PROJECT NAME	**:**	PRE-FEASIBILITY STUDY INTO MEASURES TO IMPROVE THE MANAGEMENT OF THE LOWER ORANGE RIVER AND TO PROVIDE FOR FUTURE DEVELOPMENTS ALONG THE BORDER BETWEEN NAMIBIA AND SOUTH AFRICA
REPORT TITLE	**:**	Hydrology, Water Quality and System Analysis Volume B: Hydrology
AUTHOR	**:**	S Crerar and HG Maré
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Submitted on behalf of the Project Team by Lower Orange River Consultants:

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Task Leader		Study Leader	

PERMANENT WATER COMMISSION

Approved for the Planning Committee of the Permanent Water Commission by:

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P Heyns (NAM)	(Date)	**PH van Niekerk** (RSA)	(Date)

LIST OF REPORTS

TITLE	REPORT NUMBER		
	DWAF RSA	DWA Namibia	LORC (NS)
Main Report	PB D000/00/4703	400/8/1/P-13	3749/97331
Synopsis	PB D000/00/4703	400/8/1/P-13	3749/97331
Legal, Institutional, Water Sharing, Cost Sharing, Management and Dam Operation	PB D000/00/4603	400/8/1/P-10	3692/97331
Specialist Report on the Environmental Flow Requirements - Riverine	PB D000/00/4503	400/8/1/P-07	3519/97331
Specialist Report on the Determination of the Preliminary Ecological Reserve on a Rapid Level for Orange River Estuary	PB D000/00/4503	400/8/1/P-08	3663/97331
Water Requirements	PB D000/00/4202	400/8/1/P-02	3486/97331
Hydrology, Water Quality and Systems Analysis (Volume A)	PB D000/00/4303	400/8/1/P04	3736/97331
Hydrology, Water Quality and Systems Analysis (Volume B)	**PB D000/00/4303**	**400/8/1/P-03**	**3485/97331**
Water Conservation and Demand Management	PB D000/00/4903	400/8/1/P-12	3487/97331
Dam Development Options and Economic Analysis – Volume 1	PB D000/00/4403	400/8/1/P-05	3484/97331
Dam Development Options and Economic Analysis – Volume 2 (Appendices)	PB D000/00/4403	400/8/1/P-05	3484/97331
Environmental Assessment of the Proposed Dam Sites on the Orange River	PB D000/00/4503	400/8/1/P-06	3873/97331
Vioolsdrift/Noordoewer Joint Irrigation Scheme: Assessment of Viability	PB D000/00/4803	400/8/1/P-11	3525/97331
Public Consultation	PB D000/00/4503	400/8/1/P-09	3869/97331
Inception Report	PB D000/00/4102	400/8/1/P-01	3365/97331

PRE-FEASIBILITY STUDY INTO MEASURES TO IMPROVE THE MANAGEMENT OF THE LOWER ORANGE RIVER

HYDROLOGY, WATER QUALITY AND SYSTEM ANALYSIS: VOLUME B - HYDROLOGY

PART 1: HYDROLOGY OF THE FISH RIVER (NAMIBIA)

EXECUTIVE SUMMARY

INTODUCTION

The Fish River has one of the largest catchment areas in Namibia. The river basin is relatively under-developed and has a low population density largely due to the highly arid and generally infertile nature of the land. There are, however, two major dams on this river system, the Hardap Dam in the Middle Fish River and the Naute Dam on the Löwen River, a major tributary towards the lower end of the catchment.

The hydrology in the Fish River was developed at a very cursory level of detail in the original South African studies and systems analyses. In view of the joint involvement of Namibia and South Africa on this project, it was thus envisaged that the Fish River hydrology would be reviewed and the current version in the Orange River data sets replaced with the updated information.

While a detailed rainfall/runoff assessment would be desirable, there is not sufficient time to carry out this work without causing major delays to the main study. Some review and limited modelling was therefore undertaken since the most recent major re-assessments were completed in 1987 and 1994 for the Naute and Hardap Dams respectively. A new study was initiated in 1995 by the Department of Water Affairs (DWA) (Namibia), but subsequently aborted due to the transfer of staff to the newly created Namibia Water Corporation Ltd (NamWater).

The work methodology *was out in the following steps:*

- *Review of data (runoff at Seeheim and other key stations and rainfall data) and any preliminary findings from the incomplete 1995 study.*
- *Collection and analysis of rainfall data from selected key rainfall stations. Data were obtained from DWA (Namibia) and Namibia Meteorological Services (NMS)*
- *Simplified rainfall/runoff modelling to improve, patch and extend Fish River runoff records at the confluence with the Orange River, and at selected potential Lower Fish River dam sites.*
- *Analysis of lower Fish River runoff under different scenarios (present state and future/maximum dam and abstraction development)*
- *Short written report commenting on results and sensitivity analysis, as well as recommendations on further work.*

The total ***water demand*** *from the Fish River Basin was estimated at approximately 50million m³/a for 1999. This demand was supplied by a combination of ground and surface water and it is estimated that groundwater contributed 7.9 million m³/a to the total requirement. Urban and Industrial demands accounts for 3.5 million m³/a (7%), stock watering 4.5 million m³/a (9%) and the remaining 84% is mainly utilized for irrigation purposes.*

Mean annual precipitation *(MAP) within the Fish River catchment is low, ranging from as little as 50 mm at Ai Ais in the south to approximately 230 mm at Isabis in the north of the catchment. Rainfall occurs as convective showers and is confined mainly to a rainy season, which extends from October to April.*

Potential evaporation *rates are high due to low atmospheric humidity, high temperatures and long hours of sunshine. Annual potential evaporation (gross A-pan) in the catchment varies from 3 800 mm in the area to the east of Keetmanshoop to approximately 2 950 mm at the confluence with the Orange River.*

RESULTS

In order to provide appropriate inputs to the system analysis to be carried out as part of this study, the total Fish River Basin was sub-divided into five sub-catchments as listed in ***Table I****. Details of the sub-catchments areas, mean annual runoff, etc., are* *summarised in **Table I.** Although a total runoff of 736 million m³/a is generated from the Fish River Basin, only 512 million m³/a reaches the Orange River under natural conditions, as 224 million m³/a is lost due to evaporation and riverbed losses. The bulk of the runoff is generated in the Hardap, Naute and Seeheim sub-cathments where the unit runoff varies between 7 mm/a to 14 mm/a in comparison with the 1 mm/a to 1.5 mm/a in the Lower Fish and Konkiep catchments.*

Table I: Sub-catchment Details

Sub-catchment	Incremental catchment area (km²)	Natural incremental runoff for period 1920 - 2000			
		MAR (million m³.a)	Standard deviation (million m³.a)	Coefficient of Variation	Unit Runoff (mm/a)
Hardap Dam	13 600	193.63	305.32	1.58	14.24
Naute Dam	8 630	61.53	86.76	1.41	7.1
Seeheim	32 800	345.34	614.31	1.78	10.53
Konkiep	32 000	48.00	85.39	1.78	1.5
Lower Fish	8 650	87.72	156.03	1.78	1.0
Total Fish	**95 680**	**736.22**			
Minus river losses		224.02			
Total Fish	**95 680**	**512.20**	**842.54**	**1.64**	**5.3**

Due to the fact that a detailed rainfall/runoff assessment was not carried out for the Fish River, it was considered necessary to carry out some sensitivity analysis. The purpose of the sensitivity analysis were to determine the effect of changes in the hydrology as well as changes in development, on the system yield and on the spills from the Fish into the Orange River.

Results from the sensitivity analysis showed that the system yield and spills from the Fish River are not very sensitive to changes in the hydrology. Increasing the hydrology by 10% will typically result in an increase in yield of between 6% and 7,5%. The impact on the frequency of specific monthly flow events was also relatively small for changes in the hydrology. Typically, the occurrence of months with zero flow increased only with 0,1% from 74% of the time for the reference hydrology to 74,1% for the 15% reduced hydrology. High monthly flows (flows higher than 1000 million m³) in return reduced from 0,4% of the time to 0,1% of the time as result of the reduced hydrology.

Development options resulted in an increase in the coefficient of variation and reduced the occurrence of low flows (less than 50 million m³). For a 3 mean annual runoff (MAR) dam in the Lower Fish the number of zero spill months for example increased by 18 months over the simulation period 1920 to 1987.

The sensitivity analysis results therefore indicated that the system yield and Fish River spills were not affected significantly by the changed hydrology but rather by increased development options.

It can therefore be concluded that the simplified rainfall/runoff modelling as carried out for this study is sufficient for the purposes of this study and that a detailed rainfall/runoff assessment is not necessary.

RECOMMENDATIONS

It is recommended that the incremental MARs and associated monthly records be accepted for utilisation in subsequent work as part of the current Management Study of the Lower Orange River (LOR).

Despite the above recommendation, it is recognised that there is a need to carry out a detailed re-assessment of the hydrology of the Fish River, in particular the Fish River downstream of Hardap Dam and it is recommended that the Department of Water Affairs should program such a study. It is however not required for the purpose of the current Management Study where the focus is on the Lower Orange River and not on the Fish River.

It is recommended that a study into the technical feasibility of constructing a gauging station in the Lower Konkiep, as close as possible to the confluence with the Fish River, be considered.

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CV – Coefficient of variation

DWA – Department of Water Affairs (Namibia)

MAR – Mean Annual Runoff

Million m^3 - million cubic meter

NMS – Namibia Meteorological Services

ORRS – Orange River Development Project Replanning Study

ORSA – Orange River System Analysis Study

Std deviation – Standard deviation

ToR – Term of Reference

WCE – Windhoek Consulting Engineers

WRYM – Water Resources Yield Model

PRE-FEASIBILITY STUDY INTO MEASURES TO IMPROVE THE MANAGEMENT OF THE LOWER ORANGE RIVER

HYDROLOGY, WATER QUALITY AND SYSTEM ANALYSIS: VOLUME B – HYDROLOGY

Part 1

Hydrology of the Fish River (Namibia)

1. INTRODUCTION

1.1 General

The Fish River has one of the largest catchment areas in Namibia. The river basin is relatively under-developed and has a low population density largely due to the highly arid and generally infertile nature of the land. There are, however, two major dams on this river system, the Hardap Dam in the Middle Fish River and the Naute Dam on the Löwen River, a major tributary towards the lower end of the catchment. The runoff potential of the Fish River is considerable and over the years, many dam sites with significant yields have been identified on the Fish River and its tributaries. However, the environmental and economic conditions for developments have not been suitable.

1.2 Scope of work

It was stated in the Terms of Reference (ToR) (for the Management Study of the Lower Orange River) that very little additional hydrological analysis would be required as part of the new study, because the hydrological data sets previously developed during the Orange River System Analysis (ORSA) and the Orange River Development Project Replanning Study (ORRS) would be used as the basis on which an agreed hydrological database would be developed. Adjustments to certain data sets would only be made where necessary, if new and more reliable information was available which was not reflected in the current data sets.

However, it was also pointed out that the one catchment area, which might require attention was the Fish River catchment in Namibia. The hydrology in the Fish River was previously developed at a very cursory level of detail in the original South African studies and systems analyses. In view of the joint involvement of Namibia and South Africa on this project, it was therefore envisaged that the Fish River hydrology would be reviewed and the current version in the Orange River data sets replaced with the updated information.

During the formulation of the Inception Report, it was agreed that this would form an additional task, and be incorporated into the main project. The motivation for this additional task was as follows:

When the hydrological assessment and modelling exercise was carried out as part of the ORRS, use was made of relatively unverified Fish River runoff data. The Namibian Department of Water Affairs (DWA) (Hydrology Division) was aware of the potential shortcomings with the data, and it was not consider as a major issue when used as part of a general study of the whole Orange River Basin. When considering the Lower Orange River Basin, however, the impact of the Fish River becomes more significant and an improved data set is required. While a detailed rainfall/runoff assessment would be desirable, there was insufficient time to carry out such work without causing major delays to the main study. Some review and limited modelling was therefore undertaken since the most recent major re-assessments were completed in 1987 and 1994 for the Naute and Hardap Dams, respectively. A new study was initiated in 1995 by DWA, but subsequently aborted due to the transfer of staff to the newly created Namibia Water Corporation Ltd (NamWater).

The work methodology was carried out in the following steps:

- Review of data (runoff at Seeheim and other key stations and rainfall data) and preliminary findings from the incomplete 1995 study.
- Collection and analysis of rainfall data from selected key rainfall stations. Data were obtained from DWA and Namibia Meteorological Services (NMS).
- Simplified rainfall/runoff modelling to improve, patch and extend Fish River runoff records at the confluence with the Orange River, and at selected potential Lower Fish River dam sites.
- Analysis of lower Fish River runoff under different scenarios (present state and future/maximum dam and abstraction development).
- Short written report commenting on results and sensitivity analysis as well as recommendations on further work.

2. OVERVIEW OF THE INVESTIGATION AREA

2.1 Location

The Fish River Basin rises to the south of Windhoek and flows in a generally southwards direction for a distance of 635 kilometres before its confluence with the Orange River about 100 km northwest of Noordoewer. The location of the catchment within southern Namibia, as well as the position of key towns, tributaries and the Hardap and Naute Dams are shown in **Figure 2-1**.

2.2 Topography and Drainage

The Fish River and its main tributaries are shown in **Figure 2-1**. The Kam, Schlip and Kalf tributaries originate in the central highland area south of Rehoboth before joining the mainstream of the Fish, whilst the Narub and Usib Rivers flow from the eastern foothills of the Naukluft Mountains. The Hutup, Lewer and Kanibes Rivers drain from the northern and eastern parts of the Schwarzrand Mountains. The Löwen and Gaub Rivers originate in the Groot Karas Mountains and the Konkiep in the western Schwarzrand.

The average slope of the Fish River mainstream from its origin until its confluence with the Orange River is 1:450.

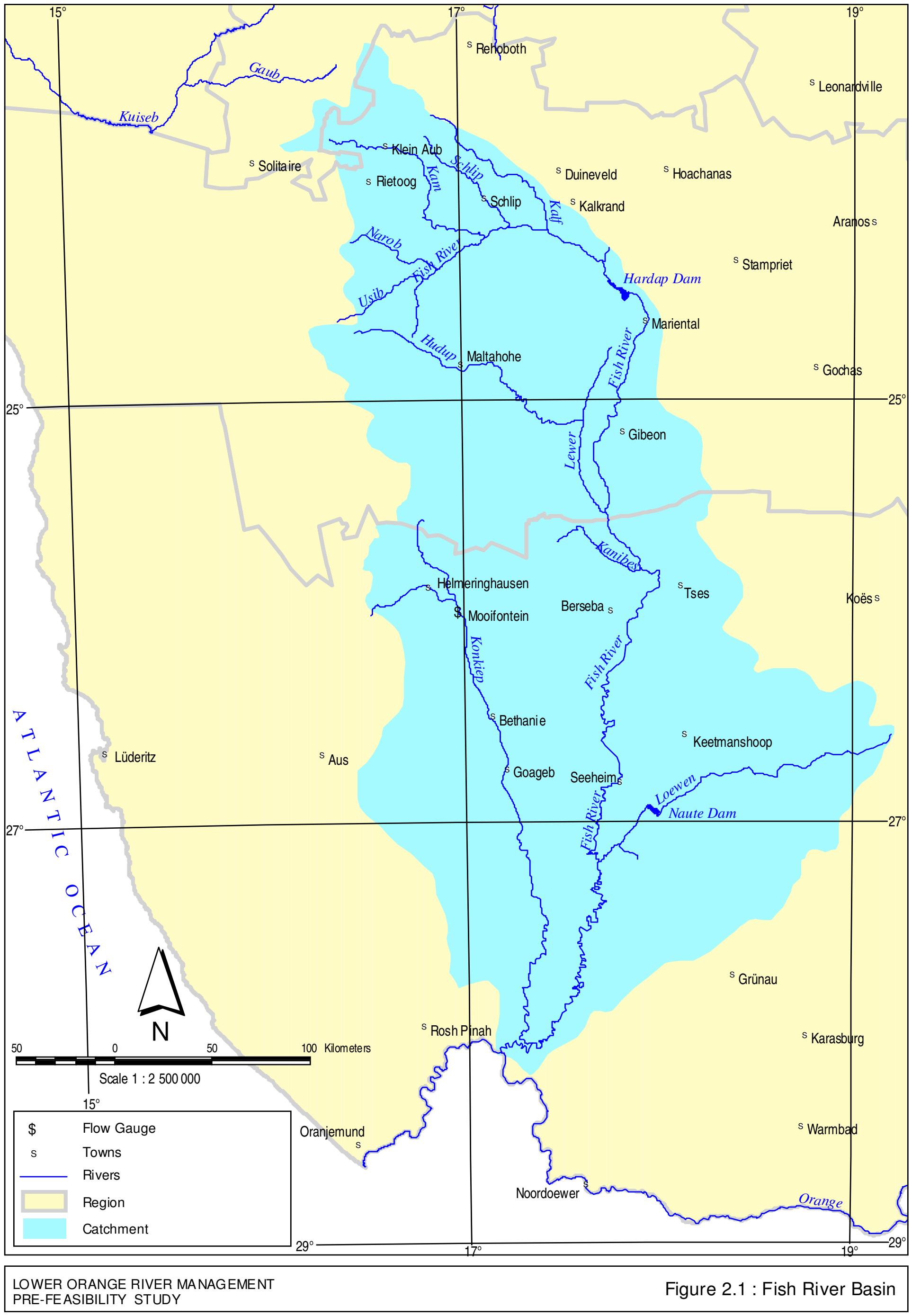
2.3 Geology

The basin of the Fish River is an erosion valley with rocky substrata and shallow sand and gravel overburden. Much of the upper basin is comprised of Nama inter-layered sandstone, limestone and mudstone. Underlying the immediate catchment of the Hardap Dam is to be found Karoo basalt lavas. Further south, both Nama and Karoo sandstones are to be found, as well as dolerite sills and some other igneous intrusions and metamorphic rocks including granite and gneiss.

2.4 Vegetation

Almost the entire Fish River catchment is classified as dwarf shrub savannah.

Figure 2-1: Orange River Basin



2.5 Population

The population density of the catchment is very low. The population of the basin numbered 64 752 in 1999 (Windhoek Consulting Engineers (WCE) 2000) corresponding to an average population density of just 0.62 persons/km^2. The largest town in the basin is Keetmanshoop, with an estimated population of 20 000. The remainder of the 53 798 urban population is to be found in Mariental (13 000), Gibeon (8 000), Maltahöhe (4 525), Schlip (2 500), Kallrand (2 000), Tses (2 000) and Bethanie (1 773). The locations of these towns are shown in **Figure 2-1**.

It is estimated that the population will rise to 66 791 (of which urban will be 57 885) by 2005, and 70 799 (of which urban will be 63 461) by 2015.

2.6 Water Related Infrastructure

There are currently only two major dams located within the Fish River catchment, the Hardap and Naute Dams. Hardap is located on the main Fish River in the upper third of the catchment close to Mariental. Hardap Dam has a gross storage capacity of 294 million m^3 and is mainly used to supply water to irrigation (2 200ha), although the total water requirement for Mariental is also supplied from Hardap Dam.

Naute Dam is located on the Löwen River, approximately 40 km upstream of the confluence of the Löwen and Fish Rivers. Naute Dam is significantly smaller than Hardap Dam and has a gross storage capacity of 84 million m^3. Naute Dam supply water to Keetmanshoop, as well as to 290 ha of irrigation.

River flow is measured at various flow gauging stations of which the records for Hardap Dam, Naute Dam, Seeheim weir on the main Fish River and Mooifontein in the Upper Konkiep River was used for the purposes of this study. For the period before the completion of Naute Dam gauge 0497M01 on the Naute River was also used.

Several potential dam sites have been identified in the Fish River for possible future development as part of previous studies. The two most notable possible dams that were investigated are Brukaros and Neckertal Dams. The proposed site for Brukaros is located on the main Fish River close to Tses, which is about halfway between Hardap Dam and Zeeheim. The proposed Brukaros Dam can be classified as a medium sized dam with a storage capacity of 30.2 million m³ (DWA-N, 1994b). Brukaros Dam is intended to be used mainly for irrigation but will also supply the village of Tses and smaller settlements in the area.

The propose Neckertal Dam is located on the main Fish River just upstream of the Zeeheim flow gauge, close to Keetmanshoop. A relative large dam of 397 million m³ was investigated at this site. Although Neckertal Dam is the best possible future dam in terms of yield, it is located in a remote area. The size of the dam and the distance from the dam where the water can be used, makes it a very expensive dam. It was therefore concluded in these reports that the development of the dam could not be recommended (DWA-N, 1988b).

For the purpose of this study, it has been assumed that these dams will not be developed in the near future.

3. CURRENT AND FUTURE WATER DEMAND

3.1 Introduction

Total water demand from the Fish River Basin was estimated at approximately 50million m^3/a for 1999 (WCE 2000). This demand was satisfied by a combination of ground and surface water. Groundwater consumption is estimated at 7.9 million m^3/a and surface water consumption at 42 million m^3/a (WCE 2000).

3.2 Domestic and Industrial Demand

Domestic (urban) and industrial demand accounts for 3.5 million m^3/a (7%) of the total demand. Only 0.9 million m^3/a is supplied from surface water sources. The remainder (2.6 million m^3/a) originates from groundwater sources. Growth in this sector is likely to be relatively slow, growing to approximately 4 million m^3/a by 2015, which will be only 6.7% of the total catchment demand. Rural domestic demand is almost all supplied from groundwater and is estimated at 0.08 million m^3/a.

3.3 Agricultural Demand (Arable)

Irrigation is by far the biggest consumer of water in the catchment. 41 million m^3/a is supplied from surface water (Hardap and Naute Dams) resources, while approximately 0.6 million m^3/a originates from groundwater sources. Potential for significant expansion has been identified at Naute Dam and it is anticipated that irrigation demand for the catchment will rise to approximately 47 million m^3/a by 2005 and 52 million m^3/a by 2015.

3.4 Stock Watering

Almost all-stock water is supplied from groundwater sources. This was estimated at 4.5 million m^3/a in 1999, and is expected to remain relatively constant or even decline slightly in the future.

3.5 Tourism

Water demand for the tourist sector was estimated at 0.3 million m^3/a in 1999, of which approximately two thirds comes from surface water. While this sector may enjoy a faster rate of growth than most sectors, it is not expected to become a major user (0.5 million m^3/a) by 2015.

3.6 Mining

Water demand for the mining sector is minimal.

4. WATER RESOURCES OF THE CATCHMENT

4.1 Groundwater

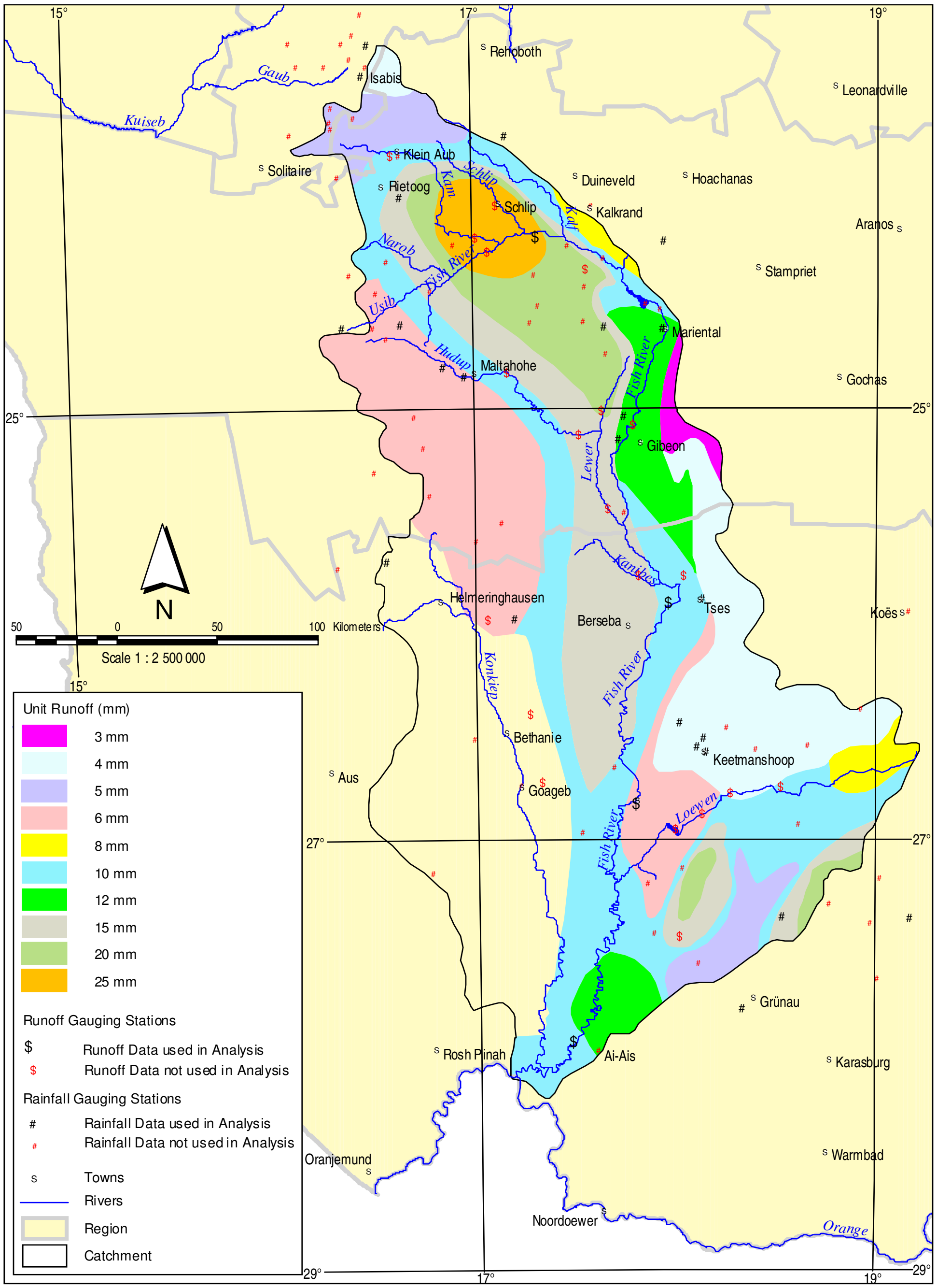
Groundwater provides an essential source of water for much of urban water supply, almost all rural water supplies and for stock watering.

4.2 Surface Water

Despite the relatively low and sporadic nature of rainfall over the Fish River catchment, it has a relatively high runoff yield. Unit runoff values are the highest of any of Namibia's ephemeral rivers. Clearly, the low level of vegetation cover and rocky nature of the catchment are two important reasons behind this phenomenon. **Figure 4.1** shows the calculated unit runoff values for the Fish River Basin (Chivell, 1992).

Incremental catchment unit runoff values are as high as 25mm/a and in many parts of the catchment reach 15% of mean annual precipitation (MAP), which is very high for Namibian ephemeral streams.

As can be seen from **Figure 4-1**, the areas of highest runoff production are mainly upstream of the Hardap Dam. The majority of the catchment upstream of Hardap Dam lies in the 20 – 25 mm/a unit runoff zone. Much of the middle catchment has unit runoff values of between 5 and 10 mm/a. To place these values in context a comparison with the headwaters of some of Namibia's main westward flowing ephemeral streams is useful. Unit runoff values(URVs) in the headwaters of the Swakop and Kuiseb Rivers do not generally exceed 8 mm/a and it is only in limited areas of the Omaruru River headwaters that values of 15-25 mm/a are to be found. Further north, values rarely exceed 8mm/a despite the fact that MAP is much higher than in the Fish River catchment.



LOWER ORANGE RIVER MANAGEMENT
PRE-FEASIBILITY STUDY

Figure 4.1 : Unit Runoff and Gauging Stations for the Fish River Basin

Figure 4-1:Unit Runoff and Gauging Stations for the Fish River Basin

5. CLIMATE AND HYDROLOGY

5.1 Climate

5.1.1 Rainfall

Mean annual precipitation within the Fish River catchment is low, ranging from as little as 50 mm at Ai Ais in the south up to approximately 230 mm at Isabis in the north of the catchment. Rainfall occurs as convective showers and is confined mainly to a rainy season, which extends from October to April. Lists of rain gauges used in the 1995 rainfall/runoff analyses (Hatutale *et al*) 1995), relevant for the Hardap, Naute and Lower Fish catchments are provided in **Appendix A** (**Tables A-1 to A-3**). The typical distribution of the monthly rainfall within a year at Hardap Dam is given in **Figure 5-1**.

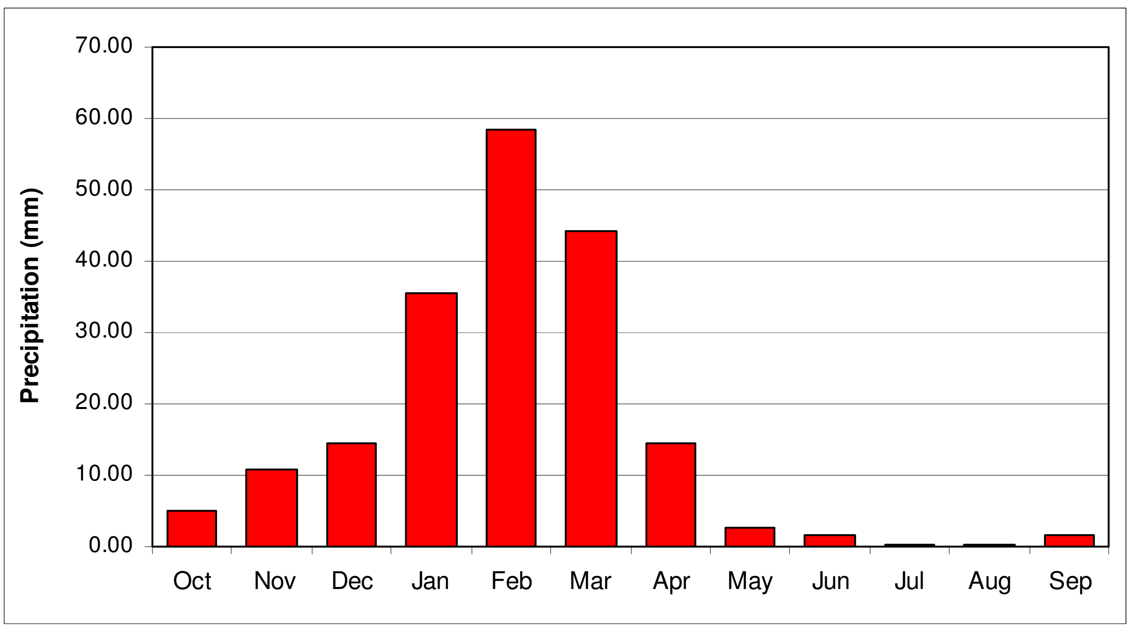


Figure 5-1: Mean Monthly Rainfall at Hardap Dam.

5.1.2 Evaporation

Potential evaporation rates are high due to low atmospheric humidity, high temperatures and long hours of sunshine. Annual potential evaporation (gross A-pan) in the catchment varies from 3 800 mm in the area to the east of Keetmanshoop to approximately 2 950 mm at the confluence with the Orange River.

During a re-assessment of the yield of the Hardap Dam carried out in 1994, the gross open water evaporation was calculated at 2 398 mm. As is standard practice following the findings of a study, which investigated A-pan/lake conversion coefficients (Sivertsen, 1991), a pan to lake conversion factor of 0.7 was used for July to December, and a factor of 0.8 from January to June. The resultant gross open water evaporation for Hardap Dam is provided in **Table 5.1.**

Average A-pan evaporation rates for Naute Dam and the Lower Fish was determined using the national evaporation map (Crerar, 1988) for Namibia. These are also included in **Table 5-1**. Although the evaporation rate for the Lower Fish, expressed as a depth and hence, not dependant on the evaporative area, is only slightly lower than that of Naute Dam and marginally higher than that of Hardap Dam, it is anticipated that the total evaporative losses will be considerably lower as a result of the better reservoir storage characteristics in the Lower Fish.

Table 5-1: Gross Open Water Evaporation

Lake Evaporation (mm)	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Total
Hardap	240	273	300	293	230	206	161	130	110	120	146	189	2398
Naute	249	283	311	346	273	244	190	153	131	124	152	196	2652
Lower Fish	233	265	291	324	255	228	178	143	123	116	142	183	2480

5.2 Runoff

5.2.1 Approach Adopted

In the ToR for this re-examination of Fish River runoff for use in an updated systems analysis, it was originally anticipated that a rapid simplified rainfall/runoff model, using selected rainfall stations, would be undertaken in order to improve, patch and extend the Fish River record at the confluence with the Orange River, as well as at selected potential dam sites on the Lower Fish River. A detailed rainfall/runoff modelling exercise was not considered feasible due to time and cost restraints. While researching data and previous studies for the assignment, however, the Project Team held discussions with one of the authors of the unfinished 1995 re-assessment of the Fish River hydrology. During these discussions, it was possible to source a large number of draft calculation computer files produced during the drafting of this report. These included weighted rainfall files based on a multi-quadric rainfall surface-fitting programme and subsequent rainfall-runoff fitting using "NAMRON".

Rainfall-runoff fits using observed data up to season 1993/94 had been performed for Naute Dam and Seeheim. For Hardap Dam catchment, the results of the 1994 study (Mostert *et al*, 1994) were used. Several results files for Seeheim and Naute Dam were available, but without indication of which was the preferred result nor any explanation of the work that had been done. The input rainfall and runoff files and a number of synthesised runoff files were examined and correlation analyses with the observed records carried out. This resulted in the acceptance of a synthesised record dating back to 1913/14 for Hardap Dam, 1916/17 for Seeheim and 1924/25 for Naute Dam.

These records were then updated to 2000/01, using observed data made available by the Hydrology Division of the Department of Water Affairs, (DWA) Namibia. Other incremental runoff records such as for the Konkiep River and Lower Fish were produced, using simplified approaches based on comparisons with Seeheim and Naute synthesised and observed data.

While this work has not reduced the effort involved with the study (since a large amount of time was spent checking computer files and carrying out crosschecks and re-calculations), the approach adopted permitted the maximum use of available detailed analytical work, which had been carried out during 1994/95. This work drew on all available catchment-wide rainfall data, the multi-quadric surface fitting of these data and modelling against observed runoff using rainfall/runoff modelling techniques, which have not since been significantly improved upon. The time spent, making use of this previous work, is considered very worthwhile and a significant improvement on the approach of using files of point rainfall as part of a simplified model. Clearly, the approach has yielded results, which can be used with more confidence than those from a simplified rainfall/runoff model. Further details and discussion are provided in **Section 5.2.2.**

5.2.2 Analysis and Results

a) Introduction

In order to provide the appropriate inputs for the total systems analysis to be carried out for the Orange River, a number of key runoff stations were incorporated into the Fish River section of the model. These are shown in **Figure 5-2**.

Table 5-2 summarises the catchment areas and stream lengths, both total and incremental. As can be seen from

Table 5-2 & **Figure 5-2**, for Naute Dam and Hardap Dam and the Konkiep, the incremental catchment is the same as the total catchment. For Seeheim, the incremental catchment is from Seeheim to Hardap Dam. For Lower Fish, it is the Fish River up to Seeheim and the Löwen River from its confluence with the Fish River up to Naute Dam (excluding the contribution from the Konkiep).

Table 5-2: Catchment Areas and Stream Lengths

Node	Total Catchment Area (Km^2)	Incremental Catchment Area (Km^2)	Total Stream Length (Km)	Incremental Stream Length (Km)
Hardap Dam	13 600	13 600	276	276
Naute Dam	8 630	8 630	190	190
Seeheim	46 400	32 800	622	346
Konkiep	32 000	32 000	465	465
Lower Fish	63 680	8 650	870	110

b) Hardap Dam

The observed runoff record for the period 1962/63 to 2000/01 is provided in **Appendix B**. It should be noted that the assessment completed in 1994 (Mostert, 1994) was based on modelling carried out for the period 1962/63 to 1990/91. This modelling utilised 40 rain gauges in and around the Hardap Dam catchment area. The key stations are listed in **Appendix A.**

Table 5-3 presents a comparison of the statistics for the concurrent observed and synthesised periods as well as those for the period 1920/21 to 2000/01. The annual observed and annual runoff totals for the concurrent period are presented in **Figure 5-3** and the combined synthesized and observed flow record is provided in **Appendix C.**

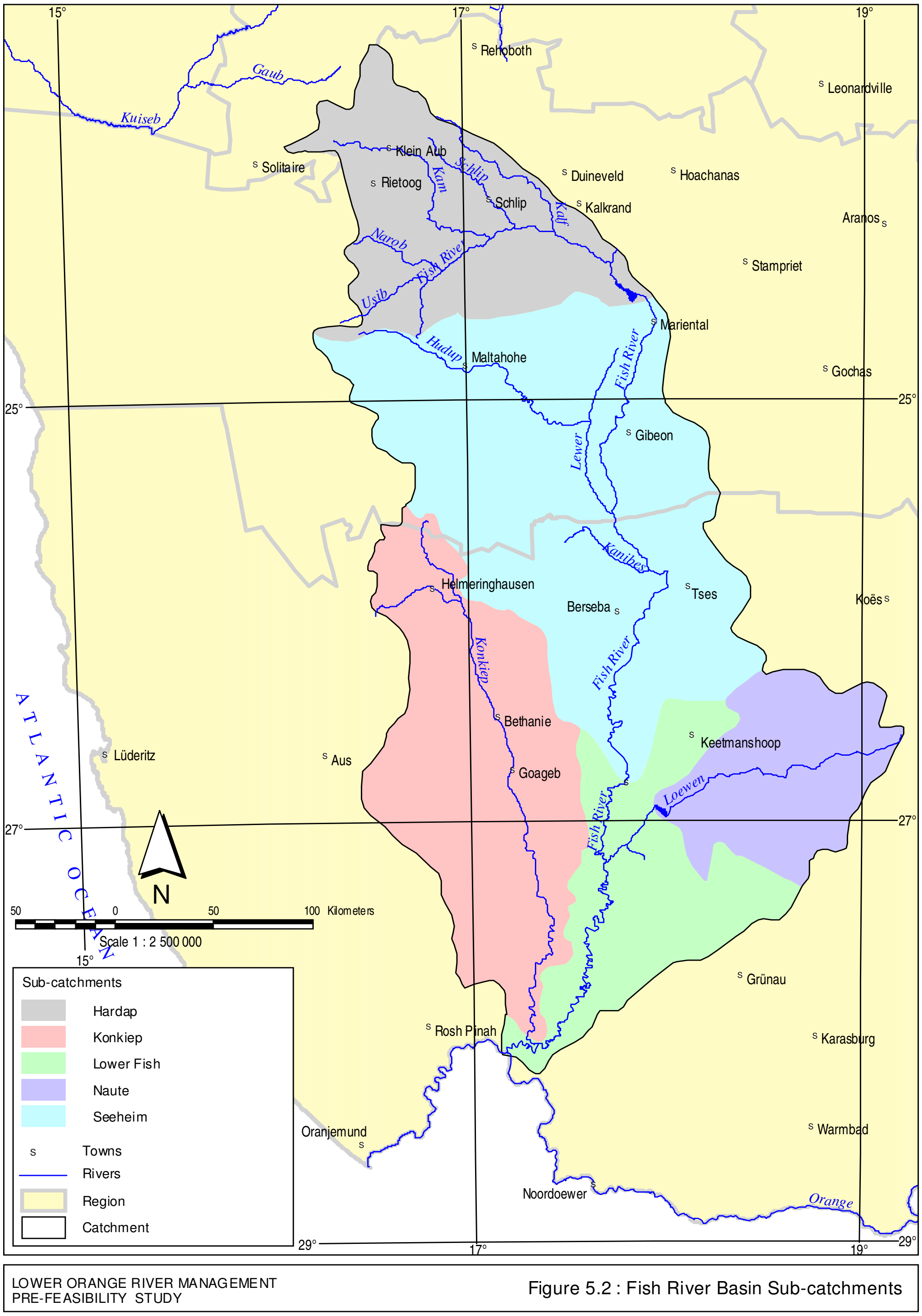


Figure 5-2: Fish River Basin Sub-catchments

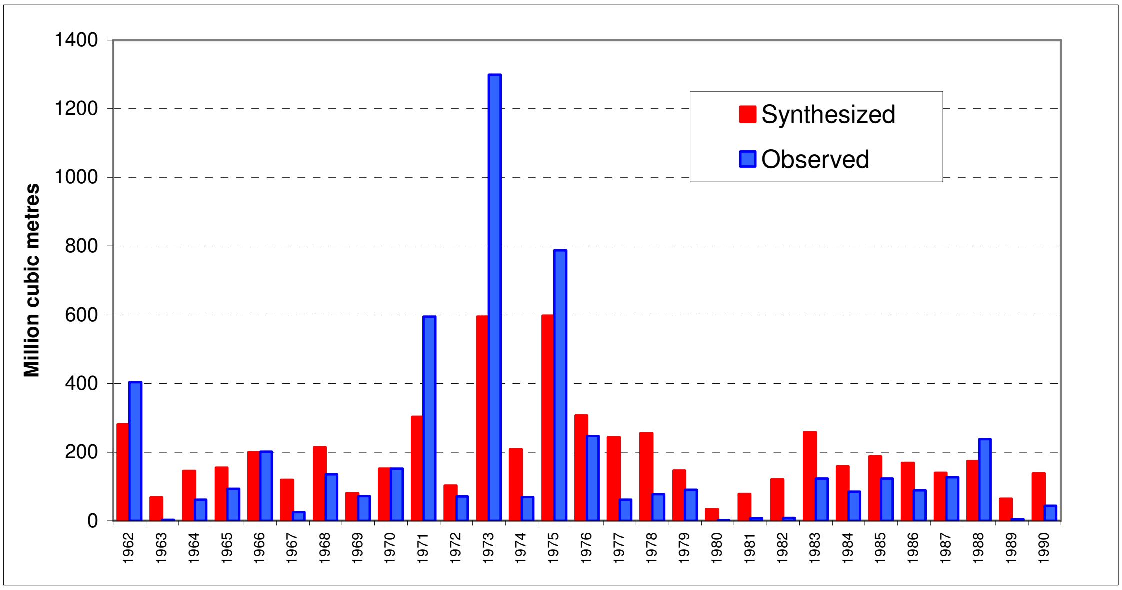


Figure 5-3: Comparison of Annual Observed and Synthesized Values (1962/63 – 1990/91)

During the course of the Hardap re-assessment (Mostert, 1994), the following relationship between weighted rainfall and runoff was derived:

Runoff = 0.410 * Weighted Precipitation + 2.342

This, however, must be used with caution since the weighted precipitation value is already the result of the modelling process. However, a correlation value of 0.82 was quoted for correlation of monthly values. This is within the norms for monthly correlation. The correlation for annual values is higher at 0.852. However, during this analysis it was discovered that the data used for the 1994 study included a serious error. The runoff total for the month December 1973 was taken as 500 million m^3 instead of 0.50 million m^3. It appears that this error was carried forward from previous analyses of Hardap Dam runoff. In the data received from the Hydrology Division for this current study, the value is correctly shown as 0.500 million m^3. In **Figure 5-3**, the corrected value is included in the annual total for 1973/74 (1298.91 instead of 1798.41million m^3). Once this is taken into account, the correlation of annual values increases to 0.893.

Clearly, the utilisation of the wrong value in the 1994 analysis would have affected the rainfall-runoff relationship, although it is considered that the effect would have been relatively minor.

Figure 5-3 shows that during lower rainfall years the synthesized record tends to over-estimate the runoff and that during the high rainfall years the runoff is underestimated. This is a common problem when trying to model runoff resulting from short duration storms using monthly rainfall data. The statistics for the concurrent period shown in **Table 5-3** reflect this phenomenon. The coefficient of variation for the observed record is 1.67, for the synthesized record it is only 1.20.

When the synthesized and observed records are combined, the coefficient of variation for the entire period is 1.58 and the standard deviation rises from 235.12 to 305.32. These values acceptably reflect the variability of the observed record.

Table 5-3: Comparison of Runoff Statistics for Hardap Dam

Record	Parameter	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Annual
Observed 1962/63-1990/91	Mean	0.99	0.82	1.73	46.46	66.56	54.90	10.55	0.03	0.05	0.00	0.00	0.00	182.09*
	Median	0.00	0.00	0.00	2.59	21.12	21.33	3.32	0.00	0.00	0.00	0.00	0.00	88.25
	Std deviation	4.93	2.10	4.86	106.32	136.02	93.10	15.62	0.14	0.27	0.00	0.00	0.00	278.19
	Coeff. Var	4.91	2.66	3.57	2.15	2.13	2.28	1.88	5.06	4.41	-	-	-	1.67
Synthesized 1962/63-1990/91	Mean	5.38	10.90	13.28	41.17	53.51	48.19	17.26	3.12	1.83	0.13	0.12	1.53	196.43
	Median	3.57	5.00	7.60	27.95	39.90	38.05	12.81	0.82	0.01	0.00	0.00	0.00	1112.5
	Std deviation	8.53	16.05	16.68	55.58	50.37	52.15	16.85	4.55	5.85	0.31	0.45	3.23	235.12
	Coeff. Var	1.59	1.47	1.26	1.35	0.94	1.08	0.98	1.46	3.19	2.30	3.63	2.11	1.20
Combined Observed and Synthesized 1920/21-2000/01	Mean	2.80	6.07	10.15	40.45	62.86	54.91	11.96	2.59	0.91	0.25	0.18	0.51	193.63
	Median	0.00	0.73	2.28	12.86	29.42	27.43	4.01	0.00	0.00	0.00	0.00	0.00	127.35
	Std deviation	8.46	12.49	17.99	75.44	112.48	105.68	18.15	7.60	3.96	1.35	0.89	1.77	305.32
	Coeff. Var	3.03	2.06	1.77	1.87	1.79	1.92	1.52	2.94	4.37	5.28	4.90	3.47	1.58

*The 1994 study calculated the mean to be 199.68 as a result of the data error for December 1973 (see text)

It should be noted that the occurrence of very large floods during 1973/74 and 1975/76 has always made modelling of the Fish River at Hardap Dam problematic. The model is a monthly one and cannot therefore take into account the extreme intensity of the rainfall storms, which caused the floods of March 1974. The peak discharge during these floods exceeded 6000m^3/s.

c) Naute Dam

The observed runoff record for the period 1961/62 to 2000/01 has been derived from two gauging stations and is provided in **Appendix B**. Before the completion of the Naute Dam, runoff was gauged at the Naute River Station (0497M01). From October 1970, the inflow record for Naute Dam has been utilised. It should be noted that the rainfall/runoff modelling was carried out for the period 1961/62 to 1993/94. Within this record period the record for the 1968/69 season was lost. During the unfinished study carried out by Hatutale and de Bruine (de Bruine, 1995), it was reported that the mean annual runoff for the observed period (not including 1968/69) was 60.66million m^3/a. According to the data supplied by the Hydrology Division for the present study the mean annual runoff (MAR) for this period (not including 1968/69) was 60.94 million m^3/a. After a careful examination of the record used for modelling in the 1995 study, it was found that there were three small errors:

- December 1985, 29.68 million m^3 was used instead of the correct value 9.68 million m^3.
- March 1986, 60.66 million m^3 was used instead of the correct value of 30.66 million m^3.
- September 1991, 0.00 million m^3 was used instead of the correct value of 3.15 million m^3.
- In 1968/69, all record was lost. In the 1995 study calculation, it has been assumed that zero flow was recorded and the year has been taken into account in the calculation of MAR.

In the running of the model, the values for 1968/69 were correctly set to lost record. Once these small errors are taken into account, the MARs are the same. The corrected value is shown in **Table 5-4**. According to a paragraph of rough text from the 1995 study written under the heading of Naute Dam, "A synthesized runoff record was generated for the same years (1961/62 to 1994/95). The MAR was 44.85 million m^3 with a CV of 1.93". However, when examining the various computer files, no reference was found to this extremely low value for the Naute MAR. However, a "NAMRON" answer file was found and carefully studied. As already stated, it included three erroneous values, which would have had a minor effect on the rainfall modelling. This NAMRON file was converted into an EXCEL file in order to check the statistics.

The monthly correlation of the (corrected) observed runoff against weighted precipitation was calculated to be 0.8229. A new regression analysis was performed as part of the current study and the resultant synthesized record was very similar to that produced by Hatutale and de Bruine. It was therefore decided to adopt the synthesized record generated in the 1995 study. The statistics are provided in **Table 5-4**, which presents a comparison of the statistics for the concurrent observed and synthesised records as well as those for the period 1920/21 to 2000/01 (combined observed and synthetic records).

Table 5-4: Comparison of Runoff Statistics for Naute Dam

Record	Parameter	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Annual
Observed 1961/62-1993/94 *	Mean	0.08	0.59	0.80	14.51	18.59	17.09	8.12	0.95	0.10	0.02	0.01	0.11	60.94
	Median	0.00	0.00	0.00	0.12	2.05	3.09	1.68	0.00	0.00	0.00	0.00	0.00	29.47
	Std deviation	0.09	1.36	2.00	31.25	49.27	33.56	13.80	4.17	0.43	0.08	0.06	0.54	101.32
	Coeff. Var	3.05	2.37	2.60	2.29	2.69	2.03	1.74	4.24	4.39	5.83	4.82	5.44	1.67
Synthesized 1961/62-1993/94 (De Bruine, Hatutale, DWA)	Mean	0.48	1.74	2.82	14.76	17.06	17.92	3.99	0.91	0.00	0.00	0.00	0.98	62.16
	Median	0.00	0.00	0.00	0.12	2.28	3.09	1.41	0.00	0.00	0.00	0.00	0.00	38.83
	Std deviation	0.26	1.35	5.16	31.25	49.18	34.37	13.85	4.17	0.43	0.08	0.06	0.04	77.81
	Coeff. Var	3.60	2.46	3.85	2.29	2.64	1.99	1.80	4.30	4.39	5.83	4.82	5.83	1.26
Combined Observed and Synthesized 1920/21-2000/01	Mean	0.03	1.55	2.24	9.98	15.78	22.85	7.83	0.73	0.38	0.03	0.02	0.10	61.53
	Median	0.00	0.00	0.00	0.24	2.18	4.11	0.38	0.00	0.00	0.00	0.00	0.00	34.76
	Std deviation	0.10	5.49	7.24	24.04	36.23	40.57	15.88	3.47	2.20	0.19	0.11	0.63	86.76
	Coeff. Var	3.67	3.54	3.23	2.41	2.30	1.78	2.03	4.72	5.71	7.24	6.64	6.28	1.41

* The observed record is derived from Naute River (0497M01) and Naute Dam (0497R01). Record lost for 1968/69, this season has been omitted from calculation of mean

As is often the case because of the difficulty inherent in making the model respond correctly to exceptionally high rainfall, the standard deviation and coefficient of variation of the synthesized record are considerably lower than those of the observed record.

Once the record is extended back to 1920/21 and forward to 2000/01, using recent observed runoff, the mean increases marginally, and the coefficient of variation also increases. The first four years of the record (1920/21 to 1923/24) have been generated through a simple correlation with the synthesized Seeheim record since there are not sufficient useful rainfall data for the Naute catchment for this period. While this is not an ideal approach, it is only for 4 years of record.

Figure 5-4 compares the annual runoff totals for the observed and synthesized records for the concurrent period. Once the record is extended back to 1920/21 and forward to 2000/01, the mean increases marginally, but the variability decreases. This is because the two highest runoff seasons are to be found in the observed period.

The combined synthesized and observed flow record for Naute Dam is provided in **Appendix C**.

d) Seeheim

Observed Runoff and total non-naturalised Runoff.

The observed runoff record for the period 1961/62 to 2000/01 is provided in **Appendix B**. It should be noted that the rainfall/runoff modelling was carried out for the period 1961/62 to 1993/94. During this period, the Hardap Dam was in existence and it was ascertained that the regression analysis was performed by modelling weighted rainfall for the Seeheim incremental catchment against the observed runoff at Seeheim, minus spill from Hardap, minus estimated bed losses between Hardap and Seeheim. Unfortunately, due to the fact that the methodology was not compiled, the details of the analysis cannot be found. In view of the fact that the work was carried out soon after the compilation of the Unit Runoff Report and Map (1992), it is assumed that the bed losses were calculated at 0,25% per kilometre, as estimated in that study. A number of generated synthetic runoff files (1916/17 to 1993/94) for the Seeheim station were found and the one with the best correlation was adopted. **Figure 5.5** shows the observed (actual observed) and synthetic annual flow volumes for the current period between 1961/62 and 1993/94. The observed spills from Hardap Dam, with allowance for transmission losses have been added to the synthetic flows modelled for the Seeheim incremental catchment. It should be noted that there was too much lost record in seasons 1962/63 and 1963/64 to include them in the regression analysis.

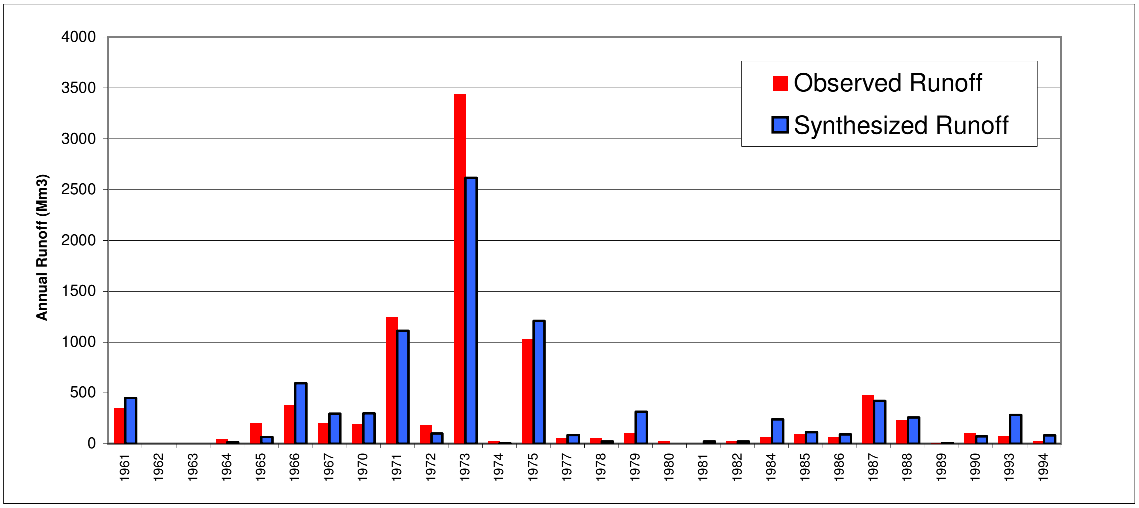


Figure 5-4: Observed and Synthesized Runoff for Seeheim

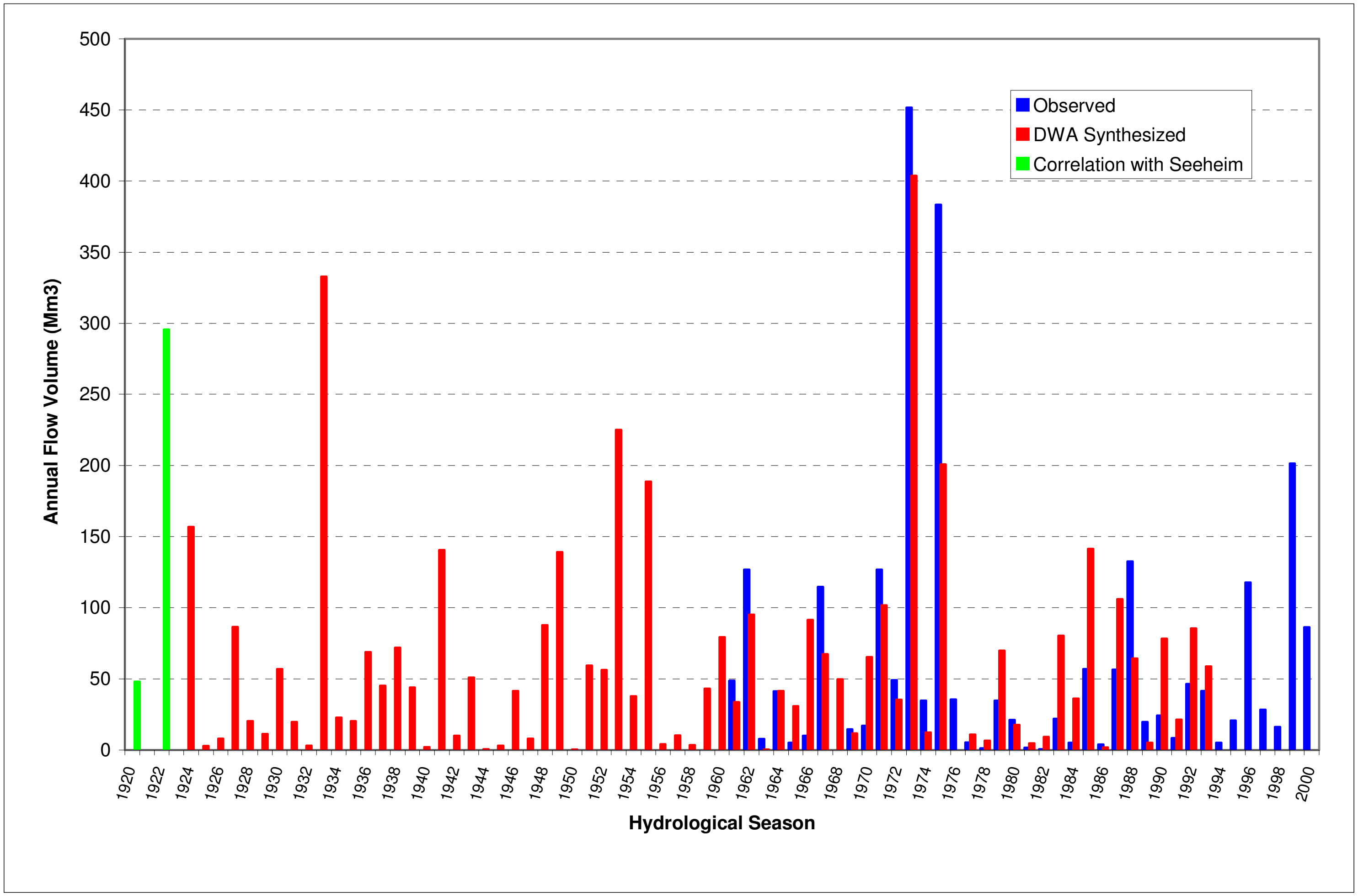


Figure 5-5: Observed and Synthetic Runoff Records for Naute Dam

The correlation coefficient for the regression analysis of the concurrent observed and synthesized values is 0.975. This would suggest that the adopted rainfall/runoff model yields acceptable results.

Table 5.5 presents a comparison of the statistics for the concurrent observed and synthesised periods as well as those for the period 1920/21 to 2000/01. The combined synthesized and observed flow record is provided in **Appendix C.**

Table 5-5: Comparison of Runoff Statistics for Seeheim

Record	Parameter	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Annual
Observed 1961/62-1994/95	Mean	0.62	1.70	8.06	70.80	115.86	107.20	26.72	5.18	1.22	0.72	0.37	0.66	339.01.61
	Median	0.00	0.00	0.00	3.43	10.00	23.88	6.12	0.46	0.00	0.00	0.00	0.00	97.65
	Std deviation	2.96	4.44	28.74	197.08	414.29	217.17	49.38	12.68	3.42	2.27	1.38	2.96	741.72
	Coeff. Var	4.80	2.54	3.46	2.71	3.47	1.97	1.80	2.40	2.81	3.06	3.63	4.36	2.13
Synthesized 1961/62-1994/55	Mean	0.72	4.99	2.71	102.45	104.37	92.76	16.01	0.10	0.00	0.00	0.00	0.22	324.33
	Median	0.00	0.00	0.00	0.00	13.23	5.00	0.00	0.00	0.00	0.00	0.00	0.00	111.98
	Std deviation	4.11	25.81	11.52	257.02	236.39	158.20	46.84	0.58	0.00	0.00	0.00	1.29	528.68
	Coeff. Var	5.74	5.17	4.24	2.51	2.27	1.71	2.93	5.74	-	-	-	5.74	1.63
Combined Observed and Synthesized 1920/21-2000/01	Mean	0.58	3.09	10.97	55.91	123.28	124.76	23.69	2.77	0.71	0.38	0.34	0.34	346.82
	Median	0.00	0.00	0.00	0.00	8.56	16.80	2.74	0.00	0.00	0.00	0.00	0.00	108.56
	Std deviation	3.40	15.76	36.41	151.88	316.05	241.38	54.01	9.13	2.53	1.57	1.88	1.98	616.94
	Coeff. Var	5.89	5.09	3.32	2.72	2.56	1.93	2.28	3.30	3.55	4.11	5.51	5.80	1.78

The systems analysis requires incremental runoff records for each of the nodes as input (see **Figure 5-2**). Since the Hardap and Naute Dam nodes do not have further nodes upstream they are already incremental runoff records. However, for Seeheim an incremental record had to be generated. In addition, this incremental record had to be a naturalised incremental record, i.e., representing the situation in which Hardap Dam had not been built and there were no demands in place. This incremental record was compiled as described in the next Section.

Generation of Incremental Runoff record for Seeheim

In summary, the following steps were carried out in order to generate a naturalised incremental record for Seeheim.

i) Calculate naturalised MAR for total Seeheim catchment based on Unit Runoff

Map/report (Chivell *et al,* 1993) and more recent modelling of Hardap Dam runoff.

ii) Route flows from a naturalised Hardap Dam catchment to Seeheim taking into account losses. Result is "remaining Hardap flow".

iii) Subtract "remaining Hardap flow" from total Seeheim catchment runoff.

iv) Consideration of derived unit runoff value.

The results were as follows:

- STEP 1: The value of MAR (total catchment) quoted in the Unit Runoff Report for Seeheim is 412.96 million m³/a. This corresponds to the period 1961/62 to 1992/93. In order to "correct" this value to correspond to the period 1920/21 to 2000/01, a scaling factor was used by making reference to the value for the period 1961/62 to 1992/93, which can be calculated from the record quoted in this report (see **Section 6.2.2.2** of this report).
- According to the current study (see **Appendix B Table B-1**), the MAR for Hardap Dam for the period 1961/62 to 1992/93 is 188.23 million m³/a. This is 2,8% less than the MAR for the period 1920/21 to 2000/01. Hence, the Seeheim value for the 1961/62 to 1992/93 period was increased by 2,8% from 412.96 million m³/a to 424.56 million m³/a.
- STEP 2: The observed and synthesized record for Hardap Dam (see **Appendix C Table C-1**) was routed the 346 km to Seeheim. According to the Unit Runoff Report, which looked at average transmission losses throughout many of Namibia's rivers, the loss is on average 0.25% of the flow per kilometre. Applying this to the Hardap Dam record, it can be calculated that 79.218million m³/a reaches the Seeheim station while the rest is lost mainly to evapotranspiration and infiltration. The record of monthly runoff calculated to reach the Seeheim station is provided in **Appendix C Table C-4**).
- STEP 3: The annual remaining flows from Hardap were subtracted from the total Seeheim catchment annual values. The resultant incremental MAR is 345.34 million m³/a.
- In order to create a monthly runoff record for Seeheim incremental runoff, the distribution of extended record summarised in **Table 5.5** and presented In **Appendix C, Table C-5** was used. Hence, the incremental record for Seeheim follows the same monthly and annual distribution as the extended un-naturalised flow record. The record is provided in **Appendix C Table C-5**).

- STEP 4: The incremental MAR for Seeheim has been calculated as 345.34 million m³/annum. The incremental catchment area for Seeheim is 23 170 km². The unit runoff is therefore 14.9 mm/a. According to the Unit Runoff Report (1993), the majority (60%) of the incremental catchment lies within the 15-20 mm/a unit runoff area, with approximately 10% in an area of 20-25 mm/a and about 30% in an area of 6-10 mm/a. This gives a weighted average of 15.4 mm/a. Taking into account transmission losses, it would be expected that the average unit runoff for the incremental catchment would be of the order calculated in this analysis.
- The incremental naturalised record for Seeheim is presented in **Appendix C Table C-5**) and the statistics are summarised in **Table 5-6**.
- The total catchment (at Seeheim) naturalised record, which includes flows from Hardap Dam is included as **Appendix C, Table C-6** and the statistics are summarised in **Table 5-6**.

A comparison of the incremental and the total catchment records shows the expected reduced mean annual runoff and an increased standard deviation and coefficient of variation.

Table 5-6: Comparison of Statistics for Seeheim Incremental and Total Catchment Runoff

Record	Parameter	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Annual
Naturalised Incremental 1920/21-2000/01	Mean	0.57	3.08	10.92	55.67	122.76	124.23	23.59	2.76	0.71	0.38	0.34	0.34	345.34
	Median	0.00	0.00	0.00	0.00	8.52	16.73	2.73	0.00	0.00	0.00	0.00	0.00	108.10
	Std deviation	3.38	15.69	36.25	151.23	314.70	240.35	53.78	9.09	2.52	1.57	1.87	1.97	614.31
	Coeff. Var	5.89	5.09	3.32	2.72	2.56	1.93	2.28	3.30	3.55	4.11	5.51	5.80	1.78
Naturalised Total Catchment 1920/21-2000/01	Mean	1.72	5.56	15.08	72.21	148.47	146.69	28.48	3.81	1.08	0.49	0.41	0.55	424.56
	Median	0.02	0.41	1.73	11.20	23.10	21.51	6.18	0.18	0.00	0.00	0.00	0.00	157.70
	Std deviation	6.22	17.95	40.51	177.70	354.73	275.77	59.14	9.62	2.91	1.64	1.89	2.07	701.16
	Coeff. Var	3.62	3.23	2.69	2.46	2.39	1.88	2.08	2.52	2.69	3.37	4.57	3.77	1.65

e) Lower Fish and Konkiep

As shown in **Figure 5-2**, downstream of Seeheim, there are two further nodes, “Lower Fish” on the Fish River mainstream just upstream of the confluence of the Fish and Konkiep Rivers, and “Konkiep” on the Konkiep River just upstream of the confluence. The incremental catchment area of Lower Fish is 8650 km², that of the Konkiep River is approximately 32 000 km². Reliable data are lacking for runoff generated in these two sub-catchments and so a combination of simplified approaches has been used to estimate an MAR and a monthly runoff series

The Konkiep is the largest (in terms of catchment area) of the Fish Rivers tributaries. It rises approximately 80 km northwest of Hemeringhausen and flows through and arid area to the west of the Fish River. Very little is known about the unit runoff values in this area, but most of the catchment lies within an area experiencing an average rainfall of less than 100 mm per annum. The river has been gauged at Mooifontein, 30 km south of Helmeringhausen since 1979. There are a number of gaps in the record, in particular during some of the higher runoff seasons. Nevertheless, for the years in which runoff data are available for Mooifontein, a comparison has been made with the runoff recorded at Seeheim, Naute and Hardap. This is illustrated in **Table 5-7**. For the years 1979/80 to 2000/01 (excluding 1984/85, 1989/90, 1998/99, 1999/00 and 2001/02), the MAR for Mooifontein has been calculated as 4.12 million m³/a . For the same years, the MARs for Naute Dam, Seeheim and Hardap Dam are 36.66 million m³/a, 114.71 million m³/a and 92.34 million m³/a, respectively. These figures correspond to 59,6%, 33,1% and 47,8% of the long-term MARs (1920/21-2000/01).

Table 5-7: Estimated MAR for Mooifontein on Konkiep River

Hydrological Season	Observed Mooifontein	Observed Naute	Observed Seeheim	Observed Hardap
1979/80	0.67	34.74	107.73	90.28
1980/81	0.00	21.28	25.74	2.11
1981/82	0.00	1.57	0.00	7.61
1982/83	1.52	0.63	23.86	8.98
1983/84	5.00	22.08	128.11	122.84
1984/85	No record	5.31	60.20	85.28
1985/86	0.00	57.05	94.39	123.15
1986/87	5.00	3.91	59.79	88.25
1987/88	0.00	56.54	478.66	127.35
1988/89	11.03	132.60	300.18	237.20
1989/90	No record	19.71	9.92	4.01
1990/91	0.81	24.19	106.29	43.55

Hydrological Season	Observed Mooifontein	Observed Naute	Observed Seeheim	Observed Hardap
1991/92	1.25	8.49	36.08	10.33
1992/93	5.16	46.53	25.82	79.49
1993/94	3.57	41.57	71.92	81.06
1994/95	6.00	4.96	24.88	38.81
1995/96	0.04	20.76	185.23	76.20
1996/97	25.00	117.84	173.41	397.58
1997/98	5.00	28.31	108.00	34.96
1998/99	No record	16.27	121.13	90.58
1999/00	No record	201.52	2033.11	1548.83
2000/01	No record	86.28	254.32	110.92
* Mean 1979/80-2000/01	4.12	36.65	114.71	92.34
Mean 1920/21-2000/01	-	61.53	346.82	193.63
Mooifontein mean scaled	9.34	6.92	12.46	8.64

* Note : Calculated leans do not include 1984/85, 1989/90, 1998/99, 1999/00 and 2001/02.

In view of the fact that these three stations cover much of the total catchment of southern Namibia, the assumption is made that taken together they provide an overall estimate of the runoff in the area. Hence, it has been assumed that the observed MAR for Mooifontein should be increased proportionately (with respect to Naute, Hardap and Seeheim) in order to obtain an estimate for long-term MAR (1920/21 – 2000/01). These estimates are shown in the final line of **Table 5.7** and range from 6.92 million m^3/a (based on Naute Dam) up to 12.46 million m^3/a (based on Seeheim). The average value, taking all three estimates into account is 9.34 million m^3/a. It is proposed that this be adopted as the MAR for the Konkiep River at Mooifontein.

The catchment area at Mooifontein is 2 080 km^2, while the catchment area of the Konkiep River at the confluence with the Fish is 32 000 km^2. Unfortunately, little information on how much water the 29 920 km^2 downstream of Mooifontein can be expected to contribute is not available. Much of the catchment area, especially to the west of the mainstream, is truly in the desert. However, much of the catchment upstream of Mooifontein is also very arid and yet the unit runoff has been calculated at approximately 4.5 mm/a. According to the Unit Runoff map, while most of the catchment lies in an un-classified desert area, there are parts of the Konkiep River catchment (around 2 000 km^2) lying to the east of the mainstream, which rise in the 10-15 mm/a and even 15-20 mm/a unit runoff areas. In calculating the MAR for the total Konkiep River, the following assumptions have been made:

- MAR at Mooifontein is 9.34 million m^3/a. This is routed over 315 km to the confluence with a loss rate of 0,25% per kilometre. The remainder is 4.193 million m^3/a.
- 20 000 $km^2$of the catchment lying to the west has no significant runoff contribution.
- 500 km^2 of the catchment lying in the 15 mm/a unit runoff zone contributes 7.5 million m^3/a.
- 1 500 km^2 of the catchment lying in the 10 mm/a unit runoff zone contribute 15 million m^3/a.
- A transition area of 1 000 km^2 lying to the east of the mainstream has an average unit runoff of 5 mm/a and contributes 5 million m^3/annum.
- The remainder of the catchment (8 170km^2) lying to the east of the mainstream has a unit runoff of average 2 mm/a (after transmission losses) and contributes 16.34 million m^3/a.

According to the above assumptions, the total MAR of the Konkiep River is estimated to be 48.033 million m^3/a. This approach is far from ideal, and there is clearly a need for a gauging station in the Lower Konkiep in order to improve estimates of the contributions of this river.

The MAR of the Konkiep River has been given an annual and monthly distribution for the period 1920/21 – 2000/01 in proportion to the Seeheim incremental runoff record, and is provided in **Appendix C, Table C-8.**

The contribution of the Lower Fish has been estimated with reference to the estimated unit runoff values given in the unit runoff report and increased by 2,8%. For the Lower Fish the following assumptions were made:

- 530 km^2 of the catchment lying in the 20 mm/a unit runoff zone contribute 10.6 million m^3/a .
- 1200 km^2 of the catchment lying in the 15 mm/a unit runoff zone contribute 18.0 million m^3/a .

- 600 km² of the catchment lying in the 12 mm/a unit runoff zone contribute 7.2 million m³/a .
- 3 300 km² of the catchment lying in the 10 mm/a unit runoff zone contribute 33 million m³/a .
- 630 km² of the catchment lying in the 8 mm/a unit runoff zone contribute 5.04 million m³/a .
- 1 580 km² of the catchment lying in the 6 mm/a unit runoff zone contribute 9.60 million m³/a .
- 800 km² of the catchment lying in the 5 mm/a unit runoff zone contribute 4.00 million m³/a.

According to the above assumptions, the incremental MAR of the Lower Fish is approximately 87 million m³/a. The incremental MAR for the Lower Fish has been given an annual and monthly distribution for the period 1920/21 – 2000/01 in proportion to the Seeheim incremental runoff record, and is provided in **Appendix C, Table C-7.**

f) Total Fish Incremental Runoff

Although this input file is not required for the systems analysis, total naturalised MAR for the Fish River has been calculated. The total naturalised catchment runoff was assumed to be the combined runoff occurring downstream of the Fish/Konkiep confluence. This runoff record was calculated by adding the following flows:

- Total catchment runoff at Seeheim (see **Appendix C Table C-6**) less transmission losses (0,1%/km) +.
- Naute runoff (see **Appendix C, Table C-2)** less transmission losses (0,1%/km) +
- Konkiep runoff (see **Appendix C, Table C-8**) +
- Lower Fish (see **Appendix C, Table C-7**).

The resultant naturalised flow record has an MAR of 512.20 million m³/a and is presented in **Appendix C, Table C-9**. The statistics are summarised in **Table 5.8.**

Table 5-8: Runoff Statistics for Total Fish River Naturalised Runoff Record

Record	Parameter	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Annual
Naturalised Total Catchment 1920/21-2000/01	Mean	1.56	6.78	17.71	85.50	175.02	180.26	37.68	4.62	1.43	0.54	0.46	0.64	512.20
	Median	0.08	0.78	1.96	9.68	23.27	30.13	6.44	0.25	0.00	0.00	0.00	0.00	195.74
	Std deviation	5.97	23.76	49.06	211.56	422.43	330.72	77.17	12.76	4.25	1.93	2.17	2.66	842.54
	Coeff. Var	3.83	3.51	2.77	2.47	2.41	1.83	2.05	2.76	2.97	3.55	4.68	4.16	1.64

6. SEDIMENTATION

Sedimentation rates can be estimated using theoretical models based on empirically generated parameters relating to geology, soils, ground cover/vegetation, land use, slope factors etc. In fact, sometimes erosion-risk maps, which themselves have been drawn up from a consideration of these factors can sometimes be useful. Unfortunately, such data are not readily available for the Fish River catchment.

Another approach is to base estimates on the results of a sampling programme. Samples have been taken in the Fish River but there are serious doubts regarding the validity of such silt samples, which can grossly overestimate silt concentration. This over-estimate results from the fact that as the velocity of silt-laden water slows to zero within the sample bottle, the silt is immediately deposited. Once the bottle is full, which will normally take only a few instants, relatively sediment-free water tends to be forced out of the opening by sediment-laden water entering the bottle. The result is that in only a few seconds the concentration of sediment in the bottle rises above that of the river water being sampled.

The most accurate way of looking at sediment or silt load is to look at the sedimentation rates within existing reservoirs. Bathometric surveys were carried out for Hardap Dam in 1980 and 1992. Details are provided in **Table 6-1**.

Table 6-1 : Sediment Surveys carried out at Hardap Dam

Description	1980	1992
Gross Capacity (million m^3/a)	297	294
Sediment Volume (million m^3/a)	8.9	12.1
Sediment as percentage of Gross Capacity (%)	2.9	3.9

During the period October 1962 until August 1980, a total of 4 440 million m^3/a flowed into the reservoir. If it is assumed that all of the silt was trapped in the reservoir then the average percentage silt concentration was 0,20%. For the period September 1980 to August 1992, a total of 860 million m^3/a flowed into the reservoir. The average percentage silt concentration was 0,36%.

The accuracy over the total period 1962/63 to 1991/92 the sediment volume was 12million m^3/a for a total inflow of 5 301million m^3/a, which corresponds to 0,23%.

It is recommended that this be taken as the sedimentation rate for any proposed dam.

7. SENSITIVITY ANALYSIS

7.1 General

A detailed rainfall/runoff assessment for the Fish River was not carried out as part of this study as already explained in **Section 1.2**. It was therefore considered necessary to include some sensitivity analyses to determine the effect of changes in the hydrology to the system yield and to the flows/spills from the Fish to the Orange River. The results from these sensitivity analyses will provide an indication of the necessity of a detailed rainfall/runoff assessment.

Future development in the Fish River will also affect the outflows from the Fish River. For this reason, it was required to carry out analyses representative of different developments, which also included a maximum possible development scenario. The affect of these developments on the flows from the Fish into the Orange River will be obtained from these analyses.

The Water Resources Yield Model (WRYM) was used to carry out the required sensitivity analyses. The total Fish River System as modelled by the WRYM is schematically shown in **Figure 7-1**. The updated hydrology and 2005-development level demands as obtained from this study was used as input to the WRYM.

7.2 Methodology

The reference scenario for the purpose of the sensitivity analysis was taken as the current system with 2005-development level demands imposed on the water supply system. The reference scenario was analysed and a monthly flow record representative of the spills from the Fish River at 2005-development level was produced.

The historic firm yield for Hardap and Naute Dams were then determined. Results from this analysis will show if there are surplus yield available at these two dams, which can be utilised by future demand growth. The surplus yield was then imposed on the dams, to represent a maximum demand scenario for the current physical water supply system. Comparing the Fish spill record from this scenario (Scenario F2) with that from the reference scenario, the effect of the higher demand on the outflow from the Fish River can be obtained.

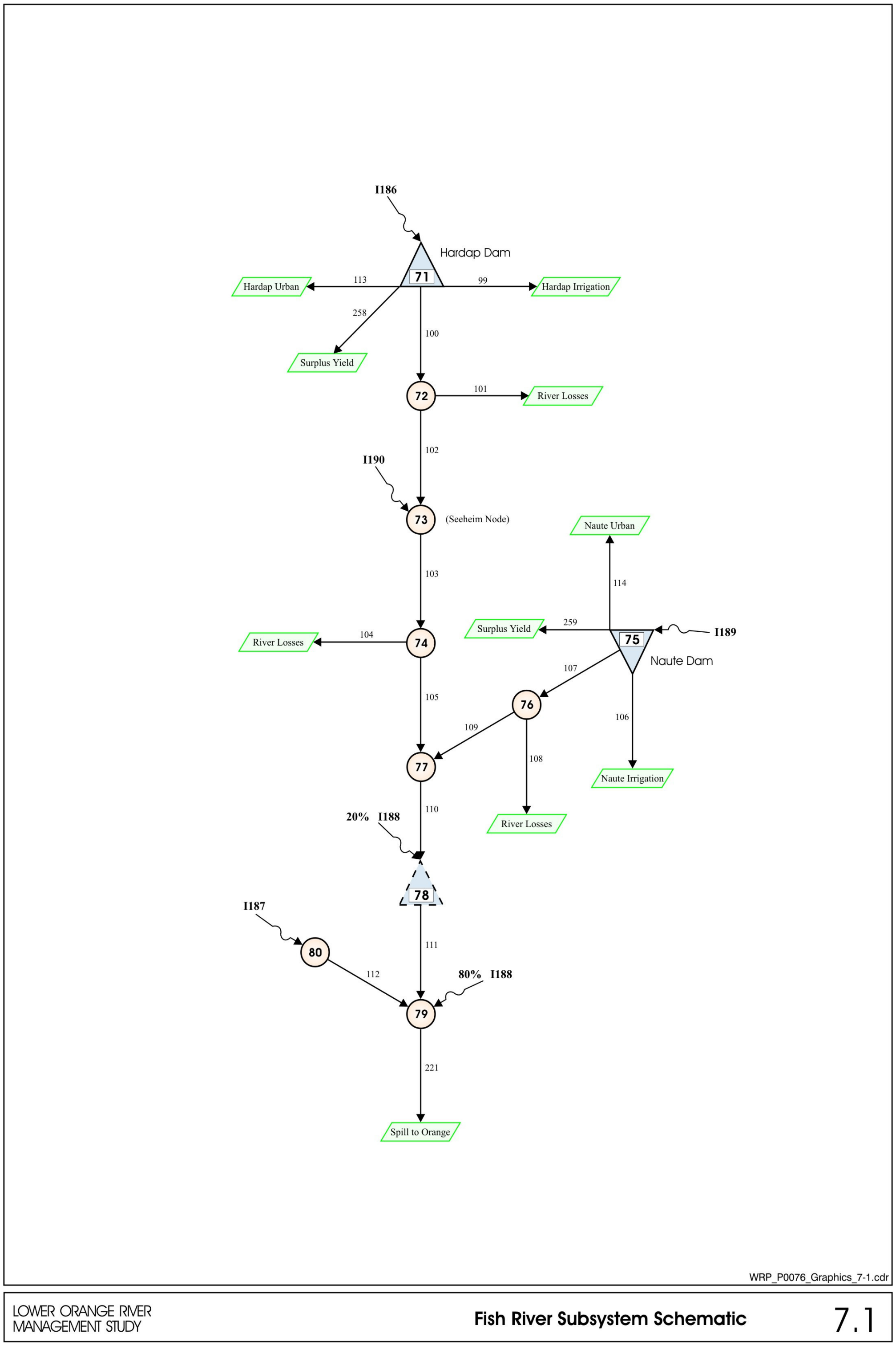


Figure 7-1: Fish River Sub-system Schematic

It was decided not to analyse the effect of the possible Brukaros Dam, as this proposed dam has a capacity of only approximately 30 million m³. The effect of this dam on the outflows from the Fish River will therefore be insignificant. To represent the effect of possible future developments, it was decided to rather model various sizes of a hypothetical dam in the Lower Fish River. The hypothetical dam on the Lower Fish is located just downstream of the confluence of the Lowen and Fish Rivers. Four dam sizes for the Lower Fish Dam were considered for the purpose of this analysis, a 0.5 MAR, 1 MAR, 1.5 MAR and a 3 MAR dam, and are respectively referred to as Scenarios F3, F4, F5 & F6.

To determine the effect of a change in the hydrology on the system yield, the natural hydrology was increased and decreased respectively by 15% and the historic firm yield of the Lower Fish River Dam was obtained for the three capacities analysed in scenarios F3 to F5 (for both the reduced and increased hydrology). These analyses resulted in a further four scenarios referred to as scenarios F3a &F3b to F5a & F5b.

7.3 Hardap and Naute Dams

Results from the Hardap and Naute yield analysis clearly showed that for practical purposes there is no surplus yield available at Hardap Dam and at Naute Dam 34% of the historic firm yield is still available for future water use (see **Table 7-1**).

Table 7-1: Historic Firm Yield Results for Hardap and Naute Dams

Scenario		2005 Demand (million m³/a)		Surplus yield (million m³/a)	Total system yield (million m³/a)
Description	No.	Urban	Irrigation		
Hardap Yield	F2a	1.02	41.70	0.01	42.73
Naute Yield	F2b	2.10	3.30	2.76	8.16

A sensitivity analysis to determine the effect of a change in the hydrology on the yield at Hardap Dam was also carried out. The results from this analysis are given in **Table 7-2**. The natural hydrology for Hardap Dam was increased and decreased by 20% and the effect of the changes in the hydrology on the system yield was determined for both scenarios. The results showed that although the hydrology was changed significantly by 20%, the effect on the yield at Hardap was less than 15%.

Table 7-2: **Hydrology/Yield Sensitivity Analysis for Hardap Dam**

Scenario		Total system yield	Increase/Decrease in yield	
Description	No.	(million m³/a)	(million m³/a)	Percentage
Hardap system using the reference hydrology as used in scenario F2a	F2a	42.73	0	0
Hardap system using 80% of the reference hydrology as inflow	F2c	36.35	-6.38	-14.9
Hardap system using 120% of the reference hydrology as inflow	F2d	48.99	6.26	14.6

7.4 Lower Fish dam

For the purpose of this scenario, the total historic firm yield of Naute and Hardap Dams were imposed as a demand on the relevant dam. The historic firm yield was determined for 0.5, 1.0, 1.5 and 3.0 MAR dams. The results are given in **Table 7.3** and are also graphically shown on **Figure 7-2**. From the results, it is evident that the yield capacity curve starts to flatten of for capacities in excess of a 1 MAR dam.

Table 7-3: Lower Fish River Hypothetical Dam, Sensitivity Analysis Results

Scenario		Storage	Historic firm yield (million m³/a)			% Increase/Decrease in yield	
Description	No.	Capacity (million m³)	Reference hydrology	85% of reference hydrology	115% of reference hydrology	#For 85% of reference hydrology	*For 115% of reference hydrology
0.5 MAR dam	F3, F3a, F3b	170	39.6	34.6	41.6	-12.6	5.1
1.0 MAR dam	F4, F4a, F4b	330	55.3	45.6	64.2	-17.5	16.1
1.5 MAR dam	F5, F5a, F5b	500	65.9	56.3	75.5	-14.6	14.6
3. 0MAR dam	F6	1000	100.6	-	-	-	-

Note: # - The decrease in yield should be compared with the decrease of 23.8% in the total inflow to the Lower Fish Dam.

* - The increase in yield should be compared with the increase of 24.9% in the total inflow to the Lower Fish Dam

For the scenarios where the natural hydrology was increased or decreased by 15%, the demands on Hardap and Naute Dams were kept constant and were not adjusted to represent the increase or decrease in yield at these dams as result of the changed hydrology. From the results given in **Table 7-3**, it can be seen that the

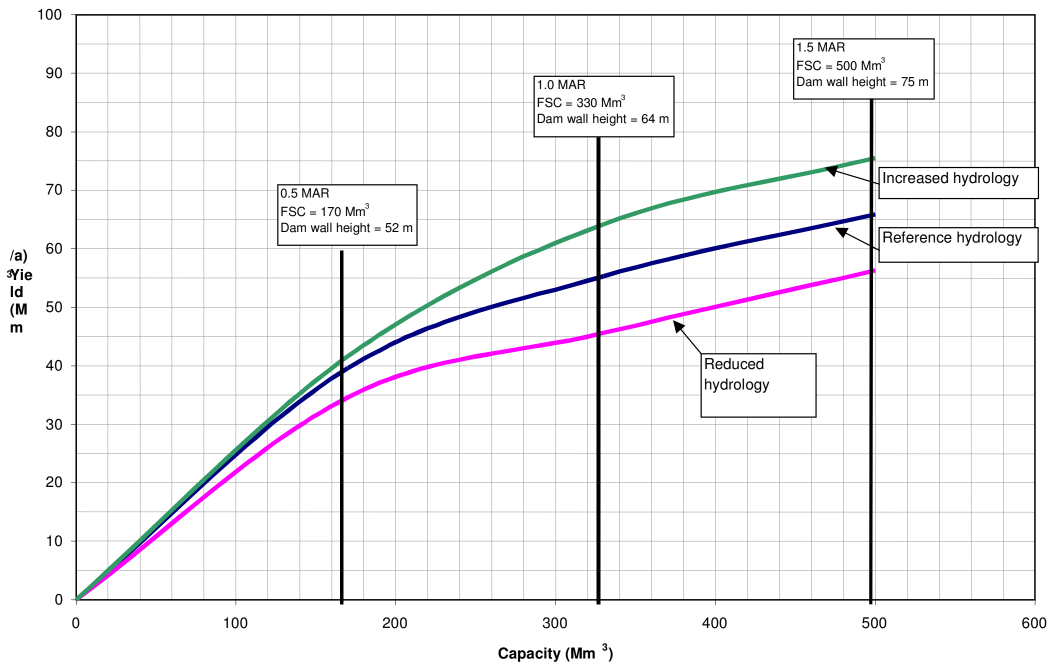


Figure 7-2: Yield Capacity Curve for Lower Fish Dam

increase and decrease in yield as result of the changed hydrology, are on a percentage basis similar to the adjustments made to the hydrology. This differs from the results obtained for Hardap Dam as given in **Table 7-2**, which indicated a smaller percentage change in yield than that imposed on the hydrology.

The reason for this was found when the inflows to the Lower Fish hypothetical dam were investigated in more detail. In comparison with the inflows as obtained from Scenario F2, the inflow to the Lower Fish Dam increased by 24,9% when the upstream natural hydrology is increased by only 15%. The water balance for Hardap Dam and Naute Dam provided further information that explained the reason for the increase in the inflow to the Lower Fish Dam, in excess of 15%.

When the natural hydrology is increased by 15%, the total inflow to the dam also increased by 15%, as it is only the one natural flow record that contributes to the inflow to Hardap Dam. Over the analysis period the total demand imposed on the dam remained unchanged, the average net evaporation over the period increased by 2,4% and the spills increased by 26,8%. When the hydrology is increased by 15%, the storage in Hardap Dam at the end of the analyses period is 65.5 million m^3 more (±24% of total storage) than that for scenario F2. The important finding, however, is that the spills increased significantly (26,8%) and a similar increase of 24,2% in the spills at Naute Dam was also evident. This therefore resulted in the increased inflow of 24,9% to the Lower Fish Dam. The increase in yield for the Lower Fish Dam from 5% (0.5MAR dam) to 16% (1.0 MAR dam) should thus be compared with the almost 25% increase in inflow to the dam and not to the 15% increase in the natural hydrology.

The small increase in yield of only 5% for the 0.5MAR dam is simply due to the fact that the storage of the 0.5 MAR dam is not sufficient to capture the increased high flows.

When the hydrology is reduced by 15% the total inflow to the Lower Fish Dam is reduced by 23,8%, this time due to a significant reduction in the volume of spills at Hardap and Naute Dams of 26,1% and 23,8%, respectively.

It is therefore clear that the yield is not particularly sensitive to changes in the hydrology and that the hydrology generated as part of this study, is of sufficient accuracy for the purposes of this study

7.5 Outflows from the Fish River

7.5.1 Effect of Development

The outflows from the Fish River into the Orange River were compared for several development options as shown in **Table 7-4**. For the maximum development option (3MAR dam in Lower Fish River) the average outflow over the analysis period reduced by 30,5%, from 459.63 million m^3/a to 319.41 million m^3/a. The coefficient of variation (CV) increased from 1,82 to 2,34 and clearly shows the increasing variability of the monthly flows in the flow record for increasing developments.

The total record period analysed included the water years 1920 to 1987 and therefore represents a total of 816 months. A summary of the effect on frequency of the monthly flow events due to the different development scenarios analysed, is given in **Table 7-5**. From the results given in **Table 7-5**, it is evident that zero monthly flows for all the development options occur for more than 70% of the total record period. By including a 3 MAR dam in the Lower Fish, the total number of months with zero flow increased by a further 18 months in comparison with the reference scenario. The results further showed that the frequency of monthly flow events between zero and 20 million m³/month are affected the most by the upstream developments, with very little effect on monthly flows above 500 million m³. Imposing the maximum demand on Naute and Hardap Dams, had an insignificant effect on the Fish River spills.

Table 7-4 : Outflow from the Fish River for Different Development Options

Scenario		Average (million m³/a)	Standard deviation (million m³/a)	Coefficient of variation
Description	No			
Reference scenario	F1	459.63	834.47	1.82
Naute & Hardap max demand	F2	458.28	833.46	1.82
0.5 MAR dam	F3	400.53	817.08	2.04
1.0 MAR dam	F4	375.55	803.03	2.14
1.5 MAR dam	F5	361.99	793.34	2.19
3.0 MAR dam	F6	319.41	749.01	2.34

The monthly flow records for the reference scenario, the 1.5 MAR and 3 MAR dam in the Lower Fish are shown respectively in **Figures 7.3, 7.4 & 7.5.** The decrease in the monthly flows with respect to the lower monthly flows is also evident from these figures.

Table 7-5: Effect of Development on Monthly Flows from the Fish to the Orange River

Monthly flow range (million cub. m)	Reference scenario		Naute & Hardap max. demand		0.5 MAR Lower Fish Dam		1.0 MAR Lower Fish Dam		1.5 MAR Lower Fish Dam		3.0 MAR Lower Fish Dam	
	(No of months)	(% of months)	(No of months)	(% of months)	(No of months)	(% of months)	(No of months)	(% of months)	(No of months)	(% of months)	(No of months)	(% of months)
Zero flows	588	72.1	589	72.2	601	73.7	604	74.0	604	74.0	606	74.3
> 3	180	22.1	179	21.9	145	17.8	143	17.5	142	17.4	138	16.9
> 10	143	17.5	142	17.4	106	13.0	102	12.5	100	12.3	98	12.0
> 20	114	14.0	114	14.0	81	9.9	78	9.6	77	9.4	73	8.9
> 50	76	9.3	76	9.3	58	7.1	56	6.9	54	6.6	51	6.3
> 100	57	7.0	57	7.0	48	5.9	44	5.4	44	5.4	37	4.5
> 500	20	2.5	20	2.5	18	2.2	18	2.2	17	2.1	14	1.7
> 1 000	3	0.4	3	0.4	3	0.4	3	0.4	3	0.4	3	0.4

Figure 7.3: Reference scenario spills from Fish River

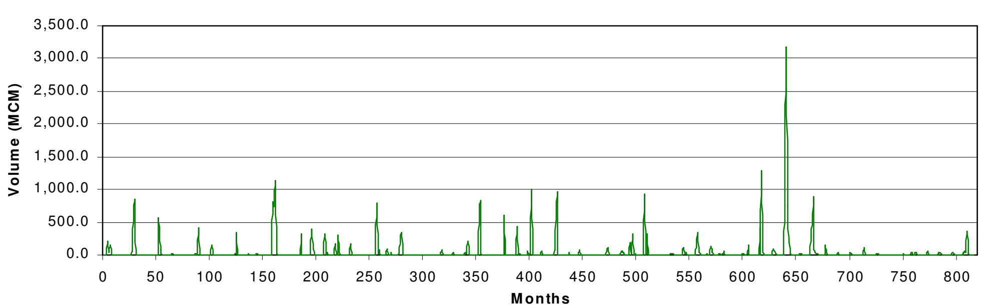


Figure 7-3: Reference Scenario Spills from Fish River

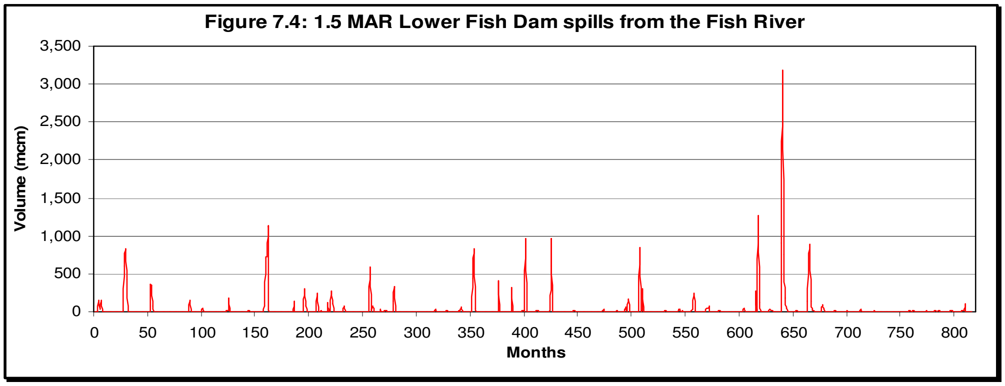


Figure 7-4: 1.5 MAR Lower Fish Dam Spills from the Fish River

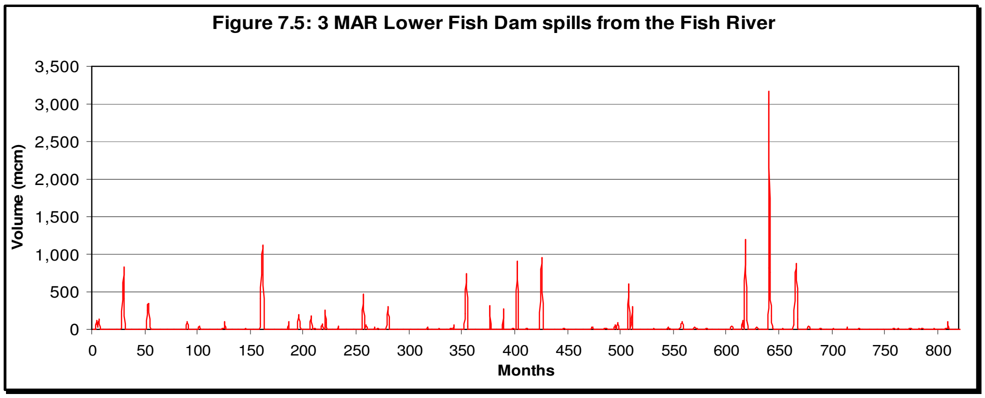


Figure 7-5: 3 MAR Lower Fish Dam Spills from the Fish River

7.5.2 Effect of hydrology

The 15% increase in the hydrology resulted in a 24,7% increase in the total average outflow from the Fish River. Similarly, the total outflow reduced by 23,4% when the natural hydrology was reduced by 15%. The reasons for the larger increase or decrease in the outflow in comparison with the increase or decrease in the natural hydrology are given in **Section 7.4**. Statistics of the different Fish River spill records as obtained from the variation in the hydrology are summarised in **Table 7.6.** From these results, it can be seen that although the average outflow changed significantly, the coefficient of variation showed a relatively small change for both scenarios (increase & decrease of hydrology).

Table 7-6 : Outflow from the Fish River for Different Hydrology Data Sets

Scenario		Average	Standard deviation	Coefficient of
Description	No	(million m³/a)	(million m³/a)	variation
1.0 MAR dam updated hydrology	F4	375.55	803.03	2.14
1.0 MAR dam hydrology increased by 15%	F4a	468.37	979.66	2.09
1.0 MAR dam hydrology decreased by 15%	F4b	287.65	626.91	2.18

The total record period analysed includes a total of 816 months (1920 to 1987). A summary of the effect on the monthly spill flows due to the different hydrology data sets as analysed, is given in **Table 7-7**.

From the results in Table 7-7, it is evident that the difference in the frequency of monthly flow events of the changed hydrology relative to the reference hydrology is not significant. The effect of the development options on the frequency of monthly flow events as given in **Table 7-5** is more severe and in particular with reference to the monthly flows less than 20 million m³. The differences in the frequency of monthly flow events also remained fairly constant over all of the listed flow ranges for the changed hydrology options.

Table 7-7 : Effect of Hydrology on Monthly Flows from the Fish to the Orange River

Monthly flow range (million cub. m)	Reference Hydrology		Decreased hydrology (15%)		Increased hydrology (15%)	
	(No of months)	(% of months)	(No of months)	(% of months)	(No of months)	(% of months)
Zero flows	604	74.0	605	74.1	603	73.9
> 3	143	17.5	136	16.7	148	18.1
> 10	102	12.5	92	11.3	111	13.6
> 20	78	9.6	70	8.6	82	10.0
> 50	56	6.9	52	6.4	59	7.2
> 100	44	5.4	39	4.8	48	5.9
> 500	18	2.2	13	1.6	21	2.6
> 1 000	3	0.4	1	0.1	8	1.0

The monthly flow records regarding the Fish River spills for the reference hydrology, the 15% increased and 15% decreased hydrology are shown, respectively in **Figures 7.6, 7.7 & 7.8**. The most significant differences in the monthly volumes are evident at the high flow months, which is as result of the constant scaling factor of 1.15, that was imposed on the total record (high and low flows).

7.6 Conclusions

The sensitivity analyses showed that the effect of the changed hydrology on the system yield is on a percentage basis less than the change in the hydrology. By improving the hydrology by 10% or 15% by means of a detailed rainfall/runoff assessment will typically result in a smaller improvement on the system yield of between 6% and 10%. A similar finding was also obtained when the change in frequency of specific monthly flows events were compared, regarding the spills from the Fish River. The results indicated that the frequency of monthly flow events was not affected significantly by the changed hydrology but rather by increased development options.

It can therefore be concluded that the simplified rainfall/runoff modelling as carried out for this study is sufficient for the purposes of this study and that a detailed rainfall/runoff assessment is not necessary.

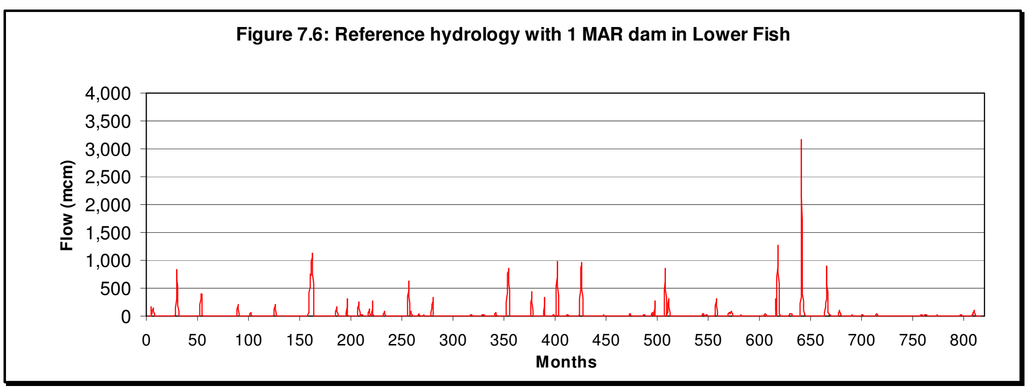


Figure 7-6: Reference Hydrology with 1 MAR Dam in Lower Fish

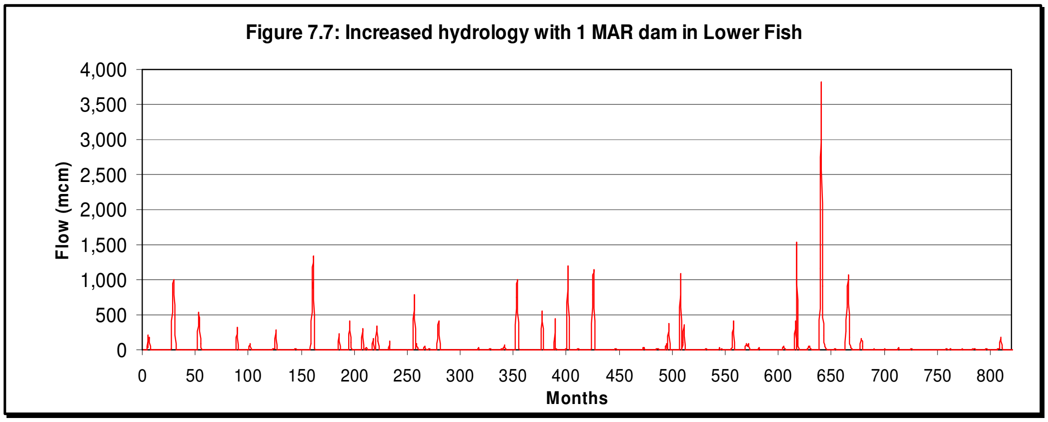


Figure 7-7: Increased Hydrology with 1 MAR Dam in Lower Fish

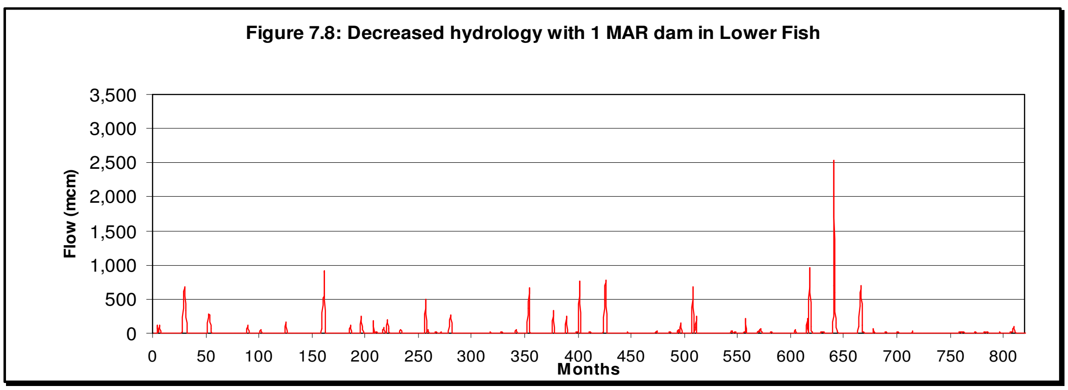


Figure 7-8: Decreased Hydrology with 1 MAR Dam in Lower Fish

8. RECOMMENDATIONS

It is recommended that the incremental MARs and associated monthly records be accepted for utilisation in subsequent work as part of the current Management Study of the Lower Orange River.

Despite the above recommendation, it is recognised that there is a need to carry out a detailed re-assessment of the hydrology of the Fish River, in particular the Fish River downstream of Hardap Dam and it is recommended that the Department of Water Affairs should program such a study. It is however not required for the purpose of the current Management Study where the focus is on the Lower Orange River and not on the Fish River.

It is recommended that a study into the technical feasibility of constructing a gauging station in the Lower Konkiep, as close as possible to the confluence with the Fish River, be considered.

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