APPENDIX 1

PREDICTION OF THE EFFECTS OF THE PROPOSED KHAN AQUIFER RECHARGE SCHEME ON DOWNSTREAM USERS

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THE PREDICTION OF THE EFFECTS OF THE PROPOSED KHAN AQUIFER RECHARGE SCHEME ON DOWNSTREAM USERS

1. INTRODUCTION

1.1 Background Information

Rössing Uranium Limited, (Rössing) are currently conducting preliminary design work and an environmental impact assessment (EIA) to evaluate the impacts of the proposed Khan Aquifer Recharge Scheme (KARS). This project has been proposed to increase the rate of supply of saline water from the alluvial aquifer of the Khan River to 7 000 m^3 per day (2,55 Mm^3/year), thereby reducing the Mine's demand for potable water from the West Coast Supply.

To date, Rössing have conducted investigation work to evaluate the potential yield of KARS and determine the likely potable water saving which could be realised from such a scheme. Although the optimal size of the dam will not be finalised until after completion of the EIA, the capacity of the dam is likely to be in the region of 6 Mm^3 to 11,25Mm^3. The evaluation has been conducted based on the assumption that the dam capacity will be 11,25Mm^3 to ensure that the magnitude of the impacts errs on the conservative side.

The KARS concept may briefly be summarised as follows :

- A gravity earth wall , spillway and decant structure will be constructed across the Khan gorge upstream of the existing Rössing wellfield to retain small and medium sized floods.
- A series of aquifer retarders will be constructed which will serve to reduce the base flow out of the mine front aquifer to the normal base outflow.

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- Immediately after flood events, water will be let out of the dam at a relatively slow rate. This water will be channelled on surface to the mine front aquifer where most of it will infiltrate into the sand to recharge the aquifer.
- Groundwater will be extracted from the portion of the alluvial aquifer several kilometres downstream of the dam adjacent to the mine front on an ongoing basis.

A more detailed description of the project is contained in the CSIR's report entitled "*An Assessment of the Potential Environmental Impacts of the Proposed Aquifer Recharge Scheme on the Khan River, Namibia*".

1.2 Issues of Concern

A consultative process has been implemented to involve the public and ensure that potential impacts of the proposed scheme are identified and investigated. The process and concerns raised by interested and affected parties are documented in the *Final Issues Report : Khan Aquifer Recharge Scheme (KARS)* of February 1997 compiled by Brian Gibson Issue Management on behalf of Rössing. The concerns which required detailed investigation using the modelling approach described further on in this document, are briefly described as follows :

- The effect of the KARS on the *silt load* downstream of the confluence of the Swakop and Khan Rivers. Sand mining which has taken place just upstream of the road bridge at Swakopmund and in the vicinity of the farm Nonidas, has resulted in the formation of several large excavations in the river bed. The operators are reliant on flood waters to re-deposit silt in these excavations. The following concerns have been raised with respect to the effect of the KARS on the silt deposition characteristics :
    - ◊ The frequency of floods may be reduced thus reducing the frequency at which the excavations are re-filled.
    - ◊ The particle size distribution of the sediment might change, causing the material which refills the excavations to be coarser or finer. This might in turn alter the recharge characteristics, evaporation and permeability characteristics of the alluvial aquifer in these regions.

◊ A reduction in the sediment load might give rise to a net erosion of sand from beaches along the coast. This would impact on the tourist potential of the town.

- The effect of the KARS on the potential for the sand dune field, located to the south of Swakopmund on the southern bank of the Swakop River, to migrate across the river and into the town. Flood events in the Swakop River are believed to play a role in preventing sand from crossing to Swakopmund. There is concern that the construction of the KARS will reduce the frequency and magnitude of flood events, thereby allowing the dunes to build up against the north bank of the river and then cross over the river bed.
- There is concern that the through flow (base flow) in the alluvial aquifer, or depth to the water table, particularly in the vicinity of the farms on the lower Swakop River downstream of the confluence, will be reduced as a result of KARS. Water is abstracted from the Swakop River by farmers and used for irrigation.
- There is concern that the quality of water in the alluvial aquifers described above will deteriorate as a result of the potentially reduced recharge from flood events, due to the reduced contribution to flood volumes in the lower Swakop River from the Khan River and reduced flood frequencies.

1.3 Terms Of Reference

The purpose of this study was to predict and quantify the incremental impact of KARS on the specific concerns described in the previous section. These impacts concern the lower Swakop River downstream of the Khan confluence and include .

- The change in the sediment load in the vicinity of the sand mining operations and at the Swakop delta.
- The change in the ability of the Swakop River to wash away sand dunes which might tend to migrate across the river bed in the vicinity of Swakopmund.
- The change in the proportion of finer particles (silts and clays) in the sediment in the area of sand mining.
- The magnitude of the impact on groundwater quantity or availability in the farming area.

- The magnitude of the impact of the groundwater quality in the area where farmers use the groundwater for irrigation purposes.

2. POTENTIAL IMPACTS OF HISTORICAL DEVELOPMENTS

The potential effect of KARS must be distinguished from the impacts of other developments and changes which have occurred primarily during the 20^{th} Century, these include :

- The construction of Von Bach Dam in 1970 and Swakoppoort Dam in 1976. Potential impacts from these dams include :

◊ A reduction in the *flood volumes* measured downstream of Swakoppoort Dam. This implies that less water is available to recharge the aquifer.

◊ A change in the *shape of the flood hydrographs* for the Swakop River downstream of the dams. Since the dams tend to retard flood waters by way of providing temporary storage between the level of the spillway crest (F.S.L) and the crest of the embankment, it is likely that the existing dams would tend to lengthen the duration of the flood hydrograph and reduce the peak intensity of the hydrograph. The implications of the change in the hydrograph shape caused by the dams includes :

⇒ a reduction in the sediment carrying capacity of the flood waters downstream of the spillway as a result of the reduced flood peak;

⇒ a reduction in the extent to which vegetation is cleared during major flood events along the path of the flood;

⇒ an increase in the proportion of the available flood volume which infiltrates into the alluvial materials and contributes to recharge of the alluvial aquifer, and a corresponding accelerated reduction in the flood volume further downstream due to the increased recharge rate.

◊ The dams reduce the *frequency of flood events* measured downstream of the spillway. This has several important potential impacts which may be summarised as follows :

⇒ Since the alluvial aquifers have a limited or finite storage capacity, they require to be re-filled or recharged at relatively frequent intervals. If they are not filled, they tend to loose their water, primarily to evapotranspiration. This gives rise to increased salinity over the period between successive recharge events.

⇒ Since vegetation in the path of the flood becomes cleared less frequently by flood waters, vegetation tends to become more established, more resistant to removal by smaller floods, more dense and larger thereby consuming greater quantities of water through evapotranspiration. This adds to the increased evapotranspiration losses and hence increases the rate of salinification of the aquifer with time.

◊ An increase in the silt size fraction of the sediment load in the flood waters for some distance downstream of Von Bach and Swakoppoort Dams due to removal of the coarse fraction of the sediment by the dams. This might affect the recharge, evaporation and the permeability characteristics of alluvial aquifers downstream of the dams.

◊ A reduction in vegetation density and the extent of wetlands due to reduced aquifer water levels.

◊ A reduction in the sediment load and sediment carrying capacity of the Swakop River due to the reduced stream power and lower peak flows and volumes.

◊ A reduction in the aquifer base flow rate due to the dam embankment which would have been constructed to reduce the seepage rate through the dam foundation.

- Borehole abstractions along the Khan and Swakop Rivers at places such as Otjimbingwe, Rössing and Usakos may reduce the level of groundwater and possibly the aquifer through flow rate.
- The construction of open trenches by farmers in the lower Swakop River, could give rise to an increase in the salinity of water as a result of evaporation from the trenches.
- Sand mining operations, particularly where mining takes place to within a metre of the water table, are likely to give rise to enhanced evaporation of the aquifer water and increased salinity.

- The existence of sand pits in the river channel which change the hydraulic properties such as the channel roughness.
- The proliferation of exotic vegetation growth (e.g. Prosopis trees) and indigenous, but invasive vegetation (e.g. Tamarisk) in the river beds will impact on evapotranspiration losses and hence the TDS of the groundwater.
- Climatic change and long term climatic trends are evident from both flood records, regional groundwater levels in various parts of the country and changes in vegetation cover. The impact of climatic changes over the past few decades must be distinguished from the other impacts, such as the construction of dams on the Swakop River.

The method used to predict the potential impact of KARS, should be capable of distinguishing the magnitude of the effects caused by other developments, from the magnitude of the effects caused by KARS. Furthermore, since the impact of a particular development may only be felt at a point downstream, several years or even decades after the development, the timing of the impact should also be assessed.

3. METHOD OF APPROACH

The approach used to predict the incremental impact of KARS on each of the issues of concern was to develop a probabilistic mathematical model which describes in mathematical terms, the behaviour of each of the following physical systems :

- The hydrological system which describes the runoff and flood volumes in the rivers.
- The hydrogeological system which describes the inflows and outflows to the alluvial aquifers and the depth to the water table.
- The sediment transport system which describes the sediment load brought down on an annual basis.
- The water quality system which describes the salt balance within each river reach.

Each of the above physical systems are inter-dependent and must therefore be solved simultaneously for each time step. For example, the flood volume at a particular point along the river, is dependent not only on the flood volume upstream of that point, but also on the hydrogeological conditions within the alluvial sediments. If the alluvial aquifer is not completely full (or recharged), a portion of the flood volume will be lost to the aquifer through infiltration.

To assess and quantify each of the specific concerns, it is necessary to understand the physical systems and inter-dependency of each system. Mathematical relationships can then be developed and programmed to construct a computer model, to simulate the behaviour of the entire system.

The mathematical model can at best be as good as our understanding of the physical systems, and their relationships to one another, and as accurate as the accuracy and resolution of the input parameters. Input parameters contain to a greater or lesser extent, an element of uncertainty and variability, variables have therefore been expressed as random variables and the simulation conducted using a Monte Carlo type approach in which the calculations are repeated many times by randomly selecting a value for each input parameter from a probability distribution. Probability distributions are assigned to each variable on the basis of the principle of entropy to ensure that the least biased distributions are applied to each input parameter . On this basis, probability distributions would be assigned as follows :

If only the possible range of values is know (minimum and maximum), a uniform distribution is assigned.

If only the expected value is known, an exponential distribution is assigned

If the expected value, mean, maximum, minimum and coefficient of variation are known, a beta distribution is assigned.

In the case of many of the parameters used in this model, there is insufficient data to determine the expected value or coefficient of variation. Estimates of the maximum and minimum likely values have therefore been made based on expert opinion and available data, and a uniform probability distribution applied. The probability distribution assigned to each parameter takes cognisance of the following factors :

- The uncertainty associated with each parameter as a result of the lack of data concerning the parameter, for example, due to lack of data, the estimate of the annual evapotranspiration loss rate is relatively unknown and uncertain.
- The degree of natural variability associated with the parameter. For example, trees are likely to reduce there water consumption during drought periods.

4. PARAMETERS TO DESCRIBE THE MAGNITUDE OF IMPACTS

For each of the issues of concern, specific parameters can be identified which if quantified, can be used to describe the magnitude of the impact of existing and proposed developments on each of the issues of concern. Assessment of the *significance* of the impact is not dealt with in this study, but is considered in the CSIR's EIA report.

4.1 Sediment Loads

A change in the annual sediment load brought down during flood events will be brought about by a change in the:

- magnitude of *annual flood volumes*,
- *frequency* of flood events,
- distribution of the *peak discharge rate,* and
- *particle size distribution* of sediment which is available for transport upstream of the point of concern.

The sediment volume passing a point in a river is dependent on a number of factors including :

- The availability of sediment and the particle size distribution of the sediment.
- The stream power.

4.2 Sand Dunes

Dune or sand migration is affected by the following factors :

- The source of sand. Distinction should be made between :
  - ◊ loose sand such as that typically blown into Swakopmund during periods of strong west winds;
  - ◊ longitudinal sand dunes which historically have tended to have a stationary footprint, but shifting crest; and
  - ◊ barchan type dunes which tend to migrate in the direction of the predominant wind direction and have a moving footprint.

Since the Swakop River is ephemeral by nature, neither KARS or any of the other existing historical impacts could have any effect on the volume of loose sand blown across the Swakop River. A reduction in the flood peak or frequency of major floods (floods of sufficient size to wash away dune material deposited in the river bed), could affect the tendency for barchan dunes and possibly the longitudinal dunes to cross the Swakop River in a north easterly direction.

- Meteorological conditions, in particular the dominant wind direction and intensity.
- The particle size distribution, specific gravity and effect of cementing of the sand particles.
- The topography and in particular factors such as the width of the river valley and the presence of terraces which might prevent the migration of sand up the north bank on the Swakopmund side of the river.
- The flood characteristics of the Swakop river which serve to occasionally clear any dune sand which might have accumulated in the river bed.

Of the above factors, developments on the Khan and Swakop Rivers, can only change the flood characteristics which may be described by the following parameters :

- the frequency of flood events,
- the annual flood volume, and
- the peak discharge rate.

Quantification of the incremental effect of KARS on the magnitude of the above parameters provides an indication of the extent to which KARS might change what ever existing tendency there may be for the dunes to cross the river.

4.3 The Alluvial Aquifer Characteristics

In order to describe the incremental impact of KARS on the alluvial aquifer, the following parameters can be used to quantify the impact on a defined reach of the aquifer :

- The percentage fullness of the aquifer.
- The general depth to the water table.
- The flux across the downstream or upstream section of the aquifer.
- The annual recharge volume from floods over a defined section of the aquifer.

4.4 Salinity of the Alluvial Aquifer

Total dissolved solids (TDS) was considered to be the most appropriate indicator of the change in groundwater quality.

5. LITERATURE REVIEW

A list of documents made available to Metago Environmental Engineers for the purpose of this study is given in Appendix A. This section of the report presents pertinent information which has been used to derive an appropriate model to simulate the behaviour of the river systems.

The literature review presents background information for each of the aspects previously identified and describes the nature of data available.

5.1 Rainfall Records

Daily and monthly rainfall records were made available by the Department of Water Affairs for gauging stations in the Swakop and Khan catchments. The prediction of flood volumes from rainfall records was considered not warranted as these records have already been used by the Department of Water Affairs to construct synthetic flood records using rainfall-runoff models. These models have been calibrated to the extent that is reasonably possible, using and flood records. The synthetic flood records and actual flood records are discussed in further detail in the next section.

5.2 Flood Characteristics of the Khan and Swakop Rivers

5.2.1 Available Flood Records

The following Khan River flood records were made available :

- Flood records measured at Ameib (station No. 2986MO1A) over the period 1967 to 1994[1]. Ameib is located some 185 km from Swakopmund (measured along the river). This record represents the most reliable flood record for the Khan River and indicates the following information :
  - ◊ the date of the flood
  - ◊ the runoff volume

[1] *Ministry of Agriculture, Water and Rural Development, letter of 10 March 1997.*

- ◊ the estimated peak flow rate
- ◊ the peak depth of flow
- ◊ the duration of flow.

The record is however limited to a relatively short period. In order to model the influence of KARS a longer record is required.

- A flood record for the Khan River measured at Usakos (station No. 2987MO1) measured over the period 1951 to 1994. This record is not considered as reliable as the Ameib record but is approximately 25 km's closer to Swakopmund and the Mine. The proposed dam site is some 100 km downstream of Ameib and 75 km's from Usakos.
- A monthly synthetic flood record prepared in 1988 for The Department of Water Affairs[2] to predict the flood volumes at Rössing Mine based on a rainfall-runoff model. The synthetic flood record was prepared for the period 1925 to 1987. Predicted flood volumes at Ameib compared favourably with the actual record. The synthetic flood record is considered to be the best long term prediction of the flood volumes at Ameib. However, in order to predict the flood volumes at Rössing, 1% of the flood volume was assumed to be lost per kilometre, between Ameib and Rössing. This is considered unreliable as the percentage of the flood volume lost to recharge is dependent on the fullness of the aquifer immediately prior to the flood, the size of the flood and the duration of the flood event. For example, had the aquifer been fully recharged due to a relatively large flood the preceding year, the percentage of the flood volume lost to recharge during the following year will be small since the aquifer would still be relatively well recharged. The transmission losses are thus dependent on the status of the alluvial aquifer at the time of the flood and a loss rate based on a fixed proportion of the flood volume is considered inappropriate. The approach used by Metago Environmental Engineers to model the flood volume losses attributable to recharge of the alluvial aquifer was considered appropriate to this study. In this approach, the status of the alluvial aquifer is represented by a

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[2] *Department of Water Affairs, 1988. The Potential yield of a Proposed Dam on the Lower Khan River.*

hydrogeological model which models the behaviour and condition of the alluvial aquifer at the start and end of each flood season throughout the simulation.

The following flood data was made available for the Swakop River :

- A record of floods for the period 1970/1 to 1978/9 at Salt Rock (Station No. 285 MO1). The station comprising a tower, was washed away in February/ March of 1975 and a new station built in December 1975. Salt rock is located some 10 km's upstream of the confluence of the Swakop and Khan Rivers on the Swakop River. This record is of very short duration and unreliable.
- A summary of flood volumes at Swakopmund for a range of periods which allow comparison of predicted flood volumes with estimated flood volumes in the vicinity of Swakopmund. These records are as follows :
  - ◊ 1892/3 to 1977/8 - a subjective record prepared by Stengel [3] of the flow rate recorded as weak, moderate, strong or very strong and a record of how close the flood came to the mouth of the Swakop River.
  - ◊ 1970/1 to 1983/4 - A record of flood volumes and peak flow rates measured at the railway Bridge near Swakopmund or at Palminhorst, located just downstream of the confluence of the Khan River.
- A generated historic inflow record for Von Bach dam from 1923/4 to 1993/4[14].
- A generated historic inflow record for Swakoppoort dam from 1923/4 to 1993/4.[1]
- Actual monthly inflows and spills for the Von Bach and Swakoppoort dams from 1977/8 to 1995/6 and from 1970/1 to 1995/6 for Swakoppoort and Von Bach dam's respectively[5].
- Flow records at Dorstrivier (station 2985MO2) for the period 1977/8 to 1993/4. The records are considered to be questionable since the station comprises an open section. The station was shifted in 1988. This station should be used as an indicator station only. Dorstrivier , located some 160 km along the river from Swakopmund represents approximately the start of the zone of depletion of flood volumes.

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[3] *Stengel : Supplied by DWA*

[4] *Central Area Water Master Plan Interim Phase.*

[5] *DWA records supplied by Mr G Van Langenhove*

- Flow records for Westfalenhof (station No. 2984M01) for the period 1961/2 to 1994/5.

The following documentation is available which sheds further light on specific flood events in the Khan and Swakop Rivers :

- Flood information notes recorded by the Department of Water Affairs over the period 1989 to 1997. The record has been compiled based primarily on information submitted to the DWA by people along the Swakop and Khan Rivers.
- 1985 flood - A daily record of the peak flow rate and flood volume in the Swakop area.
- A synthetic seasonal runoff record for the Swakop River at various sites from 1925/6 to 1984/5 prepared by Mr B A Mian of the Department of Water Affairs which include seasonal flood records at :
  - ◊ Von Bach Dam
  - ◊ Swakoppoort Dam
  - ◊ Dorstrivier
  - ◊ Riet
  - ◊ The confluence of the Swakop and Khan Rivers, and
  - ◊ Swakopmund

This record comprises a combination of synthesised runoff and actual data. It is assumed that from Dorstrivier downstream to Swakopmund only losses occur. A loss factor of 0,1 Mm^3/km was assumed from Dorstrivier to Swakopmund. This record was considered the most appropriate for flows up to Dorstrivier, since it documents not only the inflows to Swakoppoort and Von Bach Dams but also the synthetic spills from the dams. It is thus possible to use this record, to construct a synthetic record for the situation with and without Swakoppoort and Von Bach Dams, over the entire period of historical records.

The hydrological data is summarised in Appendix B for the following locations :

- Von Bach inflow and spill record (Central Area Water Master Plan (CAWMP) and DWA (Mian) record.

- Swakoppoort Dam inflow and spill record. (Central Area Water Master Plan (CAWMP) and DWA (Mian) record.
- Dorstrivier synthetic record (DWA) and Dorstrivier gauging station record.
- Westfalenhof gauging station record
- Ameib gauging station synthetic record
- Khan River at the confluence (DWA)

5.2.2 Synthetic Flood Records to Evaluate the Effect of Existing Dams on the Swakop River

For purpose of evaluating the magnitude and timing of the impact of the existing dams on the lower Swakop River, a synthetic record has been compiled from the DWA record prepared by Mian, the actual spill records for Von Bach and Swakoppoort Dams, and the Central Area Water Master Plan synthetic records(CAWMP).

The synthetic annual flood volume records for the Swakop River have been prepared for two locations, namely immediately downstream of Swakoppoort Dam and at Dorstrivier, each for no dams on the Swakop River and for the Swakoppoort and Von Bach dams existing since the start of the synthetic record.

The synthetic records for each of the above scenarios are documented in Appendix C and have been used as a long term sequential flood volume record in the hydrological modelling to evaluate the incremental impacts of the dams. The synthetic records were derived by assuming that the annual flood volume at the location of the dam wall would have been equal to the annual inflow volume to the dam had the dam not been constructed. The record extends from 1925 to 1993. The period from 1925 to 1984 uses the DWA (Mian) synthetic record, except where actual spill volumes are known, namely 1970 to 1984 in the case of Von Bach dam and 1977 to 1984 in the case of Swakoppoort Dam. The period from 1985 to 1993 was compiled using the CAWMP synthetic record and actual records of spill volumes for each of the dams.

The effect of Swakoppoort and Von Bach dams on the seasonal flood volumes immediately downstream of Swakoppoort dam and at Dorstrivier is illustrated in Figure's 1 and 2 which plot the seasonal flood volumes with and without the dams based on the resulting synthetic records.

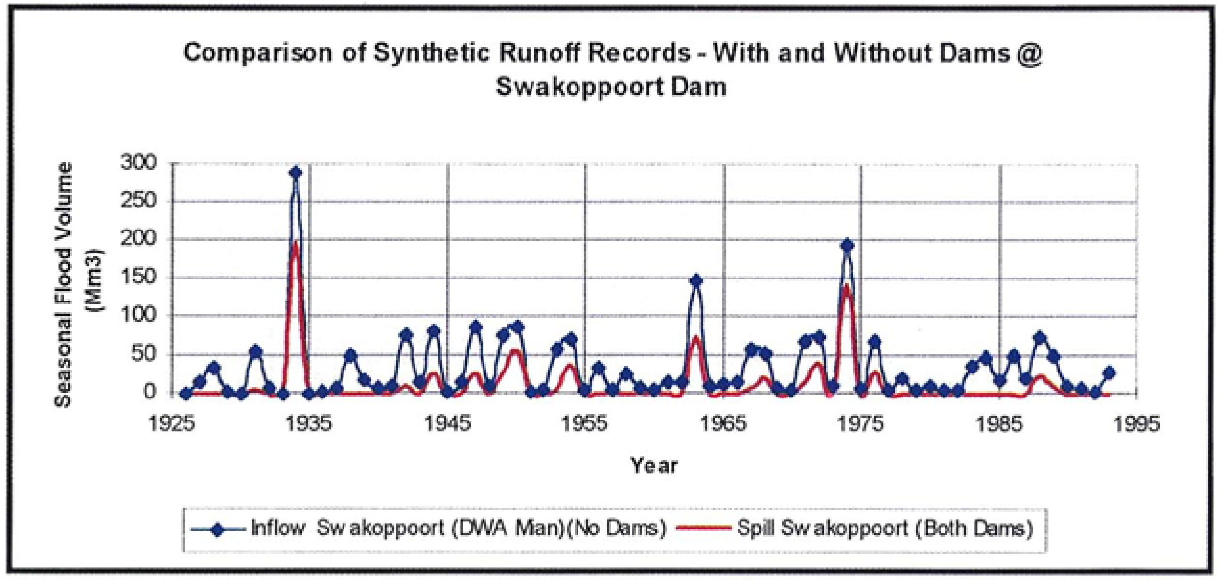

Figure 1: Synthetic Flood Records - Swakoppoort Dam

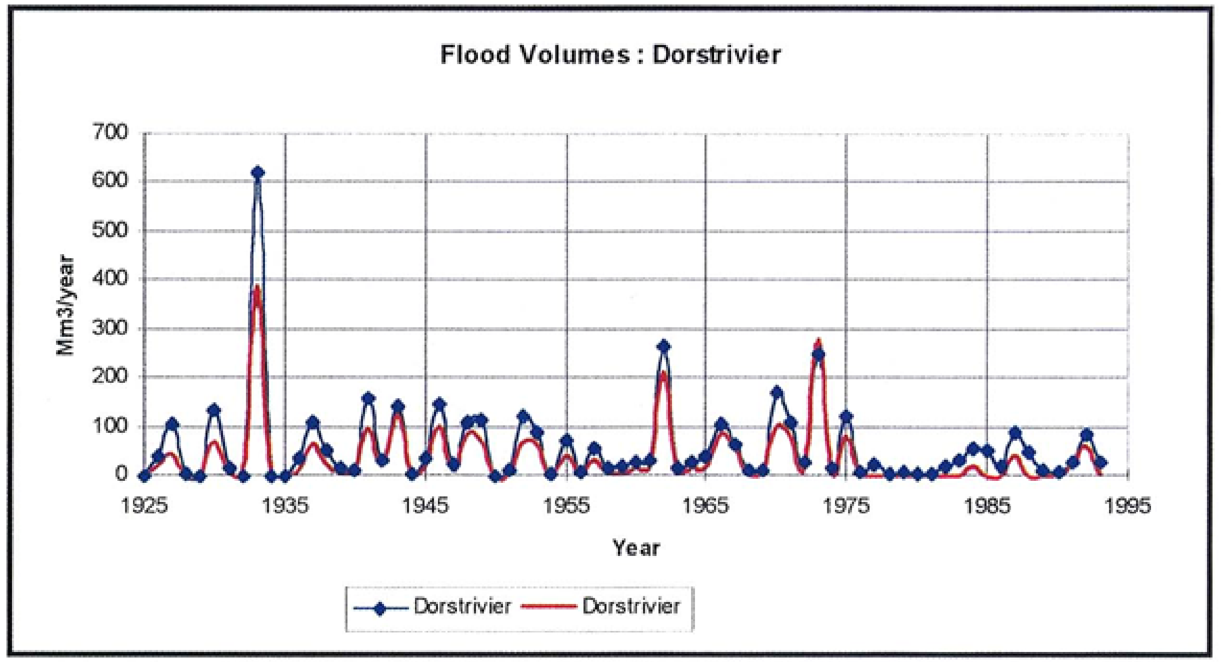

Figure 2 : Synthetic Flood Records - Dorstrivier

5.2.3 The Effect of the Existing Dams on the Flood Frequencies and Flood Volumes in the Swakop River

A comparison of the generated historic inflow and outflow record (Mm^3) for Swakoppoort Dam reveals that the dam has spilled twice from 1977 to 1995, namely in 1987/8 and 1988/9. The average inflow to Swakoppoort Dam was 13.09 Mm^3 /year between 1977 and 1993 and the average spill over the same period was 2.07 Mm^3/ year.

The synthetic runoff record makes it possible to assess the effect of the dams of parameters of interest. By changing from one synthetic record to the other during a simulation at a particular date, it is possible to assess the time it takes for the impacts of the dams to be felt downstream. The effect of the dams on flood volumes and flood frequencies are shown at two locations, namely :

- Immediately downstream of Swakoppoort Dam, and
- at Dorstrivier, which is considered to be the downstream limit of effect additions to flow in the Swakop River.

Table 1 illustrates the long term effect of Von Bach and Swakoppoort Dams on the flood volumes at each location.

Table 1 : Comparison of Synthetic Annual Flows with and Without the Swakop River Dams

	With the Dams	*Without the Dams*	*% Reduction*
	Immediately downstream of Swakoppoort Dam Site		
Mean	10,7	33,3	67,9 %
Median	0,0	15,2	100 %
COV	31,0	56,1	44,7 %
Minimum	0	0	0 %
Maximum	198,2	431,4	54,1 %
	Dorstrivier		
Mean	37,0	60,8	39,1 %
Median	11,1	30,1	63,1 %
COV	65,0	89,7	27,5 %
Minimum	0	0	0 %
Maximum	387	620,8	37,7 %

The effect of the dams on the frequency of flood events in the Swakop River can be observed by compiling histograms for the frequency of flood events within particular flood size ranges at the two locations of concern, using both the synthetic flood record for the case without the dams and the record for the case with the dams. The flood size ranges shown in the histogram were chosen arbitrarily to cover the entire range of flood events. The histograms for the flood frequencies with and without the dams are shown in Figures 3 and 4 for Swakoppoort and Dorstrivier respectively.