-1950s and the late-1980s, while no flows occur during the rest of the simulation period, which is consistent with anecdotal evidence about the occurrence or lack of flows along the lower reaches of these rivers.

3.5 MODELLING RESULTS

3.5.1 Simulated Flow Sequences

The calibrated hydrological model was used to simulate long-term naturalised and present day flow sequences for each modelling subcatchment (included in **Annexures E** and **F** respectively). **Table 3-3** summarises the natural and present day MAR for each quaternary catchment and provides an indication of the availability of water on a localised (quaternary) catchment basis. The natural runoff represents the total runoff that is generated from the net area of each quaternary catchment under natural (no development) conditions, while the present day runoff represents the actual outflow from the net area of each quaternary catchment after allowing for local demands (irrigation, urban and industrial) at present day development levels. It is important to note that these estimates include groundwater outflow from the various springs in the upper Molopo and Kuruman catchments. The losses as indicated relate to local channel losses, i.e. a channel loss is applied to the incremental runoff generated in each quaternary catchment. Consequently, the MARs in some quaternaries equal zero, i.e. the local channel loss capacity in that specific quaternary exceeds the incremental runoff generated locally in that quaternary.

Table 3-3: Incremental natural and present-day subcatchment flows (Mm^3)

River	Quaternary (Fig 3.6)	Network (Fig 3.7)	Incremental MAR (no channel losses) Natural	Incremental MAR including local channel losses per quaternary	
				Natural	Present-Day
Molopo	D41A	SB1	35.99	9.85	6.22
	D41B	SB1	12.76	4.75	4.01
	D41C	SB1	9.65	2.77	2.50
	D41D	SB1	5.99	1.22	1.19
	Z10D	B4	3.57	1.11	1.11
	Z10C	B5	16.84	3.23	3.23
	D41E	SB2	0.67	0.00	0.00
	D41F	SB2	1.94	0.00	0.00
	D41H*	SB2	0.85	0.00	0.00
	Z10F	B3	0.64	0.02	0.02
	D42C*	SB3	0.10	0.00	0.00
	TOTAL MOLOPO		**89.00**	**22.95**	**18.28**
Kuruman	D41G	S1	7.13	1.42	1.40
	D41H*	S1	1.58	0.18	0.17
	D41J	S2	3.66	0.72	0.71
	D41K	S2	4.53	1.08	1.08
	D41L	S2	30.05	6.43	6.14
	D41M	S2	0.89	0.00	0.00
	D42C*	S3	1.05	0.00	0.00
	TOTAL KURUMAN		**48.89**	**9.83**	**9.50**
Nossob	Z10A	N1	2.30	2.30	1.47
	Z10A	N2	15.83	4.13	4.13
	D42A*	SNB2	0.22	0.00	0.00
	TOTAL NOSSOB		**18.35**	**6.43**	**5.60**
Auob	Z10A	N3	1.47	0.42	0.33
	Z10A	N4	6.27	4.21	4.21
	D42A*	SN2	0.01	0.00	0.00
	D42B	SNB1	0.01	0.00	0.00
	TOTAL AUOB		**7.76**	**4.63**	**4.54**
TOTAL			**164**	**43.8**	**37.9**

4. SURFACE WATER RESOURCES AVAILABILITY

Whereas **Table 3-3** lists the localised natural and present day MAR for each quaternary catchment and also provides an indication of local channel losses within each of the quaternary catchments, it is important to note that once cumulative channel losses have been taken into account, the total cumulative runoff from each of the four main subcatchments reduces to zero, except in the Kuruman catchment where the average net outflow equals 4.11 Mm^3/a under natural conditions and 3.99 Mm^3/a under present day conditions. This highlights the excessive channel losses (infiltration and evaporation) evident in the system because of the phenomenon that part or all of the runoff that flows into a quaternary with 'spare channel loss capacity' from an upstream catchment, first has to satisfy the "cumulative" channel loss demands in the downstream quaternary before it can flow further downstream. It also explains why flow along the downstream reaches of the main rivers only occur during very extreme events and why none of the historical extreme flood events within the Molopo-Nossob catchment, managed to reach the Orange River.

Table 4-1 and **Table 4-2** present first order estimates of typical gross storage-yield characteristics for the upper parts of the Molopo and Kuruman catchments, which display similar hydro-meteorological characteristics, as well as the upper Nossob catchment. The tables provide an indication of the storage that is required to meet certain yields at different levels of assurance and show that, even in the upper part of the Molopo and Kuruman catchments, significant storage is required to provide yield at an acceptable level of assurance. An assessment of the central parts of the Molopo-Nossob catchment, situated within the drier, central Kalahari Desert, has indicated that it is not feasible for dams to be constructed in this area due to the lack of reliable runoff.

Table 4-1: Typical yield-reliability characteristics (upper Molopo/Kuruman)

	(1)Gross Yield (% MAR)		
Live Storage (% MAR)	**1:100 RI**	**1:20 RI**	**1:10 RI**
50	16	25	32
100	26	41	52
200	34	53	71

(1): Based on WR90 storage-draft frequency curves

Table 4-2: Typical yield-reliability characteristics (upper Nossob)

	[(1)]Gross Yield (% MAR)		
Live Storage (% MAR)	**1:100 RI**	**1:20 RI**	**1:10 RI**
50	3	4	4
100	6	8	9
200	12	15	16

(1): Based on results of this study

5. CONCLUSIONS

Hydrological modelling has been undertaken to provide first order estimates of typical surface water runoff volumes in the main rivers in the Molopo-Nossob catchment. The modelling was done by means of the Pitman rainfall-runoff model, local observed rainfall records and current land use information. Estimates of natural and present day surface water runoff have been calibrated based on observed flow records where available as well as on historical records of floods in the Molopo-Nossob catchment. The results of the hydrological analysis will be used during the subsequent "scheme development options" phase of the study to determine typical storage–yield characteristics at proposed development sites in the study catchments

The modelling results have shown that the total natural runoff from the Molopo-Nossob catchment, without any channel losses, equals 164 Mm^3/a. However, once losses are introduced into the system, the total cumulative runoff for each of the main subcatchments reduces to zero, except in the case of the Kuruman catchment where the average net outflow equals 4.1 Mm^3/a under natural conditions and 4.0 Mm^3/a under present day conditions

First order estimates of typical gross storage-yield characteristics for the upper parts of the Molopo, Kuruman and Nossob catchments have shown that significant storage is required to provide yield at an acceptable level of assurance. An assessment of the central parts of the Molopo-Nossob catchment, situated within the drier, central Kalahari Desert, has indicated that it is not feasible for dams to be constructed in this area due to the lack of reliable runoff.

6. REFERENCES

Dube, A. 2008. Mafikeng Municipality. Personal Communication

DWAF, 2003. Lower Vaal Water Management Area: Overview of Water Resources Availability, November 2003.

DWAF, 2003. Crocodile (West) and Marico Water Management Area. Overview of Water Resources Availabilty and Utilisation. DWAF Report No. P/WMA/03/000/00/0203. September 2003.

Midgley DC, Pitman WV, Middleton, BJ. Surface Water Resources of South Africa 1990. WRC Report No. 298/3.1/94. 1994