REPORT TO THE WATER RESEARCH COMMISSION

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of the P K le Roux dam

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WRC Report No 510/1/94 PRETORIA

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Members of the Steering Committee are acknowledged for their assistance and advice which has been instrumental in directing the study towards a meaningful goal.

Orange River Losses Study - Summary of Phase 1

EXECUTIVE SUMMARY

The Orange River Losses Project was commissioned as a result of recent studies which indicated that the river losses occurring from the Orange River downstream of P K Le Roux Dam are relatively large and that they must therefore be included in any water resources assessment of the Orange River. It was concluded that the losses must be quantified accurately in order to operate the Orange River system in such a manner as to avoid wastage or shortfalls at the river mouth.

The Orange River is the largest river in Africa south of the Zambezi, with a total catchment area in excess of 1 million km^2. More than half of the catchment is inside South Africa, with the remainder in Lesotho, Botswana and Namibia.

By Southern African standards the natural water resources (i.e. water available before any developments took place) of the Orange River are large at approximately 11 500 million m^3/a. This figure is of purely academic interest, however, since due to the major developments that have already taken place in the basin, the remaining available resources of the Orange River are now estimated to be in the order of 6 500 million m^3/a.

Most of the development in the Orange River Basin has taken place in the Pretoria/Witwatersrand/Vereeniging (PWV) area which forms the industrial heartland of South Africa, producing over 50 % of South Africa's Gross National Product (GNP). The water demand in this area is increasing rapidly, not only because of the growing industrial demands, but mainly to the rapidly rising urban population and associated improvement in the living standards.

Several major interbasin transfers already exist to supplement the limited water resources available to the PWV area. As the demands continue to increase, however, the need for additional resources grows. The Lesotho Highland Water Project (LHWP) is the latest, largest and most ambitious water transfer project to be undertaken in Africa and is currently one of the largest water projects being undertaken in the world. When *completed it will enable in excess of 2 210 million m^3/a of water to be transferred from the upper reaches of the Lesotho Highlands to the PWV area in the Vaal River Basin.*

In view of the limited water resources of the Orange River and the imminent implementation of Phase 1 of the LHWP, the South African Department of Water Affairs and Forestry (DWA&F) recently (1993) commissioned a study to assess the water resources of the Orange River and to evaluate the likely impacts of the LHWP on these resources.

The study was initiated in 1988 by BKS Inc. using state of the art analysis techniques developed during the Vaal River System Analysis (a joint venture with BKS, ACRES, SSO and DWA&F). The major system analysis results for the Orange River were first presented in 1992 and finalised in 1993 (McKenzie, 1993).

The results from the study indicated that the water resources of the Orange River are significantly less than originally estimated.

In the original water balance estimate there was a surplus of 1 078 million m^3/a even after full implementation of the LHWP. This can be compared to the updated estimate showing a 842 million m^3/a deficit. The difference of 1 920 million m^3/a (i.e. 1 078 + 842) is due to several factors including more reliable streamflow data over the last 20 years from the two major dams as well as a revision of the net river losses.

Obviously these figures are of major concern to the DWA&F and also to the governments of Namibia and Lesotho who both have considerable involvement in the water resources of the Orange River. As a result, it was decided to look at certain key elements considered in the water resource assessment where doubts were expressed regarding the reliability of the initial estimates made during the study. The river loss downstream of P K le Roux Dam was identified as a key component requiring detailed analysis and this led to the current study of the Orange River losses, the first phase of which is presented in this report.

From the results obtained during the course of the Orange River Losses Study it was concluded that:

- *The evaporation losses occurring from the Orange River are likely to be higher than the 800 million m^3/a initially estimated using the Symons Pan evaporation values. The evaporation calculated using the Bowen Ratio technique suggests that the evaporation from the river is in fact higher than pan evaporation. Unfortunately this conclusion is based on a very short period during which the pan evaporation measured at four different pans showed considerable scatter. It is not yet possible to confirm that the river evaporation is higher than pan evaporation throughout the year although the initial indications suggest that this is the case.*

  Using the Symons Pan evaporation figures available along the Orange River it is estimated that the total net evaporation losses occurring along the full length of the river are in the order of 960 million m^3/a. The basis for this estimate is given in ***Table 1.***

Table 1: Summary of net evaporation losses from the Orange River.

Reach	From	To	Length (km)	Areas for evaporation (km^2)			Precipitation (mm/a)	Gross Evaporation (mm/a)	Net Evaporation (mm/a)	River Losses	
				Water surface	Vegetation	Total				10^6 m^3/a	m^3/s
1	PK le Roux	Orange/Vaal	186	24,9	8,7	33,6	300	2 200	1 900	63,8	2,02
2	Orange/Vaal	Boegoeberg	283	59,9	19,4	79,3	230	2 340	2 110	167,3	5,30
3	Boegoeberg	Kakamas	236	74,3	24,4	98,7	150	2 590	2 440	240,8	7,63
4	Kakamas	20°E Meridian	77	12,6	5,4	18,0	100	2 700	2 600	46,8	1,48
5	20°E Meridian	Vioolsdrif	315	78,9	13,6	92,5	100	2 600	2 500	231,2	7,33
6	Vioolsdrif	Orange/Fish	135	32,9	3,8	36,7	50	2 400	2 350	86,2	2,73
7	Orange/Fish	Orange Mouth	145	52,8	7,7	60,5	50	2 100	2 050	124,0	3,93
Total			1377	336,3	83,0	419,3	-	-	-	960,1	30,4

It should be noted that the values given in ***Table 1*** *are based on the available Symons Pan evaporation values estimated from various gauges in the vicinity of the Orange River. Unfortunately the gauges are not situated directly adjacent to the river and are usually several kilometres from the water surface. The recent work carried* *out by Forestek indicates that there can be a significant difference between the tank evaporation at the waters edge and that only a few kilometres away. This aspect will have to be considered in the subsequent phases of the study.*

- *From the water balance analysis carried out using the gauged flows it is clear that the irrigation return flows are significant and must be included in any river loss evaluation. These return flows were disregarded in the original loss estimate and will more than compensate for the higher evaporation. The return flows will depend to a large degree on the application method and scale of irrigation. It is thought that the return flows are in the order of 10 % to 40 % of the water applied. With the available information it is not possible to quantify the return flows with more accuracy since the abstractions are not known accurately and the lag time associated with the return flows is also an unknown factor at this stage. In the event that the return flows are found to be in the order of 30 % for example, this will result in the net river losses decreasing from the 960 million m^3/a mentioned in **Table 1** to 720 million m^3/a.*

- *The analyses indicate that aerial photographs can be used to provide realistic estimates of both the water surface areas as well as the areas of sand banks and riparian vegetation. By analysing photographs of the same river reach at different flow rates it is also possible to evaluate the influence of flow rate on surface area. In the case of the Orange River the surface areas vary little as long as the flow rate remains within the normal release limits.*

  Satellite images can also be used to estimate the various areas and once processed, the images can be incorporated into a GIS which allows considerable information to be obtained very quickly. The satellite images also have the advantage that they can be obtained at short notice without the expense of flying along the river to take aerial photographs and the subsequent processing of more than 100 photographs.

  Unfortunately problems often occur when processing the satellite images resulting in areas which may be unrealistic due to misinterpretation of certain types of vegetation. For example, it is often difficult to distinguish between riparian vegetation and nearby irrigation. In such cases it is essential to verify the results *which usually involves making use of the aerial photographs and undertaking site visits to selected areas. It is therefore often more economical to base the areas on the aerial photographs and only use the satellite images in cases where the additional information from the images is required. Unfortunately the final processed areas from the satellite images were not available for inclusion in the first phase of the study but should be available for subsequent phases.*

- *Losses as a result of transpiration from riparian vegetation are significant and the total area of such vegetation is estimated to be more than 80 km^2 (i.e. 25 % of water surface). It is estimated that the water lost via the riparian vegetation is similar in magnitude to that lost directly from a free water surface. Such losses will naturally depend upon the type of vegetation (i.e. reeds or trees) and availability of water. For the purpose of the first phase of the study, however, this assumption was accepted.*

Until more detailed and reliable information becomes available, it is recommended that the losses from the Orange River be based on Symons Pan evaporation values with no pan to lake corrections. It is further recommended that return flows of 30 % be used in the calculation until more reliable information on the return flows is obtained during subsequent phases of the study. This assumption leads to a net river loss in the order of 720 million m^3/a which is very similar to previous estimates in which the return flows were neglected. It should be noted that the return flows depend on the irrigation efficiency and method of application. If irrigation efficiency is improved the return flows will decrease while the losses will remain unchanged. For this reason, the two components should be considered separately.

Due to the importance of the irrigation return flows it is recommended that this issue be addressed during the subsequent phases of the project. The lag of the return flows is also of great interest since this can influence the magnitude of the releases required to support the various water users along the Orange River. It is possible that the use of tracers can help to quantify the volume and timing of irrigation return flows and this will be investigated during the next phase of the study.

Ideally the Bowen Ratio technique should be used continuously for a period of at least a year in order to evaluate the reliability of the pan evaporation values. Unfortunately the expense of such an exercise is outside the budget of the Losses Study and it cannot be included as part of the subsequent work. It may be beneficial to the WRC or DWA&F, however, to pursue this line of study in view of the importance of reliable evaporation data in the South African context.

The single set of manual flow gaugings undertaken by DWA&F has proven to be extremely valuable and it is recommended that further gaugings be undertaken to provide additional base information both on the Orange River and other suitable rivers where losses are known to be a problem. A regular exercise similar to that carried out in the first phase of the study should be carried out until such time that the losses have been quantified with the desired accuracy. It is only with such information that the study can successfully quantify river losses with any degree of reliability. Additional gaugings are already being planned for 1994 and beyond.

The possibility of dilution gauging or using tracers will also be investigated to determine if such techniques can be applied successfully in the Orange River and other rivers where losses must be evaluated.

GLOSSARY OF TERMS

Bowen Ratio

A relationship derived by Bowen (1926), one form of which can be expressed in terms of the temperature and vapour pressure. It can be used to estimate evaporation from a surface based on an energy balance approach.

$$\beta = 6 \,.\, 10^{-4} \,.\, p \,.\, \frac{T_s - T_a}{e_s - e_a} \qquad \textit{where}$$

ß = Bowen ratio
P = atmospheric pressure (kPa)
T_s = water surface temperature (°C)
T_a = air temperature (°C)
e_s = Saturated vapour pressure at water surface temperature (kPa)
e_a = Vapour pressure of the air (kPa)

Dilution Gauging

A streamflow gauging technique using radioactive or chemical tracers, deposited upstream at a constant rate and monitored some distance downstream in order to determine the flow of water in the river.

Evaporation losses

Water lost from the river system to the atmosphere by evaporation and evapo-transpiration from the water surface and the vegetation directly adjacent to the river.

Evapo-transpiration

A collective term covering the evaporation from the water or soil surfaces together with the transpiration from vegetation.

Historic (firm) yield — The maximum constant rate of flow that could be drawn from a system/reservoir over a specified historic period (actual recorded rainfall and streamflow data) without experiencing failure.

Irrigation return flows — A proportion of the water applied to cultivated fields as irrigation which returns to the river by means of overland flow or sub surface seepage. The term also includes canal tailwater flow in some cases.

Pan evaporation — Evaporation measured from a standard evaporation pan, adjusted to take any rainfall into account. A-pan values refer to measurements from small circular class A-pans, while Symons-pan values are measured from the larger rectangular Symons pans which are used in many parts of South Africa.

Pan co-efficient — Adjustment factors applied to measured pan evaporation values to obtain estimated evaporation applicable to a reservoir. Differences in evaporation between pan and lake (or river) arise because of local effects such as site differences, edge effects and the different heat transfer mechanisms.

Riparian vegetation — Vegetation (natural or artificially seeded) unsupported by irrigation occurring on the banks of a river which is dependant upon the water in the river for survival.

System analysis — A method used to analyse often complex water resource systems using a combination of simulation, linear programming, dynamic programming and network modelling techniques.

Tailwater — Surplus (i.e. unused) water returning to the river channel at the downstream end of an irrigation diversion canal.

Tracers	Radioactive or other types of chemical which are not found naturally in water and are used in various studies to monitor or measure the flow of water in a system.
Transmission time	The time taken for water to travel between two specified points, either in a river channel or as subsurface seepage.
Transpiration	Water transmitted to the atmosphere by plants.
Water Balance	A mass balance at a selected point in the system where the various inflows and outflows are evaluated and compared to ensure continuity.
Water Resources: Current	The water resources of a river system, at current development levels. The current water resources are normally lower than the natural water resources due to man made influences such as irrigation, afforestation, domestic/industrial demands and interbasin transfers occurring within the catchment.
Water Resources: Natural	The resources of a river system as they would have been before any human development took place within the catchment.

Orange River Losses Study - Summary of Phase 1

TABLE OF CONTENTS

1. INTRODUCTION

1.1. GENERAL

The Orange River Losses Project was commissioned as a result of recent studies which indicated that the River Losses occurring from the Orange River downstream of P K Le Roux Dam are relatively large and that they must therefore be included in any water resources assessment of the Orange River. Recent studies have indicated that the available water resources in the Orange River may soon be insufficient to meet the projected demands. It was therefore concluded that the losses must be quantified accurately in order to operate the system in such a manner as to minimize wastage or shortfalls at the river mouth.

The Orange River is the largest river in Africa south of the Zambezi, with a total catchment area in excess of 1 million km^2. More than half of the catchment is inside South Africa, with the remainder in Lesotho, Botswana and Namibia.

By Southern African standards the natural water resources (i.e. the water resources of the river before any development took place within the catchment) of the Orange River are large at approximately 11 500 million m^3/a. This figure is of purely academic interest, however, since due to the major developments that have already taken place in the basin, the current water resources (at present development conditions) of the Orange River are now estimated to be in the order of 6 500 million m^3/a. In other words the remaining water available for use after the current demands have been satisfied is now only 6 500 million m^3/a.

Most of the development in the Orange River Basin has taken place in the Pretoria/Witwatersrand/Vereeniging (PWV) area which forms the industrial heartland of South Africa, producing over 50 % of South Africa's Gross National Product (GNP). The water demand in this area is increasing rapidly, not only because of the growing industrial demands, but also due to the rapidly rising urban population which is caused by the movement of people from the poor rural areas to the major centres in search of employment and higher living standards.

Several major interbasin transfers already exist to supplement the limited water resources available to the PWV area. As the demands continue to increase, however, the need for additional resources grows. The Lesotho Highland Water Project (LHWP) is the latest, largest and most ambitious water transfer project to be undertaken in Africa and is currently one of the largest water projects being undertaken in the world. When completed it will enable in excess of 2210 million m^3/a of water to be transferred from the upper reaches of the Lesotho Highlands to the PWV area in the Vaal River Basin (the major tributary basin of the Orange River - see **Figure 1.1**).

In view of the limited water resources of the Orange River and the imminent implementation of Phase 1 of the LHWP, the South African Department of Water Affairs and Forestry recently commissioned a study to assess the water resources of the Orange River and to evaluate the likely impacts of the LHWP on these resources.

The study was initiated in 1988 by BKS Inc. using state of the art analysis techniques developed during the Vaal River System Analysis (a joint venture with BKS, ACRES, SSO and DWA&F). The major system analysis results for the Orange River were first presented in 1992 and finalised in 1993 (McKenzie, 1993).

The key results from the analyses are given in **Table 1.1** which highlights the influence of the various phases of the proposed LHWP on both the total system yield as well as the available yield from the Orange River Project (ORP) at PK le Roux Dam.

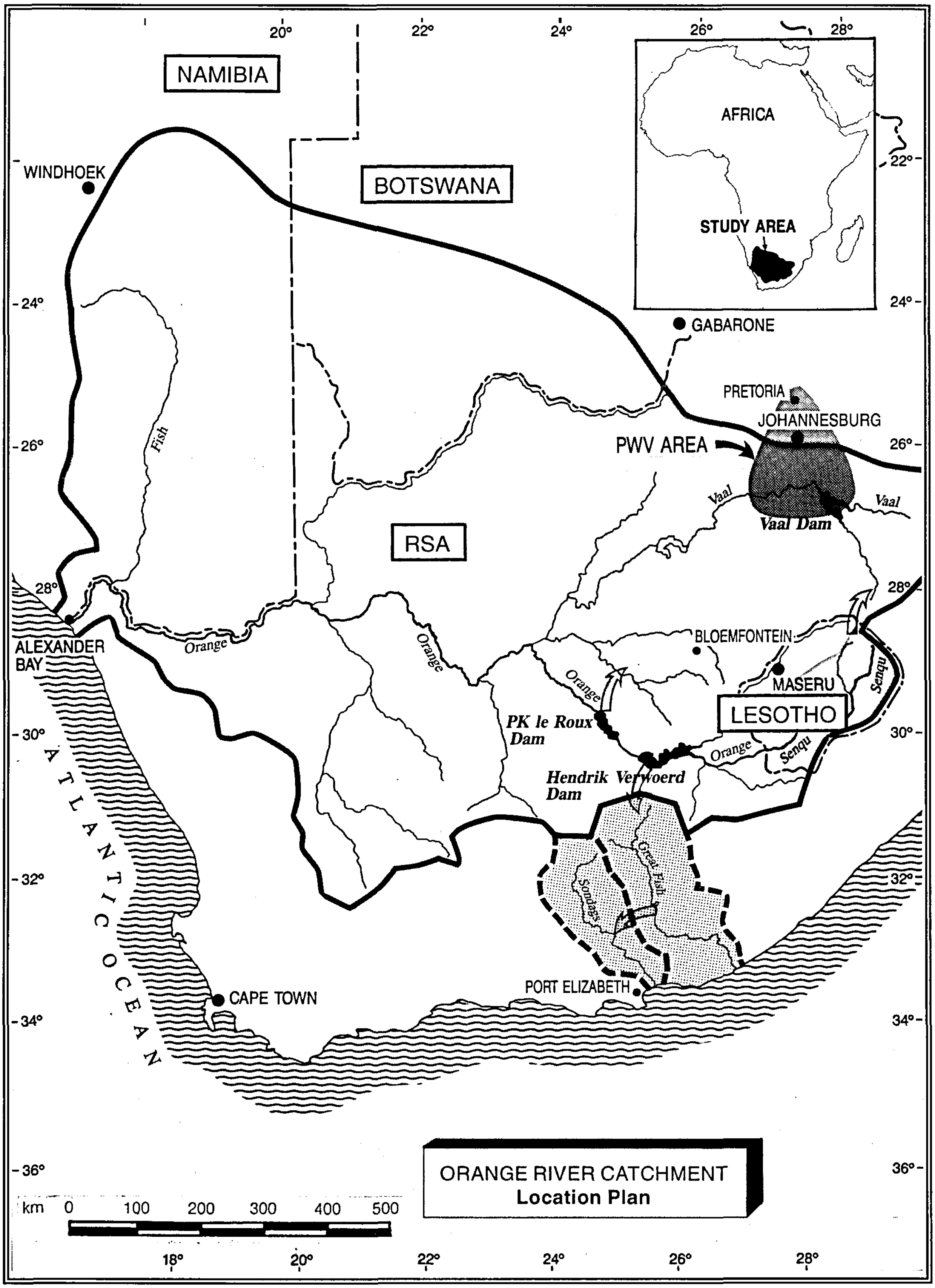


Figure 1.1 General map of the Orange River Basin

2.2 EVAPORATION AND RAINFALL

Evaporation from the Orange River is known to be one of the important components in the Conceptual Model. The Lake evaporation (ie Symons or A Pan with appropriate correction factors) appears to vary from approximately 2300 mm/a at PK le Roux Dam to over 3500 mm/a along the lower reaches of the Orange River in the vicinity of Vioolsdrif. Since the Orange River is now fully regulated from PK le Roux Dam there is flow throughout the year with the result that evaporation will occur during the full year.

The rainfall on the river surface is less important and ranges from an average of approximately 300 mm/a at PK le Roux Dam to below 50 mm/a on the lower reaches. Unlike the evaporation, however, the rainfall is highly variable and may not occur from one year to the next. In view of the sporadic nature of the rainfall, particularly along the lower reaches of the Orange River, it can often be omitted from the analysis. Such an approach will provide realistic results during the dry years and err on the conservative side during the wet years.

2.3 TRANSPIRATION

Transpiration occurs from the vegetation growing in the riparian zone along the banks of the Orange River and also from vegetation growing on the numerous small islands and sand banks. The riparian vegetation can be clearly seen on **Figure 2.2** which shows a typical stretch of the Orange River downstream of PK le Roux Dam.

Figure 2.2 View showing riparian vegetation along the Orange River

In order to determine the river losses along the Orange River it was split into seven reaches as opposed to the eight reaches used in the preliminary study. **Figure 3.3** shows the reaches and also gives the river length for each reach. For the purpose of the flow measurements the last two reaches were considered together as one reach from Vioolsdrif to Brand Karos. Brand Karos was considered as the most suitable location near the river mouth where the flow could be gauged accurately without experiencing problems with abstractions or tidal effects.

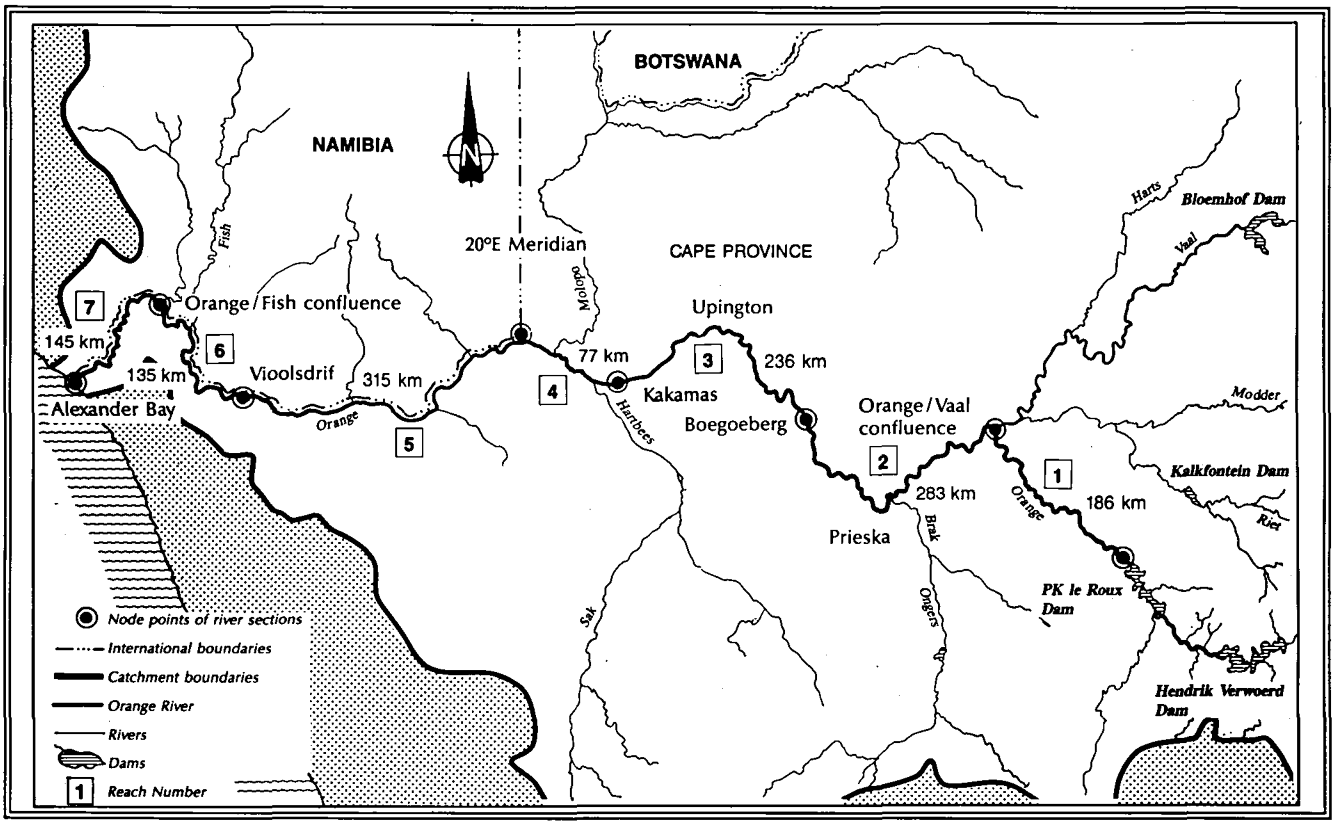


Figure 3.3 River reaches selected for the Losses Study

3.2 WATER SURFACE AREAS

The water surface areas were estimated directly from aerial photographs by manually measuring the width of the water from the photograph at regular intervals. In the initial studies (Mckenzie and Schäfer, 1989) 5 km intervals were selected. In the current study various different approaches were tested to assess the improvement in the estimate compared to the additional effort required to process the photographs.

Three different approaches were used:

- Widths taken at 5 km intervals (total sections = 280)
- Widths taken at 1 km intervals (total sections = 1400)
- River split into rectangles as required

The various methods are shown on **Figure 3.4** and the results for Reach 1 are given in **Table 3.1**.

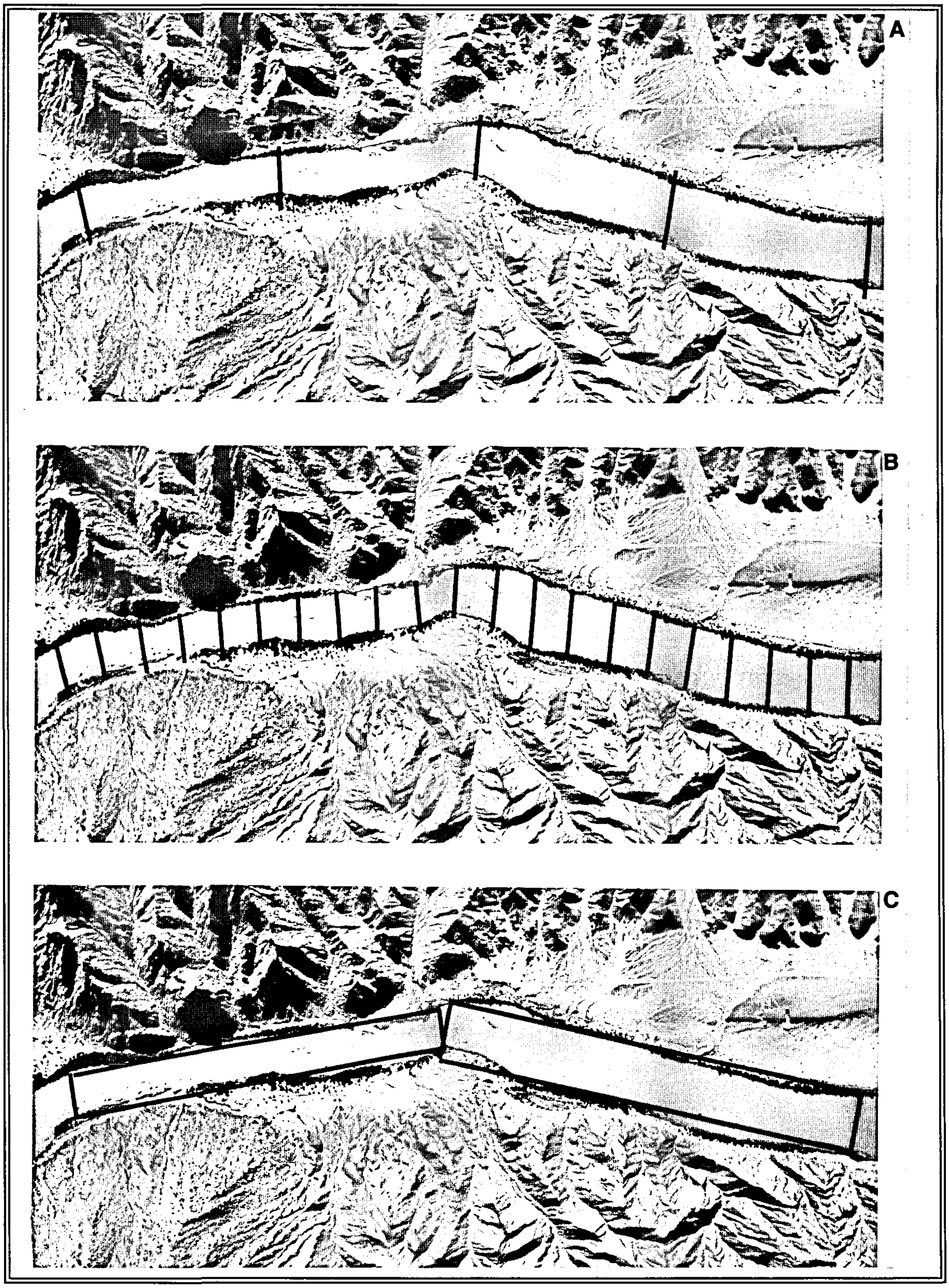


Figure 3.4 Estimation of water surface area using various approaches.

Table 1.1: Results of the historic yield analysis at PK le Roux Dam

Phase of LHWP	Historic firm yield ($10^6 m^3/a$)		
	Total at PK le Roux	From LHWP	Total
Natural	4 806	0	4 806
Current	4 456*	0	4 456*
1a	4 027*	539	4 566*
1m	3 966*	603	4 569*
1b	3 776*	915	4 691*
2	3 323*	1 577	4 900*
3	3 033*	1 955	4 988*
4	2 901*	2 123	5 024*
5	2 755*	2 347	5 102*

* It should be noted that the total yields at the PK le Roux Dam include the yield at Hendrik Verwoerd Dam as well as the 450 million m^3/a Orange-Fish Tunnel transfer and the 250 million m^3/a Sarel Hayward Canal transfer. The current Caledon/Modder transfer of approximately 30 million m^3/a has not been included in the figures.

The results given in **Table 1.1** indicate that the yield from the Orange River is significantly less than originally estimated. When the overall water balance is considered, as given in **Table 1.2**, the significance of the results becomes apparent. It should be noted that many of the figures given in **Table 1.2** are best estimates made at the time of the Orange River System Analysis and should not be taken as the final values. The water balance at current development levels and at Phases 1B and 5 of the LHWP are given to enable the likely surplus or deficit to be quantified. It should also be noted that certain key items have not been reflected in the water balance calculation including the environmental demands and return flows from irrigation.

In the original water balance estimate only items 1 to 6 were considered in the water balance i.e. the environmental demands were not considered as a consumptive demand. Neglecting the environmental demands for comparative purposes, it can be seen in **Table 1.2** that in the original water balance there was a surplus of 1 078 million m^3/a even after full implementation of the LHWP. This can be compared to the updated estimate showing an 842 million m^3/a deficit.

Table 1.2: Estimated water balance for current and future conditions (McKenzie, 1993)

Details	Full LHWP development (Phase 5)				Up to Phase 1b	
	Original ($10^6m^3/a$)		Updated ($10^6m^3/a$)		Updated ($10^6m^3/a$)	
	Demand	Balance	Demand	Balance	Demand	Balance
1. Yield available at 90 % assurance	-	**3 711**	-	**2 530**	-	**3 550**
2. River losses	0	**3 711**	800	**1 730**	800	**2 750**
3. Current irrigation demands	1 271	**2 440**	1 496	**234**	1 496	**1 254**
4. Imminent irrigation development	340	**2 100**	362	**- 128**	362	**892**
5. Schemes under construction: a) Riet River b) Orange/Riet c) Lower Sundays d) Lower Fish d) Orange/Douglas	630	**1 470**	322	**- 450**	322	**570**
6. Some other possible schemes a) Augrabies b) Middle Orange c) Lesotho d) Namibia	392	**1 078**	392	**- 842**	392	**178**
7. Environmental demands at the river mouth	-	-	244	**- 1 086**	244	**- 66**

If the environmental demands at the river mouth are considered as a consumptive demand with a similar priority of the other demands (i.e. the environmental demands will be met by releases from storage if necessary) the estimated deficit will increase to 1 086 million m^3/a.

Obviously the figures given in **Table 1.2** are of major concern to the DWA&F and will also be of interest to the governments of Namibia and Lesotho who both have considerable involvement in the water resources of the Orange River. As a result, it was decided to look at certain key elements considered in the water resource assessment where doubts were expressed regarding the reliability of the initial estimates made during the study. The river loss downstream of P K le Roux Dam was identified as a key component requiring detailed analysis.

The losses occurring from a given river reach can often be estimated by examining the streamflow records at various gauges along the river and taking any abstractions and return flows into account. There are many flow gauges along the Orange River downstream of P K Le Roux Dam and daily flows are available at several of them including Prieska (D7H002), Boegoeberg (D7H008), Upington (D7H005) and Vioolsdrif (D8H003/D8H009). The appropriate data at these gauges were collected and examined by McKenzie (1989) and it was concluded that the errors associated with the flow measurements were too high to enable the losses to be evaluated directly from the data. The problems can clearly be seen by comparing even the annual totals as given in **Table 1.3.** It should be noted that when the analysis was undertaken, only the flow data to the 1987 water year were available. In view of the contradictory flows it was not considered worthwhile to extend the comparison to include more recent data.

Table 1.3: Annual flow data at various locations along the Orange River

Water Year	Annual Streamflow (million m^3)			
	Prieska D7M02	Boegoeberg D7M08	Upington D7M05	Vioolsdrif D8M03/9
1971		8 217		
1972		2 673		
1973		16 713+		
1974		14 535+	11 963	
1975		29 196+	27 100	
1976		11 436	8 307+	
1977		9 919	7 302	
1978		4 974	4 461	
1979		3 241	3 459	2 417+
1980	4 926	4 769	4 297	3 171
1981	3 763+	4 244	3 989	2 987
1982	1 251	1 563	2 387	1 645
1983	1 894	2 237+	2 740	2 076
1984	1 312	1 494	2 276	1 446
1985	2 560+	2 839	3 239	2 160+
1986	4 072+	3 992	3 983	2 590+
1987	26 768	26 933	25 300	24 100

+ = Incomplete record

It should also be noted that the data from the gauges listed in **Table 1.3** were never intended for use in detailed low flow calculations. The quantity of water in the Orange River had never been a problem and for this reason the accuracy of low flow measurement was not considered to be of high priority. The accurate measurement of low flows along the Orange River requires expensive weirs and continual manual gauging due to the problems caused by sediment movement. The gauges along the Orange River were designed primarily for flood peak estimation - a function which they achieve well.

The first estimates of the river losses were made by McKenzie (1989) based on eight river reaches. Two estimates of 1200 million m^3/a and 950 million m^3/a were made based on the A-pan and Symons Pan evaporation rates. In the report the lower value of 950 million m^3/a was recommended as the more realistic value.

In 1992 the estimated losses were revised (McKenzie and Schäfer,1992) to 800 million m^3/a using the same Symons Pan evaporation values but also applying the lake reduction factors in order to arrive at the actual river surface evaporation. The basis for the estimate is summarized in **Table 1.4**.

Unfortunately, reliable information on the key components in the loss calculation were unavailable. The evaporation rate applicable to a free and moving water surface for example was based on available Symons Pan evaporation data together with lake factors. Sensitivity analyses were undertaken to determine the influence of using straight A Pan values as opposed to the adjusted Symons Pan values. The estimated river losses increased to over 1 200 million m^3/a. Other factors such as the variability in surface area with river flow, water lost through riparian vegetation and river bed losses etc., were all identified as factors which could influence the loss calculation and were not clearly defined.

The evaluation of river losses from the Orange River became a priority issue in 1992/93 due to the water shortage experienced in the Orange River System. For the first time since the system had been commissioned there was insufficient water in P K Le Roux and Hendrik Verwoerd Dams to generate power and as a result the system operators were placed in the position of trying to release only sufficient water from P K le Roux Dam to meet the downstream requirements without allowing excess spillage into the Atlantic Ocean. This task was further complicated by the 8 week transmission time as well as the variability of the downstream irrigation demands and river losses.

Table 1.4: Preliminary estimates of river losses between P K le Roux Dam and the Orange River (McKenzie and Schäfer, 1992)

Reach No.	Location	Length (km)	Average width (m)	Surface area (km^2)	Rainfall (mm/a)	Evapo-ration (mm/a)	Net evapor-ation (mm/a)	River loss ($10^6 m^3/a$)
1	P K le Roux Dam to Orange/Vaal confluence	186	137	25,5	300	1 892	1 592	40,6
2	Orange/Vaal confluence to Prieska	168	195	32,8	250	1 978	1 728	56,6
3	Prieska to Boegoeberg Dam	115	203	23,3	200	2 064	1 864	43,5
4	Boegoeberg Dam to Upington	163	266	43,3	150	2 150	2 000	86,7
5	Upington to Augrabies	115	374	43,0	100	2 322	2 222	95,6
6	Augrabies to Vioolsdrif	350	374	130,9	100	2 236	2 136	279,6
7	Vioolsdrif to Orange/Fish confluence	135	374	50,5	50	2 064	2 014	101,7
8	Orange/Fish confluence to Orange River Mouth	145	374	54,2	50	1 806	1 756	95,2
Total	PK Le Roux to Orange River Mouth	1 377	287	403,6	-	-	-	799,5

In order to release the correct volume of water it is essential that the various components significant to the water balance are known with some accuracy. In view of the large uncertainty concerning the river loss estimate, it was identified as an area requiring urgent attention and for this reason the estimation of the Orange River Losses was given a high priority by the DWA&F who agreed to provide logistic and manpower support as well as the Water Research Commission who agreed to provide the necessary funding.

1.2. PURPOSE OF THE STUDY

In 1992 a proposal to evaluate the river losses occurring between PK le Roux Dam and the Orange River Mouth was submitted by BKS Inc to the Water Research Commission (WRC) for consideration. A key facet of the proposal was the close co-operation between BKS Inc and the Department of water Affairs and Forestry (DWA&F), which was considered essential for the success of the project.

In view of the magnitude of the preliminary loss estimates and the development of the LHWP, the study was regarded by DWA&F as a top priority requiring immediate attention. The Water Research Commission also considered the proposal favourably in view of the practicality of the project and absence of any similar work in this field applicable to major rivers. The project was finally accepted and funding for the first year was provided to BKS Inc by the WRC.

The primary objective of the study was to improve the reliability of the loss estimate made in the course of the Orange River System Analysis. This objective can only be achieved by identifying the main processes influencing the losses and incorporating them into a conceptual model. Each process can then be examined individually to assess the sensitivity of the overall loss estimate to the reliability of the specific process. In this manner the most productive use of the available resources can be determined.

The main components in the water losses estimate initially envisaged were:

- Water surface area;
- Area of riparian vegetation;
- Variability of water surface area with flow;
- River bed and bank seepage;
- Evaporation from the water surface;
- Evapotranspiration from the riparian vegetation.

In order to carry out the study it was considered essential to gather some physical data on which the results could be based. Initially it was envisaged that this would include field measurements of surface areas and manual flow gaugings. Such information is required to verify the results obtained from other sources such as flow weirs and aerial photography. It was envisaged that after the completion of the first year of the study, areas requiring further detailed investigation would be identified and documented to form the basis for subsequent research.

The ultimate aim of the study is to provide a reliable methodology for estimating river losses through evaporation which can be used in an operational model of the Lower Orange River. The techniques suggested should also be suitable for application in other rivers in Southern Africa and provide a simple and systematic approach for such work.

1.3. PURPOSE OF THIS REPORT

The purpose of this report is to document the work undertaken and findings of the First Phase of the Orange River Losses Study. This includes details of the field investigations, as well as the documentation of other relevant work undertaken by others which was considered of use in the study.

The report also provides a summary of the key findings and areas requiring additional research. This will be used to assist with the preparation of the work plan for further phases of the project.

The report is set out in the following manner:

- Chapter 1 - Background and general details;
- Chapter 2 - Description of main physical processes;
- Chapter 3 - Basic methodology and procedure;
- Chapter 4 - Field Studies;
- Chapter 5 - Conclusions;
- Chapter 6 - Recommendations;
- Chapter 7 - References.

2. DESCRIPTION OF THE MAIN PHYSICAL PROCESSES

2.1 CONCEPTUAL MODEL

The conceptual model incorporates the important processes that influence the water losses occurring from the Orange River. The proposed conceptual model for the Orange River Losses Study is shown in **Figure 2.1** which incorporates the following processes:

- Rainfall on the water surface
- Evaporation from the water surface
- Evapotranspiration from the riparian vegetation and sand banks
- Losses from the river bed
- Seepage into and out of the river banks
- Municipal and industrial abstractions from the river
- Irrigation abstractions from the river
- Irrigation return flows to the river
- Natural river inflows

Some of these factors are more important than others and in many cases it is difficult or even impossible to distinguish between the different components. It is therefore necessary to consider the various processes either individually or in groups and to assess which are the dominant and therefore the most important factors to consider. In this manner, the resources available for research and detailed investigation can be utilized in the most effective manner.

The remainder of **Section 2** will provide brief descriptions of the following individual processes considered in the Conceptual Model.

- Evaporation and rainfall;
- Transpiration;
- Bed and bank flow
- Demands and return flows

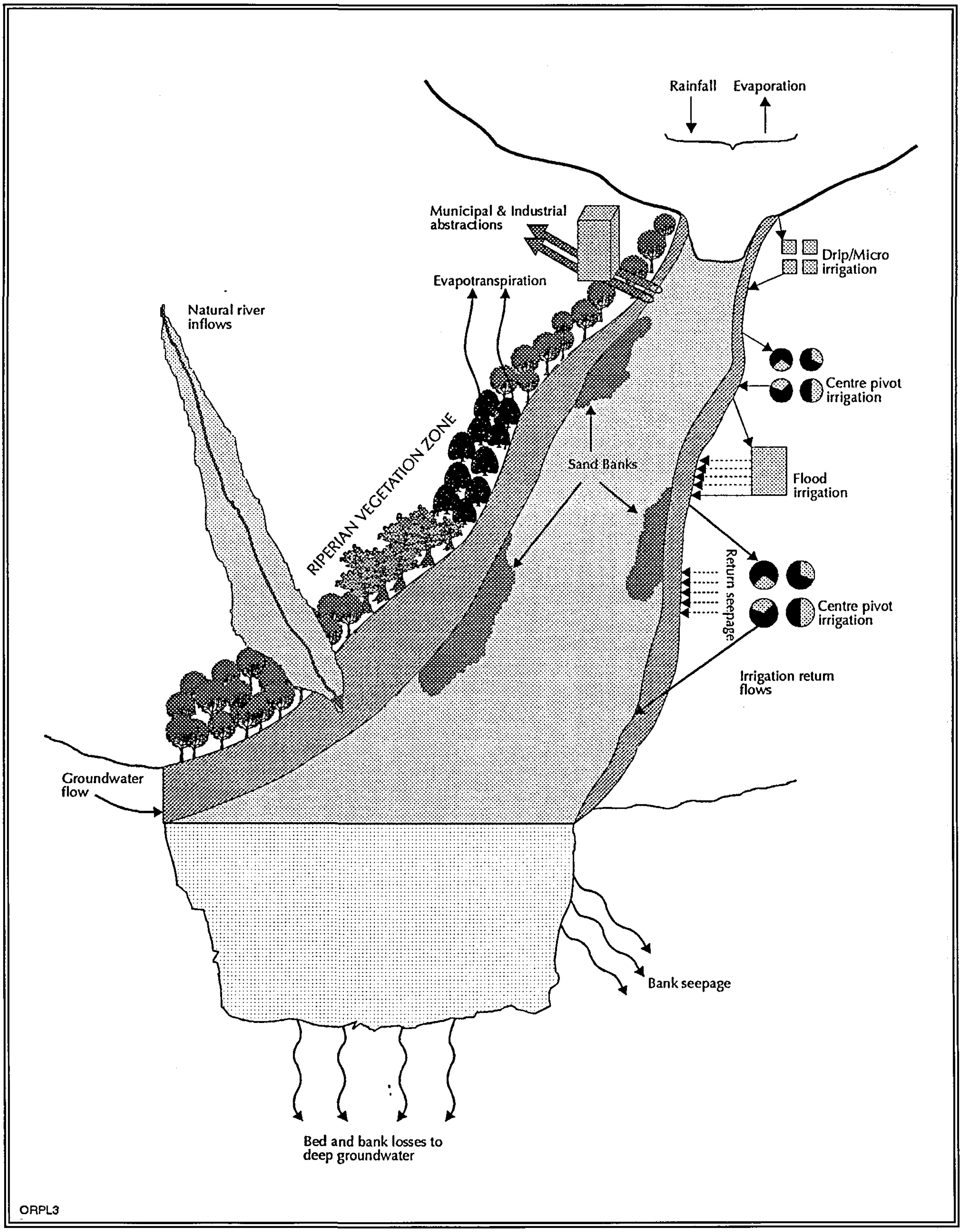


Figure 2.1 Conceptual model

Obviously such vegetation can survive only by utilising water from the main river and as such should be considered in any Conceptual Model. In some cases the influence of such vegetation will be insignificant in comparison to other factors and in such cases it can be ignored. In other cases the water used by such vegetation can be substantial and must be taken into account. This is certainly the case with the Orange River where the continual flow in the river caused by continuous regulation enables not only reeds and shrubs to survive but also trees which can be substantial as shown in **Figure 2.3.**

Figure 2.3 Close up view of riparian vegetation

2.4 BED AND BANK FLOW

River flow can normally be considered as comprising two major components - surface flow and subsurface flow. The latter can be sub-divided into interflow which travels close to the ground surface and groundwater flow which generally occurs at greater depths. The relative magnitudes of the various components can vary considerably from one area to another and in the case of the Orange River both are low when compared to the average flow in the river. Surface flow via rivers and small tributaries to the lower reaches of the Orange River occurs rarely and there may be periods of many years with no surface flow. The Fish River is the notable exception to this and generally flows for several months in each year.

Although the net inflow to the Orange River from both surface and subsurface flow is known to be low relative to the overall water resources, there are times when water from the river can seep into the adjacent soil through the river bed and banks. This is an important consideration in cases where water is released from storage into a dry river bed and in such cases the losses associated with the bed and bank seepage can be very high.

Bed and bank flow represent losses or inflows to the river from the adjacent land. In some of the more arid areas there may be no surface flow although there may still be considerable subsurface flow. This would represent an inflow to the river in such cases. In the case of water flowing onto a dry river bed or one in which the flow is confined to a small portion of the river bed, there are often substantial losses through the remaining portions of the river bed to be overcome before the water can flow over the full bank width. This is not the case with the Orange River since the flow in the river is controlled by the releases from PK le Roux Dam and the releases are usually high enough to produce flow over the full river bed.

After discussions with leading soils and geological experts it was concluded that the losses and accretions via the river bed and banks due to natural flows are likely to be low relative to the more dominant processes such as evaporation and evapotranspiration for example.

2.5 DEMANDS AND RETURN FLOWS

There are four main users of water which must be considered when evaluating the demands and return flows :

- Irrigation
- Municipalities
- Industries
- Environment

In the case of the Orange River, the abstractions from the river for municipalities and industries are closely monitored and measured which allows them to be taken into account in any water balance analyses.

With regard to the irrigation which is by far the most dominant user of water in the Lower Orange River, the controls are not as effective with the result that the volumes abstracted cannot be estimated with the same reliability as the municipal/industrial abstractions.

In most instances the municipalities and industries using Orange River water do not return any water to the river. Most return flows from effluent treatment plants are utilized for irrigation or allowed to evaporate from pans and evaporation ponds. The only return flows of any significance are associated with the irrigation. Such return flows were neglected in the initial loss estimates but have been included in the Conceptual Model for completeness. It should be noted that the magnitude of the return flows will depend, to a large degree, upon the mode of application e.g. drip, centre pivot, flood etc. since irrigation practices may change and become more efficient, the return flows cannot be considered as a reliable source in the overall water resource assessment. In future years, when the available resources become scarce, the return flows may decrease significantly as the farmers convert from inefficient flood irrigation for example to more efficient centre pivot or even micro-irrigation.

Environmental demands have been omitted from all previous water resource studies of the Orange River since there has always been a considerable surplus water in the system and certainly sufficient to exceed any reasonable environmental demands. Recent analyses have, however, indicated that the water resources of the Orange River are now considered to be limited, with the result that the environmental demands must be taken seriously and included in any future analyses.

3. BASIC METHODOLOGY AND PROCEDURE

3.1 GENERAL

Many people calculate river losses based on the observed flow data from gauges situated at various locations along the rivers in question. In most cases the errors associated with the observed flow records (measurements) are in the same order of magnitude or larger than the losses they are trying to estimate. In the case of the Orange River there are numerous gauges along the river as shown on **Figure 3.1.**

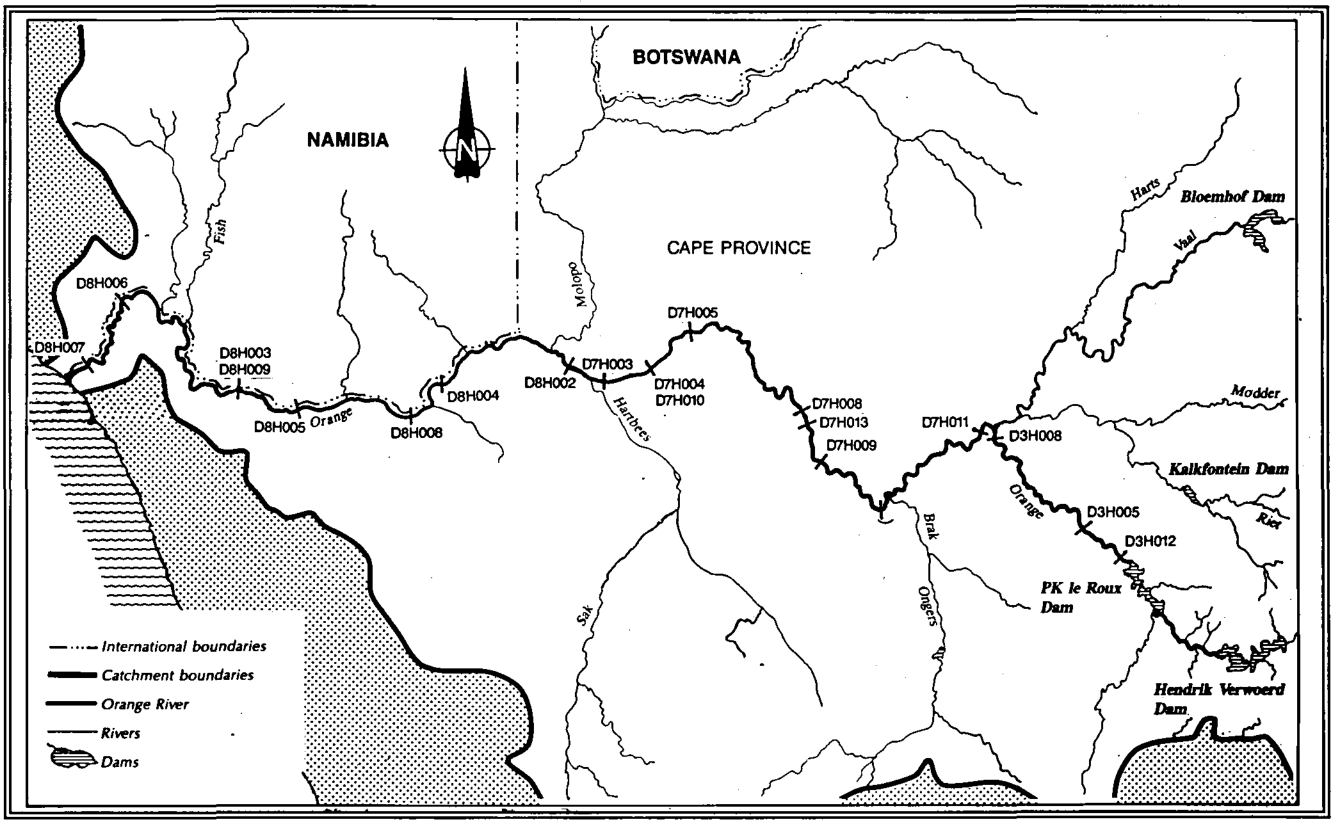


Figure 3.1 Flow gauge locations along the Orange River

Unfortunately, as mentioned previously, the gauges on the Orange River were not originally designed to measure low flows with the result that it was not possible to evaluate the losses directly from the gauged records. In recent years the situation has improved to some degree with the upgrading of the Marksdrift Weir (D3H008) just upstream of the Orange/Vaal confluence as shown in **Figure 3.2.**

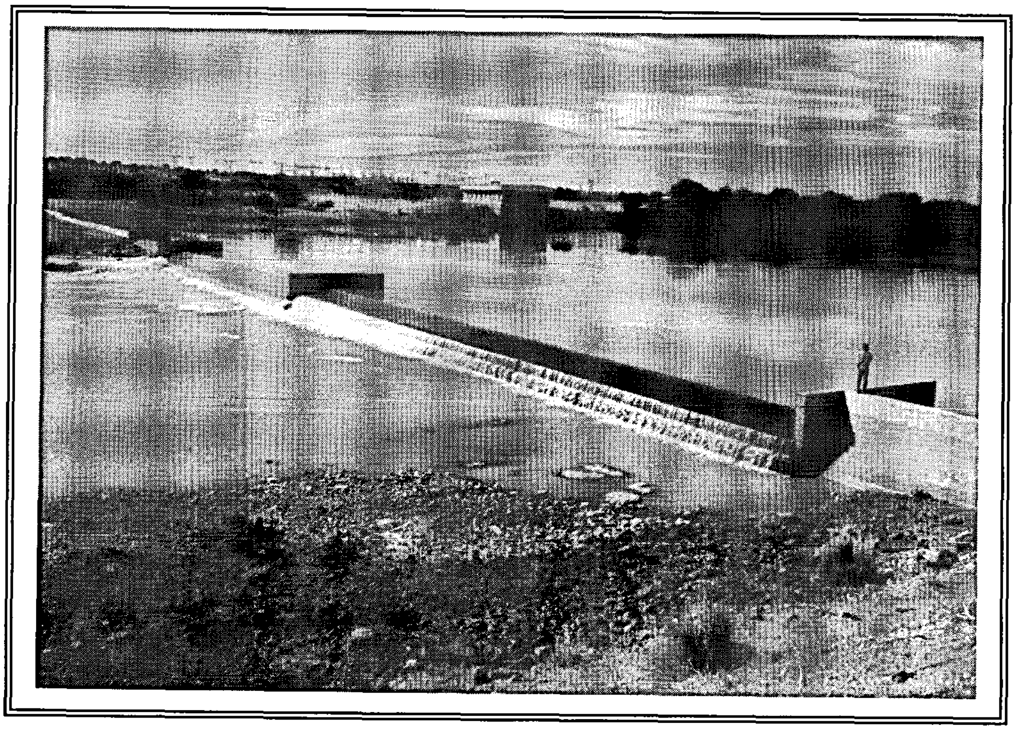


Figure 3.2 Marksdrift Weir upstream of the Orange/Vaal confluence

As can be seen in **Figure 3.2** the weir is substantial and should be capable of measuring the low flow with reasonable accuracy. Unfortunately the inflows from the Vaal River cannot be assessed with the same degree of accuracy and neither can the flows lower down on the Orange River.

Since it was clear that the river losses could not be evaluated directly from the available flow data, it was decided to base the study on results obtained directly from river gaugings undertaken simultaneously at various locations on the river during a period when the release from PK le Roux Dam remained constant.

Obviously it is difficult to know how much water is being abstracted for irrigation and how much return flow is occurring. For this reason the first set of gaugings were undertaken during a period of low irrigation demand at the beginning of July 1993. The intention was to repeat the exercise later in the year when both the irrigation demands and evaporation are higher, however, this was not possible due to unforseen circumstances which resulted in the release from PK le Roux Dam varying during the period scheduled for the second set of gaugings.

Table 3.1: Average widths calculated using different methods for reach 1

Method of calculation		Estimated average width (m)		
		Water surface	Sand	Vegetation
A	Sections at 5 km intervals	134 (139)	59 (82)	46 (49)
B	Sections at 1 km intervals	141	63	50
C	Uniform rectangles	138	66	48

From the analyses it was found that the results from Method A as shown in **Figure 3.4.A** (using sections at 5 km) exhibited a large scatter and were sensitive to the sections used in the analysis particularly for relatively short reaches. In other words the resulting water surface estimated from the measured widths was found to vary significantly when different starting points were used due to the smaller number of sections used when adopting the 5 km interval. This problem was resolved when using Method B in which sections are taken every kilometer as shown in **Figure 3.4.B.** The second set of values given in brackets highlights this point and provides the widths based on sections taken at 1 km, 6 km and 11 km etc. as opposed to the first set based on sections taken at 0 km, 5 km 10 km etc.

After examining the results it was decided to adopt Method C which involves splitting river and vegetation into uniform rectangles as shown in **Figure 3.4.C.** This method involves approximately the same effort as Method B but is considered to be more accurate since sections can be taken where they are most required. In practice it was found that it takes approximately 6 hours to process 100 km of river using either Method B or Method C.

The remaining river reaches were processed using Method C and where possible, more than one set of photos were used. In this manner it was also possible to evaluate the influence of flow rate on the surface areas. The results from this exercise are given in **Table 3.2.**

This method was considered to provide a good balance between accuracy and effort. It is also ideally suited to the use of digitisation, however, it should be noted that if digitisation is adopted, one of the manual techniques should still be used to ensure that the results obtained are realistic since automated techniques are often prone to processing errors.

Table 3.2: Summary of surface areas measured on aerial photographs

Reach	Date	Flow * (m^3/s)	Surface area (km^2)		
			River	Sand	Veg
1	1960/1961/4,18 22, 28 Apr 1965	22 - 389	24,90	11,94	8,67
2	27 May 1988	353 - 40	59,91	7,03	19,43
Orange/Vaal to Prieska	27 May 1988	353 - 40	35,73	4,79	10,60
Orange/Vaal to Prieska	4,5 Nov 1970	90	28,49	10,46	9,76
Koegas to Boegoeberg	27 May 1988	353 - 40	12,17	1,44	5,03
Koegas to Boegoeberg	3 Jul 1979	124 - 18	9,15	3,32	5,66
3	3,4 Jun 1974	407 - 41	74,31	9,75	24,42
Albany to Kakamas	3,4 Jun 1974	407 - 41	48,22	5,25	16,71
Albany to Kakamas	Aug/Sep 1972	80 - 160	33,58	12,89	23,71
4	14 July 1988	232	12,63	4,22	5,34
Kakamas to Augrabies	14 July 1988	232	6,88	3,01	4,02
Kakamas to Augrabies	29 Jun 1987/ 2,10 Jul 1987	70 - 119	5,06	1,48	5,18
5	27,28 Apr 1988 14 Jul 1988	188 - 99	78,92	25,01	13,57
6	27,28 Apr 1988	814 - 99	32,92	4,40	3,83
6	Feb 1965	101 - 15	21,81	9,06	6,12
7	27,28 Apr 1988	822 - 10	52,78	9,82	7,72
7	Feb 1965	13 - 155	28,98	26,70	10,97

* In many cases the aerial photographs for an individual reach were taken over a few days or weeks during which time the flow rate was estimated to vary between the limits indicated in the table. It should be noted, however, that the flow range is still relatively small when compared to the large floods which can occur where flows can exceed 25 000 m^3/s.

As can be seen in **Table 3.2** the surface areas do vary with flow although the variability in surface area is low relative to the flows. For example, a 100 % increase in flow will usually result in an increase in surface area of approximately 25 %. In the event that the river flows are held reasonably constant (as is usually the case) at between 100 m^3/s and 200 m^3/s for example, the surface areas will also be reasonably constant.

For the purpose of Phase 1 of the losses study, the following surface areas were adopted. The areas used for evaporation are simply the sum of the water and vegetation areas. It was assumed at this stage that the water lost through vegetation is similar in magnitude to that lost directly from the free water surface.

Table 3.3: Surface areas adopted in the study

Reach number	Reach length	Surface areas (km^2) for evaporation			
		Water	Sand	Vegetation	Total for evaporation
1	186	24,9	11,9	8,7	33,6
2	283	59,5	7,0	19,4	79,3
3	236	74,3	9,7	24,4	98,7
4	77	12,6	4,2	5,4	18,0
5	315	78,9	25,0	13,6	92,5
6	135	32,9	4,4	3,8	36,7
7	145	52,8	9,8	7,7	60,7
Total	1 377	336,3	72,0	83,0	419,3

3.3 EVAPORATION AND TRANSPIRATION

Very little work has been carried out to determine the evaporation from the surface of a flowing river. This is in contrast to the evaporation from a static reservoir surface where considerable research has resulted in lake evaporation estimates which are generally slightly lower than Symons Pan evaporation.

Although there are several theoretical objections to the use of pans and monthly "pan to lake" factors, the resulting lake evaporation values have been found to be sufficiently accurate for most applications. In general the variability in evaporation is low relative to the rainfall or streamflow with the result that the errors associated with the evaporation also tend to be lower than those associated with either the streamflow or rainfall.

Jobson (1980) conducted an investigation into the evaporation from a canal in California, U.S.A. Variables such as solar radiation, wind speed, air temperature, water temperature and water depth were monitored at various locations in the canal for a 1 year period. A one-dimensional, finite-difference, thermal-balance model was used to interpret the data and calculate the evaporation. Although it may be impractical to apply a similar approach to a 1 300 km stretch of river, Jobson's results may offer useful guidelines. He obtained an annual average pan-to-canal coefficient of 0,91; with the monthly coefficient varying from 0,51 to 1,34. This variation suggests that a pan does not accurately model the evaporation from a canal or river.

Bosman (1993) measured the evaporation loss from two isolated sections of the Sarel Hayward Canal and compared this with evaporation from a nearby Symon's tank. This resulted in the following equation.

$$y = 2{,}3903\, x^{0{,}8223} \qquad \text{Eqn 3.1}$$

where y = monthly canal evaporation (mm)

x = monthly Symon's tank evaporation (mm)

Over the range of monthly evaporation values found along the Orange River, this results in an average pan-to-canal coefficient of 1,03 indicating that the evaporation from the canal is slightly higher than that from the pan.

The problem has also been approached from a purely theoretical viewpoint. Brutsaert and Yeh (1969) derived an expression for the ratio of evaporation from a small circular surface to the evaporation from an infinitely long narrow strip.

$$\frac{E\ circle}{E\ strip} = \frac{(4\ x_o^2)^{\mu}(\frac{1}{2} - \mu)\ r^2\ (1/2-\mu)\ 4^{1/2-\mu}}{(\pi r^2)^{\mu}\ \pi^{1-\mu}\ (1-\mu)\ r^2\ (1-\mu)} \qquad \text{Eqn 3.2}$$

where x_o = width of strip

μ = a function of the wind speed and water vapour density profiles. Brutsaert recommends $\mu = m^2$, where m is the exponent in the power law describing the wind profile

r = radius of small circular area

This equation could be used to calculate the ratio of evaporation from a pan (a small circular area) to evaporation from a river (an infinitely long narrow strip). Taking x_o = 100 m, μ = 1/7 and r = 0,6 m the ratio is calculated to be 2,4 which implies a pan-to-river factor of 0,42. This is clearly unrealistic in the case of the Orange River where the river evaporation is considered to be in the same order as the pan evaporation - i.e. a factor close to unity is expected. The standard pan to lake factor used in South Africa is generally in the order of 0.87 which is used to reduce the pan evaporation to take the influences of the larger water body of the lake into account. It is unlikely that the evaporation from a thin ribbon of water crossing through a desert with warm day winds will be lower than that from a lake and therefore a factor of greater than 0.87 seems most likely.

Since the pan approach appears to be problematic and also due to the scarcity of pans in the lower Orange River, estimating the evaporation by means of meteorological data was also investigated.

The best known equation in this field is that of Penman (1948). Before publication of Penman's paper, evaporation was estimated by the mass-transfer approach (based on the difference between the saturated vapour pressure of the air and its actual vapour pressure) or the energy-balance approach (estimating the proportion of incoming solar energy used for evaporation). Penman combined the two approaches and obtained the following equation:

$$\text{Evaporation} = \frac{Qn\,\Delta + Ea\,\gamma}{\Delta + \gamma} \qquad \text{Eqn 3.3}$$

where	Qn	=	net radiation energy
	Δ	=	slope of the saturation vapour pressure vs. temperature curve
	γ	=	psychometric constant
	Ea	=	$f(u)(e_s - e_a)$ (Dalton's equation)
where	$f(u)$	=	function of the wind speed u
	e_s	=	saturated vapour pressure of the air
	e_a	=	actual vapour pressure of the air

Linacre (1977) felt that certain of the terms in Penman's equation were difficult to measure and substituted functions of temperature for these terms. He obtained the following:

$$\text{Evaporation} = \frac{600Tm \,/\, (85-\phi) - 56 + (5+4\mu_{ms})(T_a - T_d)}{80 = T_a} \qquad \text{Eqn 3.4}$$

where	T_m	=	$T_a + 0{,}006\ \Delta_m$
	T_a	=	mean air temperature
	Δ_m	=	altitude
	$Ø$	=	latitude
	μ_{ms}	=	average daily wind speed
	T_d	=	dew point temperature

The necessary meteorological data were obtained at several weather stations along the Orange River so that the Penman and Linacre equations could be used. Results were interpolated between the stations and a mean evaporation figure for the entire river determined. The results are compared with those obtained from evaporation pans in **Table 3.4.**

Table 3.4: Comparison of river loss based on various approaches

Point evaporation data used	Mean evaporation (mm/a)	Net river loss* (million m^3/a)
Original estimate	1 981	800
Symons pan evaporation	2 454	960
A-Pan evaporation	3 144	1218
Penman equation	3 159	1 224
Linacre equation	2 867	1 106

* Based on surface area, mean evaporation and rainfall on river surface.

As can be seen in **Table 3.4**, the estimates vary considerably from a minimum of 800 million m^3/a to more than 1 200 million m^3/a.

It is also not clear whether or not the total loss due to evaporation should be assessed by "point evaporation times area" due to the presence of extensive edge effects. These are mainly in the form of advection, defined as "the exchange of energy due to horizontal heterogeneity in conditions at the surface". (Houman, 1971)

Philip (1969) discussed the basic theory of advection. From purely theoretical considerations, he derived the following equation for the evaporation from a water surface downwind of the edge of an irrigated area.

$$\boldsymbol{E = ax^{-p} + b} \qquad \text{Eqn 3.5}$$

where	$\boldsymbol{x}$	=	distance from edge of surface
	$\boldsymbol{a,b}$	=	constants
	$\boldsymbol{p}$	=	$m/(1+2m)$ where m is the exponent in the power law describing the wind profile

The exponent m varies from 1/7 over a smooth surface to 1/4 over crops, with a corresponding variation in p of 1/6 to 1/9. The work of Rao, Wyngaard and Coté (1974) produced a similar result.

This theoretical relationship was confirmed by Long, Evans and Ho (1974) who measured the evapotranspiration from a flood irrigated rice field downwind of a dry boundary. Their results were consistent with equation (5) with $p = 1/6$.

It thus appears reasonable to expect the evaporation across a river to vary according to equation (5). Unfortunately the constants a and b remain undefined and thus (5) cannot be used at this stage to determine total river losses due to evaporation.

From the above, it is clear that there are numerous theoretical approaches that can be used to estimate the evaporation from a water surface. The range in the estimates is relatively large and for this reason it was proposed to assess the evaporation from the water surface using the Bowen Ratio energy balance technique. This technique had previously been used to assess the transpiration from a forest canopy by Dr. C.S. Everson at the Cathedral Peak Forestry Research Station. Dr. Everson agreed to set up his equipment in the Orange River in order to evaluate evaporation from the water surface and details of the exercise are given in **Section 4.3.**

3.4 STREAMFLOW MEASUREMENT

Due to the inaccuracy of the numerous flow gauges along the Orange River at low flows it was considered necessary to undertake manual streamflow gaugings at various points in the river.

Originally it was intended to carry out these gaugings for the river reach downstream of Kakamas since the irrigation upstream is extensive and likely to influence the gauging results. After discussions with DWA&F, however, it was decided to undertake gaugings along the full length of the Orange River in order to assess the influence of the irrigation and the corresponding return flows.

Full details of the flow gaugings are given in **Section 4.2**

3.5 IRRIGATION DEMANDS AND RETURN FLOWS

Since irrigation is an important user of Orange River water downstream of PK le Roux Dam it is necessary to evaluate the irrigation demands so that they can be taken into account in the mass balance calculation. By quantifying the demands it is also possible to evaluate whether or not the irrigation demands (and return flows) are likely to have a significant influence on the results. In areas where the irrigation demands are small relative to the estimated losses it will be possible to place more reliance on the loss estimates than in the areas where the irrigation demands are in the same order of magnitude or higher than the losses.

Based on the figures given by McKenzie and Schäfer (1992) the irrigation demands for each reach were calculated and are given in **Table 3.5.** The demands were estimated directly from the scheduled areas of irrigation and the corresponding water quotas. In some cases the farmers do irrigate more than their official allocation, however, in such cases it is often found that the full water allowance is spread over the larger area rather than using additional water.

Table 3.5: Net Irrigation demands along the Lower Orange River (million m^3)

River reach	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Annual
1	13,05	15,12	14,75	22,36	19,96	15,16	5,41	0,00	0,00	0,91	1,55	8,79	117,05
2	19,78	24,12	24,58	31,92	27,29	18,03	5,60	0,00	0,00	1,23	2,16	12,12	166,82
3	12,78	18,18	19,47	21,90	17,49	11,15	4,46	0,53	0,10	0,59	1,15	5,61	113,42
4	30,40	43,63	44,38	50,10	39,48	25,21	11,10	2,29	0,48	1,84	3,51	13,79	266,22
5	4,65	6,43	6,07	7,02	6,28	4,55	1,59	0,39	0,12	0,39	0,65	2,90	41,06
6	0,37	0,47	0,48	0,56	0,51	0,37	0,16	0,03	0,01	0,03	0,06	0,23	3,29
7	1,14	1,44	1,37	1,72	1,40	1,01	0,47	0,12	0,04	0,10	0,19	0,71	9,72
Subtotal	82,18	109,40	111,11	135,58	112,41	75,48	28,78	3,37	0,75	5,09	9,26	44,15	717,58
Proportion	0,11	0,15	0,15	0,19	0,16	0,11	0,04	0,00	0,00	0,01	0,01	0,06	1,00

For the purpose of the initial water balance evaluation the return flows from irrigation were neglected since they were thought to be small relative to the other major components considered in the water balance. The timing of the return flows also causes problems when trying to model the system since the lag associated with the return flows is unknown at this stage. Recent field studies have indicated the return flows to be significant and future work will have to take them into account.

The more recent report by Van Veelen (1993) suggests the return flows to be in the order of 10 % to 40 %.

3.6 INDUSTRIAL/MUNICIPAL DEMANDS AND RETURN FLOWS

The water used by industry and municipalities along the Lower Orange River is small relative to both the river losses and irrigation demands. Despite the fact that the demands are small they are nevertheless strategically important and must therefore be taken into account. A summary of the water demands is given in **Table 3.6** (McKenzie and Schäfer, 1992) and as can be seen the net annual abstraction is only in the order of 31 million m^3.

Table 3.6: Average annual demands and return flows for the main urban and mining centres making use of Orange River water downstream of PK le Roux Dam

	Demand centre	River reach	Volume (million m^3/a)		
			Abstraction	Return flow	Net use
1	Hopetown	1	0,30	0,00	0,30
2	Douglas	1	0,90	0,00	0,90
3	Prieska	2	1,00	0,40	0,60
4	Groblershoop	3	0,35	0,00	0,35
5	Karos-Geelkoppan Rural Supply Scheme	4	0,06	0,00	0,06
6	Kalahari West Rural Supply Scheme	4	0,40	0,00	0,40
7	Upington	4	11,00	3,00	8,00
8	Kakamas	5	1,20	0,00	1,20
9	Keimoes	5	0,80	0,00	0,80
10	Pelladrift Water Board	6	4,00	0,00	4,00
11	Springbok Water Board	6	3,60	0,00	3,60
12	Various small users (Noordoewer, Aussenkehr, etc.)	7	1,20	0,00	1,20
13	Rosh Pinah	8	1,20	0,00	1,20
14	Oranjemund	8	7,00	0,00	7,00
15	Alexander Bay	8	1,50	0,00	1,50
TOTAL			34,51	3,40	31,11

The various demands were also grouped according to the river reaches used in the analysis and the monthly demands for each reach are given in **Table 3.7.**

Table 3.7: Average net monthly urban and mining water demands (million m^3) for the reaches as used by McKenzie and Schäfer (1992)

River Reach	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Annual
1	0,11	0,13	0,14	0,13	0,11	0,10	0,08	0,08	0,07	0,07	0,08	0,09	1,20
2	0,05	0,06	0,07	0,07	0,06	0,05	0,04	0,04	0,03	0,04	0,04	0,05	0,60
3	0,03	0,04	0,04	0,04	0,03	0,03	0,02	0,02	0,02	0,02	0,02	0,03	0,35
4	0,76	0,89	1,02	0,93	0,80	0,72	0,59	0,55	0,47	0,51	0,59	0,63	8,46
5	0,18	0,21	0,24	0,22	0,19	0,17	0,14	0,13	0,11	0,12	0,14	0,15	2,00
6	0,68	0,80	0,91	0,84	0,72	0,65	0,53	0,49	0,42	0,46	0,53	0,57	7,60
7	0,11	0,13	0,14	0,13	0,11	0,10	0,08	0,08	0,07	0,07	0,08	0,09	1,20
8	0,87	0,99	1,12	1,04	0,91	0,82	0,70	0,65	0,57	0,61	0,70	0,74	9,70
Total	2,80	3,27	3,73	3,42	2,96	2,64	2,18	2,02	1,71	1,87	2,18	2,33	31,11
Proportion	0,09	0,11	0,12	0,11	0,09	0,09	0,07	0,07	0,06	0,06	0,07	0,08	1,00

3.7 BANK AND BED FLOWS

The question of bank and bed flows is an extremely difficult item to consider. A group of experts were assembled to discuss the importance of bed and bank seepage either into or out of the Orange River. After long discussions it was concluded that in the case of the Orange River, the losses or accretions from or to the river are likely to be small relative to the overall water balance. This assumption is based on the fact that the river is constantly flowing and has done so for many years with the result that the groundwater storages will be in equilibrium. It is possible that underground water can enter the Orange River in some areas, however, the quantities involved are likely to be small and will therefore be masked by the abstractions and losses.

For the purpose of the study it was assumed that the natural groundwater flows (i.e. excluding irrigation return flows) are small relative to the larger evaporation and transpiration losses with the result that it was not considered practical to differentiate between them. The losses considered in this report therefore also include the influences of any groundwater inflows and outflows.

4. FIELD STUDIES

4.1 FLOW MEASUREMENTS

4.1.1 Objectives

The primary objective of the manual flow gaugings carried out on the Orange River is to provide some reliable flow data which can be used to determine the losses occurring from various river reaches. The data obtained must be of sufficient accuracy to enable the losses to be calculated without being masked by the errors associated with the flow measurements.

In order to measure streamflow accurately it is necessary to use experienced personnel and adopt standard and generally accepted gauging techniques. The river cross-section is usually split into numerous panels and the flow velocity is then gauged at three or more different depths. In this manner the average velocity in the panel can be determined and then multiplied by the panel area to provide the flow in the panel. By adding the flows in the various panels the flow for the whole cross-section can be determined.

If the gauging is carried out carefully and the section is suitable for such an exercise, the flow can be within 5 % of the actual value. If the conditions are not ideal and the depth is changing during the period over which the gauging is carried out, the accuracy of the measured flow will be lower.

For the purpose of the Orange River Losses Study the DWA&F agreed to hold the releases from PK le Roux Dam constant for a period of 6 weeks in order to provide equilibrium in the river. This was only possible during the June 93 and July 93 because the irrigation demands are at or near their lowest and ESKOM had stopped generating power for the first time since the Hendrik Verwoerd and PK le Roux dams were built due to insufficient head in the reservoirs. This was an ideal opportunity to carry out such a gauging exercise and one that may not be repeated for some time.

Before the gaugings could be carried out it was necessary to investigate and select suitable gauging sites. A field trip was made in May 93 in co-operation with several key personnel from DWA&F and the following ten sites were eventually selected for manual gaugings:

- 1. Just down stream of Pk le Roux Dam on the farm of Mr Potgieter
- 2. Old wagon bridge at Hopetown
- 3. Marksdrift
- 4. Katlani
- 5. Upstream of bridge at Prieska
- 6. Zeekoebaard
- 7. Seekoeisteek
- 8. Pelladrift
- 9. Downstream of bridge at Vioolsdrift
- 10. Brandkaros

The locations of the gauging sites are shown on **Figure 4.1** and it is interesting to note that the only existing gauging station considered suitable at the time of the exercise was at Marksdrift. This gauge was shown in the previous section (**Figure 3.1** and was re-surveyed and re-calibrated prior to the study and is currently considered to be very reliable.

Another gauge which may now also be reliable is at Zeekoeibaard just downstream of Boegoeberg Dam. This gauge had never been surveyed or calibrated due to the fact that the flows from Boegoeberg Dam were constantly too high to enable the weir to be examined. During the recent period of water restrictions, however, the DWA&F personnel (Cape Region) were able to survey the weir and have since undertaken numerous flow gaugings which have been used to produce a reliable Discharge Table. Although the flows at this gauge were not used in Phase 1 of the study it seems likely that realistic low flow measurements can now be obtained from this gauge for use in future studies. The weir at Zeekoeibaard is shown in **Figure 4.2.**

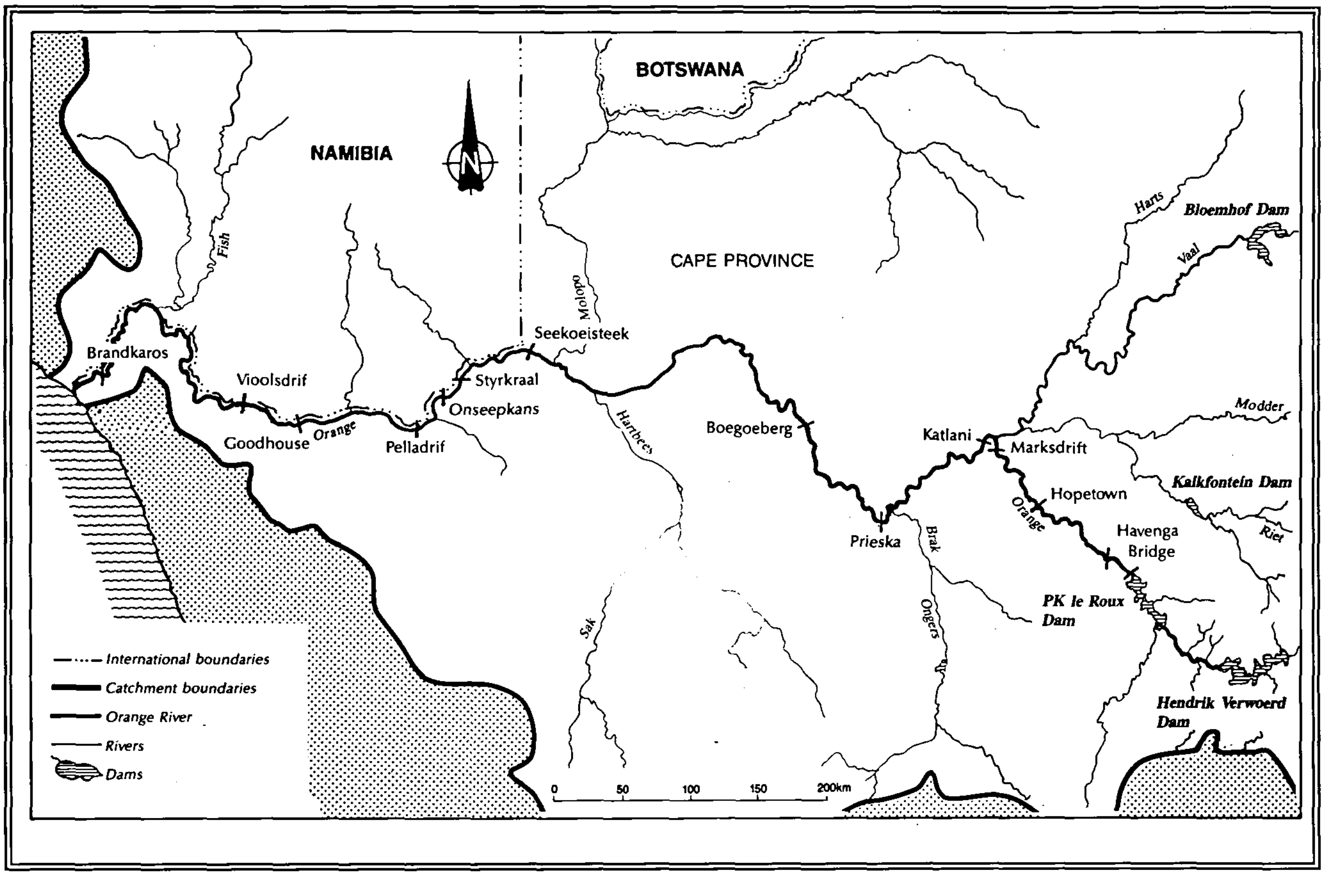


Figure 4.1 Locations of gauging sites

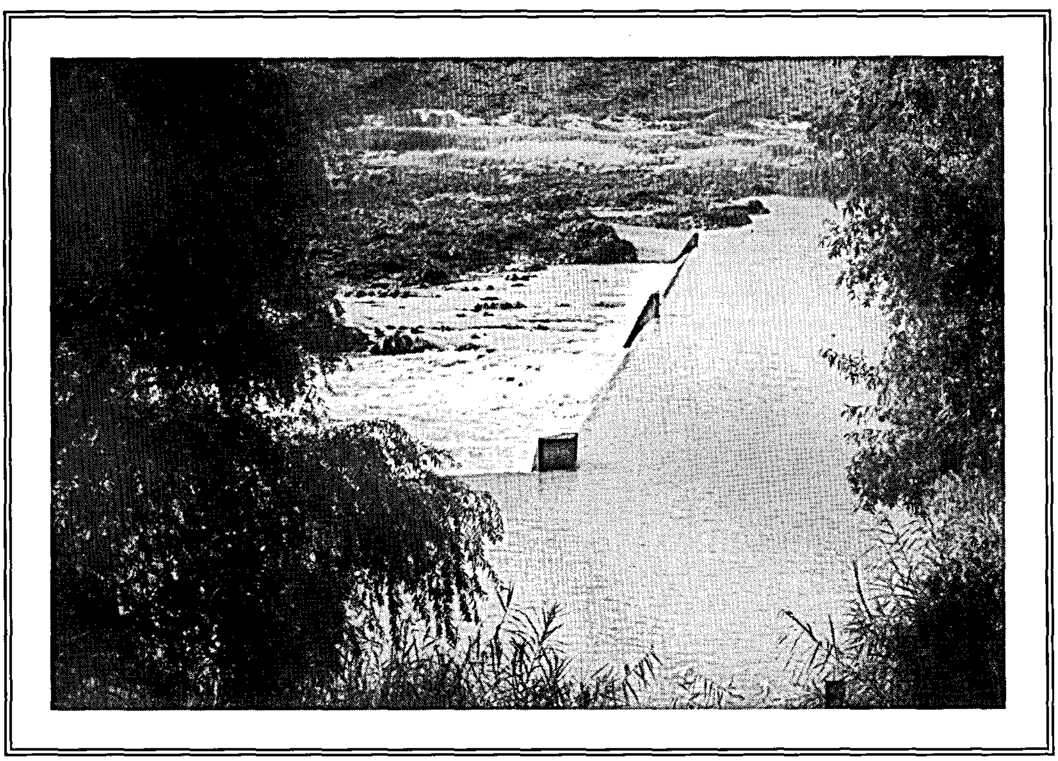


Figure 4.2 Zeekoebaard Weir

4.1.2 Results

Four teams of experienced personnel from DWA&F carried out the gaugings between 5 July 93 and 9 July 93 using boats and temporary cableways where necessary. Several gaugings were carried out at each section and great care was taken to ensure that the results were as accurate as possible. Since the river had been stabilised by constant releases from PK le Roux Dam the gaugings could be carried out over the whole day without the problem of a rapidly varying discharge which can cause considerable problems.

The results of the gaugings are presented in full detail in four separate reports:

- *Stroommetings vir die bepaling van verliese. Trajek: PK le Rouxdam - Douglas, 5 - 8 Julie 1993.* Internal DWA&F report by FP le Roux.

- *Oranjerivier verliesbepaling. PK le Roux - Hopetown Trajek.* Internal DWA&F report by J van Bosch.

- *Oranjerivier stroommetings : Prieska terrein en Pelladrift terrein.* Internal DWA&F report by M Kriel and T Brandt.

- *Vloeimetings in die Oranjerivier gedurende die week : 5 Julie 93 - 9 Julie 93.* Internal DWA&F report by W Wentzel and H Mettler.

The reports are all well written and contain considerable useful information which will also be valuable for the subsequent phases of the Orange River Losses Project. The costs associated with the trips were in the order of R15 000 per team which excludes the costs associated with the earlier reconnaissance visit. Any subsequent gaugings will also involve similar costs.

The results of the gaugings are summarized in **Table 4.1.** It should be noted that the flow at Marksdrift has been estimated directly from the weir record and is not based on manual measurements. The flow recorded by the weir is considered to be as accurate if not more accurate than the flow calculated by manual gauging techniques.

Table 4.1: Summary of results from the flow gaugings

Location	Date	Discharge (m^3/s)	Comments
1. PK le Roux Dam	6 - 7 July 93	27,7 29,6 27,8	Average value = 28,4
2. Hopetown	6 - 7 July 93	29,7 30,2 28,8 29,7 28,5 29,9 29,5	Average value = 29,6
3. Marksdrift	6 - 7 July 93	29,5	From weir record
Douglas	6 July 93	2,5	Inflow from Vaal River
4. Katlani	6 - 7 July 93	30,7 29,6 31,3	Average value = 30,5
5. Prieska	6 - 7 July 93	29,9 30,2 30,8 29,9 29,0 29,2	Average value = 30,2
6. Zeekoebaard	6 - 7 July 93	29,8 29,2 27,0 27,9	Average value = 28,5
7. Zeekoeisteek	6 - 7 July 93	27,9 27,7 26,8	Average value = 27,5
8. Pelladrift	-	-	Site unsuitable
9. Vioolsdrift	8 July 93	22,0 22,3 21,2	Includes approximately 1 m^3/s for the left bank irrigation canal Average value = 21,8
10. Brandkaros	8 - 9 July 93	19,4 19,4 19,6	Gaugings carried out just upstream of the pumphouse. Average value = 19,5

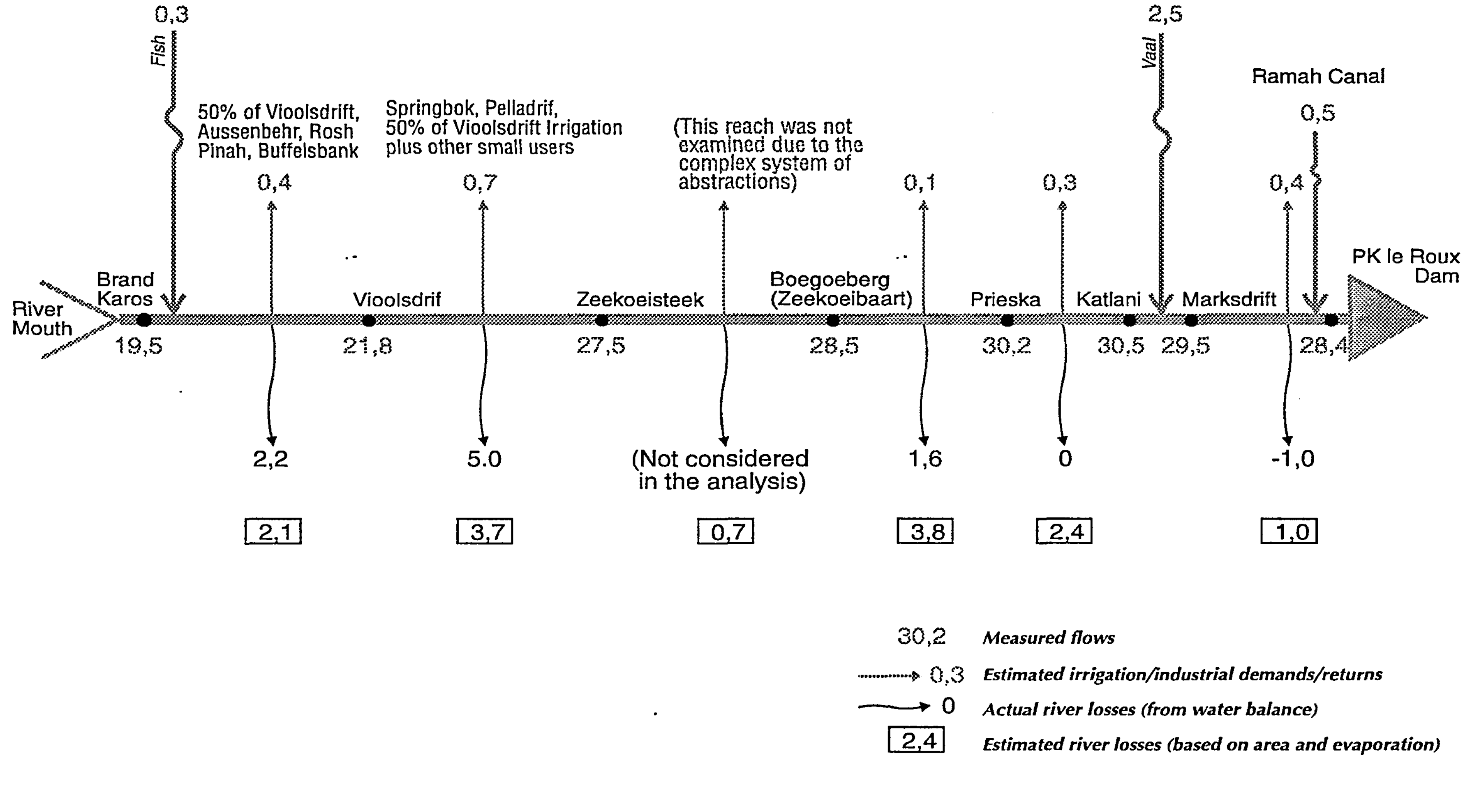
From the figures in **Table 4.1** it is rather hard to appreciate the significance of the results particularly in view of the irrigation and municipal abstractions. To illustrate the situation the water balance for the whole river downstream of PK le Roux Dam is given in **Figure 4.3.** It can be seen that for the purpose of the gauging exercise, the river has been split into six reaches and not the seven previously identified. The first five reaches are basically the same as before while the last reach now covers the stretch from Vioolsdrif to Brand Karos. This was necessary due to the absence of suitable and accessible gauging sites in the vicinity of the Orange/Fish confluence.

It should be noted that the estimated losses shown in the figure are based on the combined water and vegetation areas, together with the net Symons Pan evaporation values. A summary of this calculation is given in **Table 4.2.**

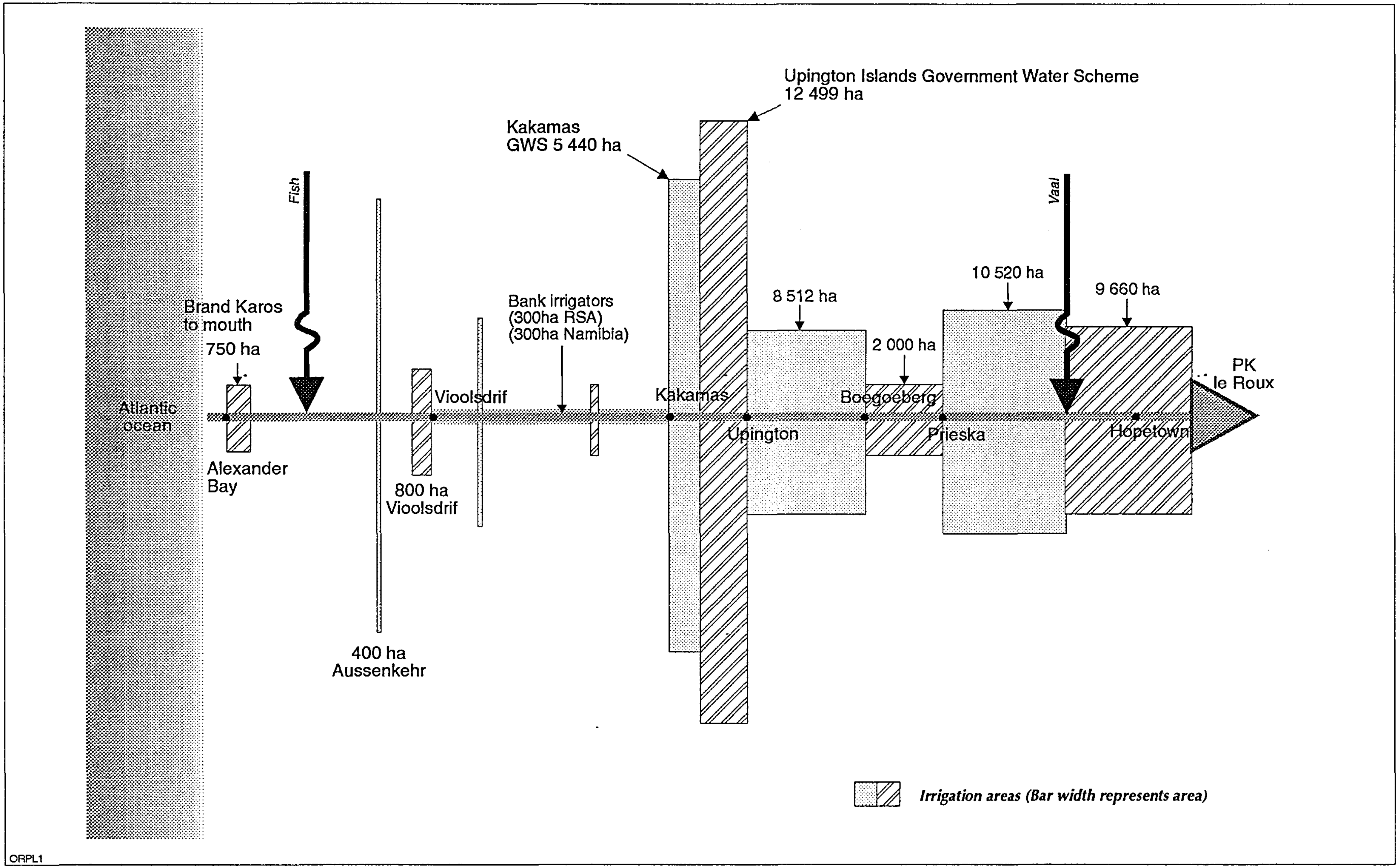
Table 4.2 Estimated Orange River losses for July

Reach No	Surface area (km^2)	Net evaporation (mm)	Estimated Loss	
			($10^6 m^3$)	(m^3/s)
1	33,6	80	2,7	1,0
2	79,3	81	6,4	2,4
3	98,7	104	10,3	3,8
4	18,0	111	2,0	0,7
5	92,5	107	9,9	3,7
6	67,9	84	5,7	2,1

From an initial inspection the results from the gaugings appear to be inconsistent and even indicate accretions to the river rather than losses. When the major irrigation areas are identified as shown in **Figure 4.4**, however, it can be clearly seen that the bulk of the irrigation takes place upstream of Zeekoeisteek (i.e. upstream of Augrabies), indicating that the apparent accretions or very small losses are caused by significant return flows from irrigation.


0,3
Fish
50% of Vioolsdrift, Aussenbehr, Rosh Pinah, Buffelsbank
0,4
Springbok, Pelladrif, 50% of Vioolsdrift Irrigation plus other small users
0,7
(This reach was not examined due to the complex system of abstractions)
0,1
0,3
2,5
Vaal
Ramah Canal
0,5
0,4
River Mouth
Brand Karos
Vioolsdrif
Zeekoeisteek
Boegoeberg (Zeekoeibaart)
Prieska
Katlani
Marksdrift
PK le Roux Dam
19,5
21,8
27,5
28,5
30,2
30,5
29,5
28,4
2,2
5.0
(Not considered in the analysis)
1,6
0
-1,0
2,1
3,7
0,7
3,8
2,4
1,0
30,2 Measured flows
0,3 Estimated irrigation/industrial demands/returns
0 Actual river losses (from water balance)
2,4 Estimated river losses (based on area and evaporation)
ORPL2

4 - 7



ORANGE RIVER LOSSES STUDY

Irrigation areas downstream of PK le Roux Dam **4.4**

The return flows were originally excluded from the analyses to avoid over estimating the available resources. It is clear from the gaugings, however, that the return flows are very important and must be included in any subsequent analyses. It is therefore important to differentiate clearly between the actual irrigation return flows through the soil to the river and the canal tail water flows which are effectively diverted flows.

Unfortunately, estimating return flows is a very difficult task requiring considerable field verification. Estimates of the return flows vary considerably and can vary from as little as 5 % to more than 40 %. Ninham Shand (1985) found that, on average for the whole of South Africa, irrigation return flows amount to 37 % of the diversions or releases to large irrigation schemes. The Ninham Shand report included the Boegoeberg Government Water Scheme and the Kakamas Government Water Scheme and estimated return flows from the schemes to be 72,5 % and 74 % respectively. These return flows may seem abnormally high ,however, the schemes are operated from full canal flow which is often significantly higher than the demands with the result that the figures also include the unused water (canal tail water) which flows directly back to the river. Van Veelen (1993) estimated the return flows along the Orange River to be in the order of 10 % to 40 %. In reality such return flows will depend upon many factors including

- Type of irrigation (drip, flood, centre pivot etc.)
- Type of soil
- Distance of irrigated land from river

It is not possible at this stage to resolve the water balance between PK le Roux Dam and Kakamas due to the complex interaction between the irrigation abstractions, irrigation return flows and river losses. Further field investigations are necessary in order to clarify this problem area.

The river losses occurring downstream of Kakamas appear to tie in reasonable well with the predicted losses and it seems as if the actual losses are slightly in excess of the predicted values.

It should be remembered that the values given in **Figure 4.3** are for one time period taken during the low evaporation winter period. Further field measurements are required during different periods of the year to provide a comprehensive estimate of the annual losses.

4.2 EVAPORATION MEASUREMENT

4.2.1 Objectives

The main objective of the evaporation measurement was to provide a more reliable estimate of the evaporation from a moving water surface. Previous estimates ranged considerably from significantly lower than Symons Pan to significantly higher than A-pan values. In view of the influence of the evaporation on the estimated losses, it was considered worthwhile to assess the evaporation using an energy balance approach rather than the normal evaporation pan method.

A one month trial was undertaken by Forestek (Everson,1994) during July 1993 using Bowen Ratio technology. The equipment used is shown in **Figure 4.5** and was set up in the middle of the Orange River with considerable assistance of DWA&F. A class A evaporation Pan was also set up by DWA&F on the river bank in the immediate vicinity of the equipment to provide corresponding pan evaporation figures.

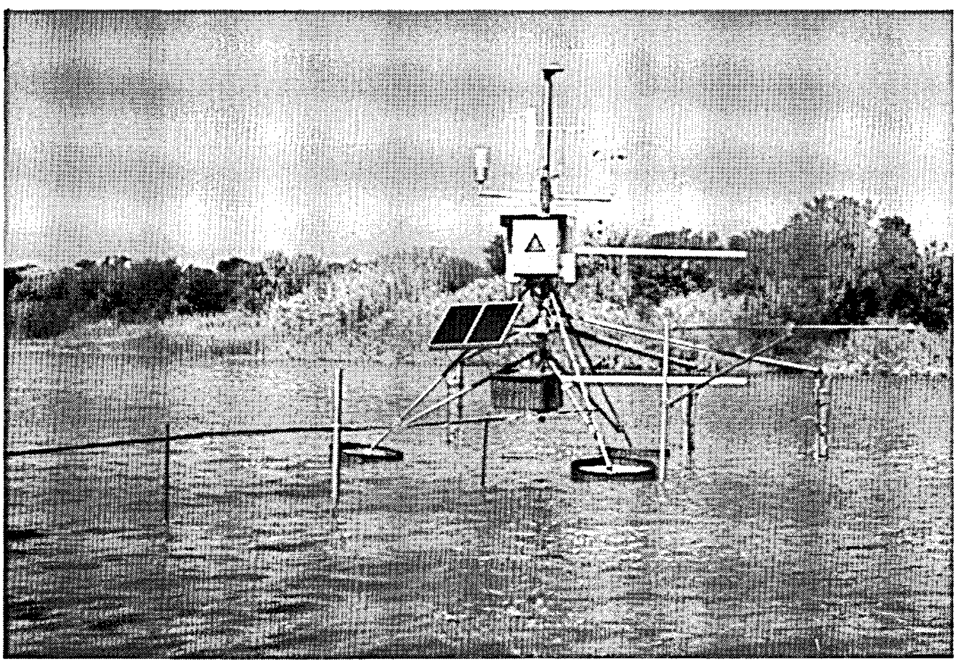


Figure 4.5 Bowen Ratio equipment used to measure evaporation from the Orange River surface

4.2.2 Results

The full results of the evaporation analysis using the Bowen Ratio equipment are given in the report by Everson (1994). The results are quite detailed and are not repeated in this summary report. The conclusions and recommendations given in the report are of particular interest and are repeated below for reference:

Conclusions

- The study demonstrated that the Bowen ratio energy technique can provide valuable insights into the energy budgets of the Orange River with a view to determining river evaporation and has shown that there are numerous difficulties in predicting river evaporation from pan data.

- During the study, estimates of evaporation from the A-pan were found to be significantly lower than the evaporation estimated from the Bowen Ratio energy balance approach. The degree of this underestimation varies with the location of the A-pan site.

- Estimates of river evaporation using the equilibrium formula from standard automatic weather station data (temperature and solar radiation) show great promise. During the 30 day study period, the difference between the actual evaporation above the river and that predicted using land based measurements of the equilibrium rate was only 2.5 mm.

Recommendations

- Land based weather data measured in South Africa should be calibrated against actual river evaporation to enable accurate predictions of evaporation from a moving water surface.

- Since the initial study was only carried out over a 30-day period during the Winter, a further 12-month investigation is required to verify the data and gain a better understanding of seasonal trends in evaporation from the Orange River.

- Direct measurement of evaporation by lysimeters, or indirect measurement using energy balance techniques are expensive and cumbersome. By contrast, atmometers (porus surface evaporimeters) are small, easy to install and less expensive to maintain. Atmometers have been widely used in the northern hemisphere to estimate evaporation from dams and other surface water bodies. Their small size enables a rapid response to changing atmospheric conditions, especially above water. It is recommended that automated atmometers (calibrated against a direct measurement technique) be tested in South Africa to determine the pattern and processes of evaporative demand in the variety of climatic zones along the Orange river.

- The use of weather-based data in predicting evaporation from other water surfaces such as reservoirs and dams needs to be tested to provide accurate measurements for South Africa's water budget.

In the course of the study, the data from six evaporation pans in the vicinity of Upington were considered. The six pans were located at:

(a) Gifkloof	- An A-pan at water's edge adjacent to the Bowen Ratio equipment approximately 10 km upstream of Upington. This pan was set up and manned by DWA&F personnel specifically for the study.
(b) DWA&F	- A-pan at DWA&F offices in Upington.
(c) SADOR Farm	- A-pan.
(d) Upington Airport	- A-pan
(e) Upington Airport	- Symons pan
(f) Agricultural Research Station	- A-pan

Everson (94) found that the evaporation measured at the different pans varied considerably and that there were large discrepancies between all evaporation pan estimates and the Bowen Ratio estimate. The Bowen Ratio estimate was generally 2 mm to 3 mm per day higher than the corresponding A-pan estimates. Of major concern was the finding that the daily variation in evaporation measured at the A-pans could be as high as 80 %.

It was concluded that part of the problem was associated with the different site conditions at the pans. For example, the Gifkloof pan at the river's edge was set up to CSIR specifications and allows free air flow under the pan. By contrast the DWA&F pan is mounted on wood with no allowance for air flow beneath the pan. The SADOR pan is mounted on metal and painted red on the inside which will affect the validity of the measured evaporation values. The airport pans, although seemingly well maintained, were full of algae which will cause problems and the results from the Agricultural Research Station pan may be influenced by the weeds growing beside the pan which will prevent free air flow beneath the pan.

The monthly pan evaporations recorded at the various pans are compared with Bowen Ratio estimate in **Table 4.3.** The corresponding daily data are given in the report by Everson (1994).

Table 4.3: Comparison of pan and Bowen Ratio evaporation values (from Everson, 1994)

Description	Corrected monthly evaporation (mm)
Bowen ratio	230
Gifkloof A-pan	163
DWA&F A-pan	192
Research Station A-pan	171
Airport A-pan	260
Airport Symons pan	220

The figures clearly indicate the variability of the evaporation measured at the different pans and that even pans within close proximity of each other can provide significantly different estimates of evaporation. The figures also tend to suggest that the pans are underestimating the actual evaporation assuming that the Bowen ratio estimate is close to reality.

Unfortunately it is impossible to draw any firm conclusions from a one month trial and further investigations in this regard are required.

5. CONCLUSIONS

From the results obtained during the course of the Orange River Losses Study the following conclusions were reached.

Orange River Losses

Based on the results from the study it appears that the net evaporation losses occurring from the Orange River are likely to be higher than the 800 million m³/a initially estimated using Symons Pan values and pan to lake correction factors. The evaporation calculated using the Bowen Ratio technique suggests that the evaporation is in fact higher than pan evaporation. Unfortunately this conclusion is based on a very short period during which the pan evaporation measured at several different pans showed considerable scatter. It is therefore not possible at this stage to conclude that the actual evaporation is higher than pan evaporation although the indications are that this is the case.

If the Symons Pan values are used directly without any reduction factors the annual net evaporation is estimated to be in the order of 960 million m³/a. The basis of this figure is given below in **Table 5.1**

Table 5.1: Summary of net evaporation losses from the Orange River.

Reach	From	To	Length (km)	Areas for evaporation (km²)			Precipitation (mm/a)	Gross Evapo-ration (mm/a)	Net Evapo-ration (mm/a)	River Losses	
				Water surface	Vegeta-tion	Total				10^6 m³/a	m³/s
1	PK le Roux	Orange/Vaal	186	24,9	8,7	33,6	300	2 200	1 900	63,8	2,02
2	Orange/Vaal	Boegoeberg	283	59,9	19,4	79,3	230	2 340	2 110	167,3	5,30
3	Boegoeberg	Kakamas	236	74,3	24,4	98,7	150	2 590	2 440	240,8	7,63
4	Kakamas	20°E Meridian	77	12,6	5,4	18,0	100	2 700	2 600	46,8	1,48
5	20°E Meridian	Vioolsdrif	315	78,9	13,6	92,5	100	2 600	2 500	231,2	7,33
6	Vioolsdrif	Orange/Fish	135	32,9	3,8	36,7	50	2 400	2 350	86,2	2,73
7	Orange/Fish	Orange Mouth	145	52,8	7,7	60,5	50	2 100	2 050	124,0	3,93
Total			**1377**	**336,3**	**83,0**	**419,3**	-	-	-	**960,1**	**30,4**

It should be noted, however, that the influence of irrigation return flows has not been taken into account in **Table 5.1** or in the original loss estimate of 800 million m^3/a. Such return flows were shown to be significant and it is likely that they will more than offset the higher evaporation estimates used in **Table 5.1** if they are confirmed during the second phase of the study. If return flows of 30 % are assumed, the estimated net river loss drops to 720 million m^3/a.

Irrigation return flows

From the water balance analysis carried out using the gauged flows it was apparent that the irrigation return flows are significant and must be included in any river loss evaluation. The return flows will depend to a large degree on the application method and scale of irrigation. It is thought that the return flows are in the order of 10 % to 40 % of the water applied. With the information currently available it is not possible to quantify the return flows with more accuracy since the abstractions are not known accurately. The lag time associated with the return flows is also an unknown factor at this time.

Water and vegetation areas

The analyses indicate that aerial photographs can be used to provide realistic estimates of both the water surface areas as well as the areas of sand banks and riparian vegetation. By analysing photographs of the same river reach at different flow rates it is also possible to evaluate the influence of flow rate on surface area. In the case of the Orange River, the variation in surface area with flow rate is relatively small as long as the flow rate remains within the normal release limits, (i.e. 80 m^3/s to 200 m^3/s).

Satellite images can also be used to estimate the various areas and once processed the images can be incorporated into a GIS which allows considerable information to be obtained very quickly.

Unfortunately problems often occur when processing the satellite images resulting in areas which may be unrealistic due to misinterpretation of certain vegetation. For example, it is often difficult to distinguish between riparian vegetation and irrigation occurring nearby. In such cases it is essential to verify the results which usually involves processing the aerial photographs. It is therefore often more economical to base the areas on the aerial photographs and only use the satellite images in cases where the additional information from the images is required. Unfortunately the final processed areas from the satellite images were not available for inclusion in the first phase of the study but should be available for subsequent phases.

Losses from riparian vegetation

In the case of the Orange River the areas of riparian vegetation are significant and total more than 80 km^2 (i.e. 25 % of water surface). It is estimated that the water lost via the riparian vegetation is similar in magnitude to that lost directly from a free water surface. The losses will naturally depend upon the type of vegetation (i.e. reeds or trees), however, for the purpose of the first phase of the study this assumption was accepted.

6. RECOMMENDATIONS

Orange River Losses

Until more detailed and reliable information becomes available, it is recommended that the losses from the Orange River be based on Symons Pan evaporation values with no pan to lake corrections. It is further recommended that return flows of 30 % be used in the calculation until more reliable information on the return flows is obtained during subsequent phases of the study. .This assumption leads to a net river loss in the order of 720 million m^3/a which is very similar to previous estimates in which the return flows were neglected.

Irrigation return flows

Due to the importance of the irrigation return flows it is recommended that this issue be addressed during the subsequent phases of the project. The lag of the return flows is also of great interest since this can influence the magnitude of the releases required to support the various water users along the Orange River. It is possible that the use of tracers can help to quantify the volume and timing of irrigation return flows and this will be investigated during the next phase of the study.

Evaporation from the water surface

Ideally the Bowen Ratio technique should be used continuously for a period of at least a year in order to evaluate the reliability of the pan evaporation values. Unfortunately the expense of such an exercise is outside the budget of the Losses Study and it cannot be included as part of the subsequent work. It may be beneficial to the WRC or DWA&F, however, to pursue this line of study in view of the importance of reliable evaporation data in the South African context. Further investigations into the possibility of estimating evaporation using atmometers or weather based data are required to assess if such techniques are viable. These aspects will be considered in more detail during the next phase of the study.

Manual flow gaugings

The single set of manual flow gaugings has proven to be extremely valuable and it is recommended that further gaugings be undertaken to provide additional base information both on the Orange River and other suitable rivers where losses are known to be a problem. A regular exercise similar to that carried out in the first phase of the study should be carried out until such time that the losses have been quantified with the desired accuracy. It is only with such information that the study can successfully quantify river losses with any degree of reliability. Additional gaugings are already being planned for 1994 and beyond.

The possibility of dilution gauging or using tracers should also be investigated to determine if such techniques can be successfully applied in the Orange River and other rivers where losses must be evaluated.

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