Evaporation Losses from South African Rivers

RS McKenzie • AR Craig

Report to the Water Research Commission
by
BKS Inc (Pty) Ltd

WRC Report No 638/1/99

87

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WRC Report No : 638/1/99
ISBN No : 1 86845 507 6

BKS Project No : P513101
December 98

Title:	***Evaporation Losses from South African Rivers***
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Project name:	*River Losses Study - Phase 2*
BKS Project Number:	*P513101*
WRC Project Number:	*K5/638*

ACKNOWLEDGEMENTS

The authors would like to express their thanks to the Water Research Commission for supporting the project over the past four years, and to the steering committee who provided direction and advice. The Steering Committee comprised the following persons:

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The authors would also like to thank the many personnel from the Department of Water Affairs

Evaporation Losses from South African Rivers

EXECUTIVE SUMMARY

South Africa is a semi-arid country where, in many areas, the available water resources within the river basins are unable to supply the rapidly increasing local water requirements. The Orange River is the largest river in South Africa, both in terms of surface area and runoff. More than half the basin's 1 million km^2 surface area lies within South Africa, incorporating parts of six of South Africa's nine provinces. The remainder of the catchment falls within Lesotho, Namibia and Botswana, although the latter seldom if ever contributes to the flow in the Orange River.

Most of the Orange River's runoff is generated in the high rainfall regions in the eastern part of the catchment. The river then flows through desert regions with very low rainfall and very high evaporation rates which result in low natural runoff and high evaporation losses. Due to the highly variable nature of the runoff, the evaporation losses usually exceed the runoff generated from tributaries, unlike most other rivers where evaporation losses are small relative to incremental runoff. In cases where the evaporation losses are small the hydrological analyses normally incorporate such losses implicitly as a reduction in natural incremental runoff. In the Orange River, however, evaporation losses from the main stream must be calculated separately from incremental runoff.

Until recently, the water resources o the Orange River were well in excess of the various existing water requirements. As a result, releases could be made in excess of downstream requirements for generating hydroelectric power, and the flows reaching the river mouth were often well in excess of the estuary requirements. In recent years, however, due to increased water requirements and erratic rainfall, water shortages in the Orange River system have occurred for the first time since the construction of Gariep and Vanderkloof Dams. In times of water shortage, the operation of Vanderkloof Dam is particularly difficult, since the dam is located almost 1 400 km from the river mouth. Releases therefore have to be made accurately in order to satisfy downstream water requirements without shortfalls or excess spillage at the river mouth. It is therefore becoming increasingly important to accurately quantify the evaporation losses from the Orange River between Vanderkloof Dam and the river mouth.

With this background, BKS (Pty) Ltd was commissioned by the WRC to carry out research into river losses. The first phase took place in 1993, followed by a second phase from 1994 to 1997. The purpose of the Phase 2 of the River Losses Study was to refine estimates of evaporation losses from the Orange River between Vanderkloof Dam and the river mouth, and to derive a general methodology for calculating losses from other rivers in South Africa.

Based on the results presented in this report, it is concluded that Phase 2 of the River Losses Study has been successful in improving estimates of river losses downstream of Vanderkloof Dam and in developing a methodology for calculating evaporation losses from South African rivers. Specific results obtained during the course of the study, with relevant conclusions, are highlighted below:

Surface Areas of Water and Riparian Vegetation

The areas of water surface and riparian vegetation were determined for the Orange River at different flows for each reach of the river using aerial photographs. Very few aerial photographs exist of the Orange River at low flows, and an extrapolation technique was therefore applied to estimate the water surface areas at low flows. Satellite images and hydraulic modelling were also used to help establish realistic estimates of the water surface areas and areas of riparian vegetation. Approval to fund the collection and processing of aerial photographs of the Orange River at low flows was granted by DWAF in 1996, however, due to higher than normal river flows during the winter months of 1996, 1997 and 1998 it was not possible to carry out low flow aerial photography. DWAF still intends to have these photos taken to increase confidence in loss estimates for the Orange River.

Evaporation rates applicable to moving water surfaces and riparian vegetation

Information on evaporation rates from flowing water was derived from a Bowen Ratio energy balance study carried out by Environmentek on the Orange River near Upington (Everson, 1997). Further evaluation of the results indicated that the best estimate of river evaporation is given by the A-pan equivalent evaporation prepared by Schulze and Maharaj (1991, 1997), which varies from 2 500 mm/a to almost 3 000 mm/a on the Orange River. A-pan evaporation data is therefore recommended for use in calculating river losses from South African rivers. The evapotranspiration rates for reeds and trees used in the study were based on research into riparian water consumption in the Kruger National Park (Birkhead, et al, 1996), where high gross evaporation of approximately 2 000 mm/a is also experienced.

Validation of results using hydraulic model

Three sets of manual flow gaugings were carried out on the Orange River, in July 1993, November 1994 and November 1995, to assist in the verification of the river loss methodology. The flow gaugings were processed using a sophisticated hydraulic model which indicated that the actual river losses were approximately 14 % lower than the theoretical estimate based on the surface areas and evaporation rates discussed previously. Flow gaugings in October 1996 on the Vaal river also produced similar results. The discrepancy is most likely due to overestimation of the surface areas at low flows, since aerial photographs of the Orange River at low flows could not be obtained. It is possible that the Schulze and Maharaj (1991,1997) evaporation figures also overestimate river evaporation, however, the proposed methodology was not adjusted, to avoid overestimating the available water resources of the Orange River.

The calculated evaporation losses from the Orange River derived from this research range from 575 million m^3/a *at an annual low flow release of 50* m^3/s *to 989 million* m^3/a *at an annual release of 400* m^3/s*. The variation in evaporation losses is due to the change in surface area with flow. In the first phase of the River Losses Study, the losses were estimated to be 960 million* m^3/a *based on surface areas for flows between 400* m^3/s *and 1 000* m^3/s*, together with S-pan evaporation values (without pan-to-lake factors). Although the river evaporation has now been estimated to be higher than the S-pan values, the reduction in surface area produces a net reduction in the total loss estimate of approximately 380 million* m^3/a*. This is a significant quantity of water in terms of the available water resources of the Orange River. The basis for the estimates is provided in* ***Table (i)****, and illustrated graphically in* ***Figure (i)****.*

Table (i): Evaporation losses from the Orange River

Reach	From	To	Gross Evap (mm)	Rainfall (mm)	Area of Water (km²)		Area of R. Veg (km²)		Losses (10⁶ m³/a)	
					50m³/s	400m³/s	Reeds	Trees	50m³/s	400m³/s
1	Vanderkloof	Marksdrift	2 665	301	17,8	31,3	0,5	7,7	52,4	83,1
2a	Marksdrift	Prieska	2 761	257	23,8	38,7	1,2	8,4	73,1	107,4
2b	Prieska	Boegoberg	2 795	216	14,8	23,8	1,0	3,5	45,2	65,9
3a	Boegoberg	Gifkloof	2 865	178	23,2	40,0	1,3	9,9	79,3	120,8
3b	Gifkloof	Neusberg	2 885	146	11,0	26,0	1,7	6,0	43,1	79,5
4	Neusberg	20°E	2 920	109	8,3	17,0	1,5	5,1	34,7	54,9
5a	20°E	Pella	2 938	75	16,8	36,0	1,4	6,0	60,8	111,6
5b	Pella	Vioolsdrift	2 921	42	19,5	46,0	2,4	7,4	73,8	143,1
6	Vioolsdrift	Fish	2 942	31	12,0	32,0	3,1	4,7	50,7	100,0
7a	Fish	BrandKaros	2 925	29	9,4	24,5	2,7	2,0	38,1	73,9
7b	BrandKaros	Mouth	2 765	39	4,1	14,2	1,0	7,5	24,1	48,9
Total	Vanderkloof	Mouth	2 849	145	160,7	329,5	17,9	68,2	575,2	989,0
							Factor	Factor		
							1,0	0,5		

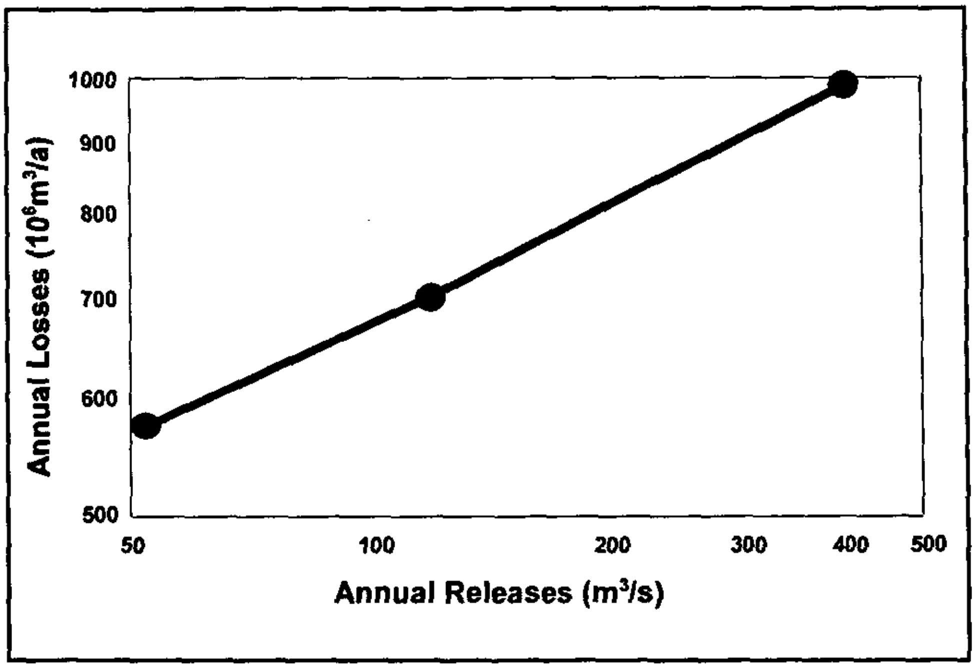

Figure (i): **Average annual losses versus releases**

Guidelines for estimating evaporation losses from South African rivers

A set of guidelines for estimating evaporation losses from South African rivers has been prepared, based on the research carried out on the Orange River.

It is recommended that surface areas be measured from aerial photography, although checks for scale anomalies should also be carried out. Satellite imagery can be used, but extensive *visual verification and field visits should be undertaken to validate the digital classification. River evaporation should be determined from map overlays or digital 1'x1' grid information produced by Schulze and Maharaj (1991, 1997), obtainable from the Department of Agricultural Engineering at the University of Natal. Rainfall estimates needed to estimate the net evaporation can be obtained in the same format as the evaporation data from the Computing Centre for Water Research (CCWR). The rainfall information from Surface Water Resources of South Africa 1990 (Midgley, et al, 1994) may also be used. The Schulze and Maharaj evaporation may also become available from the CCWR in due course.*

Net evaporation losses can then be estimated from the surface area of water and riparian vegetation (with factors applied) multiplied by the net evaporation rate described above. A map of net annual evaporation is presented as an appendix to this report, to highlight areas where river losses are likely to be most significant.

The theoretical estimate of river losses derived from the above methodology can also be compared to a water balance of the river is suitable data are available. This will improve the confidence in the results, and will help to highlight additional problem areas such as losses to groundwater, or data errors in abstraction information. This method relies heavily on accurate flow measurements, which can often be improved by manual flow gaugings, as well as accurate abstraction information. Depending on the specific nature of the river and the scope of the study, varying levels of detail can be applied in performing the water balance. If a hydraulic model is not used, then it is important that the volumes of water entering and leaving the reach should be integrated over a sufficiently long period to minimise the effects of hydraulic attenuation. It is also important to examine flow data carefully to ensure that travel times can be taken into account.

From the research discussed in this report, the following recommendations are made:

- *The guidelines set out in this report should be used to estimate evaporation losses in future water resource studies on South African rivers.*
- *A set of aerial photographs should be taken of the Orange River during low flows. This will improve the accuracy of the loss estimates, and also provide useful information for a number of other applications.*
- *The Schulze and Maharaj (1991, 1997) 1'x1' data should be provided in digital format through the CCWR, so that this data can be used for loss estimates on South African rivers.*

- *Results from the ongoing research into the water consumption from riparian vegetation being carried out on the Kruger National Park rivers should be considered for use in future loss estimates on South African rivers.*
- *Hydraulic modelling should be considered in future studies to improve the understanding of the behaviour of rivers, and evaluation of abstractions and losses. Hydraulic modelling can also be considered as a tool to assist with the simultaneous calibration of various gauging stations that are currently calibrated in isolation from each other.*

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1. INTRODUCTION

South Africa is a semi-arid country where, in many areas, the available water resources within the river basins are unable to supply the rapidly increasing local water requirements. As the number and size of inter-basin transfers increases, more detailed water resource analysis and planning studies are being undertaken in both the donor and recipient basins. Evaporation losses are one of the many components evaluated in such studies, particularly in rivers where the net evaporation is significant relative to the water resources. In order to address the issue of evaporation losses from rivers, attention was directed primarily at the Orange River, due to its size and importance, after which the techniques developed on the Orange River can be applied to other rivers in South Africa.

1.1 BACKGROUND TO THE STUDY

The Orange River is the largest river in South Africa, both in terms of surface area and runoff. More than half the basin's 1 million km^2 surface area lies within South Africa, incorporating parts of six of South Africa's nine provinces. The remainder of the catchment falls within Lesotho, Namibia and Botswana, although the latter seldom if ever contributes to the flow in the Orange River (McKenzie *et al*, 1998). A locality plan of the Orange River basin is shown in **Figure 1.1** below, which also indicates the natural runoff in million m^3/a generated by the various sub-catchments.

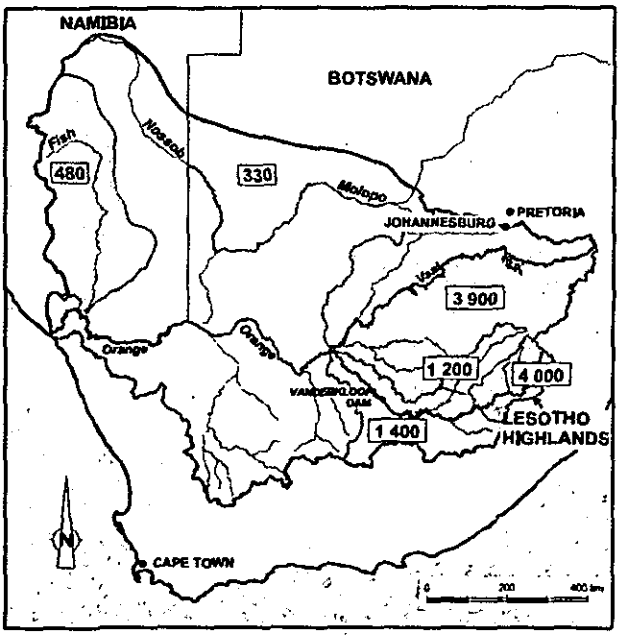


Figure 1.1 Map of the Orange River basin

From the figure, it is evident that most of the runoff is generated in the eastern part of the catchment, where the rainfall can be as high as 2 000 mm/a in parts, and gross evaporation less than 1 200 mm/a. From its source in the Lesotho Highlands, the Orange River flows approximately 2 300 km westward through progressively drier terrain towards the Atlantic Ocean. Near the river mouth, the river passes through one of the driest desert areas in the world, with rainfall less than 30 mm/a and gross evaporation of up to 3 000 mm/a.

Discounting the effect of development, the natural runoff of the Orange River is approximately 11 300 million m^3/a, which represents more than 20 % of the natural runoff for the whole of South Africa. This figure can vary depending on the period of historic record used in the evaluation, and on the assumptions made with respect to the river losses.

The Orange River basin is already highly developed, particularly in the catchment area of the Vaal River which is the main tributary of the Orange River. The Vaal River supplies water to Gauteng, the economic hub of South Africa, where rapidly increasing urban and industrial water requirements in the region have already necessitated a number of large inter-basin transfers. The most recent of these is the Lesotho Highlands Water Project (LHWP), the first phase of which is currently under construction. It is designed to transfer water from the upper reaches of the Orange River, called the Senqu River in Lesotho, to the Vaal River basin for use in Gauteng. Water from the Orange River is also transferred from Gariep Dam through the Orange / Fish Tunnel to the Eastern Cape for irrigation and urban use in the Fish and Sundays River basins. As a result of these developments in the Orange River basin, it is estimated that less than 50 % of the natural runoff currently reaches the river mouth. The runoff reaching the river mouth can vary considerably due to the erratic runoff patterns and the regulated nature of the river. For example, the runoff reaching the river mouth in a drought year can drop to below 1 000 million m^3, while during flood events more than 26 000 million m^3 can reach the river mouth in one year.

Most of the Orange River's runoff is generated in the high rainfall regions in the eastern part of the catchment. The river then flows through desert regions with very low rainfall and very high evaporation rates which result in low natural runoff and high evaporation losses. Due to the highly variable nature of the runoff, the evaporation losses usually exceed the runoff generated from tributaries, unlike most other rivers where evaporation losses are small relative to incremental runoff. In cases where the evaporation losses are small the hydrological analyses normally incorporate such losses implicitly as a reduction in natural incremental runoff. In the Orange River, however, evaporation losses from the main stream must be calculated separately from incremental runoff.

The first detailed study of the Orange River's water resources using modern resource analysis techniques, the Orange River System Analysis (ORSA), began in 1987. The study was the first to analyse the proposed LHWP together with the remainder of the Orange River basin, and thereby highlight the impact of the LHWP on the remaining water resources. It was also the first study to consider the environmental water requirements and evaporation losses from the lower Orange River. Previously, evaporation losses had been considered to be in the same order of magnitude as the incremental runoff generated downstream of the Orange/Vaal confluence, and both were therefore ignored. In the new study, the yield of the system was calculated up to Vanderkloof Dam (previously PK le Roux Dam), and the river losses were then considered together with irrigation as a water requirement to be supplied from the Dam.

During the first phase of the ORSA study, McKenzie (1989) attempted to calculate river losses downstream of the Orange/Vaal confluence using annual flow records, accounting for irrigation abstractions. River losses can often be established by such a water balance procedure. On the Orange River, however, many of the gauging stations were designed as irrigation diversion structures and not as low flow gauging structures. As such, they are used mainly to estimate flood flows, but are inaccurate at low flows with the result that they cannot be used to determine the losses. Accurate low flow measurement on the Orange River is very difficult due not only to the expense of constructing specialised measuring structures, but also the large sediment loads carried by the river. As a result, low flow measurement requires continual manual flow gaugings to revise discharge tables in addition to costly maintenance of the weirs to prevent sedimentation.

As a result of these problems, McKenzie (1989) also estimated the losses indirectly by dividing the Orange River into 7 reaches and measuring the average water surface width from aerial photographs. The average water surface width for the Orange River downstream of Vanderkloof Dam was found to be in the order of 300 m, and was assumed to remain reasonably constant over a range of flows. Evaporation from a river surface was assumed to be similar to pan evaporation, which is derived in South Africa using the Symon's Pan (commonly called the S-pan). A net evaporation rate was therefore calculated from gross S-pan evaporation (without pan-to-lake reduction factors), minus rainfall. This rate was multiplied by the surface area to produce a loss estimate of 950 million m^3/a, as indicated in **Table 1.1**. A-pan evaporation rates were also used as a check, producing a loss estimate of 1 200 million m^3/a. The lower value of 950 million m^3/a was however considered to be the more realistic estimate.

Table 1.1: Initial estimate of evaporation losses from the lower Orange River

Location	Length of section (km)	Average width (m)	Net evaporation (mm/a)	Evaporation losses ($10^6 m^3/a$)
Vanderkloof Dam to Vaal confluence	180	137	1 900	47
Vaal confluence to Prieska	155	195	2 100	63
Prieska to Boegoeberg	110	203	2 300	51
Boegoeberg to Upington	160	266	2 500	106
Upington to Vioolsdrift	450	374	2 600	438
Vioolsdrift to Fish confluence	140	374	2 400	126
Fish confluence to river mouth	140	374	2 250	118
Total	1335	294	2415	949

This estimate was later revised using updated surface areas (similar in magnitude) and S-pan evaporation rates, but applying pan-to-lake reduction factors. This yielded a net loss of 800 million m^3/a, which was adopted for the second phase of the ORSA study (McKenzie and Schäfer, 1990, 1992, McKenzie, *et al*, 1991, McKenzie and Stoffberg, 1993).

The calculation of losses has a direct influence on the yield available from the Orange River System. Since releases from Vanderkloof Dam are based on the calculated losses, overestimation of the losses will result in unnecessary excess water flowing into the Atlantic Ocean. The reduction from 950 million m^3/a to 800 million m^3/a makes 150 million m^3/a available for consumption elsewhere, which would otherwise not be *available. This can influence the phasing of possible future augmentation schemes* which in turn can result in a considerable saving for the national economy.

Until recently, the water resources of the Orange River were well in excess of the existing water requirements. This meant that releases could be made in excess of downstream requirements for generating additional hydroelectric power, with the result that the flows reaching the river mouth were often well in excess of the estuary requirements. In recent years, however, due to increased water requirements and erratic rainfall, water shortages in the Orange River system have occurred for the first time since the construction of Gariep and Vanderkloof Dams. In times of water shortage, releasing the correct flow from Vanderkloof Dam is particularly difficult since the dam is located almost 1 400 km from the river mouth. It is therefore important to calculate the required releases accurately in order to satisfy downstream water requirements without shortfalls or excess spillage at the river mouth. It is therefore becoming increasingly important to quantify the evaporation losses occurring from the Orange River between Vanderkloof Dam and the river mouth with greater accuracy.

1.2 ORANGE RIVER LOSSES STUDY - PHASE 1

As a result of the water shortages, and the magnitude of the losses as indicated by the ORSA study, a research proposal was submitted through BKS to the Water Research Commission. In 1993, funding was approved for a one year first phase study, with support also to be provided by the DWAF. The study was entitled the Orange River Losses Study - Phase 1 (McKenzie *et al*, 1993, McKenzie and Roth, 1994, McKenzie and Stoffberg, 1995a). The primary objective was to improve the ORSA estimates of evaporation losses between Vanderkloof Dam to the river mouth. Although further reference will be made to specific aspects of this study later in this report, the main procedures followed and pertinent results are summarised below:

- A workshop was held, to which experts in various disciplines were invited to contribute. The principal components influencing river losses were identified as 1) the water surface area, 2) variability of surface area with flow, 3) area of riparian vegetation, 4) evaporation from the water surface, 5) evapotranspiration from the riparian vetetation, and 6) river bed and bank seepage. With regard to the last item, namely bed and bank seepage, some delegates suggested that seepage would constitute a net loss from the Orange River, while others thought that there may be a net contribution to the river from groundwater. For the rest of the first phase, it was therefore assumed that losses or accretions due to groundwater interaction were small relative to the dominant processes of evaporation and evapotranspiration, and could thus be ignored.

- Surface areas of water and of riparian vegetation were measured from aerial photography. Some different sets of aerial photos were examined, but the change in water surface area with flows was thought to be small enough to assume a constant area over a range of flows of approximately 100 m^3/s to 200 m^3/s.

- S-pan data were used to calculate the evaporation losses, based on the surface areas given above. The surface area of riparian vegetation was added to the surface area of the water, assuming that the evapotranspiration from the vegetation is similar to that of an open water surface. A summary of the results is presented in **Table 1.2**.

Table 1.2: Summary of net evaporation losses from the Orange River

Reach	From	To	Length (km)	Areas for evaporation (km²)			Precipitation (mm/a)	Gross Evaporation (mm/a)	Net Evaporation (mm/a)	River Losses	
				Water surface	Vegetation	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

Besides S-pan data, various other evaporation measurements were also considered, including A-pan data and indirect equations based on meteorological data, such as the Penman and Linacre equations. The table showing the comparison is reproduced here to highlight the influence of evaporation measurement on the net loss calculation:

Table 1.3: Comparison of river loss based on various approaches

Point evaporation data used	Mean evaporation (mm/a)	Net river loss* (million m³/a)
Original estimate	1 981	800
S-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.

The CSIR were also approached to carry out a study involving the establishment of Bowen ratio equipment on the Orange River at Upington to measure the energy balance. During a 30 day period in July 1993, the Bowen ratio approach suggested that the evaporation rates from the river were generally higher than A-pan data. Variations in daily A-pan measurements were found when figures from the control pan next to the river were compared to figures from other nearby pans. The data showed considerable scatter (as high as 80 % on some days), indicating that it is extremely difficult to predict river evaporation from pan data, especially on a daily basis. Although it was only based on a short period of measurement, the study suggested that the evaporation rates from a moving river surface are likely to be higher than originally anticipated (ie higher than S-pan data).

- A set of manual flow gaugings was carried out on the Orange River during July 1993. Prior to the gaugings, the releases from Vanderkloof Dam were held constant at 30 m^3/s for eight weeks in order to maintain some form of equilibrium. This allowed simultaneous flow gaugings at various locations along the river, from which the losses for various reaches could be calculated. On the upper and middle reaches of the river, however, where large areas are irrigated close to the river, the losses were masked by irrigation return flows. Return flows had previously been ignored in water balance calculations, in order to prevent overestimation of the water resources. The flow gauging exercise, however, did produce useful results in the lower reaches of the Orange River, where irrigation activity is relatively small and the return flows are negligible. In these reaches the losses were found to be similar in magnitude to the theoretical estimates based on areas and evaporation rates (960 million m^3/a).

Following the preliminary findings of the first phase, approval was granted by the WRC in 1994 for a four year project (River Losses Study - Phase 2) to evaluate the river losses in more detail. Once again, the DWAF provided considerable support which contributed greatly to the success of the study. At the same time, a study was also initiated by DWAF to extend and improve the water resource analyses of the ORSA study, and establish a framework for the future development, allocation and utilisation of Orange River water. It was anticipated that the latter study, called the Orange River Replanning Study (ORRS), would run in parallel to the River Losses Study and make use of its findings.

1.3 PURPOSE OF THE STUDY

The purpose of the Phase 2 of the River Losses Study was to investigate the processes driving evaporation losses in order to refine the previous estimates of evaporation losses from the Orange River between Vanderkloof Dam and the river mouth, and also to derive a general methodology for estimating losses from other rivers in South Africa.

Although rough calculations of the river losses had been made, concern had been expressed regarding the accuracy of these estimates. Although the first phase of the Losses Study was able to answer some of the questions, many uncertainties still existed since very little research in this field had been undertaken anywhere else in the world. As described previously, the Orange River had already been experiencing water shortages, and concern was expressed by many that the development of the LHWP would further aggravate the situation. It was therefore important to derive a more accurate estimate of the losses downstream of Vanderkloof Dam, since it had been established that the losses constitute a significant portion of the Orange River's water resources.

An additional reason for using the Orange River as a case study, is the fact that the losses are significant in terms of the overall water balance, particularly on the lower reaches of the river. The lower 600 km of the Orange River, from Augrabies Falls to the river mouth, is subject to extremely high evaporation, low rainfall, and very little irrigation. As a result, evaporation loss measurements in this reach are not influenced significantly by errors in rainfall data or in the calculation of irrigation abstractions and return flows. This lower portion of the river was therefore ideal for an intensive evaluation of river losses, from which a methodology for estimating river losses elsewhere can be derived. It was also envisaged at the start of the study that the methodology derived from the work on the Orange River would be verified on at least one other river, such as the Vaal River, to validate its applicability to other rivers in South Africa. A set of guidelines could then be prepared indicating the most suitable methods for calculating evaporation losses from South African rivers.

In order to achieve these goals, it was important to identify the key issues requiring attention. Based on the experience gained during the first phase of the River Losses Study, the following areas were identified for further investigation:

- Water surface areas;

- Variability of water surface areas with flow;
- Riparian vegetation areas (both trees and reeds);
- Evaporation rates from flowing water;
- Evapotranspiration rates (both trees and reeds).

In this research project, it was important to understand and quantify the different components influencing the calculation of evaporation losses. It was also important to test and verify the proposed methodology, using a variety of different techniques to ensure that the proposed methodology is realistic. In the case of river losses, physical verification is undertaken using a water balance approach. In order to carry out an accurate water balance, additional factors influencing the water balance, which may not be related to the losses, need to be quantified. These include:

- Rainfall on the water surface,
- Inflows from tributaries,
- Water abstractions (irrigation and municipal/industrial),
- Return flow volumes (irrigation and municipal/industrial),
- Retention time of return flows (applicable to irrigation only),
- Accuracy of flow measurements (weirs and/or manual gaugings),
- Hydraulic attenuation of flow in the river.

With regard to water abstractions and return flow volumes, the study team's intention was to work closely with the ORRS project team, who would also require this information. It was furthermore decided to investigate the use of tracer technology in evaluating the retention time of irrigation return flows, since the impact of the retention time on the water balance was unknown.

As mentioned previously, the flow recording stations on the Orange River are not sufficiently accurate at low flows to allow calculation losses directly from the flow data. It was therefore decided to carry out further manual flow gaugings in order to improve the estimates of flow for the water balance. It was also decided to use a hydraulic model to process the results of the flow measurements, in order to incorporate the effect of hydrograph attenuation. These aspects are discussed in more detail in the course of the report.

1.4 PURPOSE OF THIS REPORT

The purpose of this report is to document the methods used and main findings resulting from Phase 2 of the River Losses Study. Improved estimates of evaporation losses downstream of Vanderkloof Dam are presented, together with the general methodology which was developed for calculating evaporation losses from South African rivers. The structure of the report is as follows:

- In **Section 2**, the various processes influencing river losses and their calculation are identified.

- In **Section 3**, the available methods for estimating surface areas of water and of riparian vegetation are discussed. The specific methods used in this study are addressed in more detail, and surface areas of the Orange River are presented.

- In **Section 4**, the available methods for estimating evaporation and evapotranspiration rates are discussed. In this section, the work carried out by the CSIR using Bowen ratio energy balance technique is evaluated, and evaporation rates used for calculating evaporation losses from the Orange River are presented.

- In **Section 5**, the verification of the river loss methodology by field measurements is discussed. Results of a tracer study into irrigation return flow retention times are discussed, and water requirements and return flows used in the water balance are presented. The manual flow gaugings undertaken for loss verification on the Orange and Vaal Rivers are discussed in detail, together with the application of the hydraulic model in processing the results.

- In **Section 6**, summarised guidelines for calculating river losses are presented. A GIS map of net annual evaporation is also presented, which highlights areas where losses are likely to be significant, and which can be used to obtain a first order estimate of river losses.

- Finally, conclusions are drawn and recommendations made in **Sections 7 and 8** respectively.

2. METHODOLOGY

2.1 CONCEPTUAL MODEL

A preliminary estimate of losses from a river can usually be obtained indirectly by measuring the surface areas of water and riparian vegetation, for example by using aerial photos, and multiplying the water surface area by an appropriate evaporation rate, for example from evaporation pan data. Alternatively, losses can also be determined directly from flow measurements on the river using a water balance approach, accounting for water which may enter or exit the river by other means. The latter approach may also used in conjunction with the first approach, to improve the confidence in the final answer. If the water balance approach is to be used, factors influencing the calculation must be identified and their relative importance quantified. Some of the more important components are listed below, and are also illustrated graphically in **Figure 2.1**:

- Water surface areas, excluding sand banks, from which evaporation takes place. The water surface area varies with flow and therefore also with time and space. The variation of flow with time will be subject to hydraulic attenuation, which is a function of many variables and varies strongly from place to place along the river. The evaporation from the water surface varies both temporally and spatially. Rainfall on the water surface will also vary temporally and spatially.
- Riparian vegetation areas, comprising both trees and reeds, from which evapotranspiration takes place. The reeds often grow on sand banks close to the water's edge, and may therefore become partially or completely inundated at higher flows. The rate of evapotranspiration from trees and reeds will differ from each other, and will also vary temporally and spatially.
- Inflows from tributaries, which vary with time. These can occur as surface flow or as subsurface flow which is difficult to identify or quantify.
- Water abstractions for irrigation and municipal/industrial purposes, which will vary with time. Irrigation abstractions in particular exhibit a strong seasonal distribution, and may also vary diurnally or weekly depending on the amount of off-channel storage and whether the application is automated or not.

- Return flows from irrigation and municipal/industrial centres. Return flows from irrigation will be subject to retention in the soil, and will vary with time as well as with the irrigation abstraction.

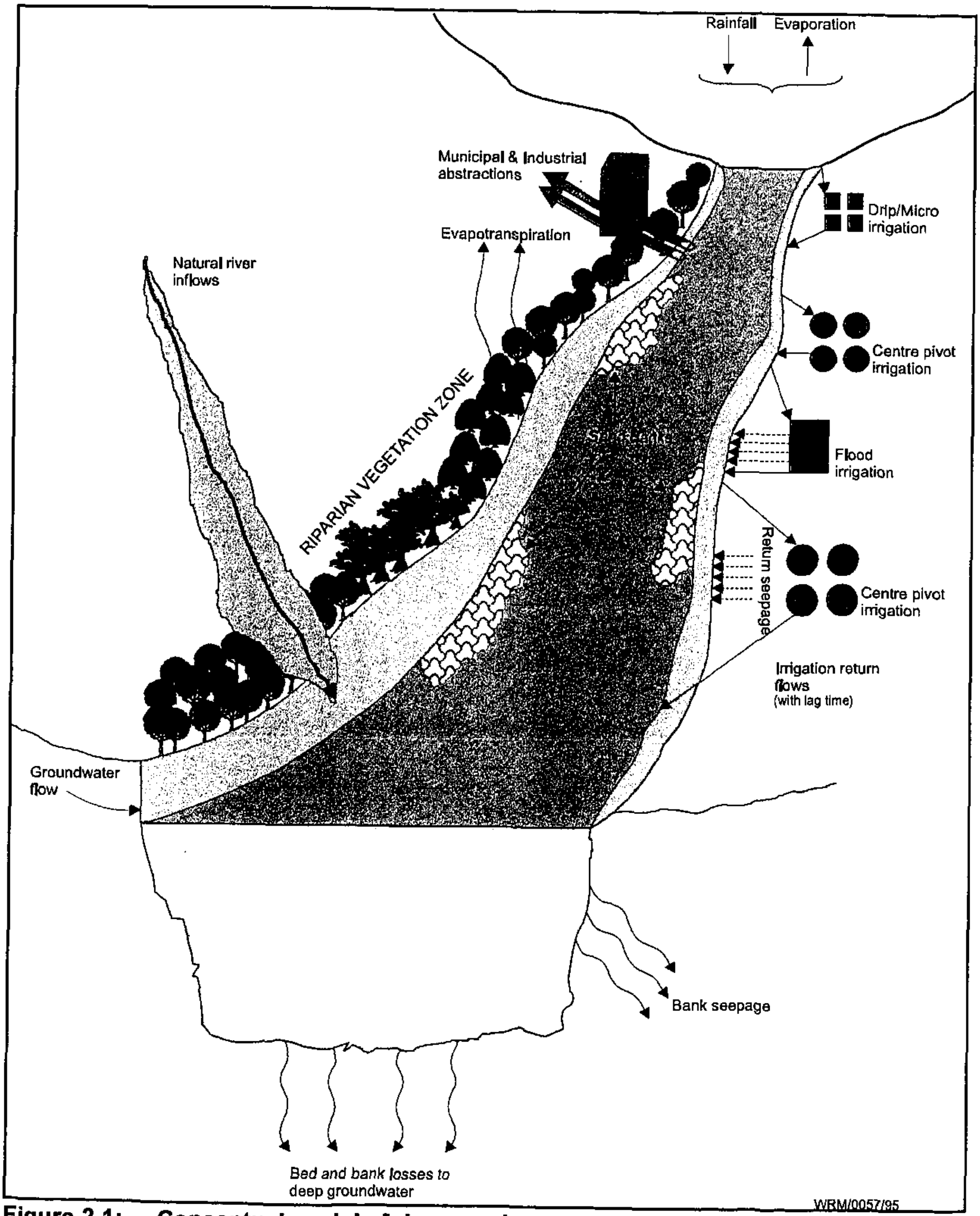


Figure 2.1: Conceptual model of river reach

2.2 APPROACH ADOPTED IN THIS STUDY

In accordance with the scientific method, the basic approach followed in this study was to first calculate a theoretical loss estimate indirectly based on a measured evaporation rate multiplied by the relevant surface areas. This theoretical estimate was then tested directly using the water balance approach, based on field measurements of the flow. The comparison of theoretical calculations with practical loss measurements on the Orange River was then used to verify and refine the methodology, which was then verified on a portion of the Vaal River. Various procedures are described in detail as evaluated or used in the study during the development of the methodology. The recommended methodology is summarised at the end of the report in the form of guidelines for calculating evaporation losses from other South African rivers.

3. EVAPORATION AND EVAPOTRANSPIRATION AREAS

3.1 METHODS AVAILABLE FOR ESTABLISHING AREAS

There are a number of different methods which can be used to establish the surface area of a river and its riparian vegetation. These include satellite image analysis, airborne videography, aerial photography and field surveys. These are each discussed briefly below, along with some general considerations which apply to all the methods.

3.1.1 General considerations

Before embarking on an exercise to measure the surface area of a river for the purpose of loss a calculation, there are some basic decisions which have to be taken. One of the first decisions is the flow at which the surface area is required. In most natural rivers, the flow has a significant influence on the water surface area. The range of applicable flows must therefore be identified and will usually include low flows, since accurate information on the losses is usually most critical during long dry periods when water shortages occur. It is therefore desirable to collect information about the river while flows in the river are within the desired range. Additional sets of information, showing the river at different flows, may also be required if estimates of losses are required over a large range of flows. If existing information is to be used, such as existing satellite images, aerial photographs or surveys, then it is important to establish the dates on which the data were collected, so that the flows represented by the data set can be established from the flow records. In certain rivers, the time of data collection may also have an influence on the riparian vegetation, for example reed beds may vary seasonally or may have been removed by flood events.

Two further decisions required are the method to be used to estimate the surface areas, and the level of detail. These are particularly important, since the available finances and time must be balanced with the importance of the results and the consequences of errors in the loss calculation. These decisions may also be influenced by additional purposes for which the results may be used. Some of the more common methods for estimating areas of water surfaces and vegetation are discussed later in this chapter, and where possible an indication of the related costs (in 1997 Rands) is given based on investigations on the Orange River.

There are also some general guidelines, applicable to all the methods, regarding the classification of water surface, sand banks, and riparian vegetation. If the process is to be automated in any way, then visual checking of the resulting classification is essential. Water surface areas, for example, can sometimes erroneously include some sand banks. Sand banks do not contribute significantly to river losses, for reasons discussed later in the report. Estimation of riparian vegetation areas is often a difficult and sometimes subjective process, even if high resolution information is available. It is important to distinguish between vegetation fed by the river and trees fed by natural rainfall events. Where possible, reeds should be distinguished from trees, since the evapotranspiration from reeds is considerably higher than from trees. Consideration must be given to the density of the vegetation, since it can influence the overall water consumption. Part of the sparse vegetation should therefore be excluded, whether visually or by digital means, so that the total resulting area represents that of dense trees or reeds. If the results are required over a large range of flows, then the extent to which reeds or trees become partially drowned at higher flows must also be considered. Different sets of information can also help to establish the degree of reed encroachment. This is particularly important in well regulated rivers where reed reduction events, such as large floods or periods of exceptionally low flow, may be spaced many years apart.

These concepts are described further below, as pertaining to each of the available methods. Specific problems encountered on the Orange River, and the results obtained by the different methods, are discussed in **Section 3.2**.

3.1.2 Satellite image analysis

Analysis of satellite images can be a cost effective method of estimating surface areas for large scale projects. Types of satellite imagery available are Russian satellite data, Spot Pan, Spot XS, and Landsat TM.

- The Russian data have a ground resolution (or pixel size) of 2-5m, and are panchromatic images (black and white). Classification by means of digital manipulation of the data is therefore difficult, and it is likely that considerable visual classification would be required. It is not certain at this stage whether panchromatic image classification can be used to measure areas of riparian vegetation. Preliminary enquiries indicated that the images would cost in the order of $25 (US) per square kilometer, to which the costs of processing the images must still be added.

- Spot Pan has a ground resolution of ±10mx10m, but is also only a panchromatic image, indicating that digital classification is difficult.
- Spot XS has a ground resolution of ±20mx20m, and has 3 frequency band sensors. The Landsat TM (Thematic Mapper) has a ground resolution of ±30mx30m, and has 7 frequency bands available.
- Landsat TM data is the most reasonable compared to the other sources and has the advantage of additional bands which are useful not only in the classification of water, but are also particularly effective in identifying vegetation.

An advantage of satellite imagery is that images can usually be obtained and processed at relatively short notice. This can make this method faster than taking aerial photos of the river, particularly for large catchments. Satellite imagery also has an advantage if different sets of information are sought at regular intervals. The data are captured in digital format, with the result that scanning of images is not required. The processing systems are also compatible with GIS systems, for ease of data extraction for other purposes. Catalogues of archived satellite images may be obtained from the Satellite Applications Centre of the CSIR, or previewed on their web site at http://www.sac.co.za . The cost of obtaining new Landsat satellite images from Vanderkloof Dam to the river mouth and analysing them to extract surface areas was estimated to be R120 000 (incl VAT).

One of the main problems encountered with the use of satellite images concerns the errors in the digital classification. For example, water surface areas may be excessively large due to the inclusion of sand banks. Vegetation, although clearly visible on infrared bands, is difficult to categorise into riparian vegetation and irrigation near the river. Over-estimation of irrigated or vegetated areas can also occur due the inclusion of non-vegetated areas. It is always important with any automated process that extensive visual and preferably also ground verification accompanies the digital classification process, to ensure that the results are meaningful. On the Orange River, for example, both the water surface area and the riparian vegetation were initially grossly overestimated by the satellite imagery. The reasons for this are discussed in more detail later, since satellite imagery was one of the methods used in this study. Similar problems have also been encountered in other studies, for example McKenzie and De Jager (1997), where some farm dams were initially excluded from classification of water bodies due to the turbidity of the water.

3.1.3 Aerial photography

Areas of water surface and riparian vegetation can be successfully measured by hand from aerial photographs. Orthophotos or orthophoto maps are preferable if available, since they have been orthogonally corrected and their scale is therefore more accurate. Care should therefore be exercised when using contact prints of aerial photographs, to ensure that scale anomalies are within reasonable limits. In South Africa, existing aerial photography of rivers can be obtained from the Department of Regional and Land Affairs (Surveys and Land Information) and also from the Department of Water Affairs and Forestry. The CSIR (Environmentek) and the Department of Transport also have photographs of selected locations. The cost of obtaining a new set of aerial photographs of the Orange River from Vanderkloof Dam to the river mouth (a distance of almost 1 400 km) at 1:20 000 scale was estimated at R280 000 for the photography, plus an additional R20 000 (incl VAT) to measure the surface areas by hand.

3.1.4 Aerial and field surveys

An aerial survey (mapping from aerial photographs) is usually more accurate than working straight from aerial photographs, but is considerably more expensive due to field work required for control of the photography, and the photogrammetric mapping. This is especially true in the case of the Orange River where inaccessible terrain results in high field work expenses. Controlled aerial photography for the 1 400 km of the Orange River downstream of Vanderkloof Dam was estimated to cost approximately R 1,3 million, without mapping.

Cartographers can now use scanned photos in conjunction with digital correction and triangulation. As long as the maps are available in digital form on computer, the areas of water surface and riparian vegetation can be marked on the maps, and then extracted digitally using one of the many programs available for such work. It may also be possible to use digital classification on scanned photos, although this is likely to be difficult due to the fact that so many images are used which may have marginally different exposures and may therefore require adjustments to the colour filters. Field surveys on their own (without photography) are time consuming and costly, and will seldom be used to measure surface areas unless the survey is also required for another purpose. Cross sections of a river from field surveys or aerial surveys at low flows can also be used in a hydraulic model to derive the water surface areas over a wide range of flows.

3.1.5 Airborne videography

Airborne videography is another potential method which comprises a video camera mounted in a helicopter flying over the river. Gathering the video information is relatively inexpensive, and this technique can therefore readily be used qualitatively, in conjunction with other techniques, for example to help distinguish reeds from trees. If quantitative output is required, then the camera is mounted together with navigational equipment (including a GPS) in the helicopter. The output from these instruments and the camera are captured synchronously in a computer database. This allows the frames to be corrected based on the height of the camera above the river, and merged into a mosaic. At the time of this study, the technique was still in the process of being developed, and was not considered cost-effective due to time-consuming processing of the images required for quantitative results. With the improvement of technology and process automation, this method may become a practical alternative in the future.

3.1.6 Airborne laser scanning

Airborne laser scanning is a relatively new technique, comprising laser equipment mounted in a helicopter flying over the river. The laser is usually set to low power, and therefore does not penetrate water. A scanned image is recorded and orthogonally corrected while flying. On top of this, the laser scanner produces a Digital Terrain Model (DTM) of the entire 500 - 700 m wide strip flown, with or without vegetation. The output can be used to generate highly accurate orthophoto maps, as well as being useful for DTM manipulation. River cross sections are one of the many products which could be extracted from the DTM. Initial estimates were given in the order of R 1 000 per kilometre of flight path, or R 1,4 million for the 1 400 km of the Orange River downstream of Vanderkloof Dam.

3.2 METHODS USED IN THIS STUDY

3.2.1 Satellite image analysis

As part of the first phase of the river losses study, and in conjunction with DWAF Project Planning and the WRC, DWAF's Institute for Water Quality Studies (previously Hydrological Research Institute) obtained and processed satellite images of the Orange River from Vanderkloof Dam to the river mouth. The images were obtained from the Landsat TM satellite, which has a pixel resolution of ±30mx30m. Three spectral reflectance bands were used to allow the digital selection of vegetation as well as water surface areas. The low pixel resolution was not expected to be a problem, since the Orange River is relatively wide, and errors in the identification of water surface should tend to balance through inclusion and exclusion of small areas of water. Problems were identified in the classification procedure, however, when the results were compared to more recent information from aerial photography. The satellite imagery was found to overestimate the water surface area by more than 50 % on some reaches. Subsequent visual inspection of the images and their resulting classifications of water, revealed that the overestimation was due to erroneous inclusion of sand banks and some types of rocks in the water surface class. The satellite imagery analysis also overestimated the areas of riparian vegetation, by more than 100 % in some reaches. This was due to inclusion of some irrigated lands since it is very difficult to differentiate between the irrigated areas and riparian vegetation, particularly in areas like the Upington Islands. Other sources of errors are the inclusion of very sparse vegetation, inclusion of vegetation remote from the river on tributaries which are not fed by Orange River water, and inclusion of certain shadowed hillsides close to the river because of similar reflectance properties. A portion of a satellite image at Torquay, just upstream of the Orange-Vaal confluence, is shown in **Figure 3.1**. Although classification markings are indicated on the image, it is important to note that these were not the final classifications.

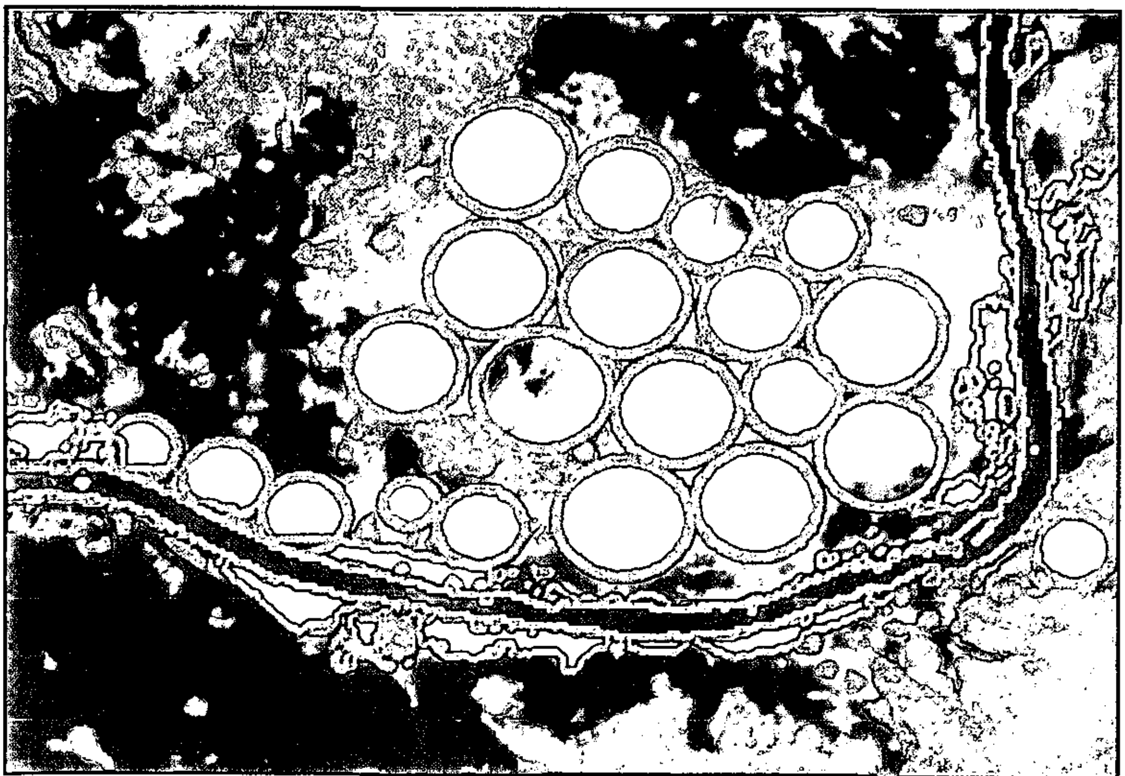


Figure 3.1: Satellite image at Torquay with classification markings

Because classification is based on reflectance, it is possible that different types of objects can have similar reflectance, and therefore end up in the same class. For example, it is difficult to distinguish between irrigated lands and riparian vegetation, since the geometric form of the irrigated lands is not always visible from the satellite images. Extensive visual verification is therefore required to ensure that the classification process provides the correct results. Existing aerial photography or videography can be useful for checking the classes for errors. **Table 3.1** below presents the results of satellite image analysis for the Orange River, as obtained by Parker (1993). The images used were captured between August and November 1992. The flows in the upper half of the river (upstream of Kakamas) were all approximately 80 m^3/s, while flows in the lower half of the river were approximately 40-50 m^3/s at the times that the images were captured. The surface areas resulting from the analysis should therefore represent a release scenario of between 50 m^3/s and 120 m^3/s.

Table 3.1: Areas obtained by satellite image analysis

Reach Nr	Description	Riparian vegetation (km^2)	Water surface (km^2)
1	Vanderkloof to Vaal confluence	20,56	38,59
2	Vaal confluence to Boegoeberg	20,88	53,61
3	Boegoeberg to Kakamas	40,95	82,01
4	Kakamas to Namibian border	42,93	18,41
5	Namibian border to Vioolsdrift	48,06	65,19
6	Vioolsdrift to Fish confluence	12,27	21,24
7	Fish confluence to river mouth	22,90	32,25
	Total	208,55	311,30

3.2.2 Aerial photography

Due to the overestimation of areas found by the analysis of satellite images, aerial photographs were used to establish the area water surface and of riparian vegetation of the Orange River. A number of sets of aerial photographs were obtained from DWAF and from Surveys and Land Information (Department of Regional and Land Affairs) in Mowbray. Comparison of different sets of photographs taken at different flows revealed that the flow in the river has a significant effect on the water surface areas. Most of the previous estimates of water surface areas for the ORSA and Phase 1 of the River Losses Study, were made from aerial photographs with flows between 400 m³/s and 1 000 m³/s. At low flows, when an accurate knowledge of evaporation losses is important, the water surface areas are considerably smaller. For example, the surface area at 50 m³/s was found to be approximately half that at 400 m³/s. An illustration of the change in surface areas with flows from different sets of aerial photographs at a location near Onseepkans is given in **Figure 3.2**.

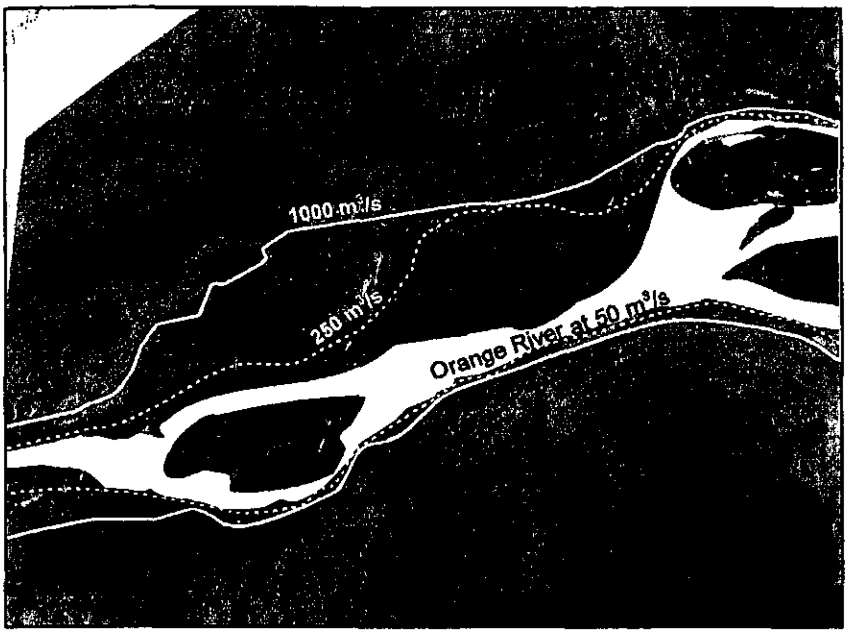


Figure 3.2: Change of surface area with flow

A photographic illustration of the change of surface areas with flow at Zeekoebaart Weir, just downstream of Boegoeberg Dam, is presented in **Figure 3.3**. Photos of the weir are shown taken at approximately 25 m³/s and 1 000 m³/s from the left bank of the river, and then from the air looking towards the left bank (the latter two photos by R.Palmer).

Unfortunately, very few aerial photographs of the Orange River exist at low flows. The low flow surface area of different reaches of the river therefore had to be estimated by examining the rate of change of surface area with flow at higher flows. An example of the method used is shown below in **Figure 3.4**. The area of the reach was measured from two sets of aerial photographs, in this example at 400 m³/s and at 100 m³/s respectively. These were then plotted on a double log graph, and extrapolated to estimate the area at lower flows, such as 50 m³/s or less. The hydraulic model was also used to check the slope of the line, particularly for reaches where the flows for the aerial photographs were close together. Although the geometry in the hydraulic model was not very accurate for low flows, the agreement with the available aerial photos was good in most reaches. The use of the double log plot was also confirmed using the hydraulic model over short reaches where detailed river bed surveys existed, which had been carried out for Instream Flow Requirements (IFR) evaluations.

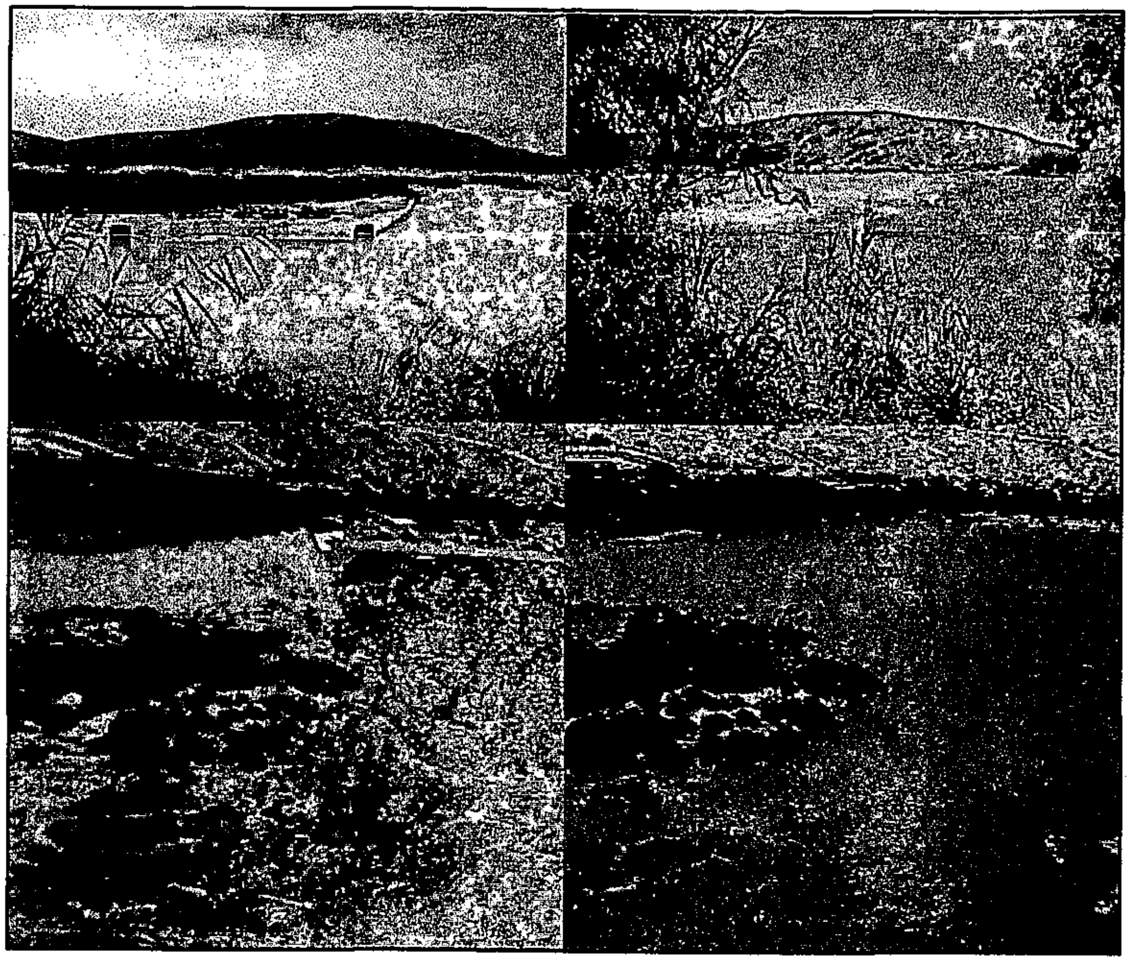


Figure 3.3: Zeekoebaart Weir at different flows

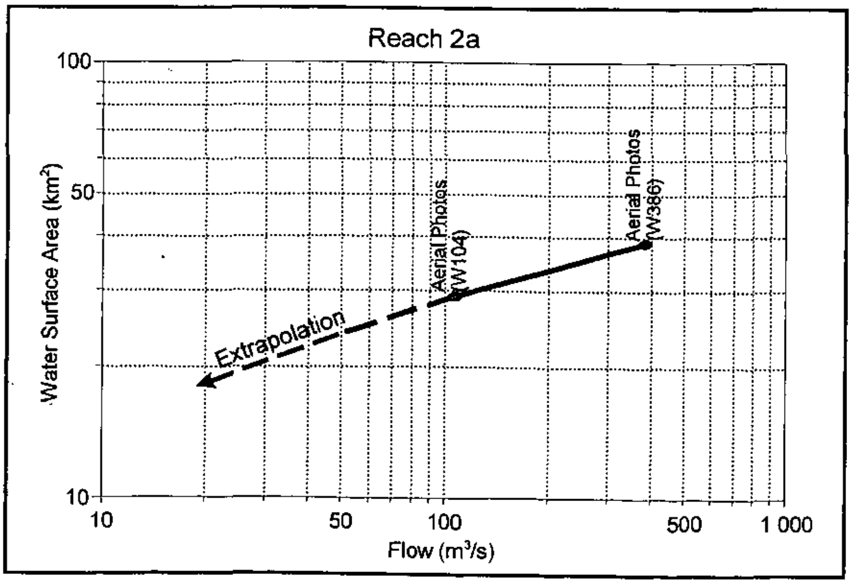


Figure 3.4: Example of area extrapolation

The areas deduced from the aerial photography, after the extrapolation had been completed, are presented in **Section 3.3**. As a result of the extrapolation of areas to low flows, the surface areas at low flows may still incorporate errors. Plans for new aerial photographs of the Orange River from Vanderkloof Dam to the river mouth to be taken during low flows, were initiated during the study in order to improve the accuracy of surface area estimates at low flows. The flows in the Orange River over the 1996 to 1998 period were too high to allow photographs at low flows to be taken. DWAF still intends to take photographs of the river at low flows taken at the next suitable opportunity, which will improve the confidence in loss estimates for the Orange River at low flows.

3.3 AREAS ADOPTED FOR THE ORANGE RIVER

As discussed previously, aerial photographs were used to measure the water surface areas at different flows, as well as the riparian vegetation along the Orange River. The results are presented in **Table 3.2** for four different release scenarios from Vanderkloof Dam, including 20 m^3/s (winter minimum flow scenario), 50 m^3/s (average annual downstream requirements), 120 m^3/s (double previous scenario), and 400 m^3/s (maximum turbine releases). The areas in the table are illustrated graphically in **Figure 3.5**, from which it can be seen that the total area versus flow no longer forms a straight line on the double log plot. This is due to the summation of different reaches which do not have the same slope (rate of change of area with flow).

Based on the different sets of aerial photos, the surface area of trees was assumed to remain virtually constant for all flows up to and including 400 m^3/s, while the reed area remains constant for all flows up to and including 120 m^3/s. In other words, most of the reeds are assumed to be drowned at flows of 400 m^3/s.

Table 3.2: Surface areas adopted for the Orange River

Reach	From	To	Area of Water (km²)				Area of Rip Veg (km²)	
			20m³/s	50m³/s	120m³/s	400m³/s	Reeds	Trees
1	Vanderkloof	Marksdrift	12,8	17,8	22,5	31,3	0,5	7,7
2a	Marksdrift	Prieska	18,5	23,8	29,0	38,7	1,2	8,4
2b	Prieska	Boegoberg	11,7	14,8	18,0	23,8	1,0	3,5
3a	Boegoberg	Gifkloof	18,2	23,2	28,5	40,0	1,3	9,9
3b	Gifkloof	Neusberg	8,0	11,0	15,2	26,0	1,7	6,0
4	Neusberg	20°E	6,6	8,3	10,7	17,0	1,5	5,1
5a	20°E	Pella	13,5	16,8	22,0	36,0	1,4	6,0
5b	Pella	Vioolsdrift	15,7	19,5	26,0	46,0	2,4	7,4
6	Vioolsdrift	Fish	9,5	12,0	17,0	32,0	3,1	4,7
7a	Fish	BrandKaros	7,6	9,4	13,4	24,5	2,7	2,0
7b	BrandKaros	Mouth	3,2	4,1	6,5	14,2	1,0	7,5
Total	Vanderkloof	Mouth	125,3	160,7	208,8	329,5	17,9	68,2

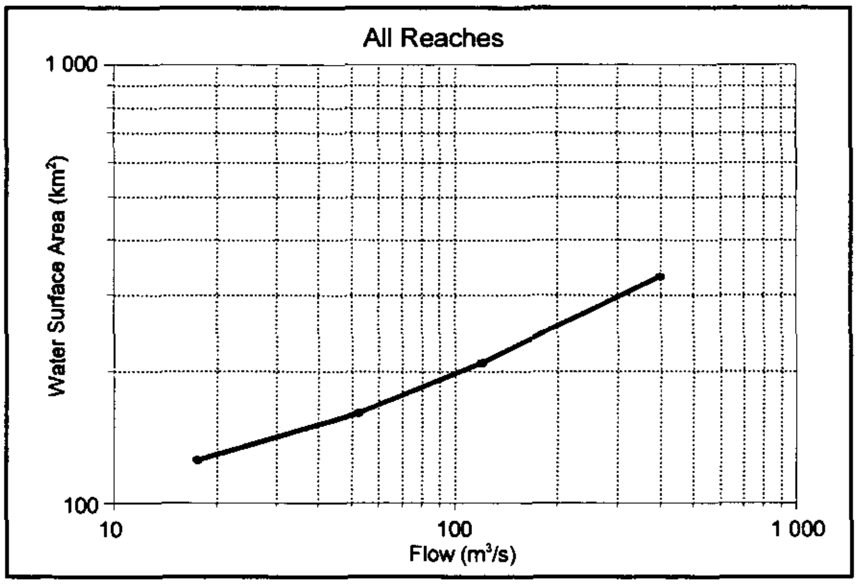


Figure 3.5: Water surface area vs flow in Orange River

4. EVAPORATION AND EVAPOTRANSPIRATION RATES

4.1 METHODS AVAILABLE FOR ESTABLISHING EVAPORATION RATES

There are many methods available for measuring potential evaporation, comprising both direct and indirect methods. The direct methods include the circular American class A-pan used in South Africa by agricultural hydrologists and the larger square Symons pan (S-pan) used in South Africa to estimate evaporation from reservoirs. The indirect methods, in increasing order of complexity and data requirements, include:

- temperature based equations (eg Blaney-Criddle);
- temperature and radiation based equations (eg Priestly-Taylor);
- combination equations which include allowance for humidity and wind (eg Penman or Penman-Monteith);
- intensive evaluations of the energy balance at the evaporating surface (eg Bowen ratio).

These and similar methods are discussed thoroughly in *Jensen et al (1990)*, where it is shown that the different methods can yield values varying by as much as ±20 % in either direction from potential evapotranspiration measurements carried out using lysimeters on standard grass reference surfaces. In other words, there can be as much as 40 % difference between the various methods. For the purpose of this study, Bowen ratio measurements were taken in the Orange River at Upington, which is described in more detail in **Section 4.2**. These results are then compared to other methods used in **Section 4.3**.

Methods for estimating evapotranspiration include applying factors to potential evaporation (measured by the techniques described above), energy balance measurements above the plant canopy, or lysimeters tests. Extrapolation of results from one site to another is difficult without extensive field data acquisition, since evapotranspiration rates can vary considerably according to species, density, season, stage of growth and leaf area index. Unfortunately, extrapolation of results from other research had to be used on the Orange River, as described in **Section 4.4**.

4.2 BOWEN RATIO EVAPORATION STUDY ON THE ORANGE RIVER

In preliminary estimates of the losses (McKenzie, 1989), it was shown that the choice of evaporation had a significant influence on the results. Estimates varied from 800 million m^3/a using S-pan evaporation with pan-to-lake factors, to 1 200 million m^3/a if

A-pan data were used. Although the lower figure was recommended as the more realistic, many uncertainties still existed. As a result, it was proposed that evaporation rates should be one of the variables examined in Phase 1 of the Losses Study. The Environmentek (previously Forestek) division of CSIR were therefore approached to set up Bowen ratio equipment in the Orange River near Upington (about half way between Vanderkloof Dam and the river mouth). A one month trial study took place during August 1993 (Everson, 1994), in order to evaluate the suitability of the technique. A picture of the equipment is presented in **Figure 4.1**, along with an A-pan set up next to the river for the duration of the experiment.

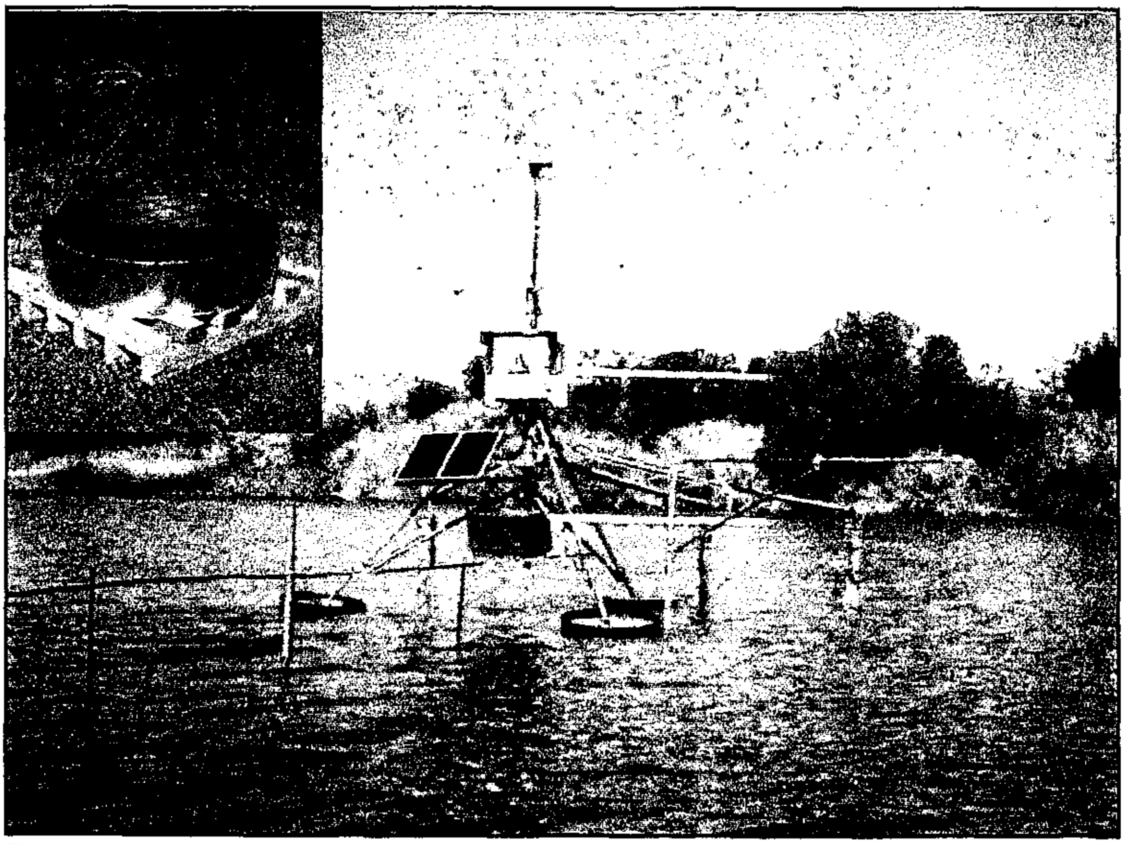


Figure 4.1: Bowen ratio equipment and A-pan

During the study, examination of data from four A-pans in Upington revealed considerable scatter, and that individual pans may vary by as much as 80 % on a daily basis. This was attributed partly to immediate environment (whether mounted on wood allowing free airflow or not, and whether surrounded by grass or bare sand), and also to observer accuracy (whether readings were taken at 1 mm or 0.5 mm intervals). Variation between the monthly totals for the pans varied by approximately 40 %, with some being higher than the monthly total for the Bowen ratio evaporation, and others below. During the study, automatic weather station data were also gathered from the

Agricultural Research station near the river. It was concluded that land based weather station data can also be used to determine evaporation rates from the surface of the river. This was based on only one month of data, gathered during winter, and it was therefore recommended that the Bowen ratio method be tested over a longer period. Due to the expensive equipment and large volumes of data to be analysed, this could not be undertaken as part of Phase 2 of the River Losses Study. As a result, separate research proposal was submitted by Environmentek to the WRC, and funding was granted for a further 18 month study (Everson, 1996, 1997), with close co-operation from the River Losses study team. The full details of research carried out will be documented in a WRC report, to be published during 1998. A brief summary of the findings is presented below, after which an evaluation of the results is presented in **Section 4.3** where they are compared with the other evaporation sources.

The Bowen ratio equipment was reinstalled in the river at the same site near Upington, for a six month period from June 1995 to December 1995. Although it was originally intended to gather data for a full year, rising water levels in the Orange River necessitated the early removal of the equipment in January 1996. Analysis of the data indicated that the evaporation from the water surface was similar in magnitude to A-pan data, depending on which pan was used. Comparison was drawn primarily to the A-pan at the Upington Agricultural Research Centre, which is relatively close to the river. Regression analyses indicated that the Bowen ratio evaporation is approximately 8 % above that of the A-pan data. The analysis was undertaken after correcting the pan data to take the screen over the pan into account. The uncorrected pan data underestimated the river evaporation by 25 %.

The evaporation from the river was also modelled using standard equations (Penman and Priestly-Taylor) from land based automatic weather station data. The data used were temperature (dry bulb), relative humidity (derived from wet bulb temperature), wind speed and solar radiation. During the study period, the Priestly Taylor equation underestimated the river evaporation by approximately 3 % or 0.2 mm/d. The Penman equation underestimated the river evaporation by approximately 9 % or 0.6 mm/d. The equilibrium equation was also tested, as it had shown good correlation with river evaporation during the one month initial trial study. Over the longer period, however, the equilibrium equation underestimated the river evaporation by 23 %. This is probably due to the extreme advection conditions found along the Orange River, particularly in summer. Land based automatic weather station data were also gathered for the whole of 1994 and 1995, in order to evaluate river evaporation for a slightly longer period. **Table 4.1** shows the results obtained using the Penman and Priestly Taylor equations.

Table 4.1: Estimates of river evaporation using land based weather data

Station	1994 (mm)		1995 (mm)	
	Penman	P-Taylor	Penman	P-Taylor
Bleskop	1 987	2 351	1 958	2 332
Upington	2 115	2 541	2 208	2 593
Vioolsdrift	2 222	2 539	2 308	2 705

4.3 EVALUATION OF EVAPORATION ESTIMATES ON THE ORANGE RIVER

Due to the large discrepancy in the loss estimates derived using various evaporation estimates, it was decided to carry out a comparison of the different available methods. The purpose of the comparison was to highlight any errors in the data, and to illustrate which methods could be used to estimate evaporation losses from other South African rivers. Data were gathered from the several evaporation pans along the Orange River, and compared to evaporation estimates derived from other sources. The first of these sources is the Surface Water Resources of South Africa 1990 (Midgley, *et al*, 1994, abbreviated WR90), which was derived from data from 70 S-pans up to the 1980 water year (Midgley, *et al*, 1983). A more recent source of evaporation estimates covering the whole of South Africa is Schulze and Maharaj (1991, abbreviated here as SM91, although also contained in Schulze *et al*, 1997), which was based on data from 570 climate stations with at least 3 years of concurrent monthly A-pan data, temperature and rainfall. A multiple regression analysis was performed on a month to month basis relating A-pan data to maximum daily temperature, radiation (derived from latitudes and seasons), altitude (digitised from maps), and median monthly rainfall. From the regression, a suite of temperature based equations was developed describing A-pan equivalent evaporation for each month of the year over 12 regions. These equations were then used to derive long term average annual and monthly A-pan equivalent evaporation on a one minute by one minute (1'x1') grid for the whole of South Africa. These data are available from the Department of Agricultural Engineering at the University of Natal, and map overlays are also available for the 1:250 000 map series.

The monthly evaporation pan data were all converted to unscreened A-pan equivalent evaporation, by converting S-pan to A-pan equivalent and applying corrections for screened pans. The data were then patched and extended (using the classing and patching programs by Pegram, 1997), to cover the 28 year period from calendar year 1966 to 1993. The shortest record used was 8 years, and the largest change in MAE introduced by the patching procedure was less than 2 %. A graph showing the various evaporation pan data from Vanderkloof Dam to the river mouth is given in **Figure 4.2**. Also shown on the figure is the WR90 evaporation estimate (converted to A-pan equivalent), and the SM91 data.

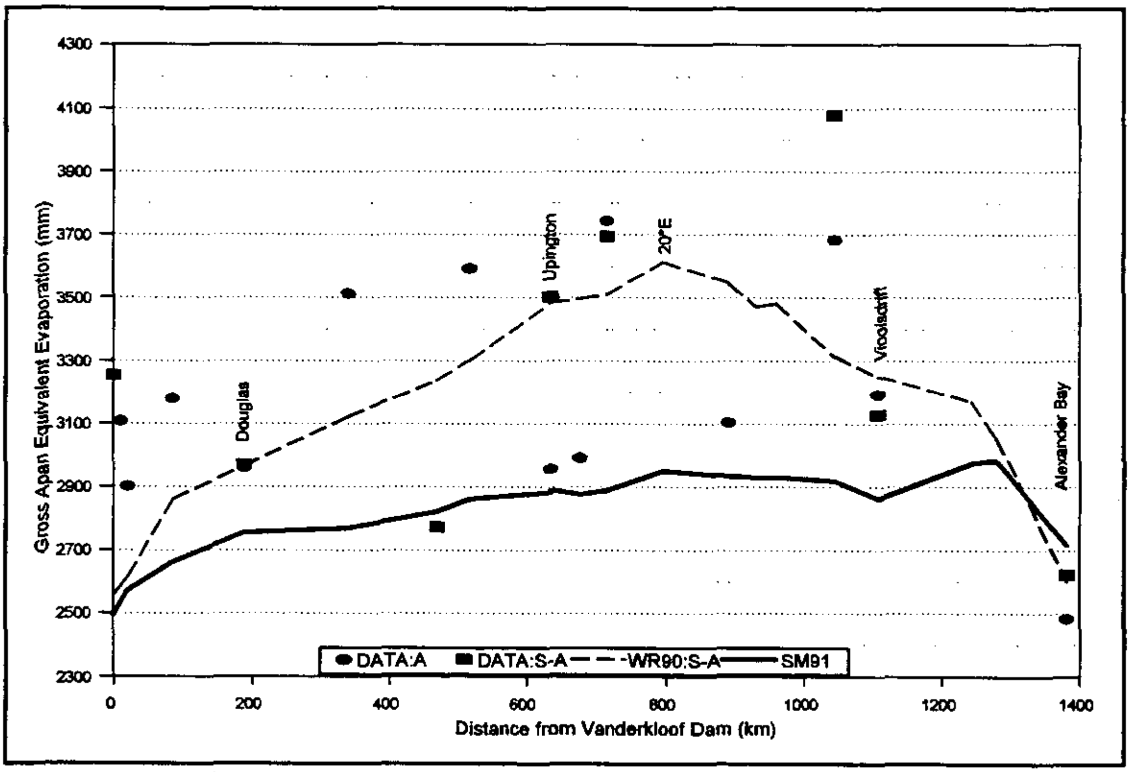


Figure 4.2: Evaporation data along the Orange River

From the figure it is evident that there is a large variation in pan data, and also that there is a significant difference between the WR90 data (converted to A-pan equivalent) and the SM91 data. Further information was therefore required, that was provided by the Bowen ratio study (Everson, 1997). In the study by Everson, linear regression revealed that the river evaporation at Upington was 8 % higher than that of the A-pan at the Agricultural Research Centre (or 25 % if no screen correction was applied). If the same relationship was assumed to be reasonable on the long term, then the long term average A-pan evaporation at the Research Centre should be increased by 8 % to obtain long term river evaporation at Upington. This would yield a long term average river evaporation at Upington of 3 190 mm. The SM91 evaporation at this point is 2 890 mm.

Everson also calculated the Penman and Priestly-Taylor evaporation for 1994 and 1995. The totals for Upington were 2 115 mm and 2 541 for 1994, and 2 208 mm and 2 593 mm for 1995 respectively. The evaporation at the Research Centre for 1994 and 1995 was 2 580 mm and 2 630 mm respectively, compared to a long term average of 2 957 mm. Using the average correlations for 1994 and 1995 to convert the Penman and Priestly-Taylor evaporation to a long term average, would suggest values of 2 453 mm and 2 914 mm. Both of these values are considerably lower than the 3 190 mm estimated from the correlation with the Bowen ratio evaporation. Even raising the Penman and Priestly-Taylor evaporation by 9 % and 3 % respectively (the underestimation by these equations compared to the Bowen ratio evaporation) produces estimates of river evaporation of 2 674 mm and 3 001 mm respectively, which are still below the 3 190 mm referred to above.

The 1994 and 1995 Penman and Priestly-Taylor evaporation at Bleskop and Vioolsdrift were also used together with those from Upington to interpolate values for the whole length of the river. These were then converted to long term average values using the various pans following the same procedure as above (including the 9 % and 3 % adjustments). The Priestly-Taylor evaporation showed evaporation similar to or slightly below the SM91 evaporation, depending on which pan was used in the correlation to long term records. The Penman long term average is consistently lower than the Priestly-Taylor evaporation, by approximately 10 % (despite the higher adjustment applied), as illustrated graphically in **Figure 4.3**. Although the Vioolsdrift Penman and Priestly-Taylor evaporation on the graph appears surprisingly low, time series plots revealed that most pans had measured average or below average evaporation in 1994 and 1995, while both pans at Vioolsdrift measured well above average. The apparent reason for this occurrence could be found.

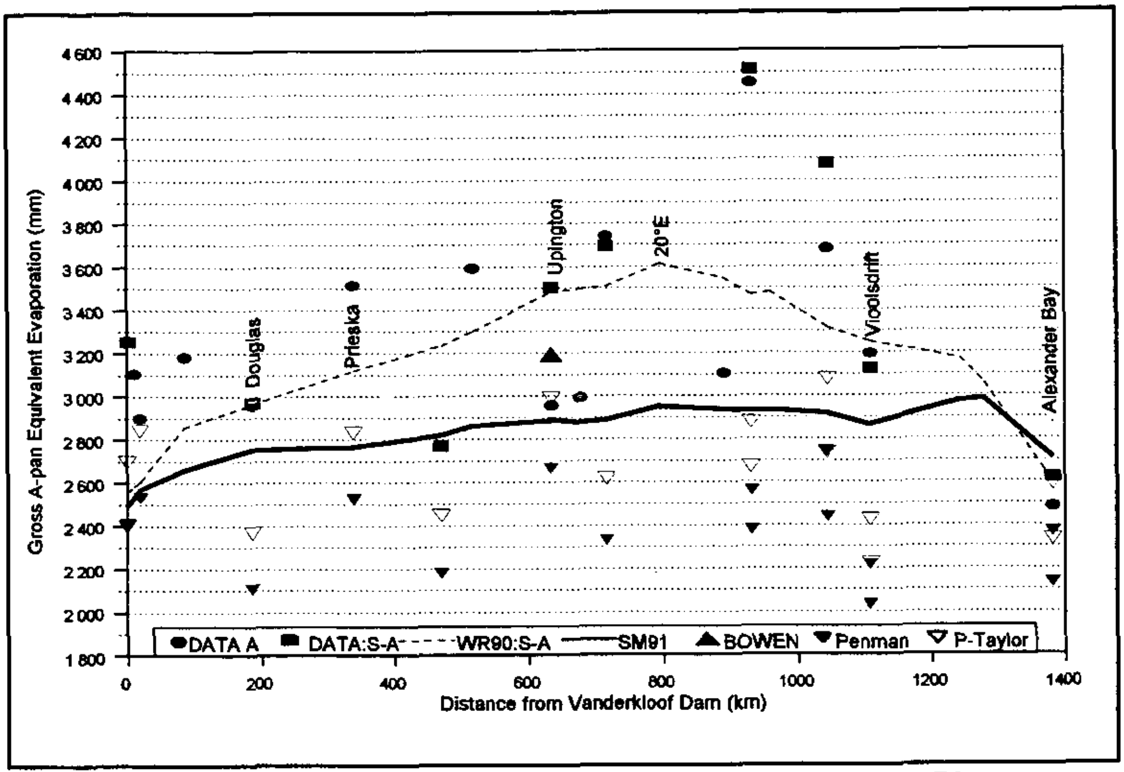


Figure 4.3: **Comparison of evaporation rates along the Orange River**

Some uncertainty still exists as to whether the river evaporation is actually 10 % above the SM91 line, as indicated by the Bowen evaporation correlation, near the SM91 line as indicated by the Priestly-Taylor equation, or 10% below the SM91 line as indicated by the Penman equation. Results from the field verification of losses indicate that the SM91 may overestimate river evaporation. Until more information becomes available, however, it is recommended that the SM91 evaporation be used to determine long term river evaporation rates for the Orange River, and for rivers elsewhere in South Africa. A comparison of SM91 and 28 years of patched evaporation pan data along the Vaal River is presented in **Figure 4.4**.

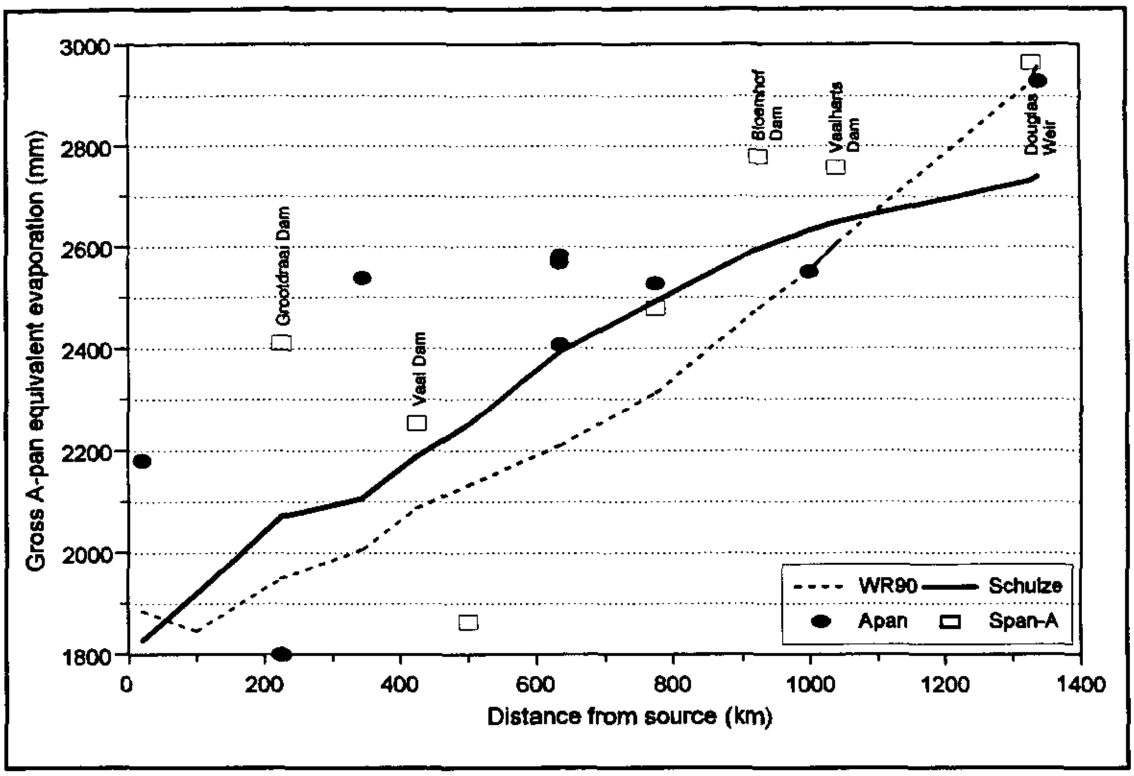


Figure 4.4: Evaporation estimates along the Vaal River

4.4 RIPARIAN WATER BALANCE STUDY ON THE SABIE RIVER

In the Orange River downstream of Vanderkloof Dam, areas of riparian vegetation were estimated at a total of 86 km^2, compared to a water surface area for low flows (50 m^3/s scenario) of 160 km^2. In other words, riparian vegetation constitutes approximately one third of the total area, representing approximately 25 % of the total loss (due to lower evapotranspiration from trees). Due to the relative importance of the evaporation from the water surface, more effort was directed towards obtaining accurate estimates of evaporation from flowing water. It was not within the scope of the River Losses Study to carry out a detailed investigation into evapotranspiration rates using Bowen ratio or other data intensive methods. Although such work may have been beneficial, the data requirements are immense, leading to practical limitations. Due to the length of the Orange River under consideration, species of vegetation, as well as typical canopy densities and leaf area indices, will vary along the length of the river, and will also vary somewhat from season to season. Reed banks may also vary with time, making the total losses from riparian vegetation difficult to quantify accurately. This implies that loss estimates from riparian vegetation will always incorporate some degree of uncertainty. Even a ±20 % error on the evapotranspiration rates for both trees and reeds (both larger or both smaller) only produces a ±7 % error on the total loss calculation.

As result of the above considerations, it was decided to make use of research into evapotranspiration rates carried out elsewhere in South Africa. A study on riparian vegetation transpiration rates was undertaken recently by Birkhead *et al* (1997), on the Sabie River in the Kruger National Park. Although the species of vegetation may differ from the Orange River, there are a number of similarities. The evaporation is reasonably high, with WR90 S-pan of 1 670 mm/a (ie A-pan equivalent of 2170 mm/a), and the SM91 evaporation (A-pan equivalent) is 1 968 mm/a. Phragmites reeds are common to both the Sabie and Orange Rivers. A photo of the study site on the Sabie River near Skukuza (called Narina) is presented in **Figure 4.5**. The Sabie River study focussed on transpiration, which excludes evaporation from the soil surface. It was assumed for the purpose of the losses study that this component would be small relative to the transpiration, and that transpiration could therefore be used as a first order estimate for evapotranspiration.

Figure 4.5: Sabie River study site (Narina)

Data were collected at the site over a three year period from 1993 to 1995. Climatic data were collected from an automatic weather station set up on the site. Leaf area indices of the trees and reeds were also measured at periodic intervals. From this data, transpiration from the reeds and trees were calculated. Due to the difficulty of measuring leaf area index of reeds, hand counts of reeds were required, which were only done over selected periods. The comparison between data from the S-pan at Skukuza and the transpiration data is shown in **Figures 4.6 and 4.7** for reeds and trees respectively.

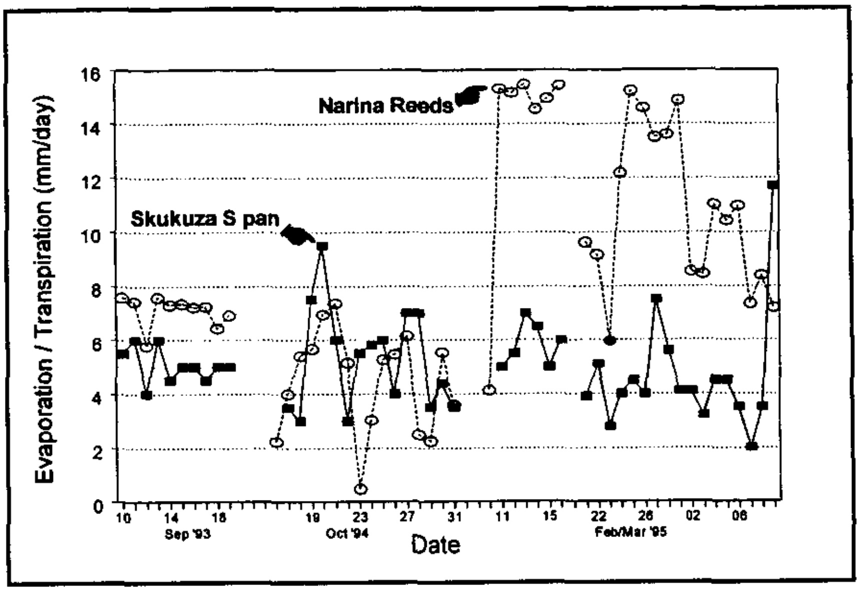


Figure 4.6: Reed transpiration compared to S-pan data

Comparison between reed transpiration and pan data gave highly variable results. During October 1994, the daily reed transpiration estimates were similar to S-pan values, while during February and March 1995 transpiration estimates were as high as 2,5 times the S-pan data. Such high transpiration is unlikely, even from reeds. A new study has therefore been initiated to further investigate transpiration from reeds. During discussion with the study team, Olbrich (*personal communication*, 1997, 1998) indicated that reed transpiration is expected to be closer to potential evapotranspiration (Penman Monteith), which is usually similar in magnitude to A-pan evaporation. As a result, until better information becomes available, reed evapotranspiration will be assumed to equal that of river evaporation.

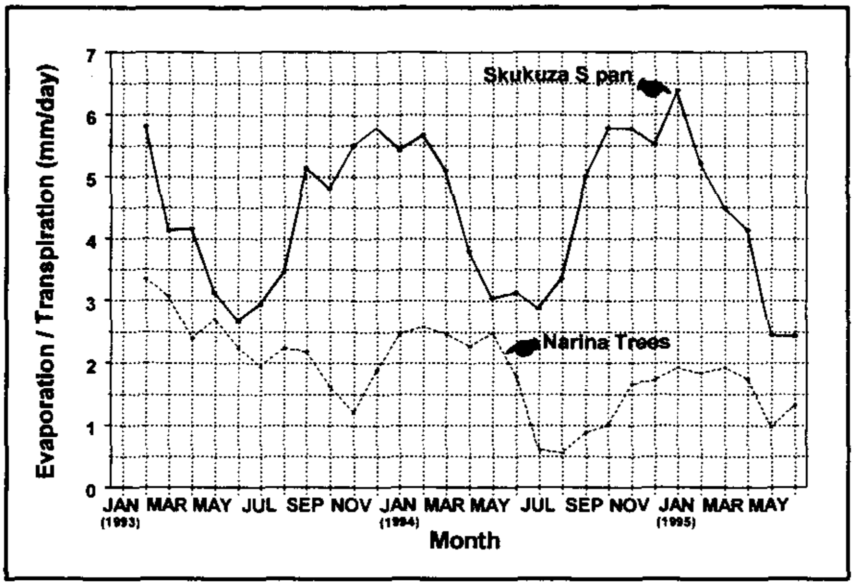


Figure 4.7: Tree transpiration compared to S-pan data

Transpiration from trees compared more uniformly with S-pan data, although they appear to be slightly out of phase. Over the period indicated in the graph, tree transpiration averaged 40 % of S-pan evaporation (ie ±33 % of river evaporation). Olbrich (personal communication, 1998) indicated that this estimate may underestimate the transpiration, and that tree transpiration could be as high as 80 % of potential evapotranspiration. Due to this uncertainty, and the fact that flow gauging results indicated an overestimation of losses, an intermediate value of 50 % of river evaporation was therefore used to estimate evapotranspiration from trees.

4.5 RATES ADOPTED FOR THE ORANGE RIVER

The evaporation rates adopted for the Orange River were based on Schulze and Maharaj (1991, 1997). Uncertainties still exist in the interpretation of the Bowen ratio evaporation measurements by Everson (1997), as indicated in **Section 4.3**. The adopted river evaporation rates are given in **Table 4.2**. Reed and tree evapotranspiration rates are calculated as a factor of the river evaporation. Based on research carried out in the Sabie River basin by Birkhead *et al* (1997) and personal communication with Olbrich (1997, 1998), the factors 1,0 and 0,5 (times river evaporation) were adopted for reed and tree evapotranspiration respectively.

Table 4.2: Evaporation and evapotranspiration rates adopted for the Orange River

Reach	From	To	Gross Evap (mm)	Rainfall (mm)
1	Vanderkloof	Marksdrift	2 665	301
2a	Marksdrift	Prieska	2 761	257
2b	Prieska	Boegoberg	2 795	216
3a	Boegoberg	Gifkloof	2 865	178
3b	Gifkloof	Neusberg	2 885	146
4	Neusberg	20 E	2 920	109
5a	20 E	Pella	2 938	75
5b	Pella	Vioolsdrift	2 921	42
6	Vioolsdrift	Fish	2 942	31
7a	Fish	BrandKaros	2 925	29
7b	BrandKaros	Mouth	2 765	39
Avg.	Vanderkloof	Mouth	2 849	145

Reed evapotranspiration factor:	1.0
Tree evapotranspiration factor:	0.5

5. FIELD VERIFICATION OF RIVER LOSSES METHODOLOGY

5.1 PURPOSE OF LOSS VERIFICATION

The purpose of loss verification in the context of this research study is to confirm that the methodology presented for theoretical calculation of losses, adequately describes and represents the physical processes. This verification was achieved using a water balance approach, with information from manual flow gaugings, demand and return flow analyses, and hydraulic modelling.

Flow measurements for loss verification can usually be taken directly from existing flow records, such as at gauging weirs in the river. The Orange River is generally wide and silt laden, and most of the flow recording stations along the river were designed as irrigation diversion structures and not as flow measuring structures. As a result, these structures tend to be unreliable when gauging low flows and in the case of the Orange River these errors are in the same order of magnitude as the evaporation losses. It is therefore not practical to estimate the losses from the flow data alone, and manual flow measurements were therefore required. The manual flow gaugings are discussed in more detail later in this section.

The water balance for loss verification may be analysed using a volumetric technique or river modelling technique. The volumetric technique comprises integrating the flow at the upper and lower end of a reach over a long period so that hydraulic attenuation does not effect the results. Alternatively, river flows may be held constant before and during measurements so that the effect of attenuation is negligible. This approach was used on the Orange River in 1993, when releases were held constant for eight weeks prior to a set of flow gaugings at various locations along the river. Subsequent analysis of recorded water level data indicated that the flow in the lower parts of the river were still variable due to uneven abstractions along the length of the river. As a result, it was decided to use hydraulic modelling as a tool in processing the dynamic water balance of the river.

In order to measure river losses using a water balance, the effect of water requirements and return flows must be taken into account. During the 1993 flow gauging exercise, undertaken as part of Phase 1 of the River Losses Study, the return flows from irrigation were found to have a significant impact on the water balance. At the start of Phase 2, uncertainties were highlighted regarding not only the volumes of irrigation return flows but also the time taken for the return flows to seep back into the river. This time lag is referred to in this report as the irrigation return flow retention time. Long retention times may for example result in large return flow volumes long after the summer irrigation peak, when irrigation requirements are much lower. Irrigation return flow retention times were therefore studied in more detail, as described in the following section.

5.2 IRRIGATION RETURN FLOW ANALYSES

5.2.1 Tracer study at Vioolsdrift

Phase 1 of the River Losses Study highlighted that irrigation return flows are important and should be considered in any water balance calculation. Irrigation is the largest water use sector downstream of Vanderkloof Dam, and the retention times can therefore have a significant impact on the measurement of river losses. A tracer study was subsequently initiated to investigate irrigation return flow retention times, with the assistance of the Atomic Energy Corporation (AEC). The investigation was carried out at Vioolsdrift during February 1995 and the study report is included as **Appendix A**. From the study, it was concluded that:

- Indium-EDTA is an effective tracer for monitoring irrigation return flow retention times, being inactive (not radioactive), environmentally safe and measurable at very low concentrations. Furthermore, Indium is a rare and stable earth metal which is not readily affected by chemical reactions or by adsorption onto clay particles.
- The site chosen at Vioolsdrift is representative of most flood irrigation along the lower Orange River. The tracer pulse was released on a field 400 m from a drainage furrow, while distances to drainage furrows on the Orange River vary from 200 m to 800 m. Approximately 95 Ha of irrigated land are served by the drainage furrow.
- The tracer was evident at significant concentrations in the drainage furrow between approximately 10 and 46 days after release into the irrigation water on the test site. The maximum concentration and mean retention time both occurred at approximately 24 days. The observed concentrations were approximately 2000 times higher than the minimum measurable level of Indium-EDTA tracer. This tracer is therefore very suitable for measuring the retention

time of irrigation return flows, and the same mass of tracer (1kg) would produce measurable concentrations in a river flowing up to 50m^3/s or more.

- The volumetric return flow from applied irrigation water was estimated from a basic water balance of the drained area to be in the order of 33 %. This is marginally higher than expected, indicating that some interaction may have taken place with river water seeping through the alluvium, which was confirmed by a tracer mass balance.

5.2.2 Return flow analysis at Louisvale

A return flow analysis was also undertaken at Louisvale, near Upington. Measuring weirs were constructed and recorders erected by DWAF on the two outlets from the drainage canals. A raingauge was also opened close to the site by the Weather Bureau. The Louisvale Irrigation Board has 1214 Ha scheduled area under irrigation (1995), of which 1000 Ha (82%) effectively drains through the two measured outlets. The flow measuring weirs on the two outlets are shown in **Figure 5.1**.

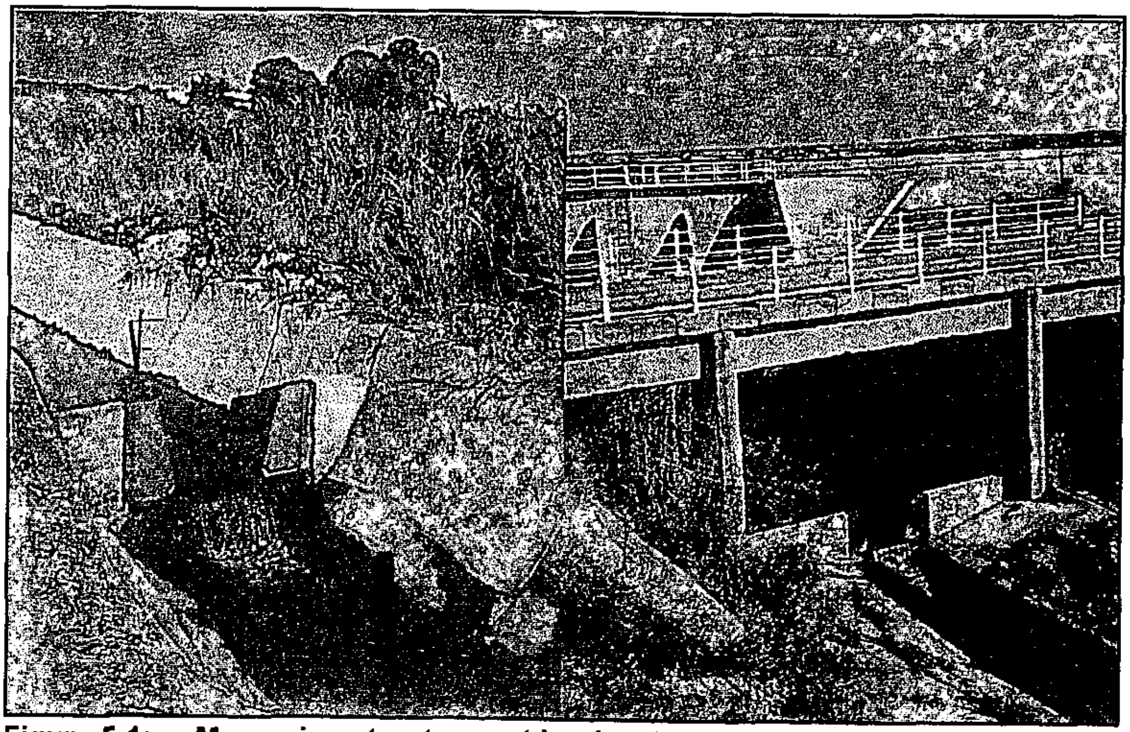


Figure 5.1: Measuring structures at Louisvale

Recorders on the canals measure irrigation in the reach, allowing a water balance to be carried out. A total of 11 months of data was collected, although interrupted by periods of high river levels and a flash flood which destroyed one of the level recorders. A return flow retention time of four weeks was assumed, based on the findings of the

Vioolsdrift tracer study. Unfortunately, a tracer study at the Louisvale site was not possible within the funds of the project. The average volumetric return flow from Louisvale was measured at 30 %. The return flow rate was considerably less variable than the applied volumes of irrigation water, even using a four week moving average of applied water. The best fit was obtained using a six week moving average, although the variations are small and therefore not highly accurate. An analysis of the water quality of the applied water versus the return flow was also carried out. The Orange River at Upington was used to represent the applied water quality, while water quality samples were taken at the two return flow measuring structures and analysed by IWQS. The average TDS of the applied water during the period was 225 mg/l, while those of the two return flow canals were 1 205 mg/l and 1 355 mg/l respectively. These constitute a 5.4 and 6 fold increase respectively, which indicate in broad terms that return flows of 15-20 % could be expected, although this method of estimation can can be influenced by soil types and irrigation practices.

5.3 WATER REQUIREMENTS AND RETURN FLOWS OF THE ORANGE RIVER

Having examined the retention time of irrigation return flows, information on the total water requirements and return flows had to be gathered. This information was needed as input to the water balance, whether by volumetric method or by dynamic simulation. Information on water requirements and return flows was therefore gathered, and in particular for the area downstream of Augrabies Falls. During the periods of flow gaugings, daily abstraction information was requested from all urban and industrial abstractors. Additional information was also gathered in this reach concerning irrigation water requirements, in conjunction with information gathered by Loxton Venn and Associates (LVA, 1997) as part of the ORRS. The LVA report incorporates two sets of data, the first of which reflects the scheduled irrigation areas and quotas. These represent the legal water allocation, and were therefore adopted for all other aspects of the ORRS study. The second set of data reflects the actual irrigated areas and calculated crop water requirements. This second set was used to calculate irrigation abstractions during the flow gauging exercise, as it is the closest representation of the actual historic scenario. The "actual" water requirements are generally larger than the "legal" requirements in the middle reaches of the Orange River upstream of Augrabies Falls, while below the falls the opposite occurs.

A brief investigation was also carried out to quantify the effect of travel time on the releases from Vanderkloof Dam. Due to the length of the river, water released can take from four to six weeks to reach the river mouth, depending on the flow. As a result, flows in a particular reach of the river in a particular month cannot be derived from the downstream water requirements in that month alone. The effect of the irrigation return flow retention time also has an influence, since return flows from one month's irrigation water will help to supply downstream users in the next month. An average travel time for each reach of the river was therefore calculated, from which the flow in each reach required to satisfy requirements in subsequent reaches could be derived. Based on these flows, the surface areas were interpolated from **Table 3.2**, and multiplied by monthly evaporation to obtain monthly losses for each reach of the river. A few iterations were necessary, since changes to the losses also result in changes in the flow in each reach. The resulting monthly distribution of the losses, based on this release scenario (equivalent to the "50 m^3/s" scenario mentioned previously) is presented graphically in **Figure 5.2**. The distribution does not depend on evaporation alone, since the flow in the river and consequently also surface areas are significantly lower during the winter months. Any major alteration from the above release scenario will have an influence on the actual losses occurring. If additional releases are made, such as for power generation, then excess spillage will occur at the river mouth. The exact magnitude of the losses are not usually critical during such times, since additional water is available in excess of the requirements. If, however, less water was released, such as during water restrictions, then the actual losses may be lower than those shown given in **Table 5.1** due to a reduction in water surface areas. Occasionally, high temperatures and associated evaporation can also cause an increase in these values.

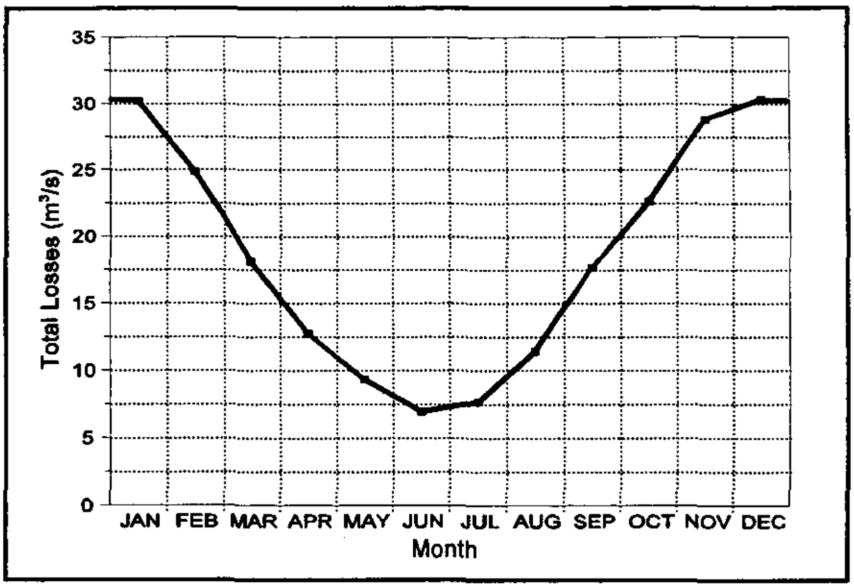


Figure 5.2: Losses downstream of Vanderkloof Dam

The calculation also allowed the required releases from Vanderkloof Dam to be derived in order to meet the downstream requirements. The results are presented in **Table 5.1**, and illustrated graphically in **Figure 5.3**. The figures are given as an average for the month and are plotted on the graph at the middle of the month, so that the required releases at any time in the month can be read from the graph. For the purpose of analysing different scenarios, an approximate release requirement can also be derived by taking 60 % of the current month's water requirement, and adding 40 % of the following month. This simpler approach provides similar results to the reach-by-reach calculation, provided that the flows in each reach are not required.

Table 5.1: Distribution of water requirements and losses

Description	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year	(106m3/a)
Irrigation Gross	49.9	44.4	27.2	11.9	6.0	4.7	7.9	15.1	32.7	44.9	53.0	46.7	28.6	903.1
Irrigation Return	-9.6	-8.5	-5.2	-2.3	-1.2	-0.9	-1.6	-3.0	-6.0	-8.2	-10.0	-8.9	-5.4	-171.5
Urban Net	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	35.0
Environment	12.0	13.5	12.0	12.0	9.0	6.0	5.0	5.0	5.0	12.0	12.0	13.2	9.7	306.5
River Losses	30.2	24.8	18.1	12.7	9.3	6.9	7.7	11.4	17.7	22.6	28.8	30.3	18.4	579.2
Total Demand	83.6	75.4	53.2	35.5	24.3	17.9	20.1	29.6	50.5	72.5	84.8	82.4	52.4	1652.3
Total Releases	82.9	67.3	45.2	28.1	19.8	17.6	23.5	36.7	62.5	79.1	87.4	79.5	52.4	1653.7

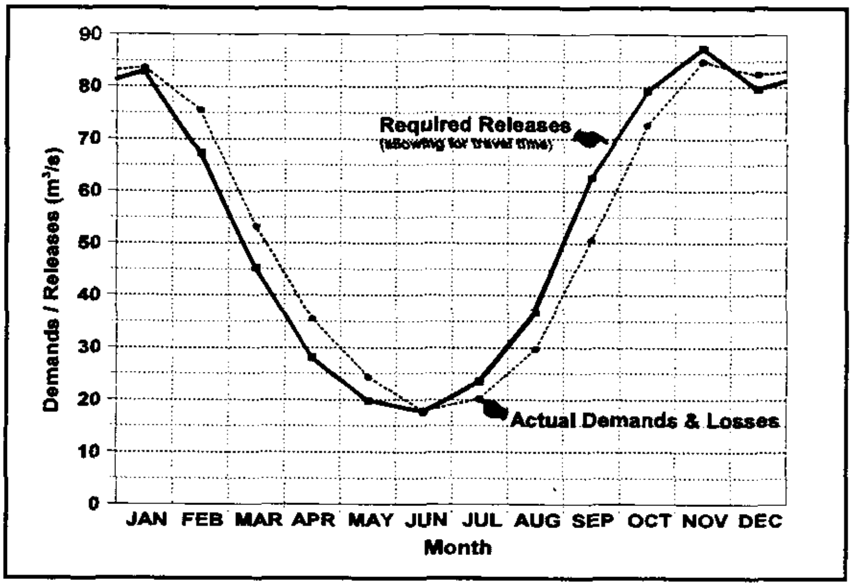


Figure 5.3: Demands and releases d/s Vanderkloof Dam

Although the required release are those required to satisfy the downstream requirements without excess spillage, there are circumstances under which releases may differ from this pattern. Additional water is often released by ESKOM during winter to generate additional electricity in terms of an agreement between DWAF and ESKOM (1984). As the utilisation of the Orange River's water resources increases, the additional allocation made to ESKOM for hydro power generation over and above downstream water requirements is likely to become smaller. As a result, there will be a gradual move towards the above release scenario. Some uncertainty also exists as to whether the environmental requirements must be supplied at the start of the estuary (Brand Karos), or whether the stated volumes have to exit the river mouth. For this reason, the evaporation losses occurring from the river estuary have been included separately in the tables of river losses. In the interim, however, it has been assumed that the full volume of environmental requirements must exit the river mouth. The low releases indicated in **Figure 5.3** were a cause for concern, as it is generally known that releases this of this magnitude lead to problems downstream. For example, some diversion structures or abstraction systems may experience problems at low flows, or the river may cease flowing altogether in the lower reaches. In order to check the figures, historical irrigation application information was gathered and processed for the Boegoeberg to Kakamas from 1989 to 1995, where available. The data set contained 26 complete years of data from the major irrigation boards in the area. The actual distribution patterns were in all cases flatter than the calculated distribution (LVA, 1997), indicating that the latter overestimates irrigation requirements in summer, and underestimates requirements in winter. The analysis is illustrated graphically in

Figure 5.4, which also shows the minimum and maximum distributions in each individual month.

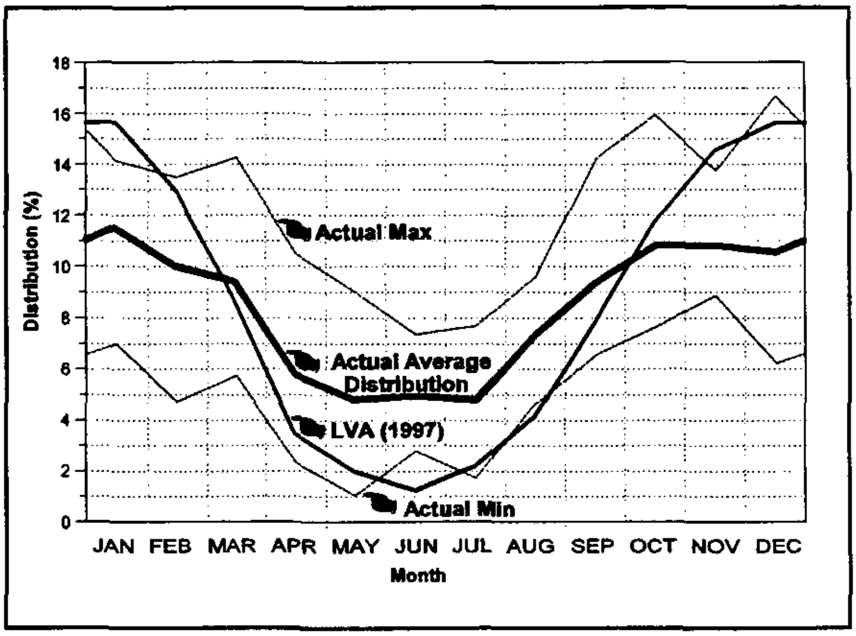


Figure 4.5: Irrigation distributions

5.4 PREPARATION OF HYDRAULIC MODEL OF ORANGE RIVER

In the initial description of the conceptual model, many variables were mentioned which can influence the calculation of river losses, although the significance of each variable was in most cases unknown. Due to the fact that a loss methodology was being developed in this study, it was important to evaluate the effect of as many variables as possible. As a result, it was decided to use a hydraulic model in the loss verification, which enables the influence of many variables to be included in the analysis. For example, the water surface area varies with flow and therefore also with time and space. The variation of flow with time will be subject to hydraulic attenuation, which is again a function of many variables and varies strongly from place to place along the river. The evaporation from the water surface (and from riparian vegetation) varies both temporally and spatially, as does rainfall.

The rates of evapotranspiration from trees and reeds will differ from each other and from that of the water surface. Inflows from tributaries, which vary with time, can also be modelled, as can variable water abstractions for irrigation and municipal/industrial purposes. Irrigation abstractions in particular exhibit a strong seasonal distribution and may also vary diurnally or weekly depending on the amount of off-channel storage and on the level of equipment automation. Return flows from irrigation will vary with time and will have a different distribution from that of the irrigation abstractions, due to retention in the soil.

The hydraulic modelling package chosen for use on the Orange River was the ISIS suite of programs developed by Halcrow and HR Wallingford (1995) in the UK. In order to simulate the distributed evaporation from a varying water surface, an evaporation module was incorporated into the ISIS model by the project team in association with the program developers. This module calculates the surface area between each pair of cross sections for each time step in the simulation. The user allocates a width of riparian vegetation to each cross section, which forms part of the surface area calculations. The user can also define the ratio of riparian evapotranspiration to water surface evaporation. The calculated area is multiplied by an evaporation rate to estimate the evaporation loss between the two sections. The evaporation rate is user-defined and can also vary with time and location within the model. The model can therefore simulate the temporal and spatial distribution of the evaporation losses from the water surface and the riparian vegetation. This allows the effect of distributed losses on the flow and the attenuation of the hydrograph to be evaluated.

There are a number of different approaches that can be taken when attempting to model the hydraulic behaviour of a river, depending on the scope of the project and the purpose for which the model will be used. At the coarser end of the scale are empirical modelling techniques such as the Muskingum and Muskingum-Cunge flow routing equations. These methods require very little data, and hydrographs are used to calibrate the travel time between two points and the roughness of the reach. On the other hand, full hydrodynamic simulation requires geometrical cross section data in addition to distance and roughness parameters, in order to simulate depth and velocity at each point in the model. Spacing and resolution of cross sections can be varied according to the specific application, and interpolated cross sections are used to simulate curvature of the water surface. Although the Muskingum approach was tested on a short reach of river for comparative purposes, most of the modelling discussed in this report made use of full hydrodynamic modelling. Full hydrodynamic modelling was selected to allow the variation in surface area with changes in flow to be simulated together with the distributed evaporation losses.

At the initial stage of preparation of the Orange River model, very few surveyed cross sections were available. Such sections were used whenever available, however, most of the cross sections had to be derived from contour maps and aerial photographs. The shape of the cross sections below the water level had to be estimated based on the prevailing slope, width and hydraulic properties, as well as local effects visible from the aerial photography. The width of the water surface calculated in the model could be checked against available aerial photographs, and the geometry revised if necessary. It was found that despite the relatively coarse geometry, the passage of hydrographs could be simulated satisfactorily without further refinement of the geometry. In the 580 km from Blouputs to Brandkaros, the model has a total of 900 cross sections with spacing varying from 55 m to 1750 m. Of the 900 sections, approximately 100 sections were estimated from the maps as described, while the remainder were made up of interpolated sections. Interpolated sections are used in cases where the basic hydraulic properties are similar within the reach, namely cross sectional area, wetted perimeter, and roughness.

5.5 RESULTS OF LOSS VERIFICATION ON THE ORANGE RIVER

Due to the lack of accurate low flow gauging structures on the Orange River, manual flow gaugings were undertaken for the purpose of loss verification. Manual flow gaugings on the Orange River present serious logistical and practical problems, due to the rugged and inaccessible terrain, high temperatures, and a lack of sites suitable for manual flow gaugings. A total of three sets of manual flow gaugings were carried out by DWAF teams along the Orange River, during July 1993, November 1994 and November 1995. The locations of the gauging sites and river reaches are shown in **Figure 5.5**, in addition to Vanderkloof Dam and Marksdrift Weir which are mentioned later. The results from the various flow gauging exercises are discussed in the remainder of **Section 5**.

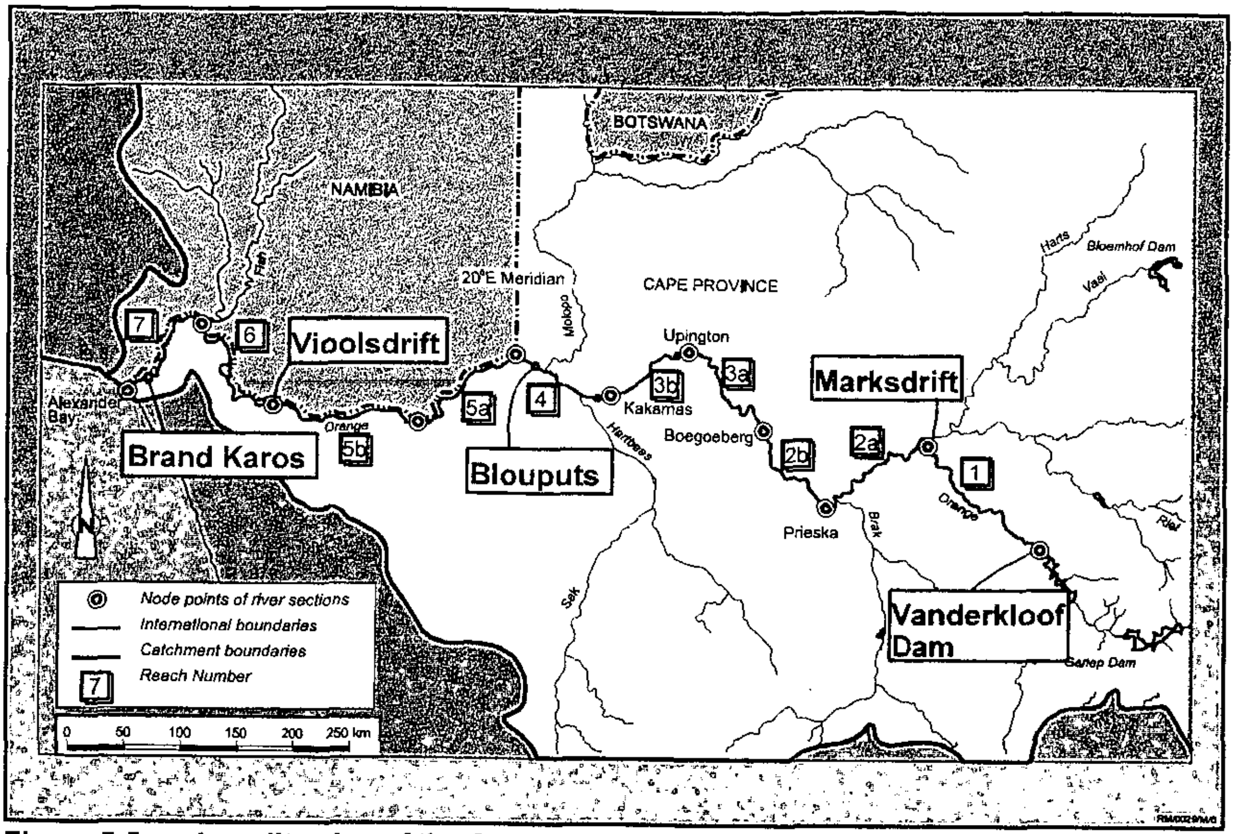


Figure 5.5: **Locality plan of the Orange River showing gauging sites and river reaches**

5.5.1 July 1993 Gauging Exercise

The first set of manual flow gaugings was undertaken in July 1993, when releases from the dam were held constant at 30 m^3/s for a period of eight weeks through prior arrangement with DWAF. On the assumption that the flow in the river would have stabilised by the sixth week, four teams from DWAF undertook simultaneous gaugings at various locations between Vanderkloof Dam and the river mouth.

The initial water balance indicated almost no losses in the middle reaches of the river where irrigation is high. This was later attributed to the exclusion of irrigation return flows in the water balance which can be significant due to the intensive irrigation which takes place in these reaches. In the lower reaches of the river, the results indicated river losses equal to or greater than the estimates based on surface areas and evaporation rates.

Subsequent analyses of the recorded water level data revealed that the flows in the river were not constant throughout the analysis period. The results were therefore reprocessed for the lower half of the river, using the hydraulic model with updated information on water abstractions. The simulation was first checked against available stage records, after which the simulated flows were compared to the manual flow gaugings in **Figure 5.6**. It is evident from the figure that the flow gaugings were not carried out on the same portion of the hydrograph, which led to overestimation of the losses by the initial static water balance. Some of the gaugings were carried out on steeply rising portions of the hydrograph, making the flows and losses difficult to calibrate accurately. The simulated evaporation which provided the best fit of the results was found to be 4.7 m^3/s between Blouputs and Brand Karos. The flows during July 1993 were more than twice those of the base scenario. Interpolating between the surface areas for different flows presented in **Section 3**, the two fold increase in flow results in a net increase in surface area (water surface and riparian vegetation combined) of 22 %. The evaporation during July 1993 was approximately equal to the long term average, with the result that the calculated loss of 4.7 m^3/s corresponds to a long term loss of 3.85 m^3/s. This is still 28 % higher than the theoretical long term loss of 3.0 m^3/s.

Due to the high flow in the river relative to the evaporation losses, errors in the flow measurements will have a significant influence on the loss estimates. No continuous record of stage or flow was available at Blouputs or Brand Karos during the gauging exercise, which makes accurate calibration of the model difficult. This difficulty is aggravated by the fact that some of the gaugings were carried out on steeply rising or falling portions of the hydrograph, which can be seen in **Figure 5.6**. These results are therefore not considered to be of sufficient accuracy to make quantitative assessments of the evaporation losses. As a result of the uncertainties, further gauging exercises were carried out in 1994 and 1995, as discussed later in this report.

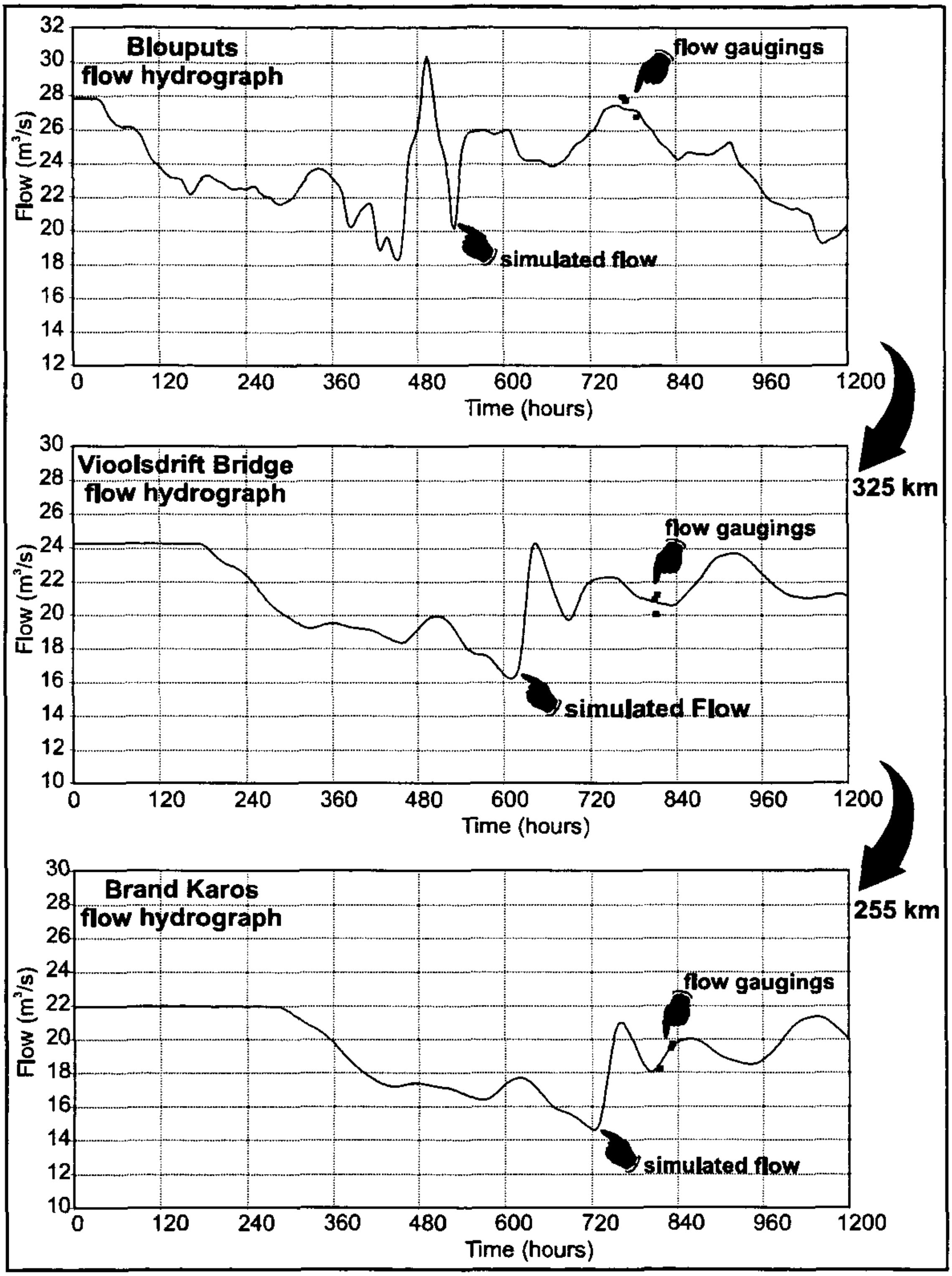


Figure 5.6: Results of 1993 flow gaugings

5.5.2 November 1994 Gauging Exercise

In November 1994, two teams carried out an intensive set of flow gaugings over a three week period, at two locations, namely Blouputs (just downstream of the Augrabies Falls) and at Brand Karos (just upstream of the river mouth). This portion was chosen due to the low irrigation abstractions and return flows, as mentioned previously. Pictures of the two locations are shown in **Figure 5.7 and 5.8** respectively. A picture of the temporary stage recorders erected for the duration of the flow gaugings is shown in **Figure 5.9**, together with an A-Ott C20 current meter.

Figure 5.7: Flow gaugings at Blouputs

Figure 5.8: Surveying of the Brand Karos gauging site

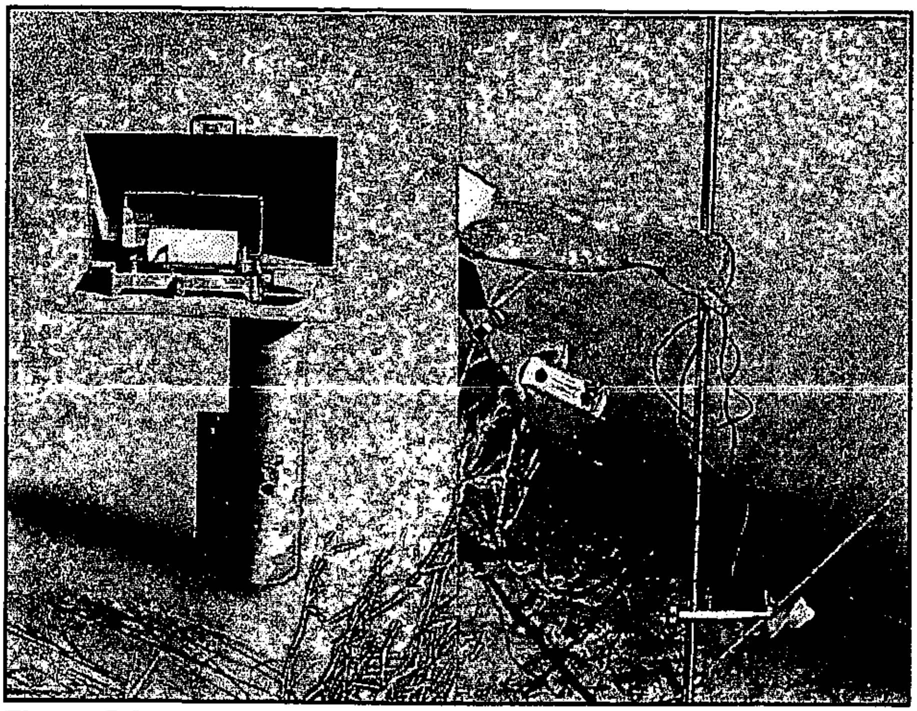


Figure 5.9: Temporary stage recorder and current meter

The stage discharge relationships derived from the flow gaugings at Blouputs and Brand Karos are presented in **Figure 5.10 and 5.11** respectively. It was discovered towards the end of the exercise that one of the cable-mounted current meters used at Blouputs was slanted upwards due to a heavy tail-piece. The results from this specific instrument were adjusted, after which the stage discharge relationship was derived using the combined results.

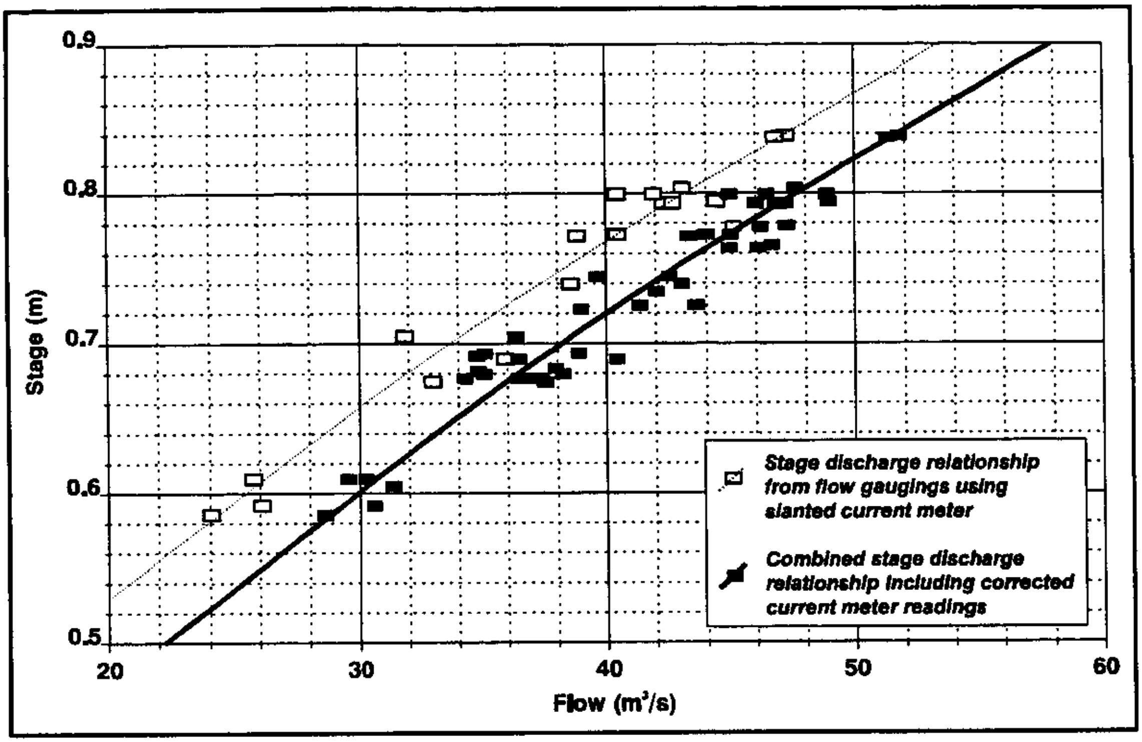


Figure 5.10: Stage discharge relationship at Blouputs

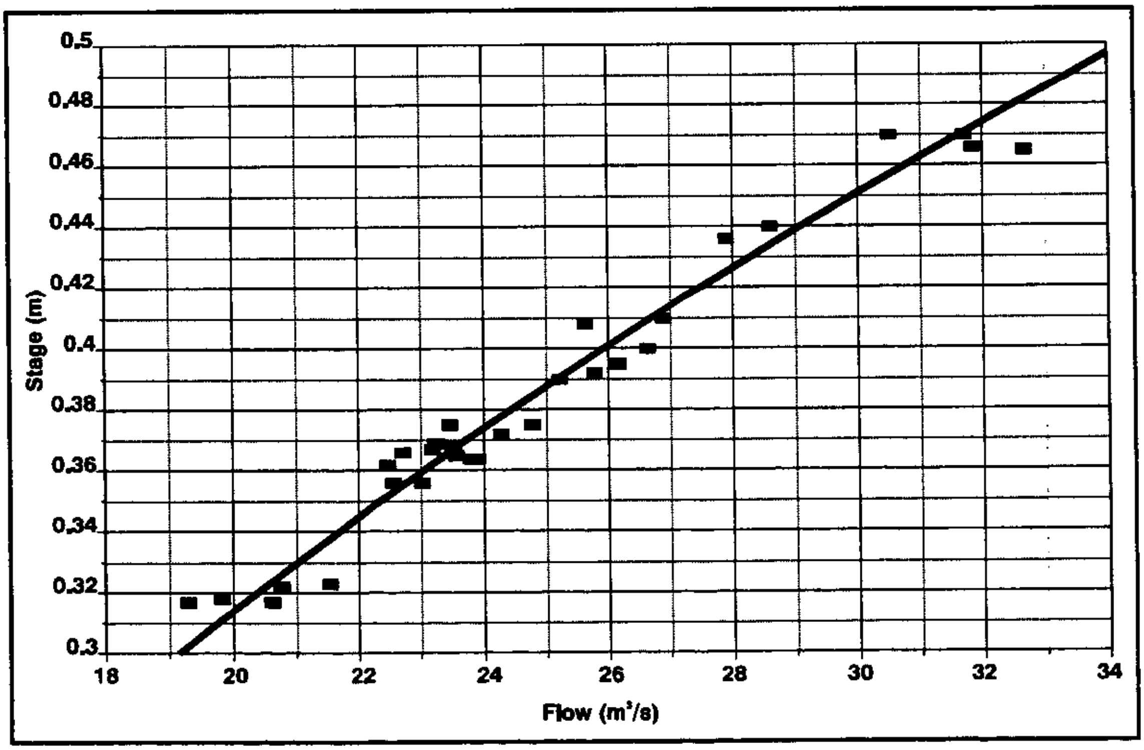


Figure 5.11: Stage discharge relationship at Brand Karos

Another factor that influenced the gauging exercise was wind. This was particularly evident at Brand Karos, where the river is shallow and strong winds occur on most afternoons. Being close to the west coast, the afternoon winds are usually on-shore, or upstream, causing a damming effect in the river sometimes called seiches. This effect is illustrated graphically in **Figure 5.12**.

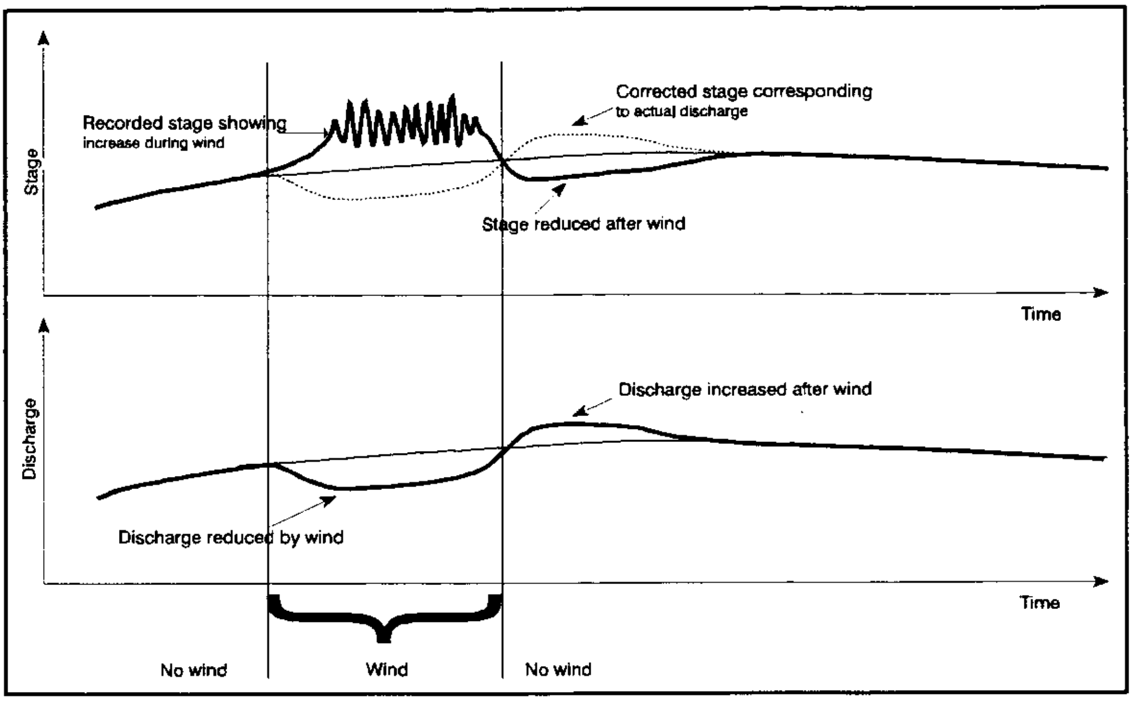


Figure 5.12: Correction of hydrographs for wind at Brand Karos

The results of the hydraulic modelling from Blouputs to Brand Karos are presented in **Figure 5.13**. Hours zero on the graph represents the start of the simulation at 0h00 on 26/10/1994. The measured input hydrograph at Blouputs is presented, followed by the stage hydrograph at Vioolsdrift Weir (an intermediate site) as well as the outflow hydrograph at Brand Karos. The Vioolsdrift site (310 km from Blouputs) shows an excellent fit between simulated and observed stage records, but did not agree with the flows derived from the DWAF discharge table for the station. The discharge table for the weir has subsequently been revised, following flow gaugings in 1995. The calibration of the flow hydrograph at Brand Karos indicates a net evaporation loss between the two gauging sites of 10.1 m^3/s. The reach being modelled is 580 km long in total, with a net water consumption (abstractions minus return flows) over the reach of only 3,6 m^3/s.

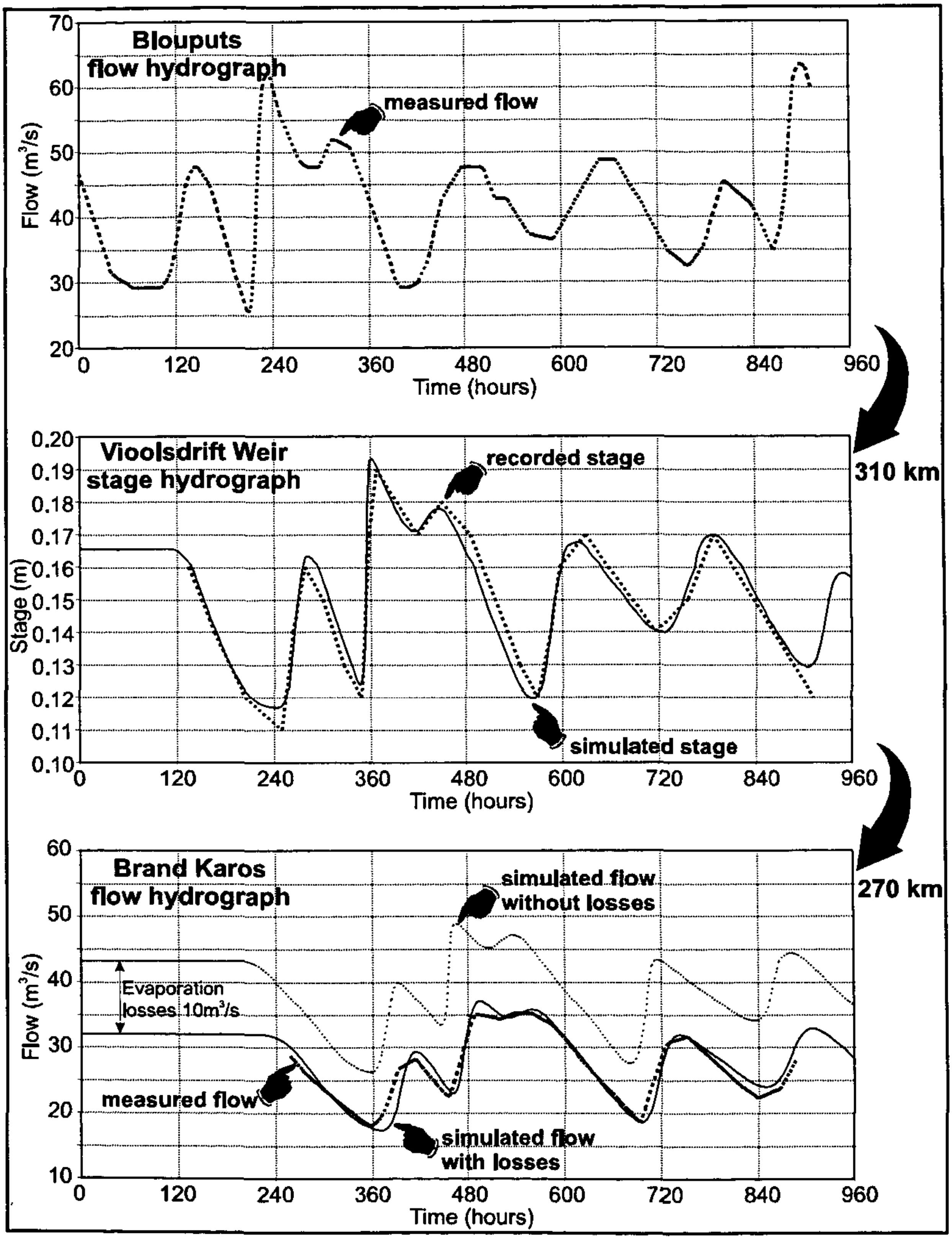


Figure 5.13: Results of 1994 flow gaugings

The total loss of 10.1 m^3/s is considered to be principally evaporation losses. The Orange River is deeply incised into the surrounding plains and is underlain by solid rock. In consultation with various geohydrological experts, the losses to bed and bank seepage were considered to be small enough to ignore in the loss calculations. The measured loss of 10.1 m^3/s can therefore be compared to the theoretical evaporation loss estimates made earlier.

The average flow past Blouputs was measured at 41 m^3/s, while the base scenario flow at Blouputs in November is 31 m^3/s. This difference in flow should give rise to an increase in evaporation of 8 % due to the enlarged water surface area. The actual pan evaporation during November 1994 was approximately equal to the long term average, with the result that the 10.1 m^3/s corresponds to a long term loss of 9.4 m^3/s. The long term theoretical loss over the same portion of the river for the base flow scenario was estimated to be 10,7 m^3/s, which is approximately 14 % higher than the 9.4 m^3/s derived from the flow gauging exercise. This discrepancy is most likely due to overestimated surface areas used in the theoretical calculation. As mentioned in **Section 3**, the surface areas at low flows were extrapolated from information at higher flows. The surface area was therefore the variable with the greatest level of uncertainty at this stage in the study, and could not be improved due to a lack of aerial photography of the Orange River at low flows. Uncertainties also existed in connection with the evaporation and evapotranspiration rates, as discussed in **Section 4**, as well as the irrigation abstractions as discussed in **Section 5.3**. It is likely that a combination of these factors contributed to the underestimation of the losses by the flow gauging exercise.

As a result of the abovementioned uncertainties, it was decided not to adjust the evaporation rates or the surface areas for the Orange River, in order to err on the conservative side until more accurate information could be obtained.

5.5.3 November 1995 Gauging Exercise

In November 1995, flow gaugings with temporary stage recorders were again carried out at Blouputs and Brand Karos. Flow gaugings were also carried out at Vioolsdrift, by both DWAF and Namibian teams, in order to address the errors in the discharge table for the weir. The flow gauging results at Vioolsdrift are shown in **Figure 5.14**, along with the original and revised DWAF discharge tables together with the stage discharge relationship derived from the hydraulic model using the 1994 results. The latter corresponds very closely to the revised DWAF discharge table.

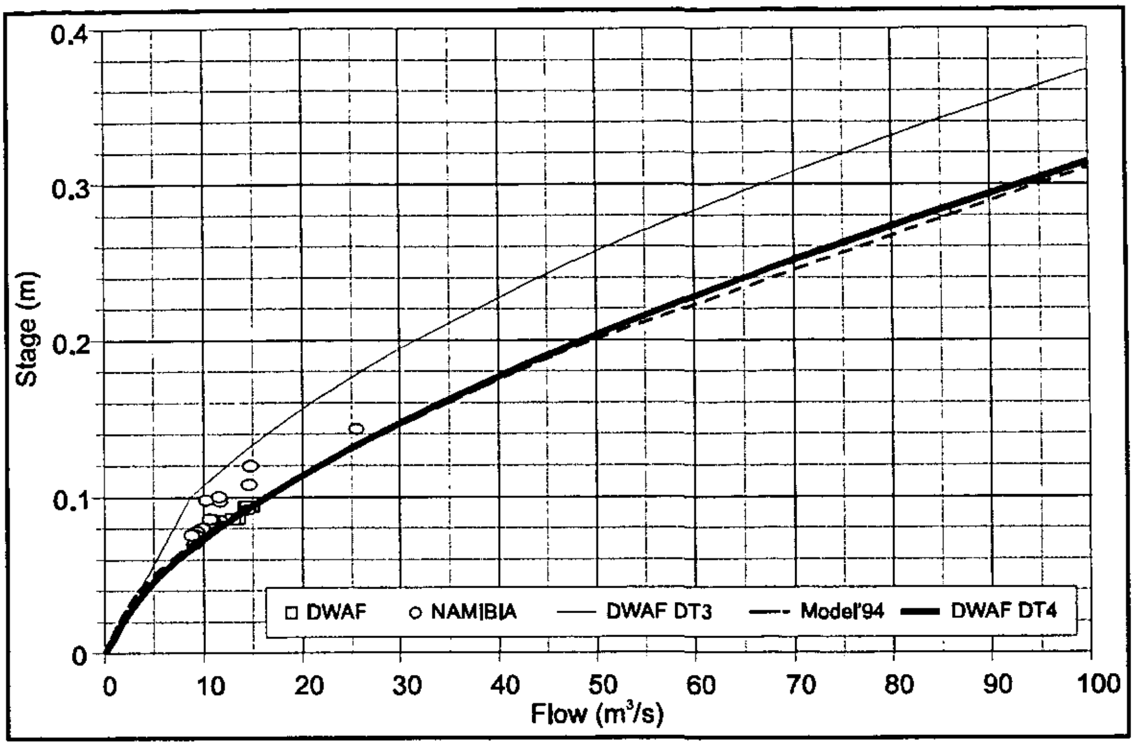


Figure 5.14: Flow gaugings and discharge tables at Vioolsdrift

Unfortunately, it was not possible to leave the temporary stage recorder at Brand Karos in the river for the desired period due to the rising water levels. The hydrograph was therefore extended using stage records at the Brand Karos pump station and at Oppenheimer Bridge, which are just upstream and just downstream of the flow gauging site respectively. Unfortunately, this extended portion of the hydrograph was not sufficiently accurate to be used in the calibration. Rainfall also occurred between Blouputs and Brand Karos on 20 and 21 November (450-465 hours in the simulation), which gave rise to inflows that could not be quantified. The rainfall and recorder problems together resulted in a very short period of data which could be used for the simulation, as indicated in **Figure 5.15**. The simulation commenced at 0h00 on 2/11/1995.

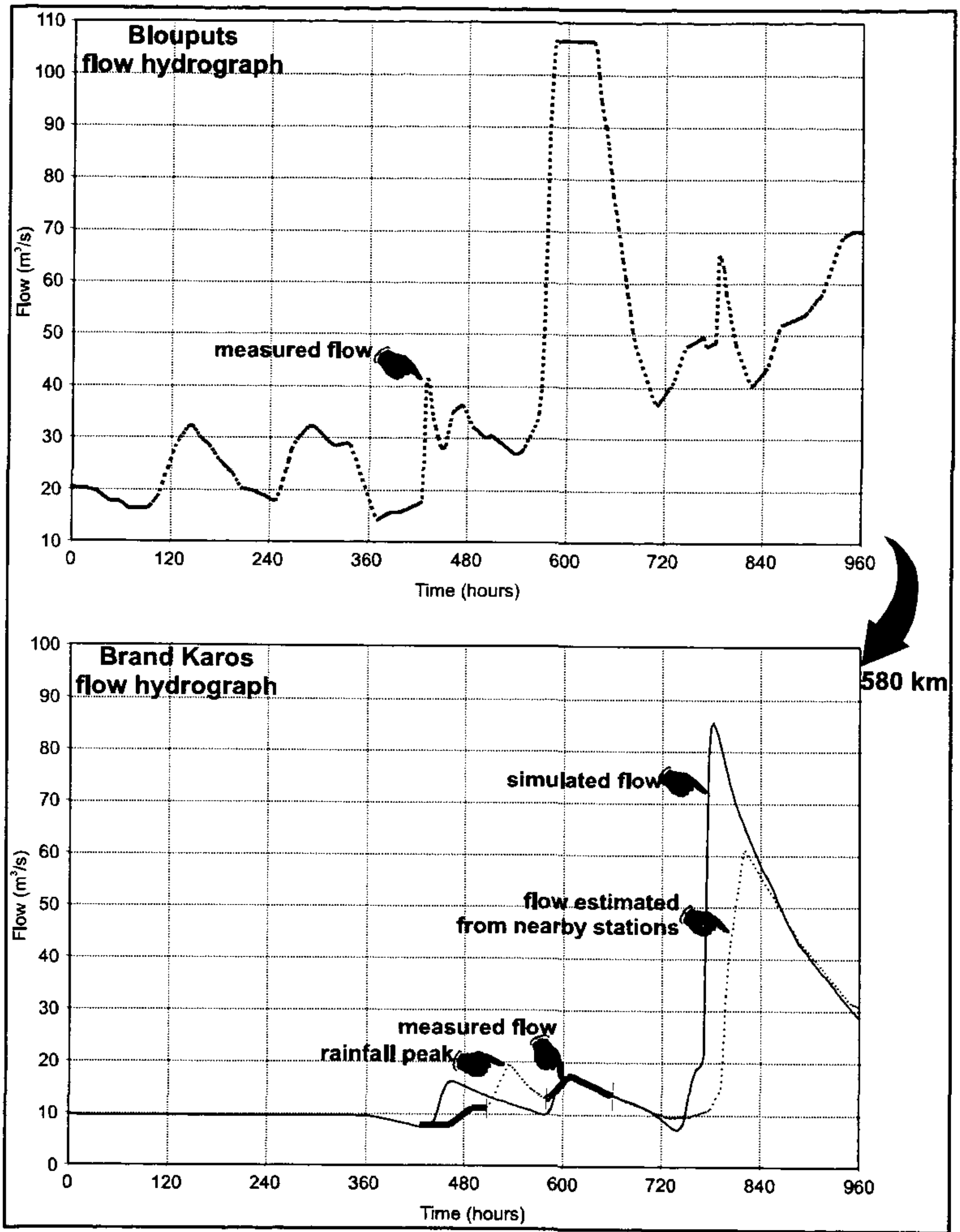


Figure 5.15: Results of 1995 flow gaugings

The flow during the calibration portion of the hydrograph was slightly lower than the base scenario, resulting in a 4 % reduction in surface areas. The evaporation in November 1995 was 12 % below average. The measured evaporation loss of 6.8 m^3/s therefore corresponds to a long term evaporation loss of 7.9 m^3/s, which is 26 % below the theoretical estimate of 10.7 m^3/s. This result is significantly lower than the 1994 result, but is less accurate due to the interruption of the hydrograph by rainfall and rising water levels. The comments regarding the underestimation of losses by the 1994 gauging exercise also apply here.

5.6 RESULTS OF LOSS VERIFICATION ON THE VAAL RIVER

An additional set of manual flow gaugings was undertaken on the Vaal River over 97 km from Bloemhof Dam to Vaalharts Weir during October 1996, which was used as an additional check of the loss methodology derived from the Orange River. Although the river temperatures on this portion of the Vaal River are likely to differ from those on the Orange River, due to the proximity to Bloemhof Dam and the storage in Vaalharts Dam, it was considered the most suitable piece of river available for a loss verification.

Gaugings were carried out at the weir C9H021 just downstream of Bloemhof Dam, and at the farm Witbank 10 km downstream of Vaalharts Weir. One gauging was also carried out near the crump weir C9H018 on the Vaalharts Canal near Vaalharts Weir, since the releases into the canal form the major portion of the flow leaving the reservoir. The Witbank gaugings were converted to flows at the gauging weir C9H008 directly downstream of Vaalharts Weir, by adjusting for the evaporation and abstractions between the two points.

The comparison of flow gaugings and DWAF discharge tables is presented in **Figure 5.16**, while the recorded hydrographs for the period are presented in **Figure 5.17**. The graphs show simulation hours starting at 0h00 on 1 September 1996, and run for 1500 hours or approximately two months. The calibration of simulated versus observed stage in Vaalharts Dam is presented in **Figure 5.18**.

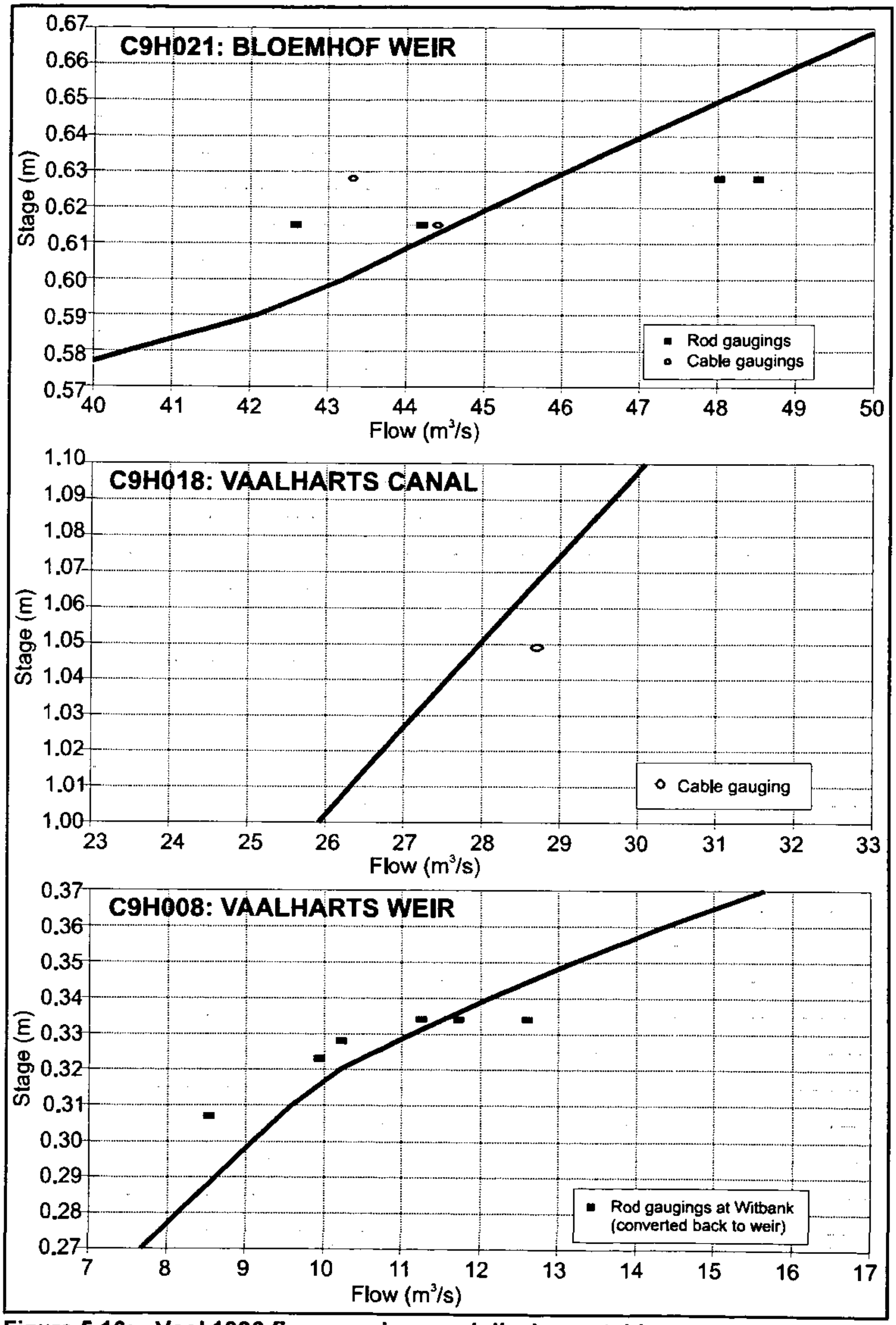


Figure 5.16: Vaal 1996 flow gaugings and discharge tables

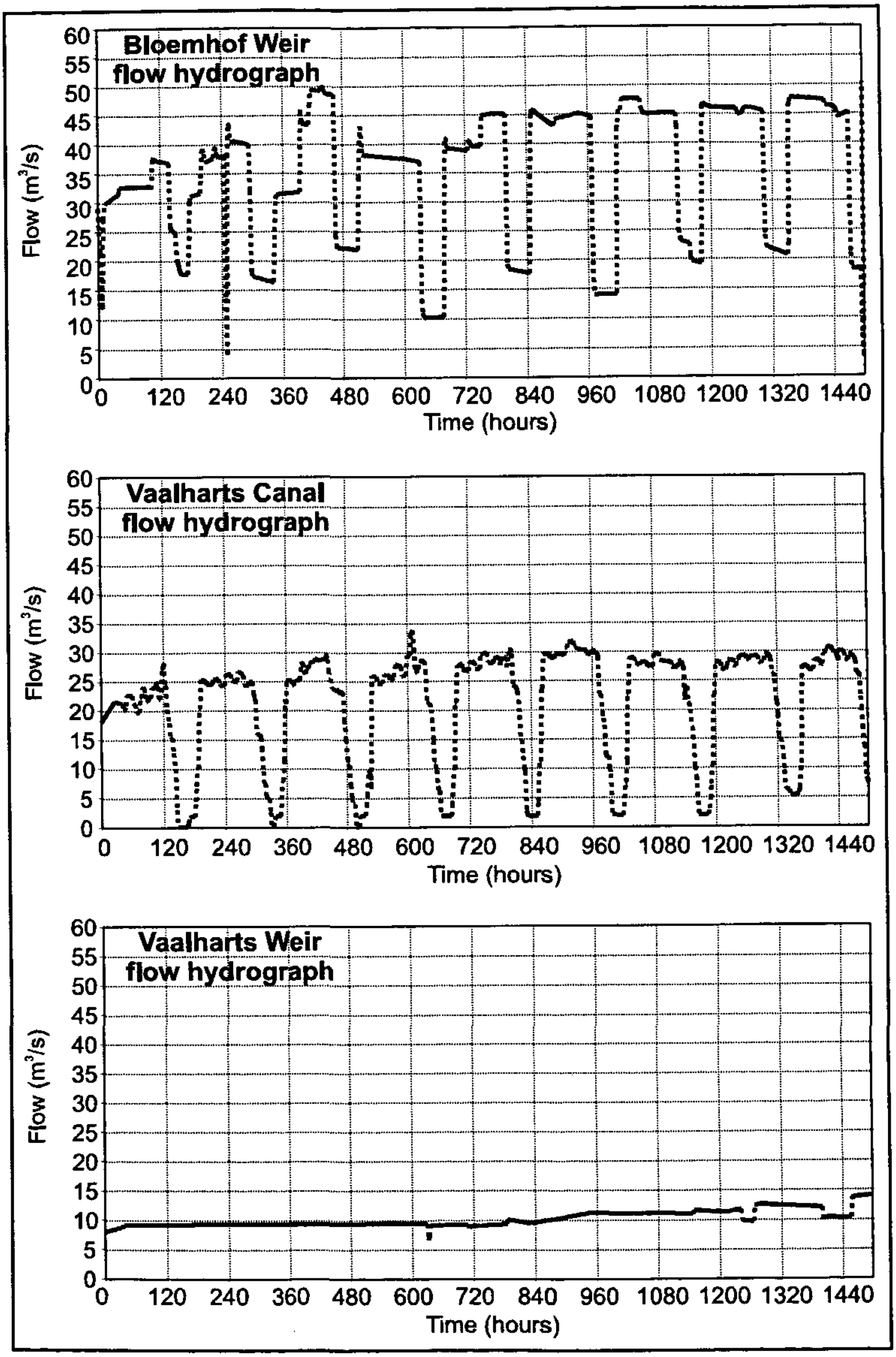


Figure 5.17: Vaal River 1996 flow hydrographs

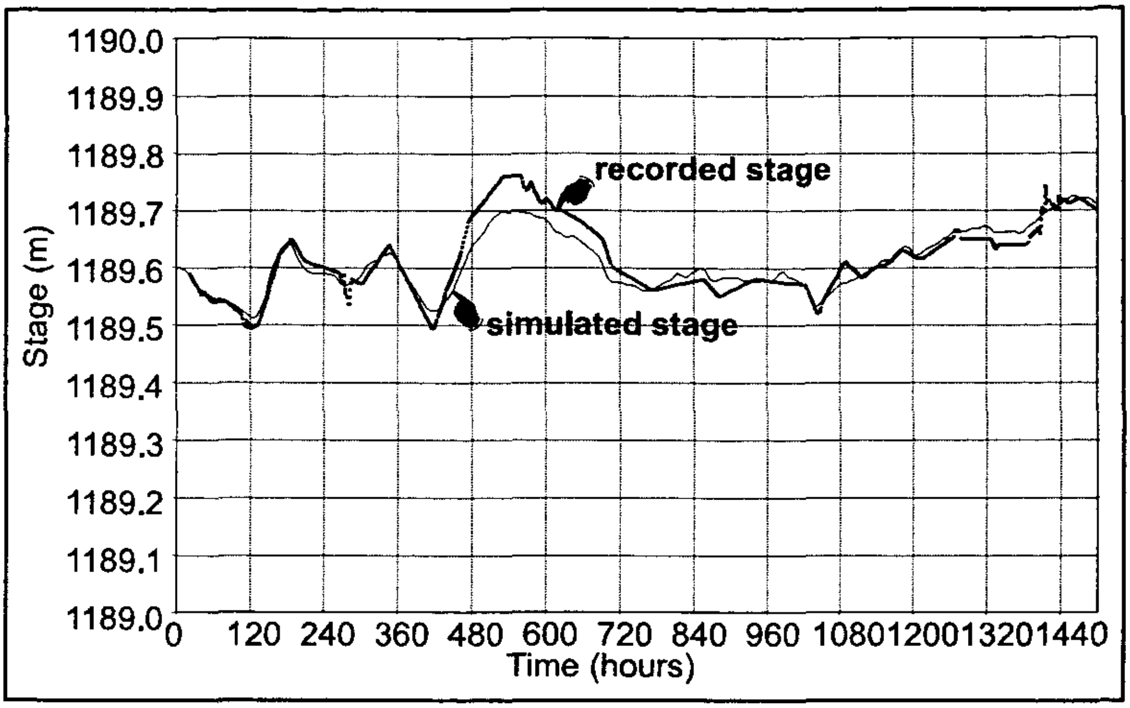


Figure 5.18: Vaal River simulation for 1996

The evaporation in the area during September and October 1996 was 10 % below the long term average. Accurate surface areas were available from the Vaalharts Dam sediment survey report (1991), with only a small portion of the river from Bloemhof Dam to Christiana having to be measured from aerial photos. The actual evaporation multiplied by the actual surface areas predicted an average loss of 2.55 m^3/s over the two month period. The net water consumption over the two month period was 1.2 m^3/s, indicating that errors in the abstraction information could also lead to significant errors in the loss calculation. In the simulation shown above, the losses were estimated at 2.30 m^3/s. Due to the large surface areas and the poor fit of weekly water level variations, however, the integration technique was considered more accurate than the above simulation. Using the integration technique, the losses were estimated to be 2.25 m^3/s, which is 12 % lower than the theoretical estimate of 2.55 m^3/s. Although this is not considered to be as accurate as the November 1994 set of data on the Orange River, the results are very similar. The fact that accurate surface areas were available, and that measured losses were still smaller than the theoretical estimate, suggests that the SM91 evaporation may overestimate river evaporation. In other words, the overestimation of losses on the Orange River is a result of both the surface areas and the evaporation rates.

5.7 OTHER APPLICATIONS OF THE HYDRAULIC MODEL

5.7.1 Modelling of rapidly varying turbine releases

Besides the model from Blouputs to Brand Karos used to process the flow gaugings, a model was also prepared from Vanderkloof Dam to Blouputs, at a reduced level of detail. Sparsely spaced sections were used representing average hydraulic properties for distances ranging from 2 km to 75 km. The purpose of the model was to check travel times to different locations along the river, and to carry out water balance analyses of the upper half of the Orange River. One aspect that was a cause of concern was the rapidly varying hydropower releases from Vanderkloof Dam.

There are two 120 MW turbines installed at Vanderkloof Dam, which each discharge approximately 200 m^3/s, although the discharge per turbine can vary between approximately 170 m^3/s and 225 m^3/s depending on the water level in the dam. The valves controlling the flow through the turbines can be opened or closed within approximately three minutes. Consequently, when one or both turbines are opened, a large surge of water travels down the river resulting in rapid changes in flow and water level. These rapid changes necessitated interpolations as short as 100 m in the first kilometre downstream of the dam, after which the interpolation distance was increased to 1 km. Initially this also necessitated short model time steps, but an adaptive time stepping capability was added into the model during the course of the study. This allowed the use of longer time steps, which were shortened only when required to simulate the rapid opening or closing of the turbines. This produced a 500-600 % improvement in the time required to complete a run. A historic turbine release hydrograph at Vanderkloof Dam, and the simulated and observed hydrographs at Marksdrift Weir (180 km downstream), are shown in **Figure 5.19**. The thin line indicates a trial simulation using the Muskingum empirical flow routing method, mentioned earlier. The latter approach was fast and required very little input data. The reach was subdivided into 5.5 km pieces, since Muskingum routing assumes only wedge storage within each reach.

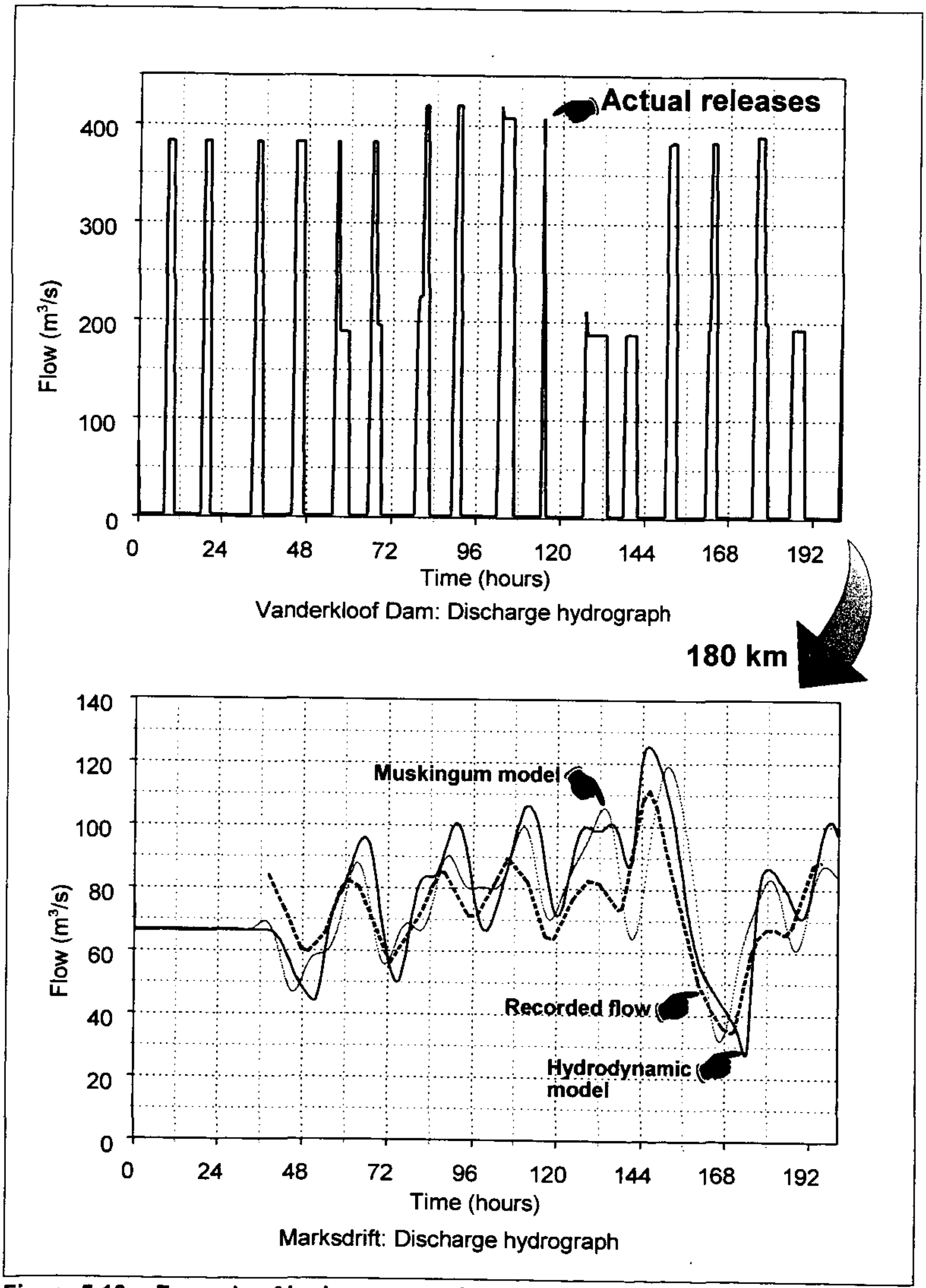


Figure 5.19: Example of hydro power release simulation

5.7.2 Operational model of the Orange River

Following the successful application of the ISIS model, including the variable loss module, a proposal was submitted to the WRC to develop an operational hydraulic model of the Orange River. This has therefore become the subject of a separate study, to extend the model to cover the whole of the Orange River at a suitable level of detail, and link it to a network of telemetry gauging stations. This will allow the new model to be used for optimising the day-to-day operation of the Orange River downstream of Vanderkloof Dam, which will significantly reduce the operational losses. Daily releases from Vanderkloof Dam can then be made more accurately based on the flow at various positions along the river, so that surplus or shortfalls at the river mouth can be minimised. This project will be carried out in close co-operation with the River Losses Study team, and will rely heavily on the modelling expertise built up during the river losses study, as well as on continued support from the DWAF.

5.7.3 Other potential applications for the hydraulic model

In addition to the applications discussed thus far in the report, the hydraulic model has also been used on other studies for DWAF. These include analysis of turbine releases downstream of Vanderkloof Dam and possible remedial measures. Detailed cross sections were also surveyed at selected locations, and processed using the hydraulic model to provide rating curves for environmental in-stream flow requirement assessments. Further potential applications for the model include flood damage assessments, verification of discharge tables at existing and future gauging stations (using a number nearby stations rather than only one in isolation), extension of flow records back in time and filling of gaps in flow records using nearby stations, and evaluating the impact of future dam development options on operational losses and on the environment. Such a model is therefore a very versatile tool which can be used for a variety of applications.

6. CALCULATING EVAPORATION LOSSES FROM SOUTH AFRICAN RIVERS

6.1 GUIDELINES FOR CALCULATING EVAPORATION LOSSES

The purpose of the River Losses Study was not only to calculate the evaporation losses from the Orange River downstream of Vanderkloof Dam, but also to prepare a set of guidelines for calculating evaporation losses from South African rivers. The purpose of this section is to present a summarised set of guidelines for calculating evaporation losses from South African rivers.

Three basic methods have been identified, namely:

- the total area times evaporation rate method,
- the water balance method, and
- the hydraulic modelling method.

The area times evaporation rate method is recommended as a first estimate in all cases whether or not the other methods are to be used. The other methods can then be applied to allow for cross-verification of the results, depending on the scope of the project. The hydraulic modelling is actually a sub-set of the water balance method, being type of water balance itself. In the hydraulic modelling, as in the other methods, there is scope for varying levels of detail depending available resources, and the purpose for which the loss calculations will be used. Emphasis is placed here on evaporation losses, which may differ from total river losses if significant groundwater interaction takes place. The methods for calculating evaporation losses can be applied to other rivers in order to distinguish evaporation losses from losses or accretions due to groundwater interaction.

6.1.1 Total area times evaporation rate method

This method comprises measuring the area of the water surface and of the riparian vegetation, and multiplying these by suitable evaporation rates. This can be done on an annual or monthly basis using applicable evaporation for each reach of river. Different surface areas may be used in different months if the flows in the river are known to exhibit a large seasonal variation. The methods available for establishing surface areas and evaporation rates are discussed in **Sections 3 and 4** respectively.

To summarise, the areas may be obtained from satellite image analysis, aerial photography, or surveys. Newer techniques, such as aerial videography or airborne laser scanning, may also be feasible depending on the specific study and the development of the technique. The flow or range of flows over which accurate loss estimates are required must be established, so that the most appropriate information on surface areas can be sought. An appropriate scale and level of detail must also be chosen according to specific circumstances. Satellite image analysis should only be undertaken with considerable visual and preferably also field verification, as errors can easily occur as a result of digital classification procedures. Aerial photography is very useful, but care should be taken to avoid scale anomalies if the photos have not been orthogonally corrected. If existing photography is used, dates of photography and flows in the river should be checked, as this may have an influence on the results. When measuring areas of riparian vegetation, distinction should be made between reed beds and trees, if possible. Very sparse vegetation should be excluded from the riparian vegetation, so that the area of riparian vegetation will represent dense trees or reeds.

For South Africa, the SM91 (Schulze and Maharaj, 1991, 1997) 1'x1' grid or map overlays of A-pan evaporation are recommended for estimating river evaporation. Evaporation pan data are usually highly variable, and should only be used as a comparison with other methods, or for correlating short periods with long term averages. If hourly evaporation figures are required, they can be estimated using the Penman equation, but a long term average should be derived if possible for comparison with the SM91 values.

6.1.2 Volumetric water balance method

The volumetric water balance method entails integrating the water balance over a longer period, rather than examining the absolute flows at a given point in time. In other words, the volumes of water passing into or out of each reach are recorded in order to determine the net losses over a certain period. The travel time of flows through the reach are estimated from flow data, so that the same portion of the hydrograph can be integrated at both the upstream and downstream ends of the reach. For example, if the travel time for a particular reach is two days, then the integration of outflows at the bottom of the reach should start and end two days later than the integration of inflows at the top of the reach. If the travel time for a reach is long, and if daily information on abstractions from large pump stations is available, then a proportional start time may be used for the abstractions too. The period integrated should be sufficiently long to reduce errors introduced by hydraulic attenuation.

This method obviously depends heavily on the accuracy of flow measurements at both ends of the river reach, as well as on accurate abstraction information. Manual flow gaugings may help to confirm the accuracy of stage discharge relationships at water level recording stations. In the absence of permanent water level recorders, temporary recorders can also used in association with manual flow gaugings to monitor flows over a short period.

A limitation to the method is that it does not take changes in surface area with flow into account. The water surface area must therefore be estimated at the average flow during the period of integration. If a long period of integration is used, such as one year or more, then attention must be given to seasonal effects. Higher evaporation rates occur in summer, when flows in the river are usually also higher. Long periods should therefore be analysed monthly, in order to estimate surface areas from the average flows in each month, and also apply monthly evaporation to these areas. These can then later be added to form an annual total evaporation loss.

6.1.3 Hydraulic modelling method

A hydraulic model is a useful tool in carrying out a water balance, especially in cases when changes in flow induce significant changes in surface area during the period under consideration. Hydraulic modelling has the advantage that the transmission time and attenuation of flows are taken into account by the model, and major abstractors can also easily be placed at the correct location within a reach. Comparison of simulated against observed data also helps to identify errors in recorded water level or flow data, or localised rainfall events which would otherwise often pass unnoticed. Although this can help to improve the accuracy of data, the modelling can only be as accurate as the flow data available.

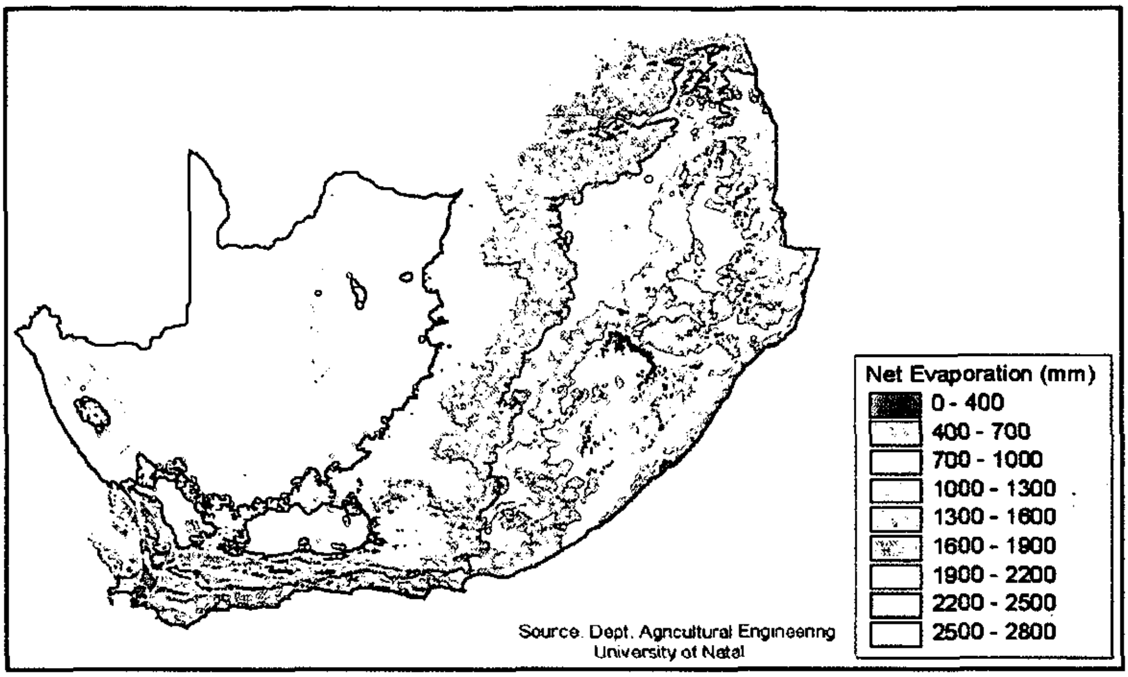
As for any of the methods, varying levels of detail can be applied. For example, Muskingum type flow routing methods can be used, with average losses over a given period grouped together with average abstraction rates, applied at a constant rate. At an intermediate level of detail, simplified cross sections may be used for hydrodynamic simulation of the transmission and attenuation, and losses still taken off as abstractions at regular intervals. Alternatively, detailed cross sections can be used to calculate the surface area dynamically, and apply distributed evaporation rates at hourly resolution calculated from automatic weather station data. If the detailed approach is adopted, sufficient detail should be incorporated into the cross sections to adequately define the surface area of the river. Allowance should also be made for riparian vegetation.

An evaporation module was incorporated into the ISIS hydraulic model for the purpose of this study. The module calculates the surface area of the river for each time increment in the simulation, and multiplies this by a user-defined evaporation rate. The time resolution of the evaporation rate can also be chosen, so that monthly, daily or hourly evaporation can be used. This is especially important for short reaches of river, where the diurnal effect of evaporation may be significant, or where extreme variations of flow and surface area occur. The user can specify a width of riparian vegetation, and a ratio of evapotranspiration to river evaporation. An average ratio can therefore be calculated to represent a mixture of reeds and trees according the reach in question. The riparian vegetation width is therefore multiplied by the evapotranspiration factor and then subject to the same evaporation rate as the river, which has the same effect as applying a reduced evaporation rate.

6.2 REGIONS OF HIGH NET EVAPORATION LOSSES

A GIS map has been produced to assist in calculating evaporation losses from South African rivers. Due to the findings outlined in **Section 4**, the Schulze and Maharaj (1991, 1997) A-pan equivalent evaporation has been recommended for use in river loss calculations. The 1'x1' grid data was therefore obtained from the Department of Agricultural Engineering at the University of Natal, along with the 1'x1' grid of rainfall in South Africa. The latter is the product of a WRC study (Dent, et al, 1987), which is available through the Computing Centre for Water Research (CCWR). The evaporation data may also become available through the CCWR at a later stage, but can presently only be obtained through the Department of Agricultural Engineering at the University of Natal.

These data sets were imported into the ArcInfo GIS program, and the mean annual rainfall subtracted from the gross A-pan evaporation to obtain a net annual evaporation. This illustrates which areas in South Africa are subject to the highest river losses. The map is presented in **Figure 6.1**, and as an enlarged version with rivers and catchment boundaries overlaid in **Appendix B**. This map may be used to obtain a first order estimate of river losses by multiplying by a surface area. It is recommended for detailed studies on rivers with high losses that the 1'x1' evaporation and rainfall data be obtained, and the values extracted according to co-ordinate points on the river. This is recommended due to the influence which local river basin topography can have on the evaporation near the river. Alternatively, overlays are also available for the 1:250 000 map series.



Source. Dept. Agricultural Engineering University of Natal

Figure 6.1: Net A-pan (river) equivalent evaporation in South Africa

6.3 EVAPORATION LOSSES FROM THE ORANGE RIVER

The surface areas of the Orange River were measured from aerial photographs as discussed in **Section 3**. The evaporation rates adopted for the Orange River, as discussed in **Section 4**, were based on Schulze and Maharaj (1991, 1997), which compared well with Bowen ratio evaporation measurements by Everson (1997). Reed and tree evapotranspiration rates are calculated as a factor of the river evaporation. Based on research carried out in the Sabie River basin by Birkhead *et al* (1997) and personal communication with Olbrich (1997, 1998), the factors 1,0 and 0,5 (times river evaporation) were adopted for reed and tree evapotranspiration respectively. From this information, theoretical loss estimates of the Orange River were calculated, and are presented in **Table 6.1**. Water surface areas and corresponding annual evaporation losses are given for two flow scenarios, namely annual average releases of 50 m^3/s and 400 m^3/s respectively. In the 400 m^3/s flow scenario, the effective area of reeds is considered to be zero, since most of the reeds are covered with water during such flows. The relationship between the annual average release rate and annual evaporation losses is illustrated graphically in **Figure 6.2**.

Table 6.1: Evaporation losses from the Orange River

Reach	From	To	Gross Evap (mm)	Rainfall (mm)	Area of Water (km²)		Area of R. Veg (km²)		Losses (10⁶ m³/a)	
					50m³/s	400m³/s	Reeds	Trees	50m³/s	400m³/s
1	Vanderkloof	Marksdrift	2 665	301	17,8	31,3	0,5	7,7	52,4	83,1
2a	Marksdrift	Prieska	2 761	257	23,8	38,7	1,2	8,4	73,1	107,4
2b	Prieska	Boegoberg	2 795	216	14,8	23,8	1,0	3,5	45,2	65,9
3a	Boegoberg	Gifkloof	2 865	178	23,2	40,0	1,3	9,9	79,3	120,8
3b	Gifkloof	Neusberg	2 885	146	11,0	26,0	1,7	6,0	43,1	79,5
4	Neusberg	20°E	2 920	109	8,3	17,0	1,5	5,1	34,7	54,9
5a	20°E	Pella	2 938	75	16,8	36,0	1,4	6,0	60,8	111,6
5b	Pella	Vioolsdrift	2 921	42	19,5	46,0	2,4	7,4	73,8	143,1
6	Vioolsdrift	Fish	2 942	31	12,0	32,0	3,1	4,7	50,7	100,0
7a	Fish	BrandKaros	2 925	29	9,4	24,5	2,7	2,0	38,1	73,9
7b	BrandKaros	Mouth	2 765	39	4,1	14,2	1,0	7,5	24,1	48,9
Total	Vanderkloof	Mouth	2 849	145	160,7	329,5	17,9	68,2	575,2	989,0
							Factor	Factor		
							1,0	0,5		

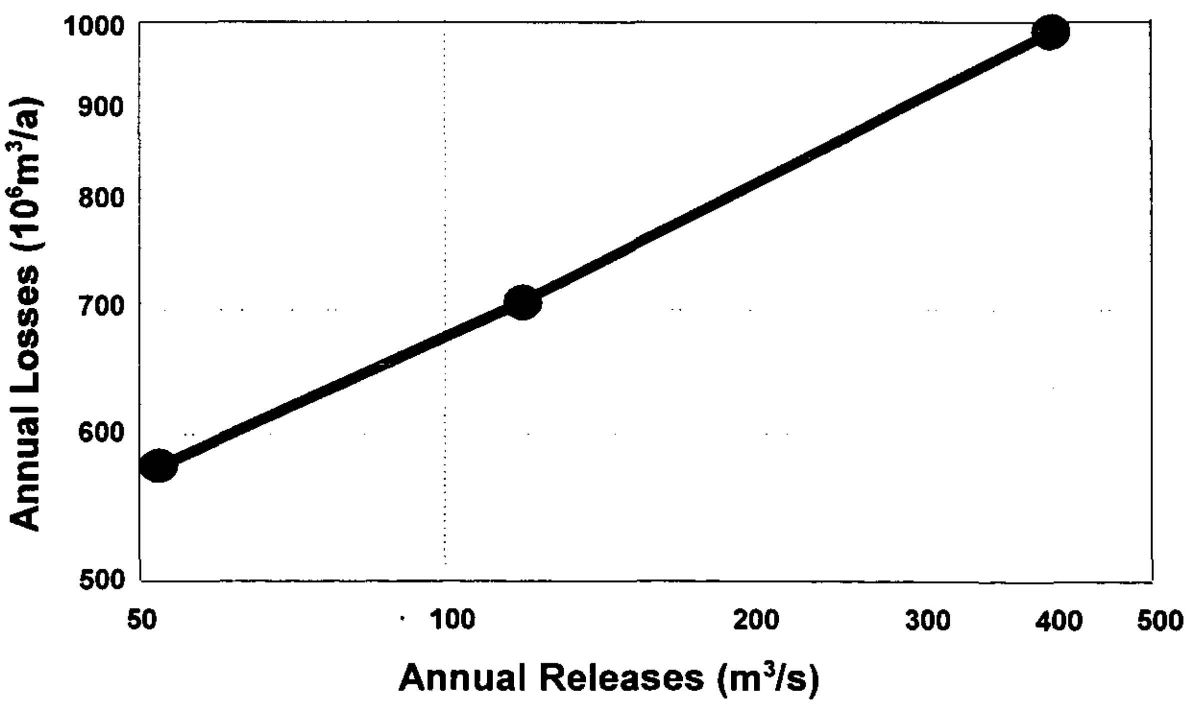


Figure 6.2: **Average annual losses versus releases**

7. CONCLUSIONS

Based on the results presented in this report, it is concluded that Phase 2 of the River Losses Study has been successful in improving estimates of river losses downstream of Vanderkloof Dam, and in developing a methodology for calculating evaporation losses from South African rivers. Specific results obtained during the course of the study, with relevant conclusions, are highlighted below:

Surface Areas of Water and Riparian Vegetation

The areas of water surface and riparian vegetation were determined for the Orange River at different flows for each reach of the river using aerial photographs. Very few aerial photographs exist of the Orange River at low flows, and an extrapolation technique was therefore applied to estimate the water surface areas at low flows. Satellite images and hydraulic modelling were also used to help establish realistic estimates of the water surface areas and areas of riparian vegetation. Approval to fund the collection and processing of aerial photographs of the Orange River at low flows was granted by DWAF in 1996, however, due to higher than normal river flows during the winter months of 1996, 1997 and 1998 it was not possible to carry out low flow aerial photography. DWAF still intends to have these photos taken to increase confidence in loss estimates for the Orange River.

Evaporation rates applicable to moving water surfaces and riparian vegetation

Information on evaporation rates from flowing water was derived from a Bowen Ratio energy balance study carried out by Environmentek on the Orange River near Upington (Everson, 1997). Further evaluation of the results indicated that the best estimate of river evaporation is given by the A-pan equivalent evaporation prepared by Schulze and Maharaj (1991, 1997), which varies from 2 500 mm/a to almost 3 000 mm/a on the Orange River. A-pan evaporation data is therefore recommended for use in calculating river losses from South African rivers. The evapotranspiration rates for reeds and trees used in the study were based on research into riparian water consumption in the Kruger National Park (Birkhead, et al, 1996), where high gross evaporation of approximately 2 000 mm/a is also experienced.

Validation of results using hydraulic model

Three sets of manual flow gaugings were carried out on the Orange River, in July 1993, November 1994 and November 1995, to assist in the verification of the river loss methodology. The flow gaugings were processed using a sophisticated hydraulic model which indicated that the actual river losses were approximately 14 % lower than the theoretical estimate based on the surface areas and evaporation rates discussed previously. Flow gaugings in October 1996 on the Vaal river also produced similar results. The discrepancy is most likely due to overestimation of the surface areas at low flows, since aerial photographs of the Orange River at low flows could not be obtained. It is possible that the Schulze and Maharaj (1991,1997) evaporation figures also overestimate river evaporation, however, the proposed methodology was not adjusted, to avoid overestimating the available water resources of the Orange River.

The calculated evaporation losses from the Orange River derived from this research range from 575 million m^3/a at an annual low flow release of 50 m^3/s to 989 million m^3/a at an annual release of 400 m^3/s. The variation in evaporation losses is due to the change in surface area with flow. In the first phase of the River Losses Study, the losses were estimated to be 960 million m^3/a based on surface areas for flows between 400 m^3/s and 1 000 m^3/s, together with S-pan evaporation values (without pan-to-lake factors). Although the river evaporation has now been estimated to be higher than the S-pan values, the reduction in surface area produces a net reduction in the total loss estimate of approximately 380 million m^3/a. This is a significant quantity of water in terms of the available water resources of the Orange River. The basis for the estimates is provided in **Table 7.1** below, and the results are illustrated graphically in **Figure 7.1**.

Table 7.1: Evaporation losses from the Orange River

Reach	From	To	Gross Evap (mm)	Rainfall (mm)	Area of Water (km^2)		Area of R. Veg (km^2)		Losses (10^6 m^3/a)	
					$50 m^3/s$	$400 m^3/s$	Reeds	Trees	$50 m^3/s$	$400 m^3/s$
1	Vanderkloof	Marksdrift	2 665	301	17,8	31,3	0,5	7,7	52,4	83,1
2a	Marksdrift	Prieska	2 761	257	23,8	38,7	1,2	8,4	73,1	107,4
2b	Prieska	Boegoberg	2 795	216	14,8	23,8	1,0	3,5	45,2	65,9
3a	Boegoberg	Gifkloof	2 865	178	23,2	40,0	1,3	9,9	79,3	120,8
3b	Gifkloof	Neusberg	2 885	146	11,0	26,0	1,7	6,0	43,1	79,5
4	Neusberg	20°E	2 920	109	8,3	17,0	1,5	5,1	34,7	54,9
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5b	Pella	Vioolsdrift	2 921	42	19,5	46,0	2,4	7,4	73,8	143,1
6	Vioolsdrift	Fish	2 942	31	12,0	32,0	3,1	4,7	50,7	100,0
7a	Fish	BrandKaros	2 925	29	9,4	24,5	2,7	2,0	38,1	73,9
7b	BrandKaros	Mouth	2 765	39	4,1	14,2	1,0	7,5	24,1	48,9
Total	Vanderkloof	Mouth	2 849	145	160,7	329,5	17,9	68,2	575,2	989,0
							Factor	Factor		
							1,0	0,5		

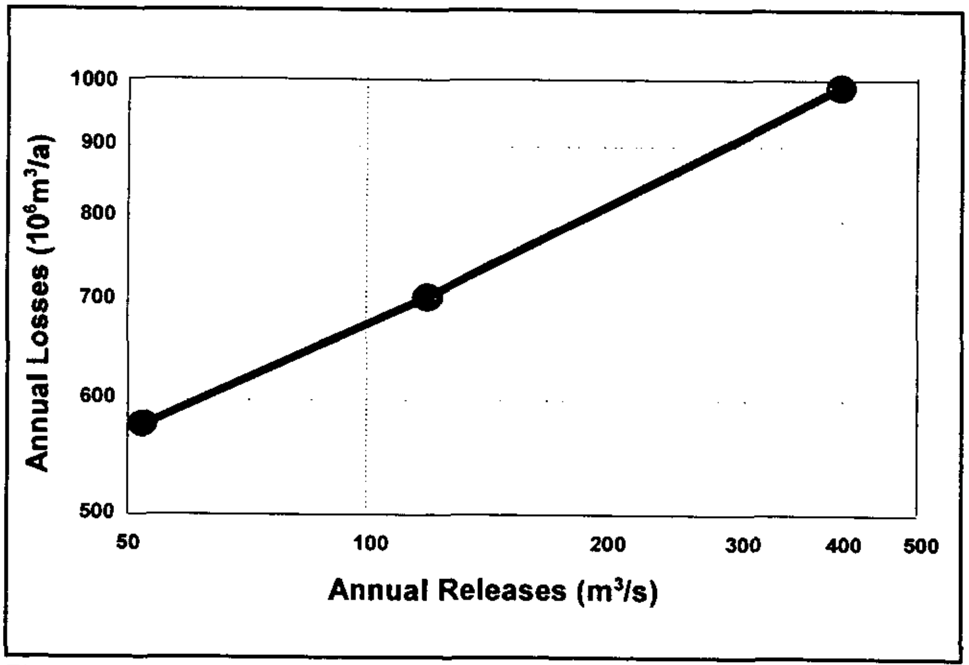

Figure 7.2: **Average annual losses versus releases**

Guidelines for estimating evaporation losses from South African rivers

A set of guidelines for estimating evaporation losses from South African rivers has been prepared, based on the research carried out on the Orange River.

It is recommended that surface areas be measured from aerial photography, although checks for scale anomalies should also be carried out. Satellite imagery can be used, but extensive visual verification and field visits should be undertaken to validate the digital classification. River evaporation should be determined from map overlays or digital 1'x1' grid information produced by Schulze and Maharaj (1991, 1997), obtainable from the Department of Agricultural Engineering at the University of Natal. Rainfall estimates needed to estimate the net evaporation can be obtained in the same format as the evaporation data from the Computing Centre for Water Research (CCWR). The *rainfall information from Surface Water Resources of South Africa 1990* (Midgley, et al, 1994) may also be used. The Schulze and Maharaj evaporation may also become available from the CCWR in due course.

Net evaporation losses can then be estimated from the surface area of water and riparian vegetation (with factors applied) multiplied by the net evaporation rate described above. A map of net annual evaporation is presented as an appendix to this report, to highlight areas where river losses are likely to be most significant.

The theoretical estimate of river losses derived from the above methodology can also be compared to a water balance of the river is suitable data are available. This will improve the confidence in the results, and will help to highlight additional problem areas such as losses to groundwater, or data errors in abstraction information. This method relies heavily on accurate flow measurements, which can often be improved by manual flow gaugings, as well as accurate abstraction information. Depending on the specific nature of the river and the scope of the study, varying levels of detail can be applied in performing the water balance. If a hydraulic model is not used, then it is important that the volumes of water entering and leaving the reach should be integrated over a sufficiently long period to minimise the effects of hydraulic *attenuation. It is also important to examine flow data carefully to ensure that travel* times can be taken into account.

8. RECOMMENDATIONS

Following the information and conclusions presented in this report, it is recommended that:

- The guidelines set out in this report should be used to estimate evaporation losses in future water resource studies on South African rivers.
- A set of aerial photographs should be taken of the Orange River during low flows. This will improve the accuracy of the loss estimates, and also provide useful information for a number of other applications.
- The Schulze and Maharaj (1991, 1997) 1'x1' data should be provided in digital format through the CCWR, so that this data can be used for loss estimates on South African rivers.
- Results from the ongoing research into the water consumption from riparian vegetation being carried out on the Kruger National Park rivers should be considered for use in future loss estimates on South African rivers.
- Hydraulic modelling should be considered in future studies to improve the understanding of the behaviour of rivers, and evaluation of abstractions and losses.
- Hydraulic modelling can also be considered as a tool to assist with the simultaneous calibration of various gauging stations that are currently calibrated in isolation from each other.

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Appendix A

Suitability of Tracers for Estimating Irrigation Return Flow Retention Time

Suitability of Tracers for Estimating Irrigation Return Flow Retention Times

(Pilot Study: Vioolsdrift 1995)

SYNOPSIS

This report describes the suitability of using tracer techniques for estimating irrigation return flow retention times, and presents the results of a pilot study undertaken at Vioolsdrift on the lower Orange River during 1995. This investigation formed part of the River Losses Study, an extensive study into water losses from rivers which was undertaken by BKS (Pty) Ltd for the Water Research Commission.

The implementation of the first phase of the Lesotho Highlands Water Project, and the growth of existing water demands along the Orange River necessitated a complete re-evaluation of the planning and management of the Orange River's water resources. The last major storage structure on the Orange River is the Vanderkloof Dam, which is almost 1400 km from the river mouth. An accurate estimate of the river losses occurring from the Orange River downstream of Vanderkloof Dam is therefore required for effective operation of the system. With this background, the WRC commissioned BKS to undertake the River Losses Study, with support from the Department of Water Affairs and Forestry (DWAF). The first phase of the study was carried out in 1993, when the principal components influencing river losses were identified and examined at a preliminary level of detail. The second phase of the study was initiated in 1994 and is currently under way to investigate several key issues identified in the first phase in order to obtain a better understanding of the processes influencing river losses from the Orange River.

The losses downstream of the Vanderkloof Dam are primarily evaporative losses, comprising a combination of direct evaporation from the water surface and evapotranspiration from riparian vegetation along the river banks. Due to the extensive farming along the river, the irrigation abstractions and return flows are two very important components of the water balance. A thorough understanding and suitable measurements of these components are therefore important in determining the overall losses from the river. Another unknown factor

was the retention time of the irrigation return flows, which could have a significant influence on the water balance due to the seasonal irrigation practices. Long retention times could for example result in large return flow volumes long after the summer irrigation peak.

In order to investigate the uncertain irrigation return flow retention times, BKS approached the Atomic Energy Corporation to assist with a pilot study at Vioolsdrift using tracer technology. This report presents the methods used and the findings of the study using Indium-EDTA as a tracer.

Vioolsdrift was selected due to the suitability of the irrigation practices in the area, the presence of suitable drainage, and also because it is relatively close to the Orange River Mouth. By selecting a site well downstream on the Orange River it avoided the possibility of additional future tracer studies being affected by left-over tracer from the initial pilot study.

It was concluded from the study that:

- *Indium-EDTA is an effective tracer for monitoring irrigation return flow retention times, being inactive (not radioactive), environmentally safe and measurable at very low concentrations. Furthermore, Indium is a rare and stable earth metal which is not readily affected by chemical reactions or absorbed into sediments.*
- *The site chosen at Vioolsdrift is typical of most flood irrigation along the lower Orange River.*
- *The tracer was evident at significant concentrations in the drainage furrow between approximately 10 and 46 days after release into the irrigation water on the test site at Vioolsdrift. The maximum concentration and mean retention time both occurred at approximately 24 days. The observed concentrations were approximately 2000 times higher than the minimum measurable level of Indium-EDTA tracer. This tracer is therefore very suitable for measuring the retention time of irrigation return flows, and the same mass of tracer (1kg) would produce measurable concentrations in a river flowing up to 50m^3/s or more.*
- *Percentage volumetric return flow from applied irrigation water was estimated from a basic water balance of the drained area to be approximately 33 %.*

It is recommended that a further program of irrigation return flow retention time studies, using tracer technology, be considered. This will allow the retention times under different types of *irrigation practices, to be evaluated. Careful sampling and monitoring of irrigation water application rates and return flow rates at specific sites will also provide further insight into volumetric return flow percentages under the different irrigation practices. This is of particular relevance in the Orange River where measures to use the irrigation water more efficiently are currently being investigated. The whole question of return flows is of particular interest in such investigations.*

Suitability of Tracers for Estimating Irrigation Return Flow Retention Times

(Pilot Study: Vioolsdrift 1995)

TABLE OF CONTENTS

Page

1. INTRODUCTION

This report describes the suitability of using tracer techniques for estimating irrigation return flow retention times and presents the results of a pilot study undertaken at Vioolsdrift on the lower Orange River during 1995. This investigation formed part of the River Losses Study, an extensive study into water losses from rivers which was undertaken by BKS (Pty) Ltd for the Water Research Commission (WRC). The purpose of the River Losses Study was to refine estimates of evaporation losses from the Orange River between Vanderkloof Dam and the river mouth, and to derive a general methodology for calculating losses from other rivers in South Africa.

The losses downstream of the Vanderkloof Dam are primarily evaporative losses, comprising a combination of direct evaporation from the water surface and evapotranspiration from riparian vegetation along the river banks. Due to the extensive farming along the river, the irrigation abstractions and return flows are two very important components of the water balance. A thorough understanding and suitable measurements of these components are therefore important in determining the overall losses from the river. Another unknown factor was the retention time of the irrigation return flows, which could have a significant influence on the water balance due to the seasonal irrigation practices. Long retention times could for example result in large return flow volumes long after the summer irrigation peak.

In order to investigate the uncertain return flow retention times, BKS approached the Atomic Energy Corporation to assist with a pilot study at Vioolsdrift using tracer technology. This report documents the findings from the pilot study by first discussing the selection of the tracer and a suitable site, after which the results of retention time measurements and return flow estimates made at the Vioolsdrift site are presented. Conclusions and recommendations are provided at the end of the report.

2. SELECTION OF A SUITABLE TRACER

2.1 CRITERIA FOR SELECTION

The following criteria were adopted in choosing a suitable tracer:

- The tracer should be environmentally friendly and not pose a threat to any facet of the ecosystem.
- The tracer must be detectable at very low concentrations, in view of the high dilution anticipated.
- The detection of the tracer should not be influenced by any other water borne substances such as sediments or salts which could influence the results.
- The tracer must follow the path of the water even at low flows, and should therefore not be subject to excessive losses through adsorption, chemical precipitation or other processes.

2.2 SUITABILITY OF AN INDIUM-EDTA TRACER

Although there are known radio-active tracers which meet the last three criteria described above, the failure to meet the first criteria precluded these from being a viable option for use on an irrigated farmland. The tracer Indium-EDTA (Indium metal in an Ethylene-Diamine tetracetic acid complex, which allows it to trace the passage of water) was selected as the most suitable tracer for the following reasons:

- Indium-EDTA is totally inert, non-radioactive, and not harmful in any way to humans or the environment.
- Indium is suited to neutron activation analysis by virtue of its high neutron absorption cross-section. Therefore, if Indium is subjected to high level radiation in the laboratory, it can easily be detected even at levels as low as 10^{-12}g/ml.
- Indium is a rare-earth metal and is normally not present in the earth's crust. Any Indium detected in the water samples taken at the tracer site must therefore originate from the tracer. It is also a highly stable element, and is not affected chemically by conditions in the irrigation water.
- Indium-EDTA as a chemical complex can trace the path of the water even at low flows, and is not subject to excessive losses through adsorption or other processes. Although chemical precipitation can be a problem in the solution form in which the tracer is

applied, the pH of the water was tested beforehand to ensure that precipitation would not occur.

2.3 TRACER PREPARATION AND ANALYSIS

The tracer was prepared from 1 kg of inactive Indium dissolved and reacted into the form Indium-EDTA, and was diluted to a volume of 25 litres at a pH of 7. After release into the irrigation water on the test site, samples were collected from the drainage furrow for irradiation and chemical analysis at Pelindaba. The activated Indium was analysed on a Sodium Iodide scintillation detector connected to a multi-channel analiser. This produced a spectral frequency curve, on which the photopeak caused by the Indium could be identified. A typical example of such a spectral frequency curve is shown in **Figure A-1**. The final concentration was derived by comparing the radiant energy of the sample with that of a separate solution of known concentration. A more detailed description of the laboratory preparation and analysis is given by Behrens *et. al.* (1977).

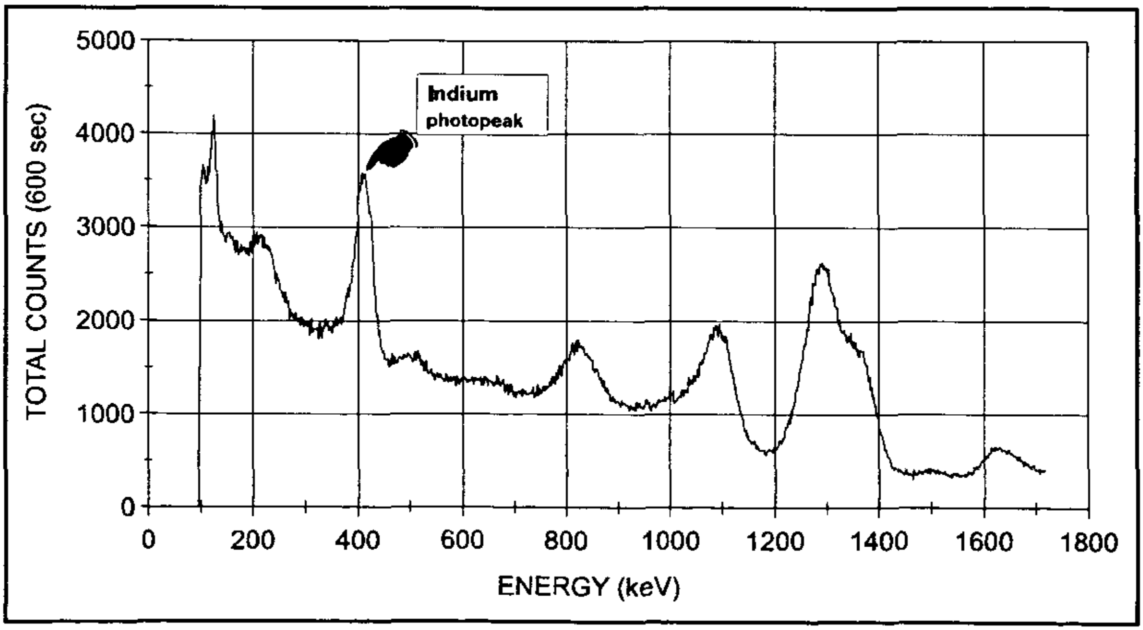

Figure A-1: Typical spectrum of a sample

3. SELECTION OF A SUITABLE SITE

3.1 CRITERIA FOR SELECTION

The selection of a suitable site was very important to ensure that the results were representative of the real situation. The following criteria were adopted in choosing a suitable site for the application of the tracer:

- The site should have a drainage system which would allow detection of the tracer before discharge into the Orange River where excessive dilution could result in the tracer concentrations below the detection limit.
- The site should be as far downstream from Vanderkloof Dam as possible. This eliminates the possibility of the tracer being detected in areas further downstream which could be used for similar studies in future.
- The site should be representative of the general farming practices applied in the Orange River.
- Local effects which may influence the passage of the tracer to the drainage system should be minimised as far as possible.

3.2 SUITABILITY OF VIOOLSDRIFT SITE

Based on the selection criteria, Vioolsdrift was chosen as the most suitable pilot site for the following reasons:

- Vioolsdrift has a drainage furrow which drains a relatively small area and therefore has reasonably small flows, thus minimising dilution of the tracer.
- Vioolsdrift is the lowest site on the Orange River with a suitable drainage furrow, and a pilot study situated at Vioolsdrift will have no influence on any similar studies which maybe undertaken upstream in future.
- Flood irrigation is being practised at the Vioolsdrift site with the result that no fields are fallow. Such fields could have had a negative influence on the results. The specific release site (shown in **Figures A-2 and A-3**) was chosen at a distance of 400 m from the drainage furrow. This is considered to be representative of most of the flood irrigation along the Orange River, where distances to the river or a drain generally vary from 200 m to 800 m.
- The specific release site was chosen 50 m from the edge of the irrigation area. This was done in order to limit undesirable edge effects such as stagnation of the tracer in

"dead pockets" or short circuiting of the tracer via preferential drainage paths at the edge of the field.

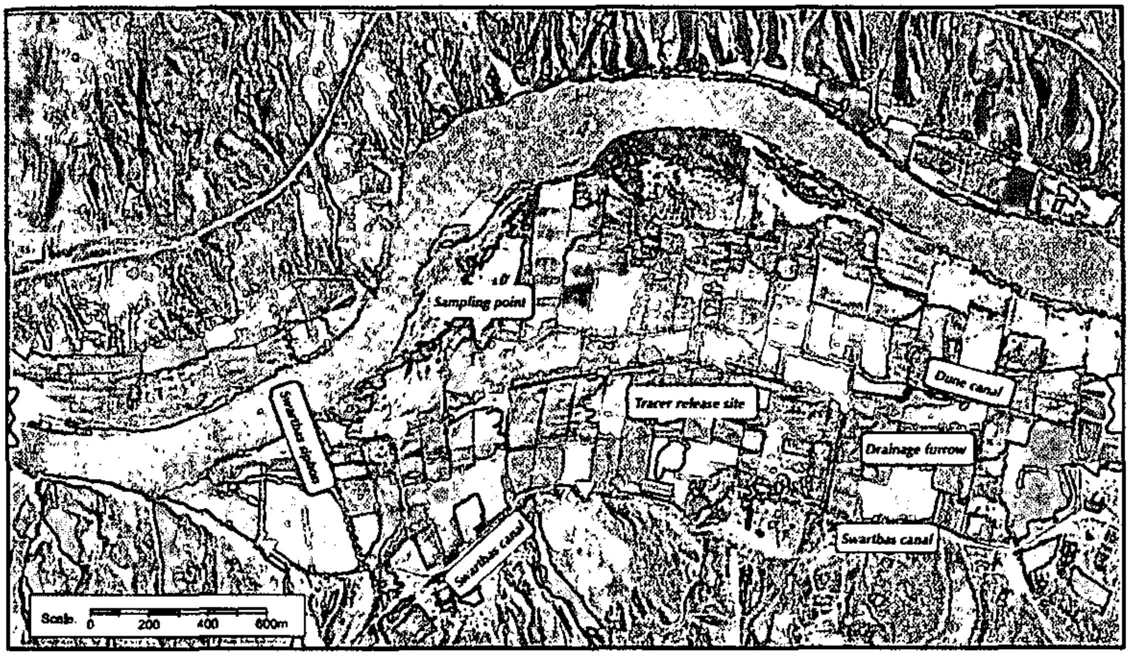

Figure A-2: Layout of Vioolsdrift test site

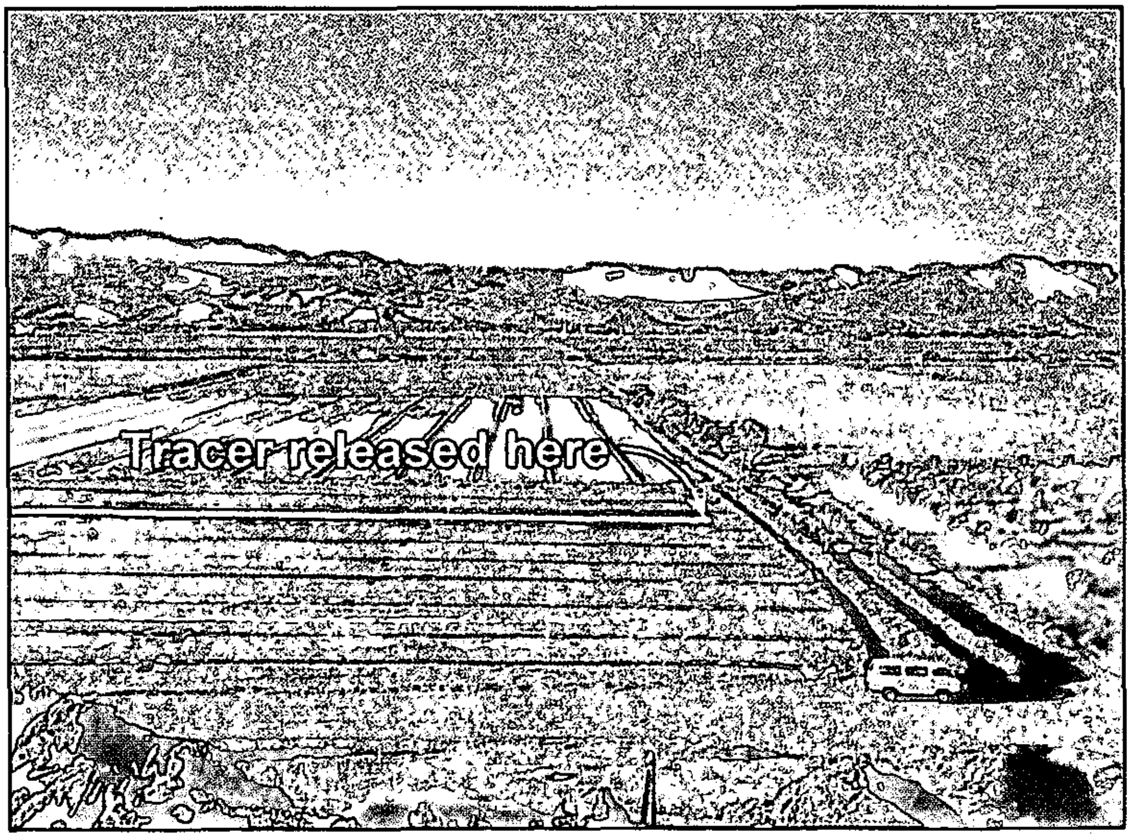

Figure A-3: View of the Vioolsdrift site

4. RETENTION TIME MEASUREMENT

4.1 TRACER RELEASE

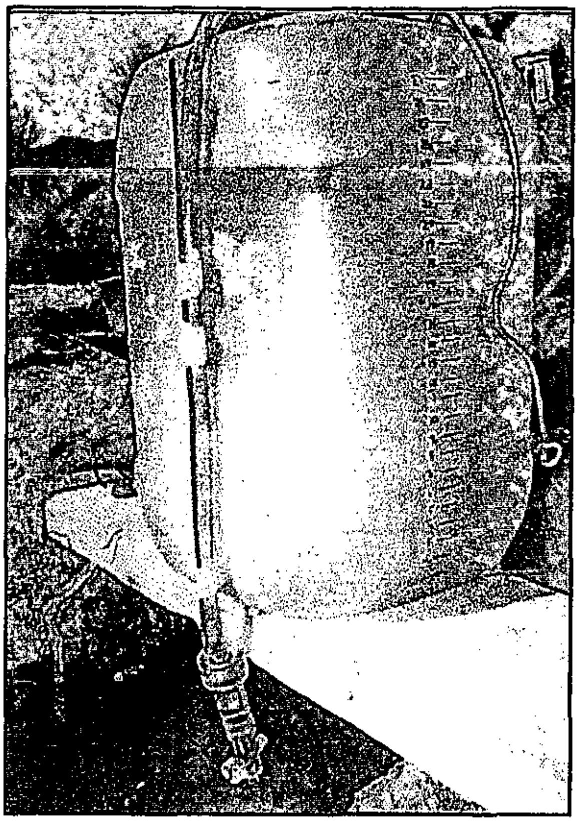

Figure A-4: **Tracer canister**

The tracer was transported to the investigation site in an aqueous solution, and released from a canister with an adjustable flow rate (see **Figure A-4**). This allowed the 25 *l* tracer solution to be released at a constant rate of 0.7 *l*/min over 35 minutes. The tracer was released into the water at the entrance to the specific part of the field being watered (see **Figure A-5**). In addition to the usual partitions along the field, small earth walls were built a short distance from the start and end of the partitioned lane. The purpose of these walls was to contain the labelled water within the specified area and away from possible preferential drainage paths near the edges of the field. A metal plate was also placed in front of the canister's outlet to ensure good mixing and distribution of the tracer. The area covered by the tracer was 100 m long and 8 m wide (i.e 800 m^2). Since the time over which the tracer was released was short relative to the retention time, the tracer pulse can be considered as an instantaneous pulse for analysis purposes.

4.2 TRACER SAMPLING

Water sampling for detection of the tracer was undertaken at the outfall of the pipe buried in the drainage furrow, just before the water enters the Orange River (see **Figure A-2**). Samples were taken in 1 litre bottles (**Figure A-6**), although only 100 m*l* was used for the analysis. The depth of flow at the pipe outfall was also measured each time a sample was taken (see **Figure A-7**) in order to monitor variations in flow rate from the pipe. The flow in the pipe remained relatively constant at approximately 0,025m^3/s during the study period. Samples were initially sent by normal postage services to Pelindaba for analysis. This was considered acceptable since the concentration of the inactive tracer is not affected by time. Unfortunately, several of the earlier samples were lost in transit, after which it was decided to use courier services.

Figure A-5: Tracer release in progress

Figure A-6: Sampling at drain outlet

Figure A-7: Measuring depth of flow

4.3 RESULTS

The results of the tracer concentration measurements are given in **Table 4.1**, and are also presented graphically in **Figure A-8**.

Table 4.1: Observed concentrations

Time * (days)	Tracer concentration (ng/mℓ)
0.08	0.00
0.73	0.00
15.60	2.51
16.02	2.90
34.08	3.02
35.06	2.14
36.05	0.44
37.04	1.51
40.17	0.13
42.08	0.07
46.04	0.01
48.08	0.23
49.08	0.19
50.08	0.02
51.04	0.02
56.06	0.20
57.08	0.20
61.08	0.01
62.08	0.02
73.08	0.02
75.08	0.21
86.08	0.00

* Time in days elapsed since tracer release on 21 February 1995 at 16h00

The mean retention time can be determined from the first moment of area of the concentration distribution. The equation is as follows:

$$T = \frac{\Sigma t.C(t).\Delta t}{\Sigma C(t).\Delta t} \qquad (1)$$

where T = mean retention time
t = time of specific sample
C = concentration of specific sample

Unfortunately, an accurate calculation of the mean retention time was not possible due to the fact that insufficient data were obtained during the earlier part of the study. By applying equation (1) to the available data, an estimated mean retention time of 24 days was obtained. Using a tanks-in-series mixing model, a curve was fitted to the data as shown on **Figure A-8**. Inspection of the graph indicates that the majority of the tracer passed between 10 and 46 days (99%).

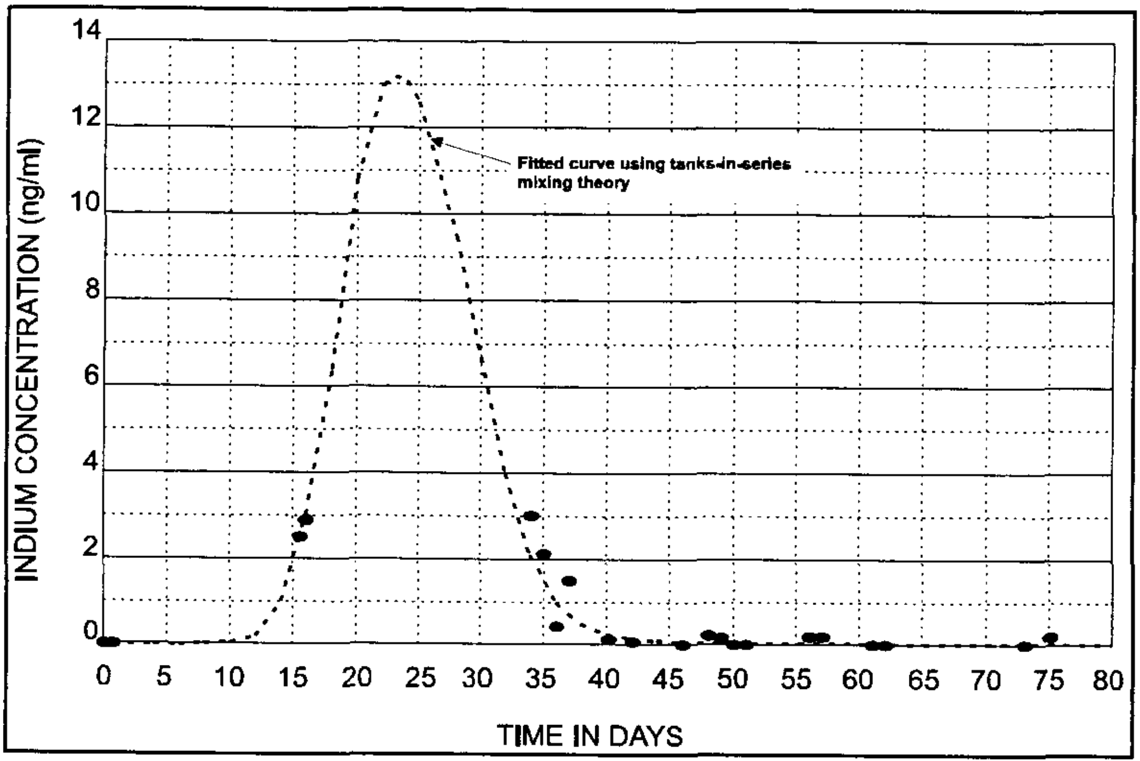

Figure A-8: Fitted concentration curve

The peak concentration indicated on the curve is approximately 13ng/mℓ, with 1ng/mℓ being a minimum level required to define the curve. Since the tracer concentration is measurable down to 0,5 x 10^{-12}g/mℓ it would have been possible to observe the tracer at 2000 times the dilution used. It would therefore have been possible to define the concentration curve from samples taken from the river flowing at 50m^3/s or more. It would therefore be possible in future studies of this type to label larger volumes of water (greater dilution), or to take additional samples from the river downstream of the drainage outfall to ensure that extra drainage does not take place into the river via other seepage routes.

5. RETURN FLOW ESTIMATES

Since the volumetric percentage return flow is one of the important variables in the water balance, an estimate of this parameter was desired to confirm assumptions currently used.

The drainage pattern of famlands near the drainage furrow was estimated by visual observation at the site in consultation with local farmers. The total area draining to the furrow was then measured from an aerial photograph, and found to be ±96 ha. This area was multiplied by an average crop requirement of 1880 m^3/ha/month for Vioolsdrift in February to find a volumetric average application rate of 0.075 m^3/s. The flow rate in the drainage furrow was then measured with the assistance of the DWAF and monitored over the period of the study. The flow was found to remain relatively constant at approximately 0.025m^3/s. The percentage return flow for the drainage area was estimated as

$$\frac{(0.025m^3/s)}{(0.075m^3/s)}=33\%.$$

Integration of the area under the curve in **Figure A-8** indicates that approximately 365g out of the original 1kg of tracer returned to the drainage canal. This is less than would usually have been expected, considering that the tracer was released onto a land which had just had a crop removed and the uptake of tracer by the new plants would have been small. It is possible that some tracer become lodged in "dead pockets" which do not readily drain to the furrow, or else that deep infiltration was occurring to sub-surface ground water aquifers. It may also be possible that the fitted curve is not very accurate due to missing data. This tracer mass balance method could, however, be applied in future studies to confirm estimates of return flow percentage and to check for other seepage effects.

6. CONCLUSIONS

Based on the information obtained by the field work as presented in this report, the following conclusions can be drawn:

- Indium-EDTA is an effective tracer for monitoring irrigation return flow retention times since it is inactive (non-radioactive), environmentally safe and detectable at very low concentrations. Furthermore, Indium is a rare and stable earth metal and is not affected by chemical reactions or changes in background concentrations.
- The site chosen at Vioolsdrift is considered representative of most flood irrigation along the lower Orange River.
- The tracer was evident at significant concentrations in the drainage furrow between approximately 10 and 46 days after release into the irrigation water on the test site at Vioolsdrift. The maximum concentration and mean retention time both occurred at approximately 24 days. The observed concentrations were approximately 2000 times higher than the minimum measurable level of Indium-EDTA tracer. This tracer is therefore very suitable for measuring the retention time of irrigation return flows, and the same mass of tracer (1kg) would produce measurable concentrations in a river flowing at up to 50m^3/s or more.
- Percentage volumetric return flow from applied irrigation water was estimated from a basic water balance of the drained area to be approximately 33 %.

7. RECOMMENDATIONS

It is recommended that a further program of irrigation return flow retention time studies using tracer technology be considered. This will allow evaluation of retention times under different types of irrigation practices, and in other areas of interest. Careful sampling and monitoring of irrigation water application rates and return flow rates at specific sites could also give further insight into volumetric return flow percentages under different irrigation practices.

An ideal site for an additional study is Louisvale near Upington, where more information is available on irrigation abstractions and where monitoring program for measuring irrigation return flow volumes is currently underway.

8. REFERENCES

1. BEHRENS, H, MOSER, H and WILDNER, E. (1977). *Investigation of ground water flow with the aid of Indium-EDTA-complex using neutron activation for the determination of the tracer.* J of Radioan. Chem. 38 (1977).
2. HILLS, A E, VERMEULEN, A, VAN DER BANK, D J. (1995) *Retention time measurement by means of In-EDTA tracer methodology.* Atomic Energy Corporation of South Africa, Internal report to BKS.
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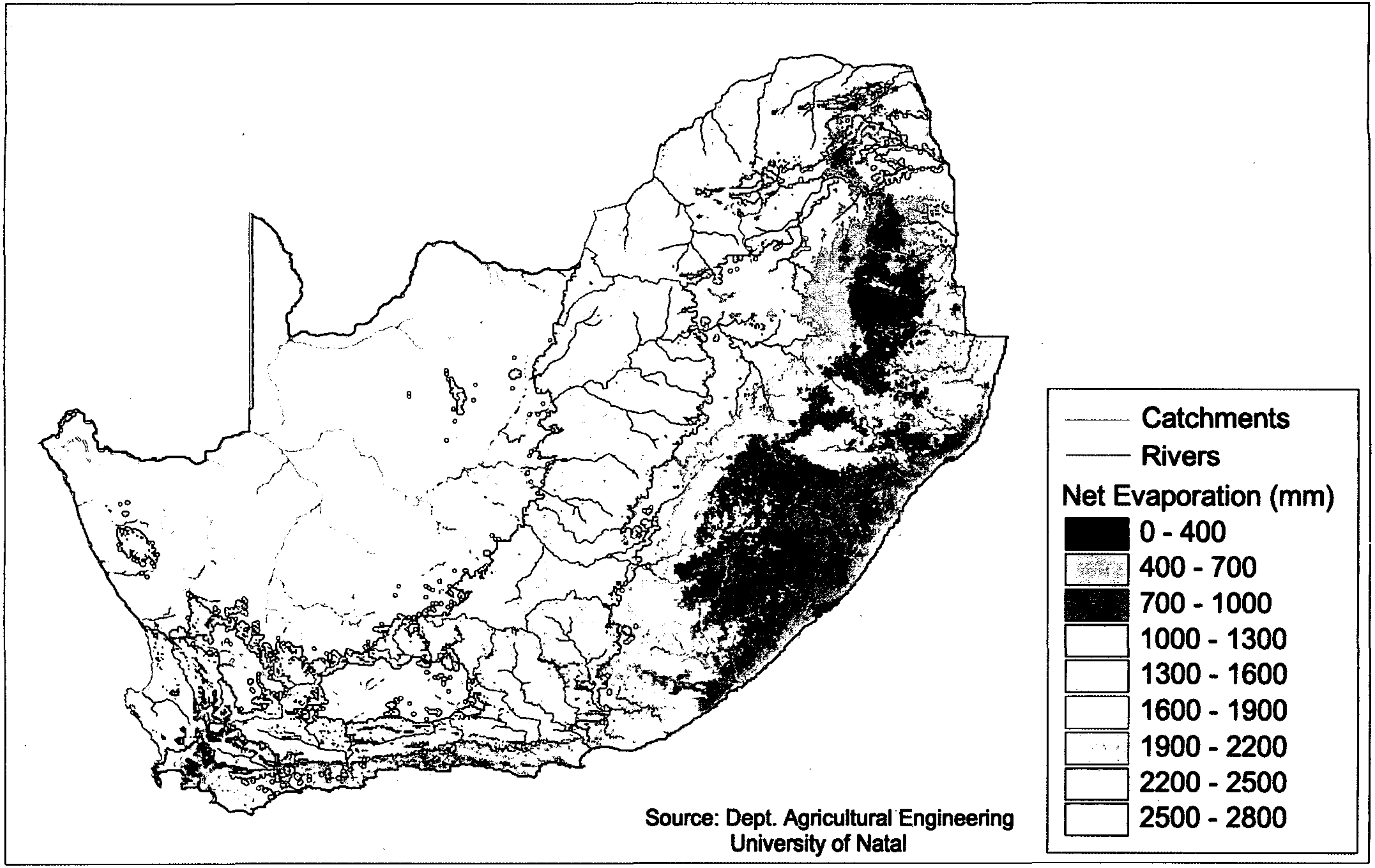
Appendix B

Map of Net Annual Evaporation over South Africa



Source: Dept. Agricultural Engineering
University of Natal

EVAPORATION LOSSES FROM
SOUTH AFRICAN RIVERS

Net Annual Evaporation