A COMPARISON OF THE ECONOMIC EFFICIENCY OF WATER USE OF PLANTATIONS, IRRIGATED SUGARCANE AND SUB-TROPICAL FRUITS

A CASE STUDY OF THE CROCODILE RIVER CATCHMENT, MPUMALANGA PROVINCE

BW Olbrich • R Hassan

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Water
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A CASE STUDY OF THE CROCODILE RIVER CATCHMENT, MPUMALANGA PROVINCE

by

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Report to the

WATER RESEARCH COMMISSION

on the project

"Holistic catchment-scale comparison of water-use efficiency of crops, focusing on the comparison between forest plantations and key irrigated agricultural crops"

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EXECUTIVE SUMMARY

The apportionment of water resources in the Crocodile River catchment has become a critical issue. A variety of sectors, such as industry, agriculture, forestry and domestic users, are demanding their fair share of the catchment's limited water. This particular investigation focuses specifically on the irrigated agricultural and forestry sectors in the Crocodile River catchment of Mpumalanga Province. These two sectors have traditionally viewed each other as competing over the water resource. The objective of this project was to compare the direct economic returns at farm gate realized from the use of water in these two sectors. This information will contribute to a basis for rational and equitable allocation of water in those parts of the country where there is a conflict between forestry and downstream agriculture.

It should be stressed that the results here are based only on the direct economic benefits derived from the various crops, and do not account for any of the forward or backward economic linkages in each of the crops. Also, while this investigation should be seen to reflect the current state of knowledge, it is not complete for the drafting of final water resource management policy. Rather, it should give direction to further studies in this area, but does provide first estimates of the economic efficiency of water use of plantations, irrigated sugarcane and subtropical fruits.

This investigation required three data sets for each of the crops investigated: the water use or streamflow reduction, the crop yield, and the economic returns. The study was based on existing data summarised by the respective research institutes considered authorities in the various crops included in this study.

The forestry regimes examined in this investigation were representative of those practised within the catchment. As a result, three species were investigated, namely: *Eucalyptus grandis, Pinus patula*, and *Pinus elliottii*. Data sets were derived reflecting the timber yield and streamflow reduction for pulpwood and sawlog regimes in each of three productivity classes and four rainfall zones. These data were then combined with published forest economics data to assess the economic efficiency of water use for the respective plantation situations.

The dominant irrigated crops grown in the Crocodile River catchment were selected for analysis, namely sugarcane, Valencia oranges, grapefruit, avocados, mangoes and bananas. The widely accepted CANEGRO model was used to simulate the irrigation yield/response relationships for sugarcane grown under the soil and climate conditions found in the sugarcane-growing areas in the catchment. For the subtropical fruit crops net irrigation and fruit yield data were derived from experimental irrigation trials. The economic data for the irrigated crops were derived from a variety of sources reflecting the market value of the irrigated crops, establishment costs and variable production costs but excluding all fixed capital costs.

In addition to the above research-based irrigation and yield data (called best-practice in the report), data were also collected to reflect the 'average practice' in the industry. The average-practice data were collected from published data and from correspondence with the various growers associations. The purpose of including the average-practice data was to get a feeling for how the data derived from highly-managed experimental trials related to general practice. Both sets of data are presented in the economic analysis.

The economic analysis standardised on 1994 data. This report presents two measures of economic efficiency of water use for each of the crops investigated. The first is the annualised net return (ANR) per unit of water used, and the second is the Net Terminal Value (NTV), and NTV per volume water for each of the crops. Because the NTV analysis accounts for the time value of money, it was felt that this is the more meaningful measure of the economic efficiency of water use.

The results of the analysis show that the NTV's ranged from R-0.052 to R19.04 per m^3 water for best practice, and from R0.165 to R10.9 per m^3 water for average practice. In general, the NTV per m^3 water of the irrigated subtropical fruit crops dominated irrigated sugarcane and the majority of the forestry regimes. In turn, of the forestry regimes only the eucalypts grown on pulp and sawlog rotations had higher NTV's per volume water than irrigated sugarcane. The lowest NTV's were recorded for pines grown on sawlog regimes. As expected, the average NTV values under best practices were higher than those derived using average-practice data. The rankings of the crops were, however, similar for both sets of data (average and best practice).

Mangos achieved the highest NTV of R19.04 m^{-3} of net irrigation water under best practice, followed by grapefruit (R14.5 m^{-3}), oranges (R8.47 m^{-3}), bananas (R5.79 m^{-3}) and avocados (R3.79 m^{-3}). The only forest rotation dominating sugarcane under current practice was eucalypts for pulp and sawlogs, achieving a maximum of R2.99 m^{-3} water compared to R1.07 m^{-3} water for sugarcane. The NTV's for the pine regimes ranged from -0.052 m^{-3} to a maximum of 0.686 m^{-3} water.

The analysis show that in terms of the direct economic returns, irrigated subtropical fruit crops are more efficient users of the water resource in the Crocodile catchment than either sugarcane or forest plantations. Also, forestry in low productivity classes and low rainfall zones generates lower direct economic gains, particularly when under pines, and hence has a weaker competitive advantage. Nevertheless, eucalypts for pulp and sawlogs dominated sugarcane in terms of economic efficiency.

The opportunity costs (net returns foregone) per unit of water reduction in runoff caused by forest plantations can be as high as the R10.9 m^{-3} of NTV achieved with mangos under current average practice (at 4% real social discount rate). If one considers only 50% of the gross margins' returns realized with irrigation agriculture to be net farm profits, this suggests that net economic returns to water, land, management and capital in the Crocodile catchment was about R5.05m^{-3} in 1994. This may indicate that a considerable margin of economic rent is generated from irrigation in excess of current water charges. On the other hand, the opportunity cost of reducing plantation area to yield extra water were calculated to be as high as R1.5m^{-3}.

The report also raises the possibility that while forest plantations and irrigation agriculture do not compete directly for land, trading between the two sectors could take place indirectly through water markets if created. Therefore, the trade-off between development strategies based on increased afforestation upstream, and expanded food or fibre production under irrigation downstream, can be guided by water allocations either through regulated markets in water or through quantitative measures (e.g. quota systems for physical allocations).

Key words: Mpumalanga, Crocodile River catchment, water use, forestry, pine *eucalyptus*, agriculture, irrigation, sugarcane, citrus, banana, avocado, mango, grapefruit, economic analysis, Net terminal value, water use efficiency.

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The steering committee responsible for this project consisted of the following persons:

Dr G R Backeberg	Water Research Commission (Chairman)
Dr G C Green	Water Research Commission
Dr M Hensley	Agricultural Research Council
Mr F A Stoffberg	Department of Water Affairs and Forestry
Mr J Bosch	Environmentek, CSIR
Dr D W Van der Zel	Department of Water Affairs and Forestry
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Mr E Schmidt	South African Sugar Association
Mrs C M Smit	Water Research Commission (Committee Secretary)

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INTRODUCTION

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1.1 OVERVIEW AND BACKGROUND

The apportionment of water resources between a number of sectors is a sensitive and often controversial issue. The issue becomes critical when the water resources are scarce. Such is the case in Mpumalanga province where a variety of sectors, such as agriculture, forestry, domestic users and industry, demand their fair share of the province's water. With increasing industrial development, and a growing population requiring more agricultural land, the competition for water resources is becoming fierce. It is apparent that all of these demands cannot be accommodated.

This particular investigation focuses specifically on the irrigated agricultural and forestry sectors in the Crocodile River catchment of Mpumalanga province. These two sectors have traditionally viewed each other as competing over the water resource. It is widely claimed that industrial plantations of exotic tree species such as pine and eucalypts cause excessive abstraction of rainfall water. This leads to significant reductions in stream flow and, consequently, reduced availability of water to down-stream users (Wicht 1949; Gevers 1950; Malherbe 1968; Nänni 1974; Schulze 1990; Scott and Le Maitre 1994; DWAF 1995). To date, this has resulted in a variety of laws that regulate the forestry industry. The aim is to safeguard streamflow and water production from the mountain catchment areas where forest plantations are concentrated. One example is the Afforestation Permit System (APS) which places restrictions on expansions in commercial forest plantations (van der Zel 1982; Bosch and von Gadow 1990; Bosch *et al.* 1993). This is particularly important in arid and semiarid environments, where water resources are relatively scarce and where industrial forestry competes with high value agricultural goods produced under permanent irrigation.

The Crocodile river catchment provides a typical example of the agriculture versus forestry debate - both enterprises require water. At present, virtually no further afforestation is allowed because of the predicted reduction in streamflow, as assessed by the APS (DWAF 1995). Plantation forestry is, however, an important source of many direct and indirect economic benefits. Irrigated farming, on the other hand, is the largest downstream user of water, and on average consumes an estimated 53.6% of the country's annual water requirement (DWAF 1997). In the eastern region of the country this figure is even higher, where 72% of the total water requirement is needed to support irrigation farming (DWAF 1997). Resolving this conflict does not only revolve around arguments of water use. We argue that the use of the scarce resource (water) should be balanced against the range of benefits derived from its use, such as the generation of income and the creation of employment opportunities.

This study is carried out to estimate the total direct economic gains from water used (in irrigation) or streamflow reduction (in forestry), and compare the direct economic return of the two sectors. The specific focus and scope of the present study were defined according to the following terms of reference:

a. The study was not concerned with land use options other than irrigation agriculture, such as dry land farming and nature conservation
b. Only industrial forest plantations and not natural forests or woodlands were compared with irrigated subtropical fruit and sugarcane
c. Other uses of water for domestic and industrial purposes were not considered
d. The efficiency of water use in plantations and irrigation was evaluated only in terms of quantity allocations and quality aspects were not addressed.
e. Only the *net irrigation* was considered in evaluating the economic efficiency of water use of the irrigated crops.

Results of the analysis and findings of the study are expected to inform policy making processes and strategic planning for land use and water resources development and allocation at both, the regional and national levels. It is intended that this information will contribute to rational and equitable allocation of the limited water resource in those parts of the country where there is a conflict between forestry and downstream agriculture.

1.2 AIMS

The specific aims of this study were to determine:

- i the direct economic returns from *Eucalyptus grandis, Pinus patula,* and *Pinus elliottii* grown on both pulp and sawlog rotations on sites ranging from both high to low productivity, and high to low rainfall in the Crocodile River Catchment,
- ii the mean annual streamflow reduction for each of the above plantation species and site/rainfall combinations,
- iii the direct economic returns from irrigated sugarcane, oranges, grapefruit, mangoes, bananas and avocados,
- iv the net irrigation water requirements for the above irrigated crops, and
- v how the returns per unit water used in growing trees compares to the returns per unit volume of water consumed in irrigating the irrigated crops.

1.3 DATA REQUIREMENTS

The three sources of data required for each of the crops were the water use, crop yield and economic return. These data were then used to calculate the *economic efficiency of water used* as the ratio between water use and direct revenue yield. No new data have were collected for this project, rather, data from existing sources were collated to make the necessary comparisons. The dominant irrigated crops in the Crocodile River Catchment selected for comparison to forest trees were citrus (Valencia Oranges and Grapefruit), avocado, banana, mango, and sugarcane.

As it was important that the data presented are credible, this report represents the collaboration between three research organisations, each specialising in specific crops studied in this report. The net irrigation and yield data for irrigated tropical crops was provided by the Agricultural Research Council's Institute for Tropical and Subtropical Crops in Nelspruit, sugarcane data were provided by the SA Sugar Association Experiment Station, and the Forestry and Forest Products Programme of Environmentek, CSIR were responsible for the Forestry data.

1.4 ANALYTICAL FRAMEWORK AND METHODS

1.4.1 Hypotheses and concepts

Based on the preceding background, the following hypotheses were advanced to provide the analytical framework of the study:

1.4.1.1 Plantation forestry does not compete directly with irrigated agriculture for land and water. The competition between the two is rather indirect through reduction of streamflow. The reason is that commercial forests are mainly planted at the higher reaches of the catchment where usually no irrigation is practised. However, tree plantations reduce streamflow and consequently river flows and water availability for irrigation at the lower parts of the catchment. Accordingly, reduction in streamflow (in excess of original natural vegetation) rather than direct water consumption *per se* is used as the more meaningful and suitable measure of water use by forest plantations for determining the impact of afforestation on water availability.

1.4.1.2 Reduction in streamflow due to forestry was assumed to vary within the catchment according to:

i. Location: allowing for variations in water yield due to variations in rainfall and temperature.
ii. Species: different tree species have different rates of water abstraction and hence different impacts.
iii. Season: the impacts on water resources and streamflow vary between seasons, e.g. High flow versus low flow periods.
iv. Soil conditions: different soil types have different physical and chemical properties that directly influence rates of abstraction, water retention capacity and streamflow.
v. Management regime: trees grown on short-rotation, pulpwood regimes have different streamflow reduction characteristics to those grown on longer rotation sawlog regimes. Given the above, the catchment was divided into 5 zones based on rainfall classes. Within each rainfall zone, three productivity classes (High, Medium and Low) were defined to allow for variations in the efficiency of forest plantations in water use, e.g. ability to produce more from the same amount of water in high productivity areas. Chapter 3 discusses these classifications in more detail.

1.4.1.3 Only the net irrigation efficiency (rather than gross efficiency) of the irrigated crops was investigated because the aim of the study was to focus on the consumptive water use by the crop. Strictly speaking, the most appropriate measure of the water use by the irrigated crops would have been gross abstraction from the river system less return flow to the river following irrigation. It is estimated that gross irrigation would be between 5 and 30% higher than the net irrigation (accounting for losses and the plant root zone). Unfortunately, however, data are not available for the proportion of gross irrigation that is accounted for by return flows.

1.4.1.4 Economic efficiency is evaluated in terms of the economic returns to water use in plantation forestry and irrigation agriculture measured as product income less variable costs. However, unlike annual field crops, trees (whether for wood or horticultural products) take several years to mature before harvesting. During the growth cycle, trees use up water as well as other economic resources (labour, capital, etc.) before the product is sold. The opportunity cost of those resources as well as output produced and the change in their time value must be accounted for. Accordingly, discounted present values of streams of net cash flows were employed to calculate comparable economic returns.

1.4.1.5 Like other economic activities, forestry and agriculture result in several indirect social costs and benefits other than their direct produce. These costs and benefits are felt in other sectors of the economy through forward and backward economic linkage multipliers. Although a complete analysis should incorporate these factors, they have not been evaluated in this report.

1.5 STRUCTURE OF THIS REPORT

The report is presented in seven parts: Chapter two sets the context of the investigation by presenting an overview of the Crocodile River Catchment, this is followed by three chapters submitted by the respective collaborating institutions on the water use and yield of the respective crops under investigation. The economic analysis is presented in Chapter six, this is followed by chapter discussing the results and their implication for policy making.

CHAPTER 2

CHARACTERISTICS OF THE CROCODILE RIVER CATCHMENT, MPUMALANGA

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2.1 INTRODUCTION

This chapter provides the background information on the Crocodile River catchment. The characteristics described include locality, topography and geology, soils, climate, vegetation, water resources, land use and demography.

2.2 LOCALITY

The catchment of the Crocodile River covers an area of approximately 10 500 km^2, and is located approximately 300 km east of the city of Johannesburg in the Mpumalanga province, formerly the Eastern Transvaal. In terms of its geographical co-ordinates, the Crocodile River basin lies between longitude 30 ^{0}03'53" and 32 ^{0}00'23" East, and between latitude 25 ^{0}05'26" and 25 ^{0}54'02" South.

The Crocodile River is the largest tributary of the Komati River, and joins the Komati River shortly before it enters Mozambique. Approximately 20 % (the north-eastern portion of the catchment) lies within the southern sector of the Kruger National Park.

The study area comprises the X200 drainage region as defined by the Department of Water Affairs and Forestry Quaternary Drainage Regions Map (1:250 000 scale, dated 1991). The study area is bounded on the south and east by the lower Komati (X100) basin, on the north by the Sabie (X 300) basin and on the west by the headwaters of the Olifants (B100 and B200) basin. Thus the Komati River is not included in the catchment area.

The Crocodile River catchment has been divided into five tertiary sub-catchments. General physical features of these sub-catchments are given in **Table 1**, based on data obtained from Midgley (1994).

Table 1 General physical characteristics of the five sub-catchments of the Crocodile River catchment (Source, Midgley *et al.* 1994). MAP = mean annual precipitation, MAR = mean annual run-off.

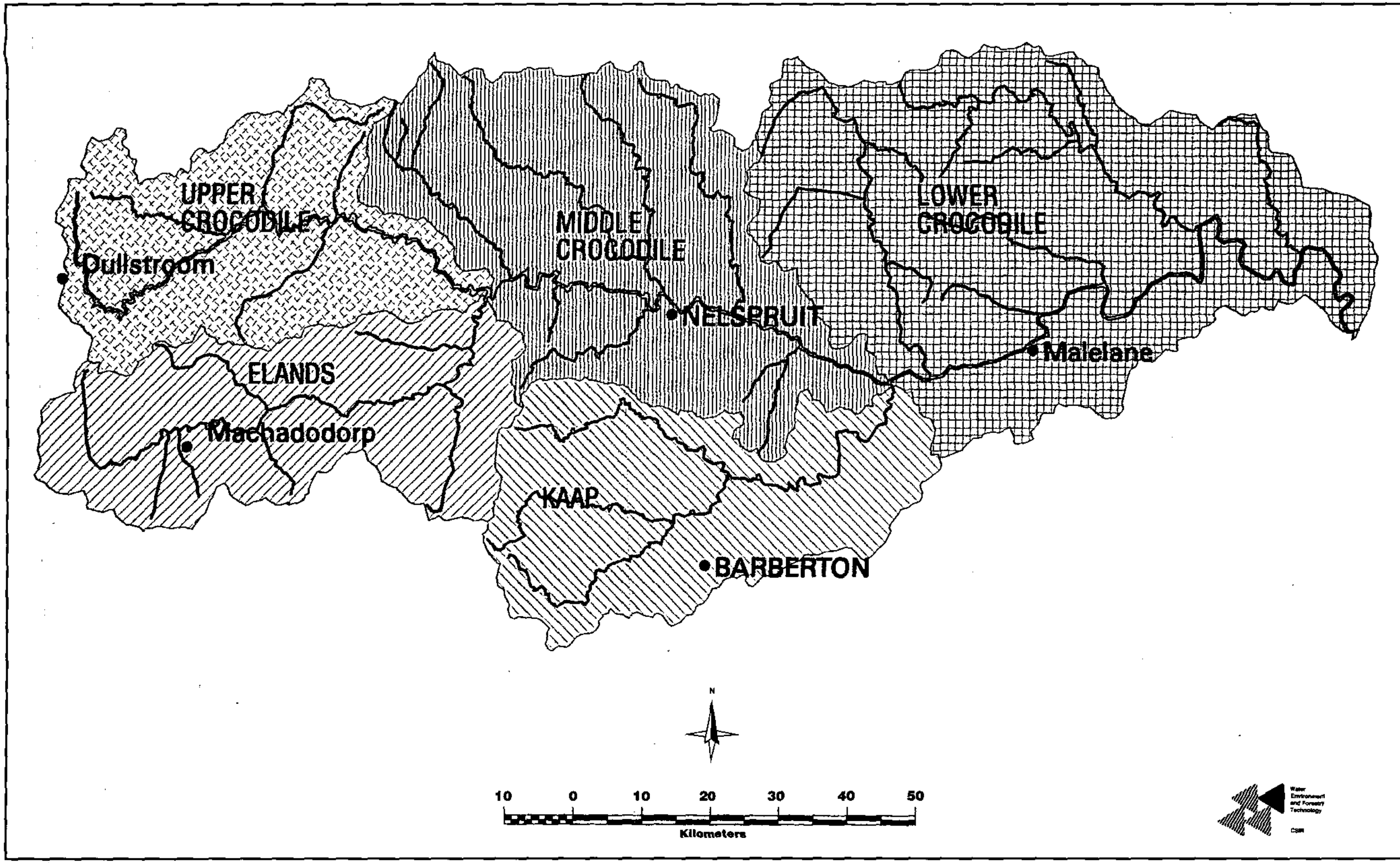
Sub-Catchment Name	Area (km^2)	MAP (mm yr^{-1})	Total incoming precipitation in the Catchment (10^6 $m^3 yr^{-1}$)	Virgin MAR (10^6 m^3 yr^{-1})	No. of Dams
Upper Crocodile	1518	825	1253	226	3
Elands River	1573	896	1409	308	3
Middle Crocodile	2366	972	2300	418	6
Kaap River	1640	901	1477	206	5
Lower Crocodile	3349	650	2176	105	4
Total (or average *) for catchment	**10446**	**865 ***	**8614**	**1263**	**21**

2.3 TOPOGRAPHY AND GEOLOGY

The geological features of the Crocodile River catchment differ widely in lithology, structural history and tectonics, and are closely related to the topographical features of the catchment. Topographically, the Crocodile River catchment has four broad zones.

i) The Eastern Transvaal Highveld Plateau (1400 to more than 2000 m above sea level)
ii) Middleveld valleys (800 - 1400 m)
iii) The Great Escarpment of the Transvaal Drakensberg range
iv) The Lowveld (150 - 800 m)

Figure 1. Sub-catchment of the Crocodile River Catchment



2.4 GENERAL CLIMATIC FEATURES OF THE CATCHMENT

The catchment is characterized by a distinct pattern of warm to hot and wet summers, followed by warm to cool, dry winters. Climatic patterns within the Crocodile River catchment are largely influenced by the topography of the region. The climate varies from wet, humid areas in the northern and southern mountainous areas in the central portion of the catchment, to hot, dry areas in the relatively flat plains zone in the east of the catchment. The higher altitude, western portion of the catchment is relatively dry and cool, and frost is often recorded during the winter months.

Moving from west to east across the catchment, the values for both mean annual rainfall and mean monthly rainfall decrease. These changes are accompanied by an increase in mean monthly temperature and maximum annual temperature. These changes indicate the presence of a relatively steep gradient of increasing moisture stress from west to east. Any agricultural crops grown under irrigation along this gradient will require increasing quantities of water, particularly during the drier winter months when moisture stresses are highest.

2.4.1 Rainfall

The Crocodile River catchment falls within the summer rainfall zone of southern Africa and approximately 85 % of the annual rainfall is received during the warm to hot summer months of November to March. The remaining 15 % of the annual rainfall is received as isolated showers during the cooler winter months of April to October. Mean annual rainfall for the whole catchment is approximately 880 mm, approximately 70 % higher than the mean annual precipitation of 500 mm for South Africa (**Figure 2**).

Mean annual precipitation (MAP) varies gradually from approximately 500 mm in the lower (eastern) reaches of the Crocodile River, to above 1600 mm in the northern and central mountainous areas, where, at the edge of the catchment near the town of Sabie, rainfalls of up to 2100 mm have been recorded. Further to the west, rainfalls decrease to approximately 750 mm per year in the Highveld portion of the catchment.

Moving from east to west, mean annual rainfall increases with increasing altitude until the upper part of the Escarpment Zone is reached. The Escarpment shelters the upper Crocodile River catchment to the west from the prevailing winds, causing a distinct rain shadow zone. At the higher elevations in the Highveld Zone, the rain shadow cast by the Escarpment causes rainfall to decrease to approximately 60 % of the maximum values recorded in the Escarpment Zone.

2.4.2 Temperature

Mean annual temperature varies from about 23 ^{0}C in the eastern Lowveld, through approximately 20 ^{0}C in the Middleveld valleys, to about 12 ^{0}C in the western Highveld areas around the town of Dullstroom. Topography has a major influence on air temperatures in the Crocodile River catchment, resulting in a decrease of approximately 0.5 ^{0}C for every 100 m increase in altitude.
Selected summary statistics of the temperature and rainfall characteristics in the three main topographical zones of the Crocodile River catchment are shown in **Table 2**.

Figure 2. Mean annual rainfall classes in the Crocodile River Catchment

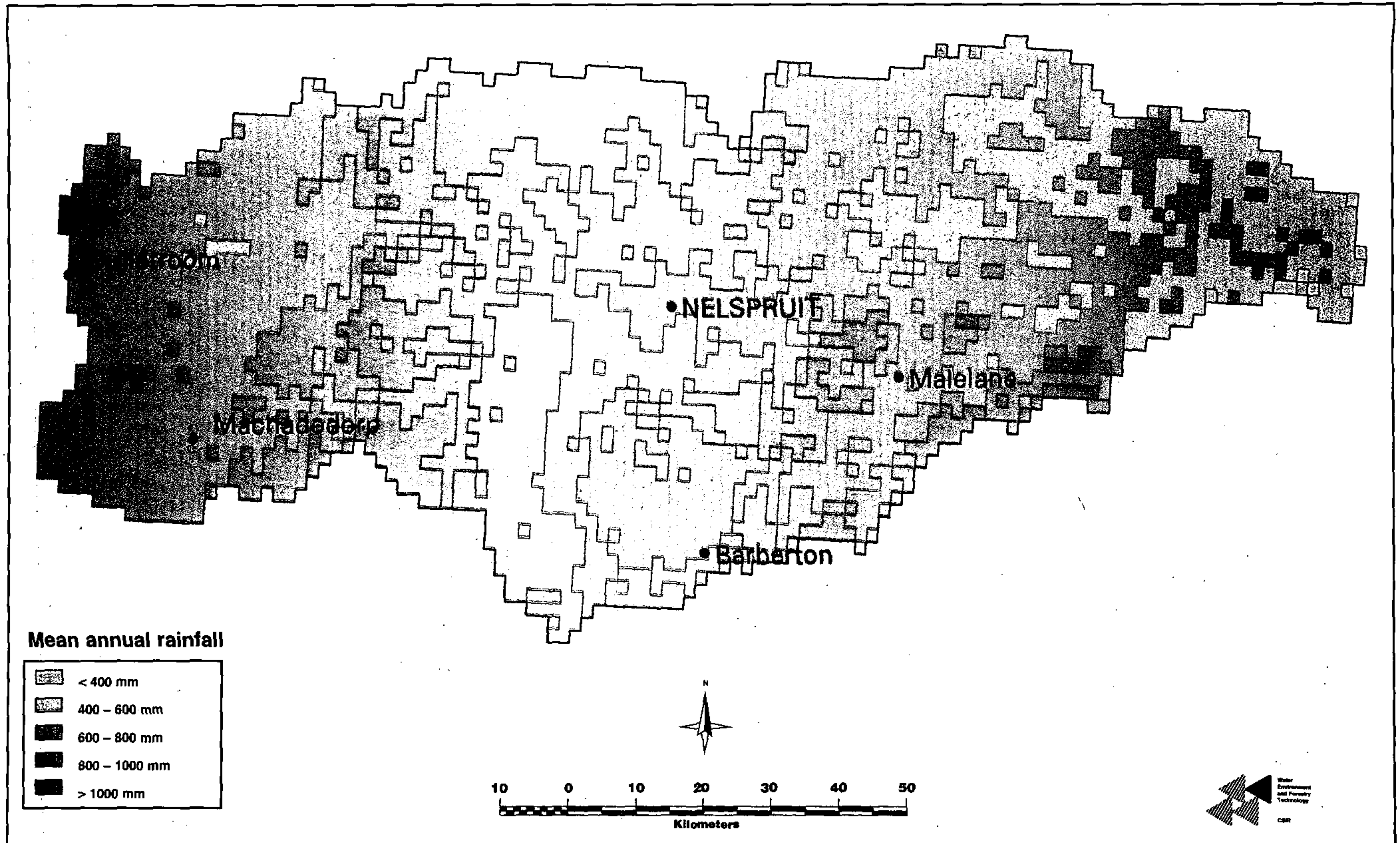


Table 2 Selected summary statistics of the summer (January) and winter (July) temperature ranges, plus absolute maximum and minimum temperatures recorded and mean annual rainfall for representative weather stations in the three main topographical regions of the Crocodile River catchment area. (NB: data from only one suitable Highveld weather station in the catchment could be used).

Sub-Region Locality and Altitude (m)	**Temperature (^{0}C)**						**Mean Annual Rainfall (mm)**
	Mean Monthly Temperature		**Mean Max.**	**Mean Min.**	**Absolute Values**		
	Jan.	**July**	**Jan.**	**July**	**Max.**	**Min.**	
1. Lowveld							
Komatipoort (146 m)	27.2	17.5	33.3	8.7	46.5	- 1.9	683.3
Nelspruit (607 m)	23.8	14.6	29.6	6.1	41.1	- 0.8	734.1
2. Middleveld							
White River (900 m)	22.5	13.9	27.8	6.5	39.4	- 1.7	882.4
Barberton (880 m)	23.3	15.6	28.5	9.3	41.1	1.7	766.6
3. Highveld							
Dullstroom (2 030 m)	18.4	7.7	22.9	- 2.1	32.8	- 10.3	734.5

The Lowveld is characterized by mild winters with moderate air temperatures, particularly at night. Light frost (temperatures less than 3 ^{0}C) may occur occasionally between May and August. Heavy frost (temperatures less than 0 ^{0}C) are recorded on less than 30 days per year, and then usually only during the months of July and August.

In contrast, winters on the western Highveld region are often very cold and heavy frost can be recorded almost every night between May and September. Dense mists and fogs are a common occurrence in the upper Escarpment Zone and at the edge of the Highveld. Similar, though less dense, mists have also been recorded occasionally in the lower altitude regions around the towns of Nelspruit and White River.

Summer temperatures are hot to very hot throughout the Lowveld area, with maximum temperatures often exceeding 40 ^{0}C for several consecutive days. This contrasts with the cooler Highveld summers, where maximum temperatures seldom exceed 33 ^{0}C for prolonged periods. As would be expected, the air temperatures recorded in the Middleveld region are intermediate between those of the Lowveld and the Highveld.

2.4.3 Evaporation

Evaluation of evaporation patterns within the Crocodile River catchment is complicated due to the scarcity of weather stations equipped to record evaporation. Nevertheless, evaporation rates are lowest in the southern and northern regions of the central Crocodile River catchment, with evaporation rates increasing to both the eastern and the western portions of the catchment. The highest evaporation rates (> 2 000 mm/year) - measured with an "A-pan" - are recorded in the east near Komatipoort.

The higher altitude central portion of the catchment has relatively low evaporation rates of between 1400 and 1800 mm/year. The increase in mean annual evaporation rate values towards the eastern portion of the catchment correlates with decreasing altitude and decreasing rainfalls; the increased rates of evaporation in the western portion of the catchment correlate with decreasing rainfalls.

The highest rates of evaporation occur during the hot summer months of October to March, with the highest values normally recorded during December (210 mm/month). Evaporation rates are lower during the cooler winter months with the minimum evaporation rate usually recorded during July (120 mm/month). The average annual evaporation rate for the catchment is approximately 1 850 mm/year, which is equivalent to 154 mm/month if seasonal variations are ignored.

Nett evaporation, or annual moisture deficit, is calculated as the difference (in mm) between gross annual evaporation and mean annual rainfall. This value indicates the additional moisture that needs to be supplied to alleviate water stress in plants and is lowest in the mountainous southern and northern portions in the centre of the catchment. Moisture deficit values increase to the west and to the east, and the highest values are found in the far eastern portion of the catchment around the town of Komatipoort.

High values for the annual moisture deficit present a serious problem for the extensive areas of irrigated crops in the Crocodile River catchment. In addition, high moisture deficit values also indicate the scale and duration of additional water requirements needed to ensure that crops survive the dry winter months.

2.4.4 *Water supply and availability*

Many factors influence the availability of water for irrigation. Rainfall is the major source of fresh water supply. High rainfall leads to larger base flows and surface streamflow as is the case during the rainy summer months of November to March. In addition to the observed seasonality, the rainfall varies significantly across the Crocodile catchment (**Figure 2**). These variations in rainfall have important implications for water availability, stream flows and consequently patterns of land use that need to be considered. The variation in evaporation over the catchment has further impacts on water availability. In addition to the above, the dramatic year to year variations in rainfall and consequently streamflow significantly impact on water availability for irrigation.

2.5 WATER RESOURCES OF THE CROCODILE RIVER CATCHMENT

2.5.1 Surface Waters

The details of the river systems contained within the Crocodile River catchment have already been provided in **Table 1**.

Several water supply impoundments have been constructed on the Crocodile River and its tributaries. These have primarily been aimed at ensuring adequate water supplies for irrigation during the dry winter months. Flow gauging weirs constructed on shallow-gradient sections of the Crocodile River also hold back relatively large stilling pools which are used as water abstraction points for canals and nearby irrigation.

Table 3 Location, size and volume (at full capacity) of registered dams in the Crocodile River catchment.

Name of Dam	Catchment Area (km^2)	Surface Area (km^2)	Capacity (10^6 m^3)	Located on River
Kwena	947	12.60	161.00	Crocodile
Klipkoppie	78	2.34	12.09	White
Friedenheim	8	0.25	1.57	White
Longmere	104	0.94	4.24	White
Primkop	262	0.41	2.02	White
Spargo	18	0.25	4.44	Buffels Creek
Thankerton	8625	0.80	0.85	Crocodile
Witklip	63	1.88	12.30	Sand

In addition to the major dams, there are over 200 small farm dams within the Crocodile River catchment. In 1981, these farm dams were estimated to have a combined total surface area of some 12 to 15 km^2 and a combined total volume estimated to be between 4 and 6×10^6 m^3. This area must have increased considerably since 1981, possibly by as much as 50-75 % (B. Bonthuys, Chunnett, Fourie & Partners, personal communication cited in DWAF 1994).

In addition to the dams which have been constructed in the Crocodile River catchment, a small quantity of water is imported into the Kaap River sub-catchment. This water is brought by tunnel and canal from the Shiyalongubo Dam which is located in the Komati River catchment to the south east of the town of Barberton. This water is supplied mainly to irrigation farmers and only a very small quantity reaches any of the tributaries of the Crocodile River.

2.5.2 Hydrology

The hydrological features of a catchment reflect the integrated effects of climate, topography, soils, veld types and land use on the distribution of surface water in time and space. In particular, land use such as irrigation agriculture and afforestation is often the major variable parameter which affects streamflow. Water supply reservoirs and weirs also exert a strong influence on surface flow patterns in river systems. At the upper end of the Crocodile River catchment, the Kwena Dam (previously Braam Raubenheimer) with a full supply volume of 160.6 million m^3, attenuates almost all the flood water peaks that enter the reservoir. The construction and commissioning of the Kwena Dam in 1984 caused a marked change in the hydrological characteristics of the Crocodile River.

An examination of a 68-year record of simulated hydrological data available for the Crocodile River catchment revealed that mean annual streamflow values varied considerably from year to year; the annual variation often being a 3- to 5-fold difference. Under current land use practices, it has been estimated that the mean annual streamflow has been reduced by at least 20 % from the streamflow which would be expected under virgin conditions.

Forestry activities are concentrated in the higher rainfall/high water yielding parts of the catchment principally in areas with an annual rainfall in excess 700 mm yr^{-1} (**Figure 2**) with roughly half the afforestation in the 700 - 900 mm yr^{-1} range. Estimates of the streamflow reduction ascribed to afforestation range from 3000-6000 $m^3ha^{-1}yr^{-1}$, or 300-600 mm rainfall equivalent. Mean reductions in streamflow over the growth cycle (or rotation) observed in South Africa are in the range of 2000-3000 $m^3ha^{-1}yr^{-1}$ (LeMaitre *et al.* 1997).

A recent report (Le Maitre *et al.* 1997) quantifies the impact of forestry on the water yields from the Crocodile, Sabie and Sand River Catchments. 16.5 % of the Crocodile catchment is afforested, which has resulted in a reduction in annual run-off of 199 $m^3ha^{-1}yr^{-1}$ (16.8%). 12.5% of the Sabie and Sand River catchments are afforested, which is estimated to have reduced streamflow by 220 $m^3ha^{-1}yr^{-1}$ (18.8%). The percentage low-flow reduction is slightly larger and is estimated at 21%, and 36% in the two catchments respectively.

Each impoundment and, to a lesser extent, flow gauging weir, attenuates flow patterns in the respective impounded river. This effect is seen particularly clearly during periods of low flow when very little water is released from impoundments other than that required for downstream irrigation or to meet international obligations relating to the limits placed on the reduction in streamflow in rivers crossing international borders.

The incised bed of the Crocodile River also helps to contain summer flood flows and limits the extent of flood damage during periods of high flow. However, excessive abstraction of water from the upper reaches of the Crocodile River has dramatically reduced the winter low flows of the river. This has allowed the development of dense stands of *Phragmites* reed beds, which then further reduce flow in the river. In the lower reaches of the Crocodile River, immediately upstream of its confluence with the Komati River, the Crocodile River has been reduced to a series of narrow channels flowing between dense reed beds. If this pattern of reed bed encroachment continues in future, the lower reaches of the Crocodile River have the potential to be transformed into an extensive swamp. This would accelerate evapotranspiration losses and reduce the quantity of water available for irrigation and for onward flow into Mozambique. Only large floods or mechanical removal of reeds would reverse this trend.

2.6 LAND USE

Broad land use categories for the Crocodile River Catchment are illustrated in **Figure 3.** Agriculture and forestry are the primary land uses in the Crocodile River catchment. The relatively steep slopes and higher rainfalls of the Escarpment Zone provide suitable conditions for the development of commercial forestry operations but are largely unsuitable for mechanized agriculture. Areas of both low (0 to 8 %) and intermediate (8 to 15 %) slopes are suitable for beef and dairy cattle ranching. Dryland farming and irrigation agriculture can also be safely practised where slopes average less than 8 % along the valley bottoms (SRK, 1990). Suitable areas for these agricultural activities are concentrated on the flatter areas in the vicinity of the Kwena Dam, as well as the Kaap-Queens River valley, the lower portion of the Middle Crocodile Basin and the eastern portion of the Lower Crocodile River Basin, south of the Kruger National Park.

2.6.1 Forestry

Forestry comprises the largest intensively managed land-use in the catchment, and is concentrated in the escarpment region of the catchment (**Figure 3**). The western half of the catchment, which contains the high rainfall escarpment belt on terrain unsuitable for conventional agriculture, has extensive exotic plantations, and some small remnant patches of indigenous forest, in areas with MAP greater than about 800 mm.

Plantations cover some 1 722 km^2, or 16.5 % of the catchment (**Table 4**). The major forestry area is in the high altitude escarpment areas in the Middle Crocodile sub-catchment, made up of Uitsoek, Brooklands, Rosehaugh, Witklip and Swartfontein State Forests, and many private plantations. Extensive plantations also occur in the Berlin State Forest and on private lands in the lower Elands sub-catchment, and in the Nelshoogte State Forest and the mountains in the upper Kaap sub-catchment. Very little afforestation occurs in either the Upper or Lower Crocodile sub-catchments (**Figure 3**).

Figure 3. Land Cover classification for the Crocodile River Catchment

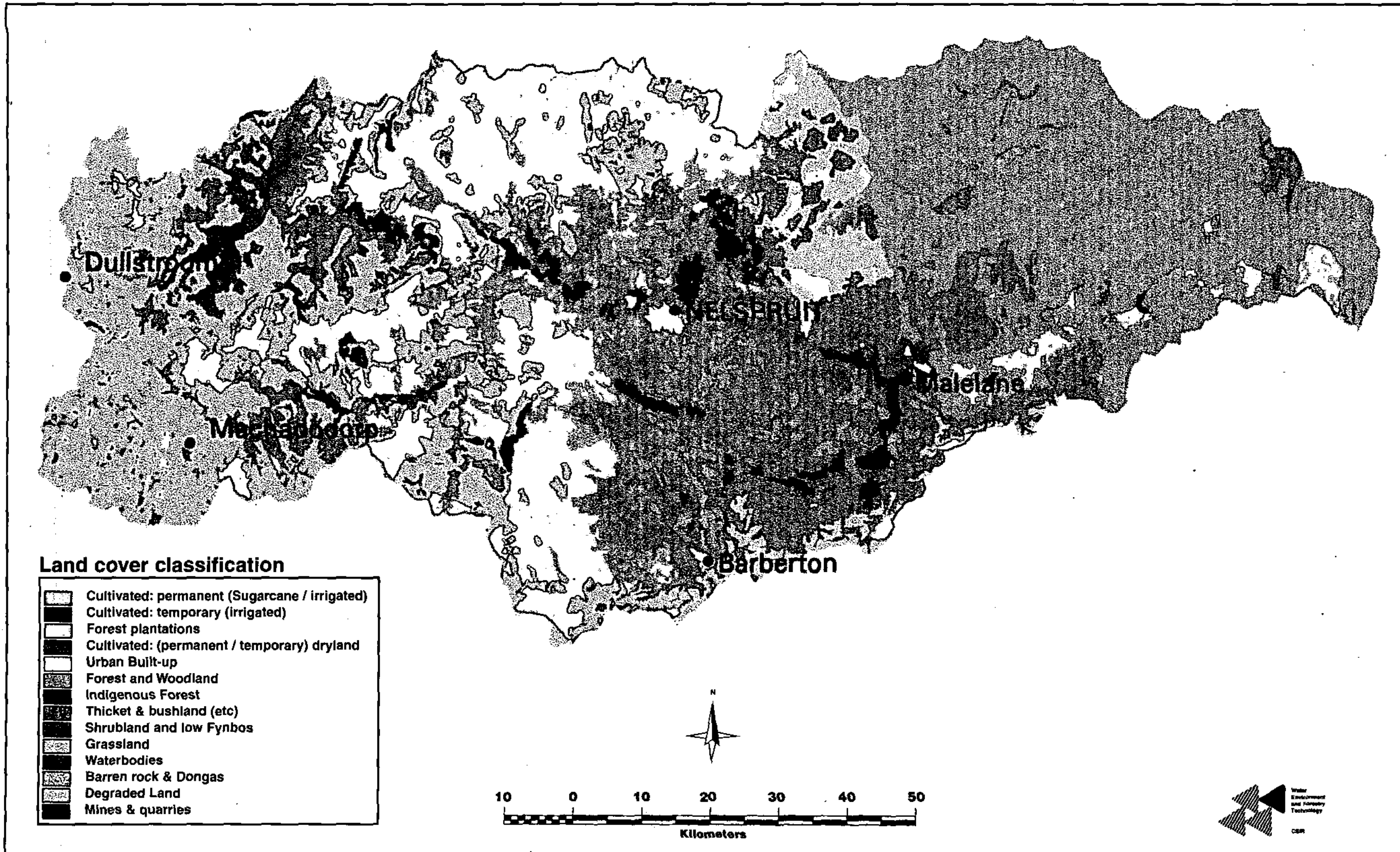
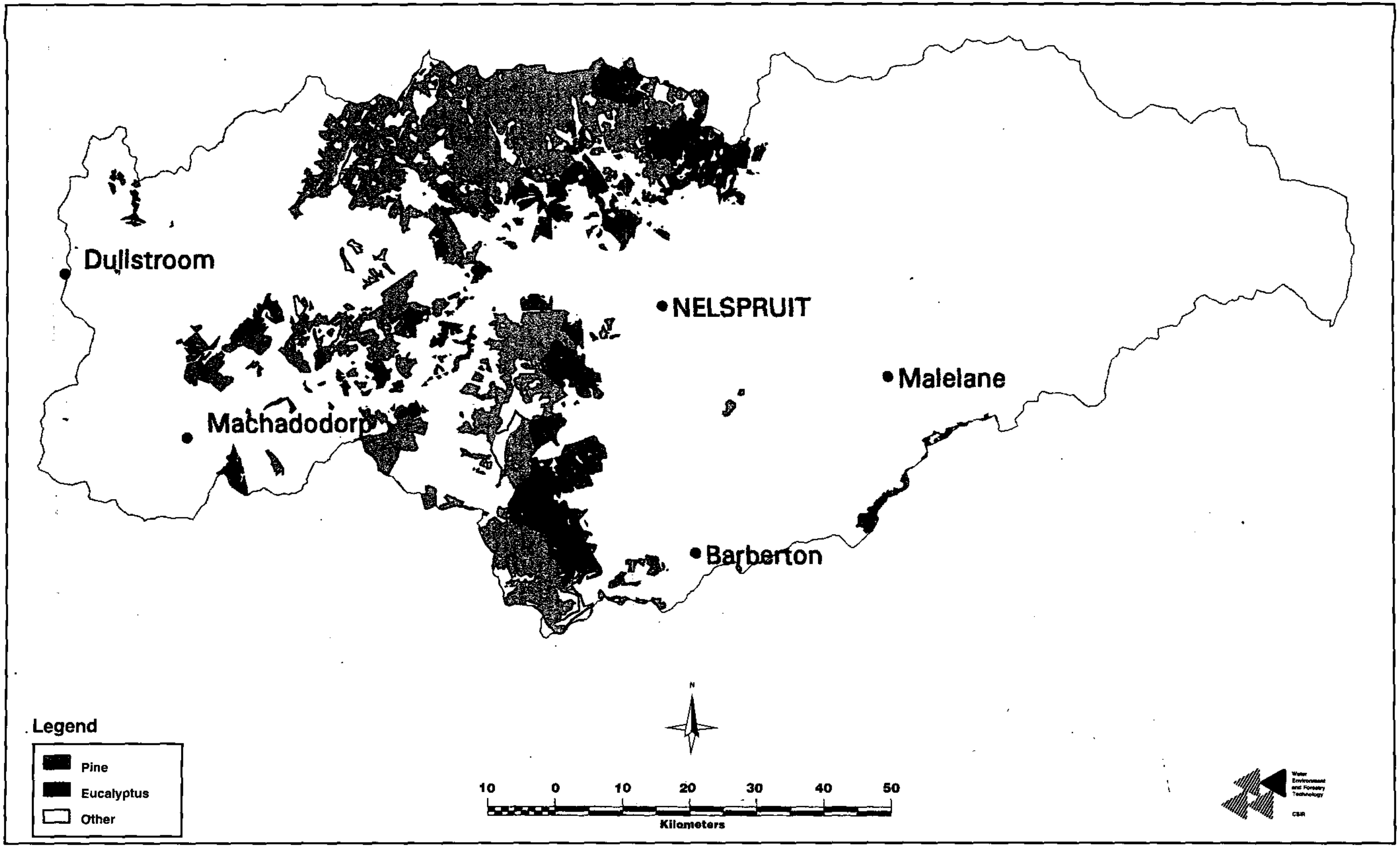


Figure 4. The location of Forestry in the Crocodile River Catchment



While Eucalypts were found to be more productive than pines in less favourable environments, they can use more water (Henrici 1946; Dye 1996). Pines tend to be more productive at the higher altitudes, and eucalypts more so lower on the slopes (**Figure 4**). Where climate and soils are ideal, the production of plantations is some 2 - 3 times that of the natural forests of the same species in their lands of origin (Van Der Zel, 1989). However, exotic species use up to 50% more water than natural forests and grasslands (Strydom *et al.* 1987; DWAF 1995). **Table 4** shows that 63% of the forestry area is planted to pines, and the remaining 37% to eucalypts. The area under plantation can also vary depending on prevailing climatic conditions. During the drought of the early 1980's some clear-felled areas were planted to citrus crops, and later replanted with trees. The demand for mining timber is very dependent on the international minerals market, and when prices are down, the demand for timber drops, requiring that these areas be put under more profitable forms of land use, or that the timber be used for another purpose (eg. pulp).

The hydrological impact of plantation forestry in terms of streamflow reduction, is more profound during periods of low flow (dry seasons and drought years) and near riparian zones (Smith & Scott, 1992). It is therefore important to consider inter and intra-year variations in rainfall. Streamflow reduction is generally measured as the incremental variation between virgin lands (under natural vegetation such as grassland) and land under forest plantations.

Table 4 Areas under commercial plantations in the Crocodile River Catchment.

Sub-Catchment	Forestry Type	Area (km^2)	%
1. Elands	Pine	257.9	15.0
	Eucalyptus	10.1	0.6
	Total	**268.0**	**15.6**
2. Upper Crocodile	Pine	8.5	0.5
	Eucalyptus	17.8	1.0
	Total	**26.3**	**1.5**
3. Kaap	Pine	188.9	11.0
	Eucalyptus	243.4	14.1
	Total	**432.3**	**25.1**
4. Middle Crocodile	Pine	636.2	37.0
	Eucalyptus	345.8	20.1
	Total	**982.0**	**57.0**
5. Lower Crocodile	Pine	0.0	0.0
	Eucalyptus	12.9	0.7
	Total	**12.9**	**0.7**
CATCHMENT TOTAL	Pine	1091.6	63.4
	Eucalyptus	630.0	36.6
	Total	**1721.6**	**100.0**

2.6.2 Agriculture

Agriculture in the Crocodile catchment is an important economic activity and consists of large irrigated areas, some dryland cropping, limited livestock *and game farming, and a relatively large aquaculture* industry. In the context of this particular study, only crops grown under irrigation were considered. The most important crops grown under irrigation within the catchment are sugarcane, citrus and mangos. In addition to the above three crops, this report also addresses avocado and bananas to cover the major irrigated crops in the catchment.

A number of individuals and organisations were approached for information on the areas covered by the crops, and their estimates differed considerably. As a consequence this report standardised on the Water Affairs and Forestry (1995) data. Accordingly, the catchment supports approximately 79 000 ha of irrigated agricultural crops, the most important being citrus (20 000 ha), and sugarcane (12 500 ha). *Indications are that there has been a 20 % increase in irrigated agriculture from 1987 to* 1992. Overall, the area under citrus appears to have increased by some 50% (7000 ha). *Pecan nuts,* avocados and bananas similarly increased, whilst the area under mango's increased by well over 400%, from approximately 1400 ha in 1987, to nearly 8 000 ha in 1992. Conversely, crops such as cotton, soya beans and guavas decreased in extent, reflecting a countrywide trend of reduced prices and demand. These relative areas fluctuate rapidly in response to climatic and market changes, and are difficult to put set figures to.

Table 5 Estimates from various sources of the areas (in hectares) covered by each crop in 1991/1992 in the Crocodile River Catchment.

Crop	Area (ha)	% of total
Orchards	**(total) 37 586**	48.2
citrus	20 000	25.6
mangoes	7 913	10.1
bananas	4 500	5.8
avocados	2132	2.7
nuts	2159	2.8
pawpaw	203	0.3
litchis	200	0.3
guavas	329	0.4
coffee	150	0.2
Sugarcane	11 000	14.1
Tobacco	5 552	7.1
Vegetables	5 350	6.9
Ginger	150	0.2
Other (mainly field crops)	18 395	23.6
Total	**78 033**	

* 1991 data for the Crocodile, Kaap rivers and associated canals (Malelane, Barvale, Hall & son, Friedenheim, Alma and Curlews)

Most irrigated agriculture in the catchment takes place in the flatter Lower Crocodile sub-catchment, within a few kilometres of the Crocodile River (**Figure 3**). There are smaller areas of irrigated crops in each of the other sub-catchments. In the Kaap sub-catchment, agriculture is largely confined to the upper valleys of the Suidkaap and Queen's rivers, whilst in the Middle Crocodile sub-catchment it is mainly along the White and Crocodile rivers. In the Elands sub-catchment, some small patches of irrigation occur along the main river between Waterval Onder and the Ngodwanaspruit. In the Upper Crocodile, the main areas are around the Kwena Dam.

There is a substantial irrigation crop water requirement in the Crocodile catchment, peaking in December and January, and lowest in June and July (Combud 1991, Du Toit 1992). This decrease in the winter months is largely due to the reduced irrigation of sugarcane in the Lower Crocodile sub-catchment. Irrigation demand not only implies a reduction in the available in-stream flow, but the amount and quality of the agricultural return flows will vary accordingly. Reliable records of actual irrigation water used are not readily available, thus these figures are estimated on the basis of the allocated quotas and average crop water requirements.

CHAPTER 3

FORESTRY

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3.1 INTRODUCTION

Forestry is the dominant land use in the Crocodile River catchment in areas with mean annual rainfall exceeding 800 mm per annum. As a consequence, the upper catchment areas are relatively heavily afforested, with an estimated 16.6% of the total catchment being afforested. Of this, approximately 109 160 ha (10.4%) constitutes pines, and 63 000 ha (6.0%) constitutes eucalypts. *Pinus patula* and *P. elliottii* are the two main pine species used, while *Eucalyptus grandis* is the dominant eucalyptus species. However, more recently there has been a proliferation of clonal eucalypts such as hybrids of *E. camaldulensis* which appear well suited to the relatively droughtier conditions in the lower catchment areas. In general, pines are better suited to the colder conditions in the upper parts of the catchment, and if eucalypts are planted *E. nitens* is the preferred species. In this investigation only commercial afforestation was considered, as social forestry only forms a very small part of the forestry activity and is difficult to quantify.

As a result of limited data availability, this study was confined to predictions from the main hardwood species grown, *Eucalyptus grandis*, and the two main pine species, *Pinus patula* and *P. elliottii*.

3.2 RESEARCH STRATEGY

Both streamflow reduction and production data were required for commercial forestry trees. The strategy employed was to consolidate the actual growth data collected for trees in a series of previous studies with the streamflow reduction predictions based on equations developed by Scott and Smith (1997) and as applied by Le Maitre *et al* (1997).

3.2.1 Growth

The first data source required in this analysis was the amount of timber produced per hectare for the observed impact on streamflow reduction. The same approach was followed as in the hydrological analysis ie. the area was stratified into three rainfall zones, <800 mm, 800 - 1000 mm, and >1000 mm per annum. In addition, as there is considerable variation in site quality which in turn impacts on productivity, the rainfall zones were further stratified into three productivity zones for each of the three species as classified in the Forestry Handbook (Ellis, 1994). Growth data were derived from three studies carried out in the Crocodile River Catchment that aimed to develop site productivity models for *Pinus patula*, *P. elliottii*, and *E. grandis* (Louw 1995).

The criteria used to select sites for the collection of the above growth data were:

- Sites were selected to cover the maximum variation in site conditions and tree growth. This was achieved by using a land classification system together with aerial photographs to select the field sites on which tree growth was measured.
- Areas of natural regeneration were not included in the study because this is not the norm in commercial forestry management practice.
- Only stands between the ages of 16 and 25 years were used in the analysis. This was done to ensure that the estimate of Site Index 20 that was derived was reliable.
- Emphasis was placed on selecting sites which were free of secondary influences such as competition from weeds, insect or fungal damage.
- No fertilised stands were selected (this excludes the standard fertilizer application at planting).

The growth measurement procedure followed was that used as a standard in the forestry industry (Forestry Handbook). The procedure involves the estimation of a parameter, the Site Index at age 20 (SI_{20}). This parameter is independent of planting density, and is therefore a suitable measure in estimating the site growth potential of forestry sites. Essentially the SI_{20} is an estimate of the height of the dominant trees on the site at age 20 years. This measure was converted to volume production estimates again using standard growth and yield equations developed specifically for each of the three species.

In total, 163 *P. patula*, 157 *P. elliottii*, and 88 *E. grandis* sites were selected. On each site the overbark diameter of a minimum of 30 trees was measured. From this sample, the 33% thickest-stemmed trees were selected and felled, and their heights measured to determine the SI_{20}. If the stand was older than 20 years then the trees were cut back and the height at age 20 determined with the aid of the growth rings. If the stand was younger than 20 years, then the SI_{20} was calculated using the formula proposed by Von Gadow (1986).

The mean SI_{20} was then calculated in each rainfall and site productivity class for each of the three species. This data was then used in the growth and yield simulator developed by the CSIR to simulate the growth and wood production in each of the rainfall and site productivity classes. Simulations were done for both pulpwood and sawlog rotations. **Table 6** summarises the rotation length, planting densities and timing of thinnings assumed in the above simulations. The regimes used below are the standard regimes recommended for the respective species in the Forestry Handbook (Schonau, 1994).

Table 6 *The rotation length, planting densities (in stems per hectare) and timing and severity of thinnings for the three tree species studied*

Species	Regime	Rotation length	SPHA at planting	1st thinning		2nd thinning		3rd thinning		4th thinning	
				Age	SPHA	Age	SPHA	Age	SPHA	Age	SPHA
P. elliottii	Pulp	18	1736	-	-	-	-	-	-	-	-
	Sawlog	30	1372	7	650	15	400				
P. patula	Pulp	18	1736	-	-	-	-	-	-	-	-
	Sawlog	30	1372	7	650	15	400				
E. grandis	Pulp	10	1666	-	-	-	-	-	-	-	-
	Sawlog	25	1300	4	750	6	500	8	350	12	225

3.2.2 Flow reduction estimates

The focus of this investigation was to estimate the opportunity cost of having forestry in the upper catchment areas. For this reason, the water use of forest plantations was not the relevant measure of that cost, but rather the impact that plantation forests have on the water yield of the catchment. Clearly, it is the change in water yield from the catchment areas that impacts on downstream irrigation activities, and this is therefore the relevant variable in investigating the conflict between forestry and irrigated agriculture.

The catchment experiments from which the streamflow reduction curves were derived are situated in high rainfall areas (1 100 - 1 700 mm per year). Le Maitre *et al* (1997) acknowledge that the application of the streamflow reduction models to lower rainfall sites poses a risk as these sites are beyond the rainfall bounds on which the models have been developed. As a consequence, a two-step procedure was followed to predict the flow reductions across all sites. The first step was to use the flow reduction curves as applied by Le Maitre *et al* (1997) to predict the flow reductions for the high productivity class (Class 3) in the high rainfall zones (800-1000mm, and >1000 mm pa). The second step was to use the streamflow reduction efficiency ratio calculated for these sites to extrapolate to the remaining sites ie. the lower productivity classes in the high rainfall zones, and all the sites in the low rainfall zone. More detail is given below. It is believed that this procedure resulted in more reliable results for the marginal sites as it combined the flow reduction data with growth data, and is based on the generally accepted principle that the flow reduction is proportional to the forest productivity on the site.

Step 1 in the procedure above: Predicting the flow reductions for the high productivity class (Class 3) in the high rainfall zones (800-1000mm, and >1000 mm pa).

The prediction of the streamflow reduction per hectare of afforestation on the high rainfall/high productivity sites followed the method used by Le Maitre *et al* (1997), in which they apply models developed by Scott and Smith (1997) and the basic approach proposed by Scott and Le Maitre (1993). These models were developed for the purpose of predicting streamflow reduction following afforestation with *E. grandis, P. patula* and *P. radiata*. For the purposes of this investigation the streamflow reduction by *P. elliottii* was assumed to be equivalent to the other summer rainfall region pine, *P. patula, and Pinus radiata* is not relevant as it is not planted in the catchment.

The models mentioned above predict the percentage reduction in the virgin streamflow (ie the streamflow under the natural grassland vegetation in mm rainfall equivalents) for eucalypt and pine stands in both optimal and sub-optimal growth zones.

The following data were therefore required to predict the streamflow reductions:

- Species
- a knowledge of the forestry management regimes used in the catchment
- the growth potential of each of the sites (optimal or sub-optimal)
- virgin mean annual streamflow for each site

The analysis done in the following section combined the virgin streamflow and mean annual precipitation data used in the WR90 study for the Water Research Commission (Midgley *et al* 1994) with the streamflow reduction curves of Le Maitre *et al* (1997). A GIS was used to perform certain of the analyses, for example the overlaying of the different spatial data sets such as the mean annual streamflow and the plantation areas.

Simulations were run to predict the annual and total streamflow reduction in mm for the three species, under both pulpwood and sawlog rotations. The 'optimal' flow reduction curve (Le Maitre *et al*, 1997) was considered the appropriate curve as it was applied to the sites considered to be of the highest growth potentials. These flow reduction data were then scaled to derive estimates of reduction in streamflow in $m^3 ha^{-1} yr^{-1}$ over the rotation for each species in each of the rainfall zones and productivity classes.

Step 2 : Predicting the flow reductions for the lower productivity classes (Class 1 and 2) in the high rainfall zones (800-1000mm, and >1000 mm pa), and for all the productivity classes in the lowest rainfall zone (<800 mm pa).

Once the flow reductions had been calculated for the sites in Step 1, the ratio was calculated between the flow reduction for those sites and the total wood yield from the sites for each of the species and forestry regimes studied. As the wood yields from the marginal sites were known (described in the growth section above), it was then possible to use this ratio to predict the streamflow reduction for each of the remaining site productivity and rainfall classes.

3.3 RESULTS

3.3.1 Tree growth and streamflow reduction

The above three data sets (one for each species) were then analysed into their respective productivity classes to establish what proportion of the total comprised each productivity class, and also to calculate the mean SI_{20} for each of the productivity classes (**Table 7**). The table shows that the majority of forestry sites sampled were in the high rainfall zone (>1000 mm pa), which reflects the location of plantation forests in the catchment. *P. elliottii* was the most widely planted species in the catchment, having sites in all the rainfall and productivity classes, followed by *P. patula*, and

E. grandis which was represented by sites only in the highest rainfall class (**Table 7**). The table also shows that *E. grandis* grows substantially larger than the two pine species, reaching an average of 52 m in height at age 20, by comparison to the approximately 25 m achieved by the pine trees of the same age (**Table 7**).

Table 7 A summary of the site index at age 20 years (SI_{20}) recorded for the three species investigated in each of three rainfall classes

Rainfall class (mm per annum)	Productivity class	*P. elliottii*		*P. Patula*		*E. grandis*	
		Mean SI_{20}	% sites	Mean SI_{20}	% sites	Mean SI_{20}	% sites
< 800	1	15.5	4	-	0	-	0
	2	18.6	4	-	0	-	0
	3	22.0	1	-	0	-	0
800 - 1000	1	15.7	3	19.4	7	-	0
	2	19.0	8	22.6	12	-	0
	3	22.9	9	27.3	5	-	0
>1000	1	16.4	1	19.3	18	36.5	32
	2	19.5	13	22.7	27	45.4	65
	3	23.8	57	26.9	32	52.0	3

The results of the analyses completed for the total wood volumes and associated flow reduction for the three species grown under *pulpwood regimes* are presented in **Table 8**. The results show that in general the highest wood volumes and streamflow reductions are associated with the higher rainfall classes and more productive sites. Also, the predicted flow reductions by pines are generally higher than those for eucalypts because of the longer rotations under which pine pulp is grown.

The data for *sawlog regimes* is presented in **Table 9**. It is noticeable that both the timber yield and the streamflow reductions are considerably higher than those cited for the equivalent sites for pulpwood regimes (**Table 8**). This reflects the considerably longer growth cycles required for sawlog regimes. The highest wood yields were for *E. grandis* on the high productivity sites with the highest rainfall, while the maximum streamflow reductions were predicted for pines also for these sites (again, because pines are grown on longer growth cycles than eucalypts).

Table 8 A summary of the mean annual growth increments (MAI), mean annual runoff reduction, total wood volumes (at clearfelling) and associated total flow reduction for the three species grown under ***pulpwood regimes*** in each of three rainfall classes.

		P. elliottii				*P. patula*				*E. grandis*			
Rain class	Production class	MAI (m^3 ha^{-1} yr^{-1})	Mean Flow red. (m^3 ha^{-1} yr^{-1})	Wood Volume (m^3 ha^{-1})	Flow red. (m^3 ha^{-1})	MAI (m^3 ha^{-1} yr^{-1})	Mean Flow red. (m^3 ha^{-1} yr^{-1})	Wood Volume (m^3 ha^{-1})	Flow red. (m^3 ha^{-1})	MAI (m^3 ha^{-1} yr^{-1})	Mean Flow red. (m^3 ha^{-1} yr^{-1})	Wood Volume (m^3 ha^{-1})	Flow red. (m^3 ha^{-1})
< 800	1	18.0	634	324	11403								
	2	23.6	830	425	14940								
	3	30.3	1064	545	19160								
800 - 1000	1	18.4	646	331	11621	20.8	981	374	17664				
	2	24.4	857	439	15419	25.4	1199	457	21590				
	3	32.1	1130	578	20333	32.6	1538	586	27677				
> 1000	1	19.6	868	353	15623	20.7	975	372	17545	37.6	636	376	6355
	2	25.3	1122	456	20204	25.6	1206	460	21716	53.9	910	539	9104
	3	34.0	1508	612	27145	31.9	1508	575	27145	67.4	1139	674	11385

Table 9 A summary of the total wood volumes (derived from thinnings and at clearfelling) and associated flow reduction for the three species grown under ***sawlog regimes*** in each of three rainfall classes.

		P. elliottii				*P. patula*				*E. grandis*			
Rain class	Production class	MAI (m^3 ha^{-1} yr^{-1})	Mean Flow red. (m^3 ha^{-1} yr^{-1})	Wood Volume (m^3 ha^{-1})	Flow red. (m^3 ha^{-1})	MAI (m^3 ha^{-1} yr^{-1})	Mean Flow red. (m^3 ha^{-1} yr^{-1})	Wood Volume (m^3 ha^{-1})	Flow red. (m^3 ha^{-1})	MAI (m^3 ha^{-1} yr^{-1})	Mean Flow red. (m^3 ha^{-1} yr^{-1})	Wood Volume (m^3 ha^{-1})	Flow red. (m^3 ha^{-1})
< 800	1	8.1	768	243	23025								
	2	10.5	994	315	29816								
	3	13.3	1261	399	37830								
800 - 1000	1	8.2	782	247	23446	11.4	848	342	25453				
	2	10.8	1024	324	30728	13.9	1039	418	31166				
	3	14.1	1335	423	40043	17.9	1335	538	40043				
> 1000	1	8.8	1051	263	31525	11.3	1147	339	34415	30.6	921	765	23017
	2	11.2	1343	336	40295	14.0	1423	421	42679	43.4	1307	1085	32671
	3	14.9	1782	446	53458	17.6	1782	527	53458	54.0	1625	1351	40635

The above tables summarise the data to illustrate the main contrasts between species, and regimes. However, the economic analysis required the data the in form of a time series, because not only are the volume yields important, but also when the yields are derived over the life cycle of the crop. The timing of thinnings, clearfelling date, and their associated volume yields were therefore required to generate the appropriate measure of economic return.

The format of the data used in the economic analysis is illustrated in **Figure 5**. *E. grandis* and *P. patula* were compared to illustrate the principal differences between the two species (**Figure 5**). The figure illustrates that not only was the final volume of wood at clearfelling greater for *E. grandis*, but also that the pine species is grown on a longer growth cycle. In addition, thinnings in eucalypts are both more frequent, and start earlier than in pines. This implies that it takes longer to derive any income from the pines which will have obvious impacts on the revenue streams. Apart from the higher initial impacts in streamflow reduction under Eucalypts, the cumulative streamflow reduction is not that different between the two species (**Figure 5**).

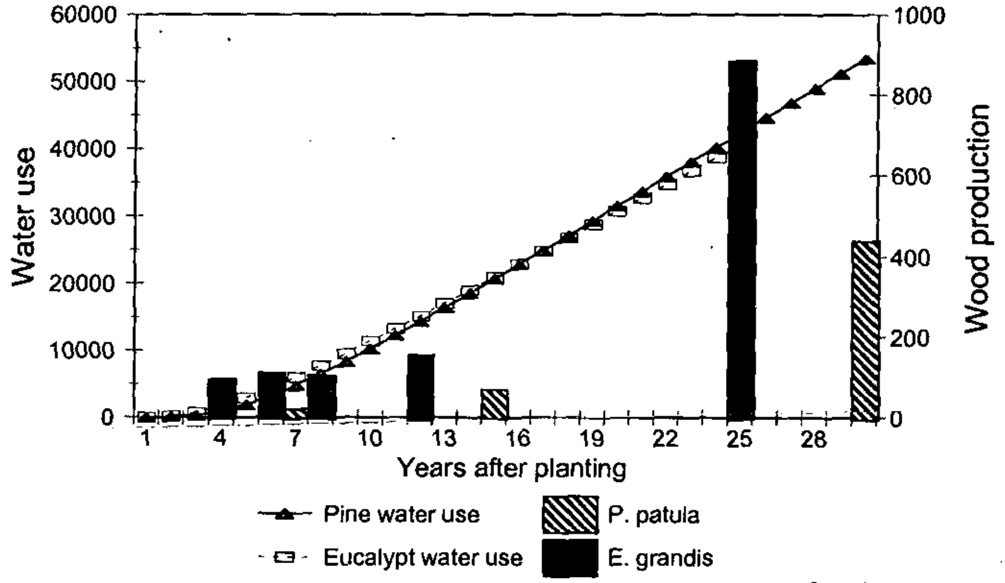

Figure 5 An illustration of the cumulative streamflow reduction in $m^3 ha^{-1}$ and timber yield ($m^3 ha^{-1}$) from thinnings and at clearfelling for P. patula and E. grandis grown on sawlog rotations for high productivity sites located in the rainfall zone > 1000 mm per annum.

3.3.2 Important factors that affect modelled water use

3.3.2.1 Limitations of the empirical models used in this study

Strictly speaking, the empirical models developed from long-term catchment studies (Scott and Smith, 1997) apply only to the catchments on which they were developed. Their use outside these catchments introduced some uncertainty. Nevertheless, the models appear to be fairly robust. For example, the model for eucalypts in optimum growth zones was verified against an independent catchment data from two catchments with a mean annual precipitation (MAP) range of 1100 - 1600 mm (Le Maitre *et al* 1997).

The models used can, however, still not address certain variables. For instance, the streamflow reductions may be smaller in catchments where the soil profiles are shallower, allowing less rain to be stored in the catchment for later use by the trees. Details of this nature have not been entered into the current simulations.

3.3.2.2 Use of the appropriate rotation length

The models are applied by integrating the flow reductions following forestry over the rotation length. Only two management options were considered, growing timber on short rotations for pulping, and growing timber on longer rotations for sawlogs. Use of a shorter rotation length than the actual length used in practice will lead to serious under-estimates of the reductions in streamflow. In order to specify this variable clearly the rotation length used is given in (**Table 6**).

3.3.2.3 Silvicultural improvements: thinning, site preparation, fertilization and tree-breeding

The models were developed from experiments in which the plantations received standard silvicultural treatments for sawlogs at that time. New silvicultural treatments aimed at improving growth rates of trees may also increase their water use, with the results that the flow reduction models of Scott and Smith (1997) would under-estimate streamflow reductions under current silvicultural practices. Research has indicated that un-thinned plantations may have a slightly greater effect on streamflow than predicted by the models (van der Zel 1970; Lesch and Scott in press). Plantations which fully occupy the site and attain canopy closure more rapidly than in the past (as a result of site preparation and/or fertilization, and/or through the use of superior genetic stock, and/or as it is a second rotation crop) can be expected to have an earlier and ultimately greater impact on water yield.

CHAPTER 4

SUGARCANE

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4.1 INTRODUCTION

Sugarcane is widely grown in the Crocodile River catchment in the lower catchment areas between Malelane and Komatipoort. Sugarcane accounts for approximately 12 500 hectares in this catchment (SASA, 1997). A further 18 500 hectares of sugarcane are grown in the Lomati and Komati catchments. Recent expansion in the region has primarily been in the Lomati and Komati catchments to supply cane to the new Komati mill.

4.2 METHOD

The water use and sucrose yield of sugarcane in the lower Crocodile River Catchment was estimated using the CANEGRO simulation model developed by Inman-Bamber and co-workers at the SASA Experiment Station (Inman-Bamber, 1991, Inman-Bamber *et al*, 1996). This model is internationally accepted and has been shown to give reproducible and realistic results when tested against field estimates of water use and yield (Inman-Bamber et *al*, 1993). The model has been used frequently in South Africa in irrigation scheduling exercises (McGlinchey *et al*, 1995), and predicting yields at a variety of harvesting times (Inman-Bamber *et al*, 1993). The model is therefore ideally suited to the current application. An advantage to using a model such as CANEGRO is that results represent long term average trends. Field trials with only a few years data can be inaccurate if the years during which measurements took place are not representative of 'average' conditions. Long term field trial data for sugarcane are not available for the study area.

Detailed soil data and daily climatic records were required as model inputs. The physical properties of well described soil profiles of the four predominant soil types in the region were used as soil inputs. Daily meteorological records for the period 1970 to 1994 from two representative SASA Experiment Station class A weather stations were used as climatic inputs (**Table 10**). In the CANEGRO crop model, potential crop water use is estimated using a Penman-Monteith approach and partitioned between soil and crop using a heat-unit based canopy development routine. Precipitation is dealt with mechanistically, ensuring that the components of the water balance are estimated accurately.

Six irrigation Scenarios were simulated for each location (soil and meteorological site). To account for the seasonal effect on yield and crop water use, simulations starting in each month of the year between May and December were chosen to represent the milling season. These annual cropping cycles were repeated each year from 1960 to 1994, thus the yield predicted for each location and irrigation level was obtained from 200 simulated crops. Further analysis was conducted using these mean results.

To investigate the response of sucrose yield to increasing amounts of irrigation water, six irrigation Scenarios were created by varying the amount of water applied between zero and a maximum of 1 026 mm per annum (**Figure 6**). This was achieved by varying irrigation cycle times only. The application amount was fixed at 45 mm net, and increasing amounts of irrigation were applied by progressively reducing the interval between irrigation events. A soil water deficit function was used to ensure that water was not applied during periods of adequate rainfall. It was assumed that irrigation was applied using overhead sprinklers. Note that all irrigation data presented are net amounts delivered above the canopy, application and reticulation losses are ignored.

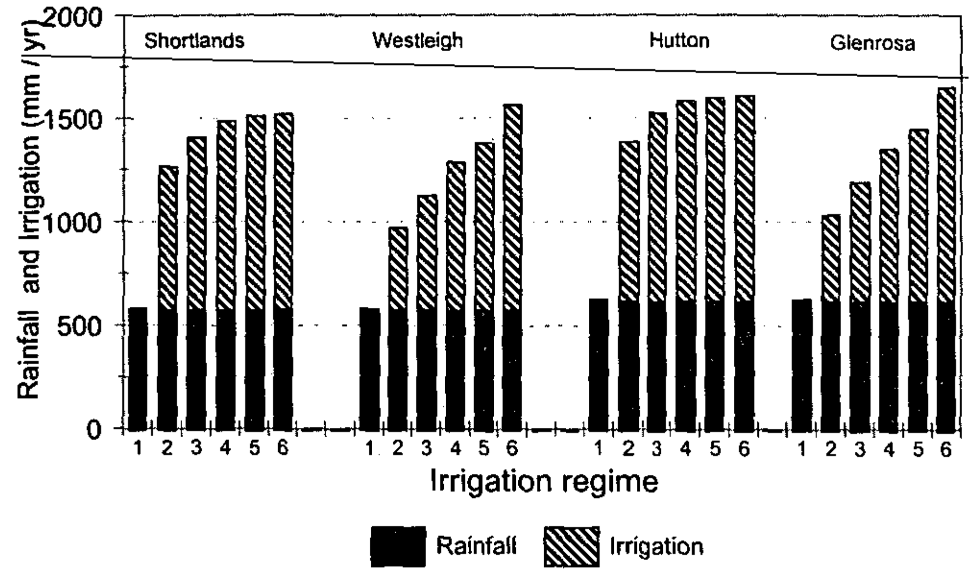

Figure 6 The mean rainfall and applied irrigation used for each of the simulations on each of the four soil types.

Table 10 A summary of the soil types and the weather station data used in the CANEGRO simulations to predict irrigation requirement and yield in two parts of the sugarcane growing area in the Crocodile River Catchment. The table presents the altitude, rainfall and evaporation data for the two sites

Area	Soil type	Weather station	Altitude (m)	Rainfall (mm)	A pan (mm)
Malelane	Shortlands	Mhlati	309	604	2007
	Westleigh				
Komatipoort/Tenbosch	Glenrosa	Tenbosch	176	629	1974
	Hutton				

4.3 RESULTS

4.3.1 Irrigation/yield response curves

Six irrigation Scenarios were simulated for each of the four locations under investigation. The mean number of stress days limiting photosynthesis experienced for each scenario is given in Figure 7. The figure illustrates progressively fewer stress days with an increase in irrigation for each of the four soil types used in the analysis. Irrigation scenario 1 simulated the conditions experienced by the crop if it were to survive purely on rainwater, and it is clear that the crop would have experienced severe stress on all four soil types. Stress levels remained high on the Westleigh and Glenrosa soil forms, even when irrigated, because of the low water holding capacity of these soils. By contrast, the Shortlands and Hutton soils typically have a higher moisture holding capacity, and are deeper, resulting in a greater degree of buffering, and lower stress levels (**Figure 7**).

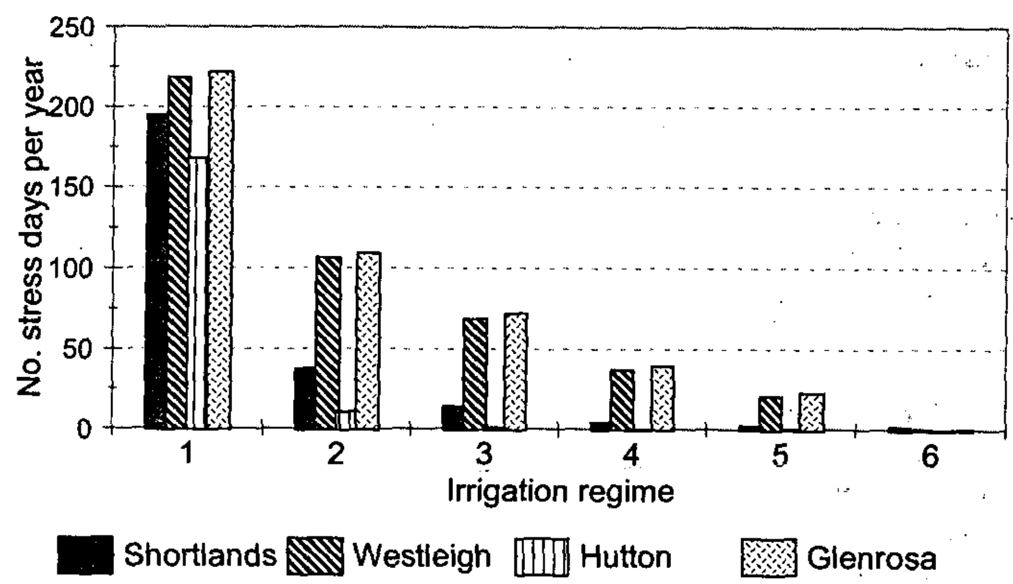

Figure 7 The number of stress days experienced by the cane crop for each of the six selected irrigation regimes on each of the four soil types.

In the poorer irrigation regimes, soil evaporation constituted a relatively greater proportion of the total evaporation than was the case in the better irrigation regimes (**Figure 8**). The highest soil evaporation was recorded on the clay soil (Shortlands) and was almost equal to transpiration for the rainfed treatment (treatment 1). In the better irrigation scenarios soil evaporation was estimated to be about 20% of transpiration. Evapotranspiration reached a peak of almost 1 400 mm yr^{-1} under fully irrigated conditions on the Hutton soil type. This value is a little lower than that measured at Pongola (1 555 mm yr^{-1}), and slightly higher than the 1267 mm yr^{1} measured at Shakaskraal and Tongaat in Southern KwaZulu-Natal (Thompson, 1976). It should, however, be borne in mind that the results of the simulations are the mean of 24 years and eight harvest months, while the other data cited above are drawn from a much shorter data set.

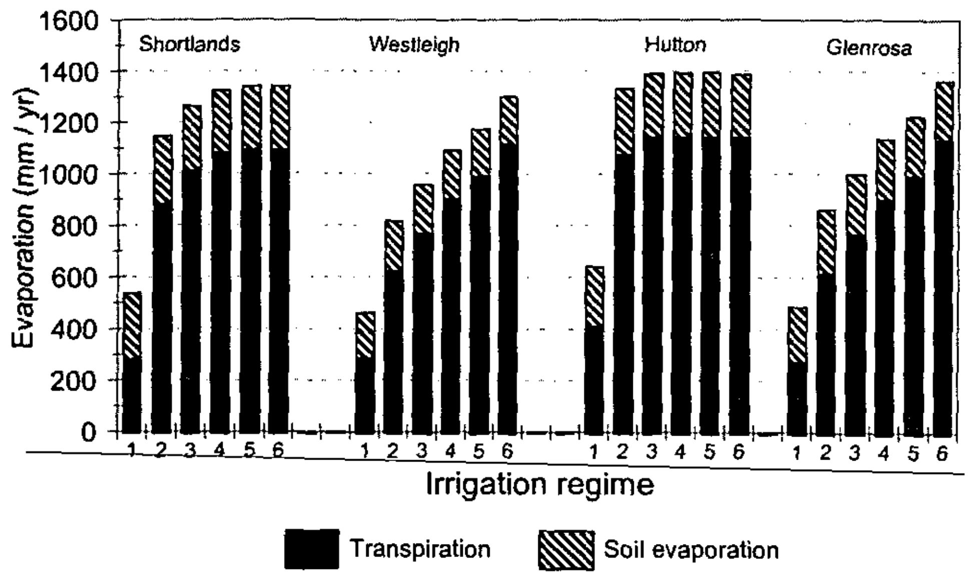

Figure 8 A comparison between transpiration and evaporation from the soil surface for each of the simulations conducted showing how soil evaporation constitutes a relatively greater proportion of the water use in the lower irrigation treatments.

Under full irrigation (Scenario 6), a total of 1 651 mm (irrigation plus rainfall) was available to the crop. Of this, 1 147 mm (69,5%) was estimated to have been transpired, 240 mm evaporated from the soil surface, 193 mm (11,7%) lost to deep drainage out of the profile, and the remainder lost through surface run-off.

4.3.2 Cane and sucrose yield

Cane yield was calculated using stalk dry matter yield estimated by the model and an average dry matter percentage of 29%. Sucrose yield was estimated from cane yield using an empirical relationship based on crop age and season. The relationship between the sum of rainfall and irrigation, and sucrose yield is presented in Figure 9. It should be noted that the curve represents long term average trends, and there would be significant variation between years. The figure shows that the results from the simulations from the Malelane and Tenbosch regions follow similar trends, with sucrose yields peaking at total water applications (rainfall plus irrigation) of approximately 1 500 mm yr^{-1}. As anticipated, the lowest yields were obtained from the poorest soil type, the Glenrosa, with the Tenbosch climate data set. It should be noted from Figure 9 that maximum sucrose yields of 19 t ha^{-1} yr^{-1} are achievable. Based on a sucrose/sugarcane ratio of 0.135, which is typical of the region, this converts to 140 tonnes of cane per hectare per annum. Some growers, however, have achieved yields in excess of 170 tc ha^{-1} yr^{-1} .

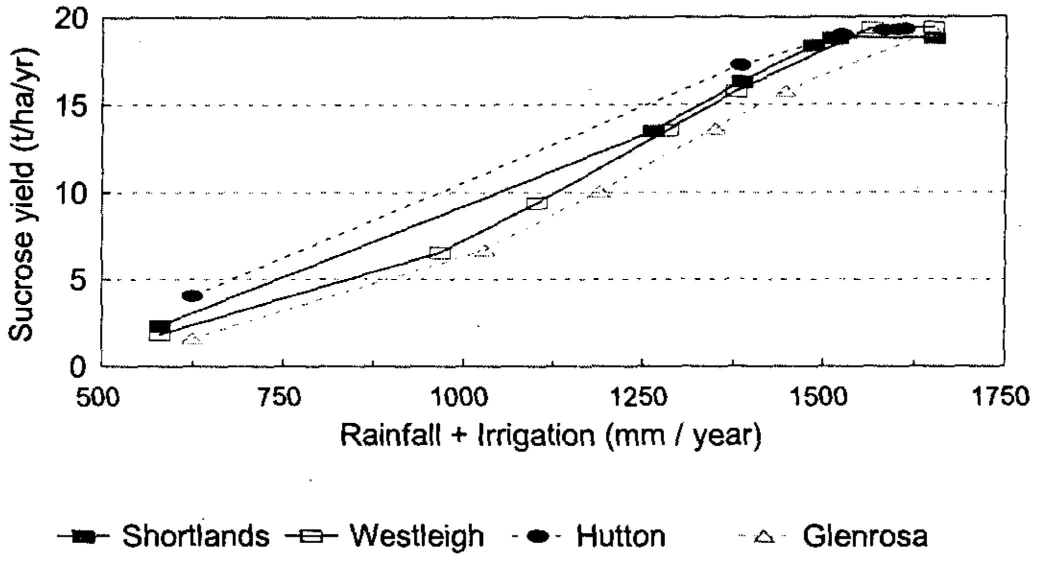

Figure 9 The relationship between total water use (irrigation + rainfall) and simulated sugar yield for the four simulations run for the lower Crocodile river catchment

The relationship between sucrose yield and nett irrigation are presented in Figure 10. This figure is equivalent to Figure 9 with the rainfall contributions subtracted.

Figure 9 illustrates that under dryland conditions (zero irrigation) sucrose yields of only 2,5 to 4 t ha^{-1} yr^{1} would be obtained which is not viable for commercial production. It should be borne in mind that each data point represents the mean yield simulated from a record of 24 years of climatic data, so there will be year to year variation depending primarily on variation in rainfall, radiation and temperature. The peak sucrose yields of 19,1 t ha^{-1} yr^{1} were achieved at a nett irrigation application of approximately 900 mm yr^{1}.

Nett irrigation application of 900 mm is equivalent to a gross abstraction of 1 300 mm from the river, when allowing for a typical application efficiency of 70%. The annual water allocation to the Crocodile sugarcane irrigators is 1 300 mm.

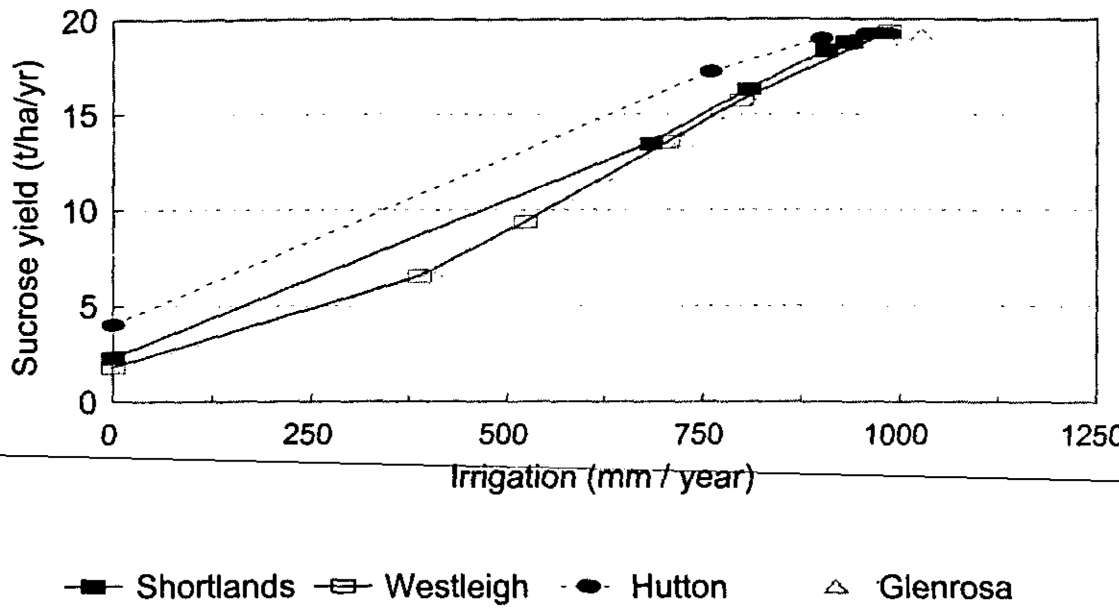

Figure 10 The relationship between irrigation and simulated sugar yield for the four simulations run for the lower Crocodile river catchment. The mean annual rainfall for the Shortlands and Westleigh sites was 580 mm and 625 mm for the Hutton and Glenrosa sites.

The above indicates that in an 'average' year, 900 mm nett irrigation will produce a crop of 19 tonnes sucrose per hectare per annum. There are, however, examples from field observations, which indicate that in certain years, and with careful irrigation scheduling, a crop of 18 tonnes sucrose per hectare per annum can be produced from only 400 mm of irrigation. This represents more than double the long term 'irrigation water use efficiency'. In such years, there is typically a high component of effective rainfall contributing to crop growth. The above emphasizes how a few isolated years of trial data can be different from long term average trends.

4.3.3 Monthly water use

The monthly water use by the crop is significant because it illustrates the seasonal demand for water. Should this not be met by rainfall, the assumption is that it will be provided to the crop through irrigation in the course of the conventional irrigation scheduling. Figure 11 illustrates that the daily water use of sugarcane follows a very strong seasonal cycle, with mean daily water use peaking during the mid-summer months at about 5,8 mm per day (**Figure 11**). Wintertime water use rates were considerably lower at 2,3 mm per day. It is significant that the water use rates begin increasing in July and reach significant levels by September and October, which precedes the rainy season in this area. This heightens the conflict between irrigation farmers and forestry, as this is also the time at which the water supply in the rivers is at its lowest. Also, particularly in poor rainfall years, the supply of water to farmers from impoundments becomes increasingly limited prior to the onset of summer rains. As was the case in the sugar yield/irrigation curves, the mean of the data supplied below will be used in the analysis with the other crops because of the similarity between the two curves below (**Figure 11**).

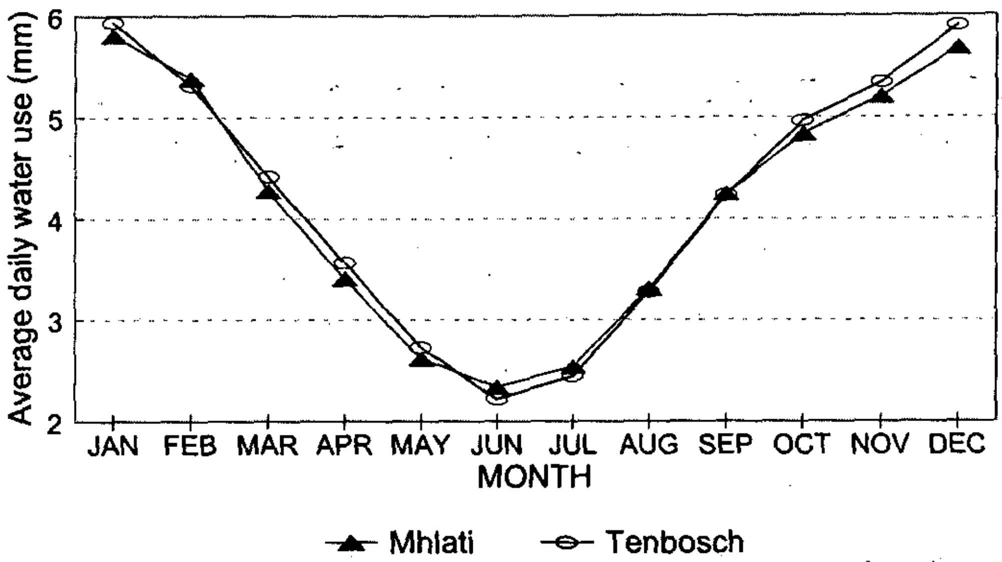

Figure 11 The daily average water use by sugarcane for the two weather stations selected for the simulation.

CHAPTER 5

WATER USE OF SELECTED TROPICAL AND SUBTROPICAL FRUIT CROPS IN THE UPPER CROCODILE RIVER CATCHMENT

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5.1 INTRODUCTION

The demand for South Africa's scarce water resources by communities, urban users, agriculture and the environment, has created pressure for its effective use. Consequently the irrigation sector which currently accounts for 50 % of the water used in South Africa will increasingly become under pressure to find solutions regarding water within agriculture and between agriculture and other water users (Anon., 1997).

Owing to limited water supplies, the possibilities for expansion of irrigation farming demand careful planning and prioritisation. Any such planning, starts with knowledge of the total annual water requirements of the particular crop. Plant water requirement, however, is not a constant, but depends on climate, cultural practices, irrigation system (e.g. partial soil wetting vs. full coverage), irrigation frequency and soil properties. In this chapter net irrigation figures are therefore based on well-defined conditions. Undoubtedly, water can be saved compared to the recommended quantities, when modern technology (not necessarily more expensive technology) is applied.

The scarcity of water and the need to conserve this precious commodity, provide a strong stimulus for irrigation research. In an overview of all irrigation research on horticultural crops conducted in South Africa between 1967 and 1991, Van Zyl and Bredell (1995) clearly pointed out distinct effects of water on crop yield and quality. In 80 % of 29 investigations, either total yield or fruit size, and in most cases both these parameters of reproductive response, increased with shorter irrigation cycles i.e. wetter soil conditions. Most fruit quality characteristics were favoured by drier conditions in contrast to total yield and above-ground vegetative growth. Horticultural produce which relies heavily on the export market and is often consumed fresh, is especially sensitive to changes in quality.

Phenological stages during which water stress has particularly large detrimental and irreversible effects, are of special importance to horticulture. Water stress during these critical phases may not only harm total yield, but also fruit size, a most important marketing factor (Van Zyl and Bredell, 1995).

This review paper also pointed out a clear need for more water-production functions in horticulture. However, two constraints are limiting in this respect *viz.,*

- Responses of tree crops to water in the field are often absent, very slow (long term) or confounded by sensitive phenological phases
- The large number of crops limits the number of experiments that can be conducted any on one crop

For the present study, the four most important fruit crops grown in the Crocodile River Catchment were selected, namely citrus, avocado, mango and bananas. Although many other crops such as litchi, papaya and guava are also commercially grown in the catchment, the areas planted to these crops are relatively small. Water use of the four selected crops has been determined in various trials in different regions over the past decade. Although the study of this basic question has not been completed and is still continuing, the emphasis in irrigation research has now shifted towards optimum yields and quality with minimum use of water. There is also new interest in fruit production under supplementary irrigation, and even under dryland conditions.

5.2 MATERIALS AND METHODS

5.2.2 Citrus

5.2.1.1 Site Description

Citrus irrigation trials at 2 sites, namely Nelspruit and Malelane, are reported on in this chapter. Both sites lie within the Crocodile River Catchment area. A trial with Valencias was conducted at the Nelspruit Experiment farm of the Institute for Tropical and Subtropical Crops at a position 25°27' latitude, 30°58' longitude and 660 m above sea level. The soil type at the Nelspruit site belongs to the Hutton form with 18-22% clay and an effective rooting depth of 800 mm. No deep soil preparation was carried out before planting.

At Malelane (25°27' latitude, 31°33' longitude and 380 m above sea level) grapefruit was chosen as the test crop. The Malelane soil was a Shortlands, containing 35-40% clay and having an effective rooting depth of 600 mm.

5.2.1.2 Climate

From climatic data presented in **Figure 12**, it is clear that Nelspruit is cooler and has lower Class A-pan evaporation than Malelane which is situated farther down the Crocodile river. Long term annual rainfall at Nelspruit is also higher (850 mm) than at Malelane (493,7 mm).

Rainfall makes a significant contribution to water use of crops in the Crocodile River Catchment. Consequently monthly rainfall figures at the different experimental sites spanning the duration of the irrigation experiments, are presented in **Table 11**. Rainfall was much below average at Nelspruit during 1992 and the following 3 years.

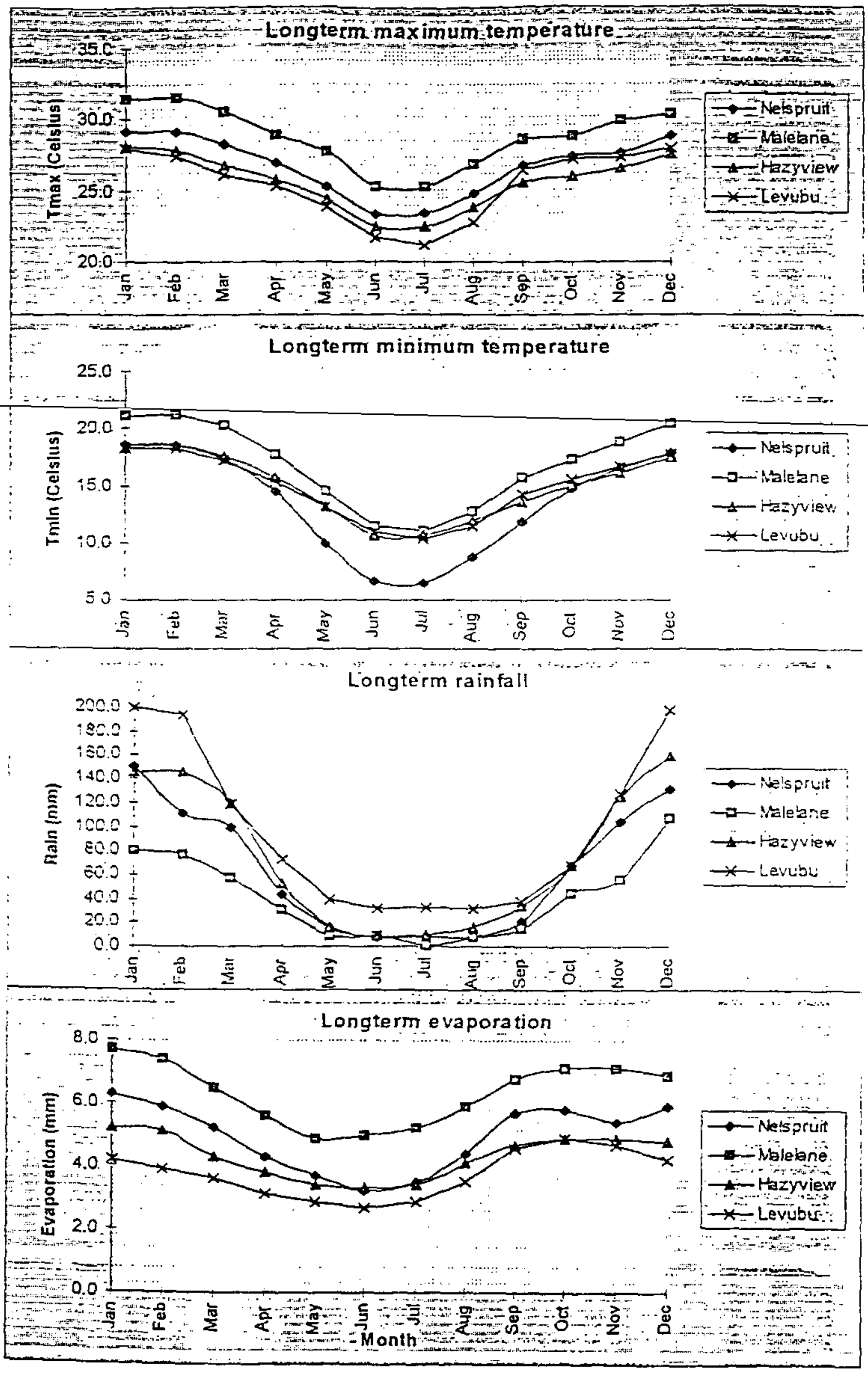

Figure 12 Long term climatic data of the different sites at which irrigation trials were conducted.

Table 11 Monthly rainfall (mm) at the experimental sites for the duration of the irrigation experiments

NELSPRUIT (official weather station)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1986	100.7	98.9	78.3	158.1	1.2	8.3	0	3.6	18.7	55.2	63.1	106.8	692.9
1987	69.9	140.8	199.6	23.7	6.5	5.7	0	48.7	111.1	69.4	68.9	171.4	915.7
1988	62.5	112.3	156.7	40.7	2.4	10.7	5.4	8.0	80.0	138.6	76.9	127.2	821.4
1989	54.3	179.3	28.6	26.3	12.7	55.3	0	2.2	5.1	89.6	188.8	204.3	837.5
1990	161.3	182.6	129.8	84.9	4.0	0	8.0	7.3	1.8	88.4	59.0	130.5	857.6
1991	277.6	108.7	109.7	0	18.1	45.8	7.0	0.5	9.7	17.8	96.4	85.5	776.8
1992	95.2	43.7	87.9	44.5	0	0.3	0	11.4	3.5	69.6	75.5	136.3	567.8
1993	62.2	86.5	205.3	7.7	21.7	0.7	2.0	16.7	4.3	33.6	61.4	70.8	572.9
1994	73.0	38.1	126.0	28.2	5.9	0	0	1.5	8.3	101.8	87.8	77.1	547.7
1995	114.7	29.8	64.4	71.1	4.3	0.5	0	14.3	1.3	39.0	162.8	143.9	646.1
1996	282.5	378.3	144.4	73.2	46.8	1.5	24.4	26.0	1.2	60.2	92.4	90.6	1221.5

NELSPRUIT (mango trial)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1988	66.0	109.8	105.3	40.5	3.0	10.6	4.3	7.3	71.4	119.0	78.9	118.2	734.3
1989	53.3	165.4	36.5	25.1	14.3	45.9	0.0	1.9	2.2	75.2	175.5	206.9	802.2
1990	161.8	161.9	94.4	68.6	2.0	0.0	7.3	3.6	1.4	79.5	64.7	114.5	759.7
1991	268.8	115.7	102.2	0.0	29.8	45.5	7.5	0.0	7.6	19.1	145.1	77.2	818.5
1992	80.8	46.1	67.3	36.8	0.0	0.0	0.0	14.6	0.0	49.2	60.5	67.4	422.7
1993	55.9	43.8	187.4	7.7	21.7	0.7	2.0	16.7	4.3	33.6	61.4	70.8	506.0
1994	73.0	38.1	126.0	28.2	5.9	0.0	0.0	1.5	8.3	101.8	87.8	77.1	547.7

MALELANE

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1990	66.5	63.0	65.7	56.0	0	0	3.5	1.0	0	47.5	16.0	86.0	405.2
1991	69.0	30.0	104.5	15.0	0	31.5	3.5	0	3.0	10.3	92.7	50.0	409.5
1992	88.5	37.5	21.0	10.0	0	0	0	0	3.0	28.1	8.2	251.8	448.1
1993	141.9	81.2	106.5	16.0	38.2	4.2	0.8	6.0	0	18.5	32.0	84.6	529.9
1994	25.0	11.6	76.0	16.5	0	0.2	0.2	0	5.5	30.6	15.7	68.0	249.3
1995	151.8	30.5	29.0	0	34.0	0	0	1.8	0	68.0	125.3	210.5	650.9
1996	113.7	125.0	31.0	24.5	55.5	0	21.0	16.5	0	56.0	104.5	63.0	610.7

BURGERSHALL (HAZYVIEW)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1990	141.9	131.3	110.1	80.9	4.1	0.3	20.5	18.9	2.4	72.6	88.8	208.3	880.1
1991	173.0	181.4	92.5	0	11.7	64.1	0	2.3	8.6	15.1	136.7	119.9	805.3
1992	64.0	30.9	100.1	57.9	2.0	6.0	0	18.2	14.0	70.2	92.2	316.1	771.6
1993	129.5	77.2	239.6	57.9	6.2	3.7	6	7.1	10.7	32.6	123.5	106.7	800.0
1994	96.2	63.0	123.7	17.5	3.1	0	0	4.5	15.0	87.5	22.2	131.5	564.2
1995	174.8	90.6	81.6	76.3	13.5	0	0	33.6	0	87.9	337.9	185.1	1081.3
1996	266.7	717.1	153.8	108.3	41.0	4.6	21.6	38.8	8.5	52.0	123.1	130.8	1666.3

LEVUBU

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1986	85.5	195.5	40.0	244.0	29	20	14.0	12.0	39.0	65.5	204.0	115.5	1064.0
1991	405.3	199.7	323.0	6.5	33.4	5.9	1.6	2.6	42.9	21.1	72.9	129.1	1244.0
1992	70.8	12.2	125.5	7.8	0	66.2	4.1	19.8	19.8	43.9	135.8	309.3	815.2
1993	109.1	199.3	66.7	38.9	3.0	18.3	56.1	36.6	8.4	82.0	251.0	283.7	1153.1
1994	238.1	76.0	39.6	31.5	0.5	5.7	2.1	5.0	16.5	91.7	54.1	112.2	673.0
1995	81.5	226.2	150.5	147.3	34.9	0.6	11.4	55.0	25.3	60.3	161.1	209.4	1163.5

5.2.1.3 Experimental Details

The test orchard at Nelspruit consisted of Olinda Valencia grafted onto Cairn rough lemon rootstock and was planted in 1968 at a density of 204 trees per ha (7m x 7m planting distance). Irrigation was applied through 2 microjets (180°) per tree. Water metres measured the amount of water applied per treatment. The trial started in 1986 when the trees were 18 years old, and continued for six consecutive years. The experiment was laid out as a randomised block design with four irrigation scheduling treatments (**Table 12**) and four replicates/treatment.

Table 12 Description of the four irrigation scheduling treatments on Olinda Valencia at Nelspruit

Treatment	Instrument	Schedule Description
A-pan 1	Class A pan	Irrigate when cumulative Et=35 mm
A-pan 2	Class A pan	Irrigate every 7 days
TM	Tensiometer	Irrigate at 50 % EAW (-30 kPa)
NP	Neutron probe	Irrigate at 50 % EAW

For the A-pan treatments, monthly variable crop factors based on lysimeter studies (Du Plessis, 1988) were used. In treatment A-pan 1, trees were irrigated when the cumulative daily evapotranspiration (Et) reached 35 mm, equal to 50 % depletion of easily available water (EAW) i.e. 50 % of the soil water content between field capacity (-10kPa) and a soil water potential of -100kPa. The 900 mm tensiometer was installed to monitor over-irrigation. In A-pan 2, irrigation was applied at a fixed interval of seven days. Cumulative Et over the 7 days as calculated with evaporation rates and the crop factor, was then applied to replenish the soil water content to field capacity.

A tensiometer station was installed in each replicate plot of the tensiometer treatment. One such tensiometer station consisted of 3 tensiometers installed at 300,600 and 900 mm depths. Irrigation on tensiometer plots started when the average of the 300 and 600 mm tensiometer readings reached -30 kPa which is equivalent to 50 % depletion of EAW.

The neutron moisture probe was calibrated on site at the different research experiments. Soil water measurements were done with the neutron probe at 150 mm depth increments and profile pits were dug immediately thereafter with a backhoe (Hoffman, 1990). Soil samples were then taken at both sides of the neutron probe access tube at the different measuring points (150 mm increments) with a core sampler of known volume and the gravimetric soil water content was determined by weighing. The calibration curve was derived from these data and the amount of water needed per irrigation cycle was estimated from the retentive profile of the soil.

One neutron probe access tube was installed in each replicate plot. Neutron probe measurements were carried out thrice weekly and irrigation was applied when the average of the 150 and 600 mm depth readings showed a 50 % depletion of EAW (Mostert and Hoffman, 1997a).

The consumptive water use of citrus was calculated using the water balance equation of Hillel (1972) as follows:

$$S = (P + I) - R - D - (E + T) \quad \ldots \quad 1$$

S = Variation in the soil water content which was measured by the neutron water probe at different depths (150 mm increments) and summed for the different depths to get the total soil water content of the soil profile.

P = Rainfall between measurements. The rainfall was measured at the site and was determined with the help of a neutron probe to be 70 % effective.

I = Irrigation applied between measurements on 70 % of the total area.

R = Streamflow from the surface - assumed to be negligible and taken as zero.

D = Deep drainage past the root zone - assumed to be zero - no over- irrigation or flooding by rainwater occurred.

E = Evaporation from soil surface - assumed to be small because only the drip area beneath trees was irrigated and not much evaporation occurred in the shaded area.

T = Transpiration of the crop and this represents the actual water use of the crop.

For practical purposes the terms (E + T) in equation 1 were combined in one term (ET) and this represents the water use by the crop. The water use between measurements throughout the season was calculated and the cumulative water use per season was computed. A Valencia season extended from August to July.

Cultural practices were carried out according to established norms applied by producers in the citrus industry. Fertilisation was based on soil and leaf analyses to ensure optimum nutrient status of the trees. Good quality water was used for irrigation throughout the duration of all the different research projects.

Fruit yield and fruit size were determined on all treatment plots at harvesting time.

<u>Malelane</u>

An irrigation trial was conducted on Nelruby grapefruit grafted on Volckameriana at Malelane in order to determine net irrigation in relation to tree age. The trees were planted in March 1986 at a spacing of 7 x 3,5 m (435 trees per ha). The statistical layout of the experiment is a randomised block design with nine treatments and four replicates (Mostert, Botha and Masinga, 1997).

Irrigation water was applied through 2 microjets (180°) per tree and the amount of water applied was measured using a water flow metre on each plot. Irrigation scheduling was done with the help of tensiometers and the neutron probe. Tensiometers at each tensiometer station (one station per plot) were installed at 300 and 600 mm depths. Irrigation took place when average readings of the 300 and 600 mm tensiometers reached -55 kPa in one treatment which is equivalent to 50 % depletion of EAW, and - 80 kPa in a second treatment. Adequate water was then applied to replenish the soil reservoir down to a depth of 600 mm. Although this trial consisted of 9 treatments altogether, only the last-mentioned two are relevant to the objective of this report.

The neutron probe was calibrated and utilised as described for the Nelspruit citrus trial. The net irrigation of grapefruit trees was calculated using equation 1.

Fruit yield and size were determined at harvesting. The grapefruit season commenced in June and lasted until end of May. Standard cultural practices as recommended by the ITSC were followed.

5.2.2 Mangoes

5.2.2.1 Site Description

Water requirements of mangoes were determined at Nelspruit in the Eastern Lowveld (30°58' E, 25°33' S) of South Africa (Mostert and Hoffman, 1997b). The soil was a typical Clovelly with 5 - 10 % clay and a depth of 1200 mm.

5.2.2.2 Climate

Long term climatic data for Nelspruit appear in **Figure 12**. Weather data were accumulated from a weather station on the experiment farm, but rainfall used in our calculations was measured at the experimental site (see **Table 11**). Effective rainfall was estimated at 70 % of total rainfall.

5.2.2.3 Experimental Details

An irrigation trial on 12 year old mango trees (cultivar Fascell) to determine the seasonal water requirements of mature trees, commenced in 1988 and continued for six consecutive years. The experimental orchard was planted at a density of 204 trees per ha (7 x 7 m spacing).

Irrigation water was applied by a microjet system (two microjets per tree) which watered 70 % of the total surface area. Irrigation scheduling was done with tensiometers installed at 300, 600 and 900 mm depths. Irrigation water was applied when the average reading of the three tensiometers reached either -30 kPa or -60 kPa depending on the treatment. At each irrigation, sufficient water was applied to replenish the soil water content fully to a depth of 900 mm. The quantity of water applied was measured by flow metres. A dryland control was also included as part of the trial.

The field trial was laid out as a randomised block design with 5 treatments and 4 replicates per treatment. Only those 3 treatments most relevant to the Crocodile River Catchment study are discussed further on in this chapter.

Fruit yield (all seasons) and fruit size (only in 1992/93 and 1993/94) were determined at harvesting which occurred in January of each year. The mango season stretched therefore from February to the end of January of the following calender year.

5.2.3 Avocado

5.2.3.1 Site Description

An irrigation trial on avocados (Hoffman, Snijder and Botha, 1997) was conducted at the ITSC Burgershall experimental farm in the Hazyview district (722 m altitude; 25°07'S, 31°05'E). A Shortlands soil with 35 % clay and a depth of 900 mm was used.

5.2.3.2 Climate

Long term climatic data supplied by a nearby weather station are presented in **Figure 12**. Although not inside the Crocodile River catchment area, Burgershall has a climate typical of the important Hazyview/Kiepersol avocado growing area.

5.2.3.3 Experimental Details

The two main avocado cultivars in South Africa, Fuerte and Hass grafted on Duke 7 rootstock, were planted in 1988 at a spacing of 10 x 5 m (210 trees per ha) in two separate blocks. The same treatments were allocated in randomised block designs to each cultivar. Six treatments replicated four times were tested and a plot consisted of five data trees.

Irrigation water was applied through microjets (2 microjets per tree) and the volume of water applied was measured by flow metres.

Treatments consisted of two soil water potentials namely -30kPa (equal to 50 % depletion of EAW) and -60 kPa, in combination with three phenological phases of the tree (post harvest, flowering and fruit set, fruit growth and ripening). For more details see Hoffman, Snijder and Botha (1997).

Irrigation scheduling was done with both a neutron probe and tensiometers. The neutron probe was calibrated as describe in 5.2.1.3 of this chapter and measurements were done at 150 mm intervals down to 900 mm.

Two tensiometer stations were used per treatment. Each such station consisted of two tensiometers installed at 300 and 600 mm depths. Irrigation was due when the average readings of the two tensiometers reached the predetermined levels of either -30 kPa or -60 kPa.

Fruit yield and size were determined at harvesting and seasons extended from May to April. All cultural practices such as fertilisation, weed control and disease (especially Phytophthora) control were done according to standard practices, recommended by ITSC and used by growers.

5.2.4 Bananas

5.2.4.1 Site Description

A series of 3 irrigation trials on bananas was conducted at the Levubu experimental farm in the subtropical North Eastern Lowveld of the Northern Province (altitude 760 m; latitude 23°05'S) (Robinson and Alberts, 1986; Robinson and Alberts, 1989; Robinson and Nel, 1994; Robinson, 1995). The soil type at the experimental site belonged to the Hutton form with a sandy loam texture from 0 - 200 mm depth (15 % clay) and a sandy clay loam from 200 - 400 mm depth (27 % clay). The soil had a water holding capacity of 51,4 mm over the effective rooting depth of 400 mm.

5.2.4.2 Climate

Long term climatic data for Levubu are presented in **Figure 12**. Levubu has the highest rainfall (mm/year) and the lowest evaporation of the 4 regions under discussion. Maximum winter temperatures at Levubu are also lower than at the other 3 regions.

5.2.4.3 Experimental Details

Seasonal net irrigation in a mature Williams banana plantation was monitored by gravimetric methods in this typically subtropical environment (Robinson and Alberts, 1989). *Suckers (bits) were* established at a density of 1 666 plants per ha.

The irrigation system consisted of low-pressure under-canopy sprinklers arranged on a permanent 6 x 6 m grid with 100 % overlap. The system applied water at 5.5 mm h^{-1} (net) and the irrigation schedule was calculated to replenish a soil depth of 400 mm to field capacity. In summer, water extraction was monitored at 16, 34, 54 and 80 % depletion of total available water. The 54 % depletion treatment was used as a standard through all seasons and is therefore selected as being the most relevant for the Crocodile River Catchment study.

Tensiometers placed at 200 mm depth were monitored daily and soil water potential remained below -30 kPa.

Gravimetric sampling took place during the second and third ratoon cycles. Five replicate soil samples were taken randomly throughout the treatment block at *100 mm depth increments down to* 500 mm. A depth of 500 mm was considered to be well below the *effective rooting zone. Sampling* occurred immediately after an irrigation and again immediately prior to the next irrigation. Further calculations to obtain evapotranspiration losses between irrigations were standard and are adequately described by Robinson and Alberts (1989). Finally, crop factors for bananas i.e. the ratio between evapotranspiration (ET) and Class A-pan evaporation (E0) were calculated for summer, winter, autumn and spring.

In a second experiment at Levubu, three experimental crop factors (ET/EO) were compared, namely 0,3; 0,6 and 1,0 in summer (September to April) and 0,15; 0,30 and 0,5 in winter (May to August). Irrigation occurred daily, replacing the previous day's evaporation adjusted by the appropriate crop factor. Water applications were monitored accurately for each treatment using water flow metres. For *each crop factor, two irrigation systems viz.*, drip and microjets were compared. Considering the fact that microjets *are recommended for bananas in the Onderberg area*, only experimental results for the latter system will be presented. Deficit *crop factors of* 0.3 *and* 0.6 *were chosen to test the impact of* water stress on yield and quality of bananas.

Effective rain was calculated as follows:

1. Rain falling each day during the year in question was recorded.
2. If less than 1 mm, it was ignored.
3. If more than 6 mm, only 6 mm was regarded as effective. i.e. on each rainy day the amount between 1 mm and 6 mm was regarded as effective, and cumulated. This calculation was justified on the basis of three factors:

    * Rain less than 1 mm can not be absorbed by roots - mostly evaporated.
    * Mean evaporation during the rainy season is 6 mm/day.
    * Actual crop factor during the rainy season is 1.0.

The experimental layout consisted of a randomised block design with split plots. Treatments were replicated four times and each plot contained 22 data plants.

The test cultivar was Williams banana, planted at 1666 plants per ha, using tissue culture planting material. Bunch yields were determined and the experiment ran for three crop cycles namely the plant crop (P), first ratoon (R1) and second ratoon (R2). These cycles did not coincide with a calender year, but lasted from planting to flowering (plant crop) or from harvesting to flowering (ratoon crops).

5.3 RESULTS AND DISCUSSION

5.3.1 Annual water use of crops

Treatments representing irrigation schedules which yielded the best results and are applicable under practical farming conditions have been selected for discussion. In the case of tree crops (citrus, mango, avocado) data are the result of localised wetting, i.e. irrigating the drip area of trees which is equal to 70 % of the total surface area. Both irrigation systems (microjets and undercanopy sprinklers) used in the banana trials gave a 100 % wetting of the soil surface.

The average monthly net irrigation (mm/day) of Valencia oranges, grapefruit, mangoes, avocados and bananas is presented in **Figure 13**. Water use figures for all five crops include effective rainfall. The peak net irrigation of Valencia oranges and grapefruit occurred during February, that of mangoes in November, while bananas and avocados peaked in January.

Bananas had the highest annual net irrigation water requirement of all the crops in this investigation (**Table 13**) and mangoes the lowest. The net irrigation water requirement of Valencia, grapefruit and avocado was much the same.

The net irrigation water requirement figure for bananas in **Table 13** was determined in Levubu which is a few 100 km distant from the Crocodile River Catchment. The following seasonal crop factors were, however, determined gravimetrically in the undercanopy sprinkler trial at Levubu.

Summer (Dec. - Feb.)	=	1,01
Autumn (March - May)	=	0,71
Winter (June - Aug.)	=	0,57
Spring (Sept. - Nov.)	=	0,67

Using these crop factors and long term Class A-pan data for Malelane, net irrigation water requirement figures for the lower Crocodile Catchment can be calculated. The calculated net irrigation water requirement figure for Malelane is 1445 mm, which is higher than the Levubu figure, but not drastically so.

Table 13 Nett irrigation applied to the five selected fruit crops determined experimentally at the different trial sites

Crop	Treatment	Nett irrigation applied (mm yr^{-1})	Total water use (mm/year)
Valencia	Tensiometers (-30 kPa)	627	1 119
Grapefruit	Tensiometers (-55 kPa)	818	1 171
Avocado	Tensiometers (-30 kPa)	634	1 115
Mango	Tensiometers (-30 kPa)	463	957
Banana	Crop factor = 1,0	1 156	1 401

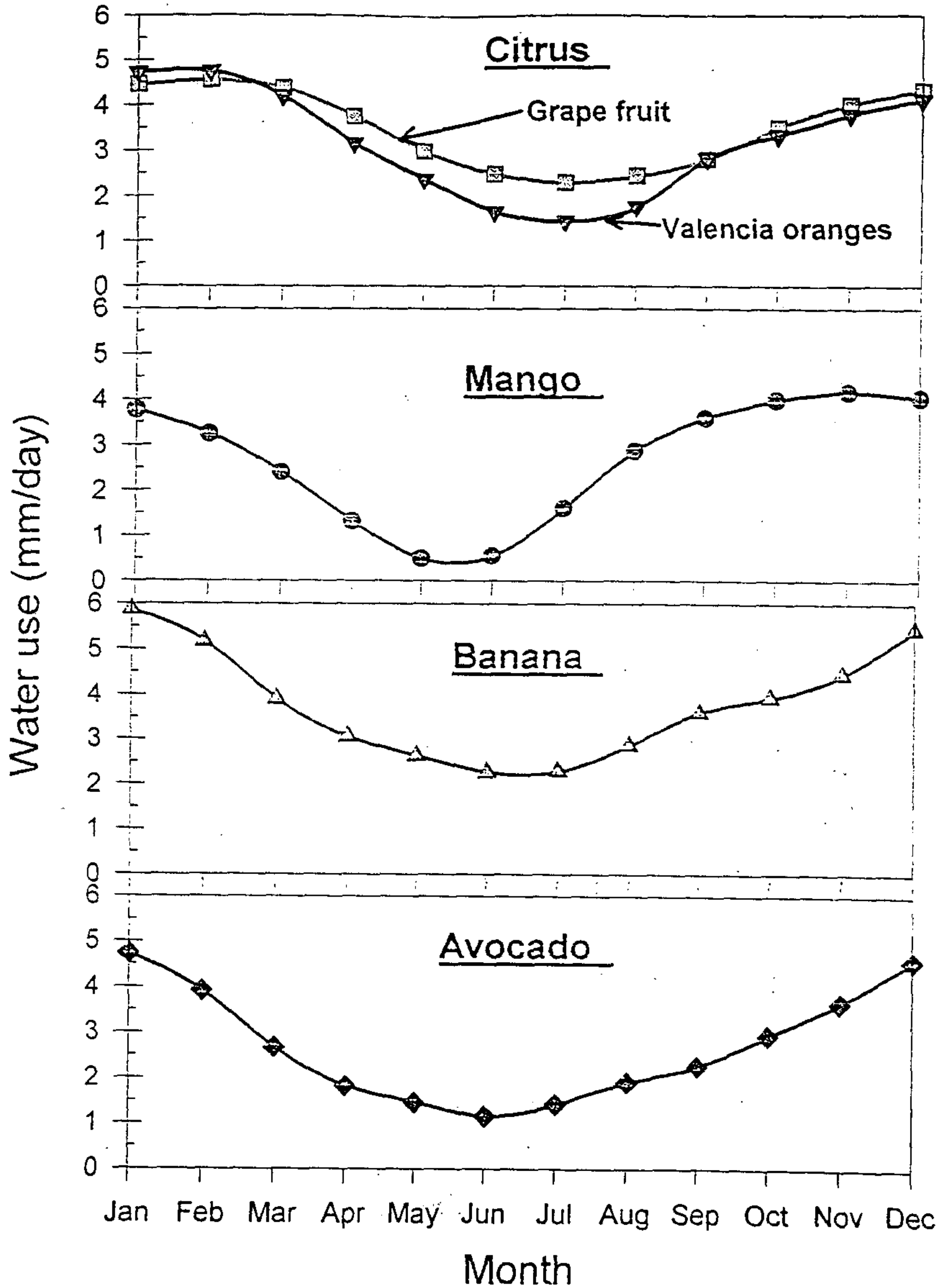

Figure 13 Monthly water use (mm/day) of Valencia oranges (Nelspruit), grapefruit (Malelane), mangoes (Nelspruit), bananas (Levubu) and avocados (Hazyview)

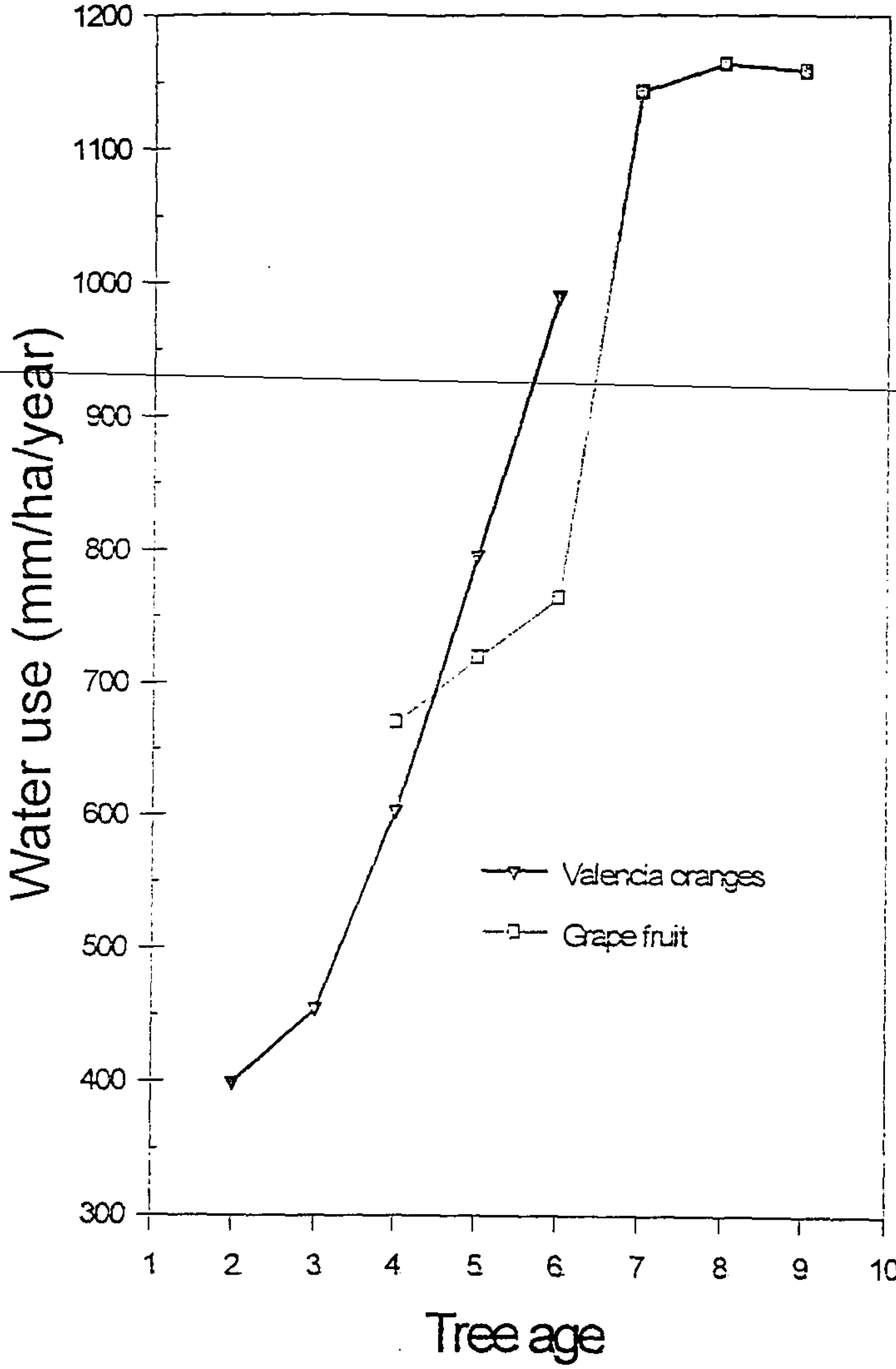

Figure 14 Average yearly water use (mm) of a grapefruit orchard at Malelane and a Valencia orange orchard at Addo according to tree age

5.3.2 Variation in annual net irrigation with tree age

In most irrigation trials, net irrigation has neither been determined on new plantings nor on young trees not yet in full bearing. This is not a serious shortcoming in the case of bananas, a crop that reaches 50 % of full leaf cover after 6 months and 100 % leaf cover at flowering (±11 months after planting).

Avocado and mango trees can be expected to reach maturity (full bearing) after 7 years. The lack of experimental data for net irrigation at the young orchard stage of these two crops, is therefore of concern.

The annual net irrigation of grapefruit trees from their fourth year until these trees were 10 years old was determined at Malelane (**Figure 14**). Water consumption increased by 82 % from year 4 until year 7 when evapotranspiration stabilised at approximately 1 150 mm per year. The net irrigation of Valencia orange trees at Addo (Mostert, Coetzee and Delimeni, 1996), was only 450 mm in the third year, but thereafter, annual increase in net irrigation was sharply linear, up to 1 000 mm in the sixth year.

5.3.3 Relationship between irrigation and yield

The yield response of perennial crops is not only a function of quantity of water applied, but also depends on many other factors such as the phenological stage at which water stress occurs and method of irrigation scheduling i.e. irrigation frequency (Mostert and Hoffman, 1997). Furthermore, total yield is often not a good indicator of financial return, since markets generally favour large fruit sizes. Large yields of small fruit may therefore have a lower value than a smaller yield of large fruit.

Valencias

Fruit yield from the tensiometer treatment (52,0 t ha^{-1}) was significantly higher than that from the A-pan nr. 1 treatment (45,5 t ha^{-1}), while the other treatments did not differ significantly from each other (**Figure 15**) There was, however, no positive correlation between quantity of net irrigation d and total yield. In fact, yield increased as net irrigation decreased (**Figures 16 and 17**).

There were no significant differences in the yield of large fruit among treatments, although the A-pan 1 treatment tended to give more large fruit than the other scheduling methods (**Figure 17**).

It should be emphasized that none of the 4 scheduling treatments induced yield-reducing water stress. In all treatments the soil water status remained in the easily available range. The reduction in total yield with the two A-pan treatments can probably be described to over-irrigation which caused negative effects such as phytophthora root disease.

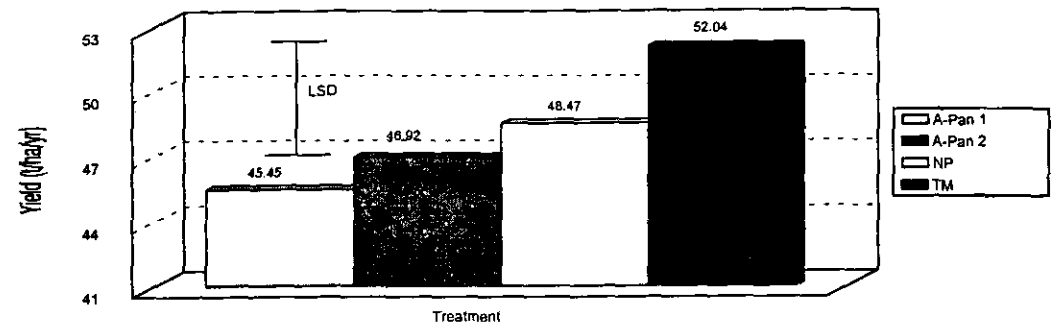

Figure 15 Fruit yield (six year averages) of Olinda Valencia at Nelspruit in response to 4 irrigation scheduling methods

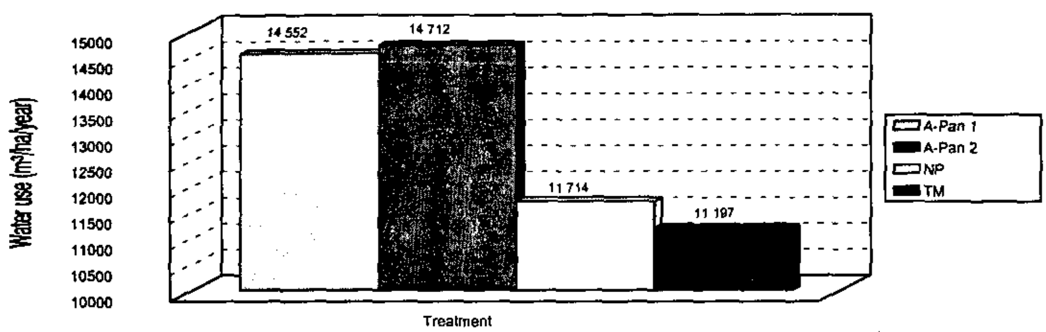

Figure 16 Average net irrigation of Olinda Valencia at Nelspruit over 6 consecutive seasons in response to 4 irrigation scheduling methods

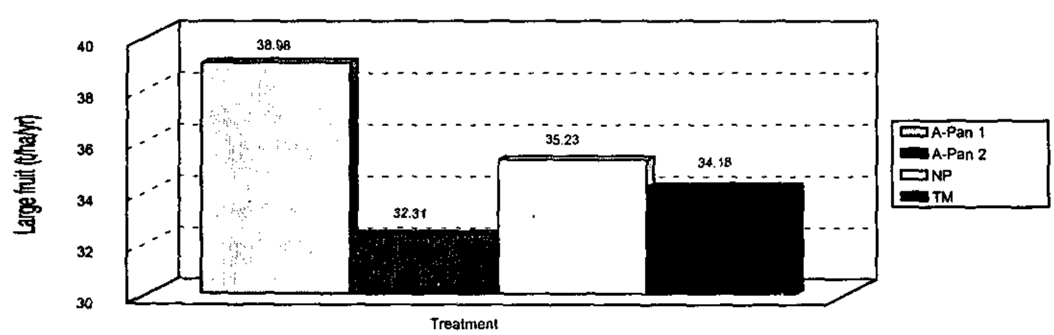

Figure 17 Yield of large fruit (six year averages) for the different scheduling methods on Olinda Valencia at Nelspruit

Grapefruit

Grapefruit trees at Malelane produced both more and larger fruit at the wetter soil water regime (-55 kPa) compared to the drier treatment (-80kPa) over a four year period (**Table 14**). The quantities of irrigation water applied in the two treatments differ by only 122 mm, illustrating the fact that in addition to water quantity, irrigation frequency can have a major effect on plant performance. Irrigation management at farm level is therefore a powerful tool in the hands of the grower to improve net irrigation efficiency.

Table 14 Average net irrigation and fruit yield of grapefruit trees at Malelane over a six year period

Treatment (tensiometer reading)	Irrigation (mm)	Effective rainfall (mm)	Total net irrigation (mm)	Total fruit yield (t ha^{-1})	Large*[1] fruit (%)
-55 kPa	818,2	352,7	1170,9	95,3 a	72,9 a
-80kPa	696,5	352,7	1049,2	76,1 b	41,1 b

a,b Figures not followed by the same letter, differ significantly ($P \leq 0,05$)

*[1] Large fruit was defined as those ≤ count 40

Mangoes

Data for selected treatments i.e. only those which include water stress during winter time are presented in **Table 15**. Mostert and Hoffman (1997b) showed that the yield of winter stressed trees was 9 % higher than yields of their non-stressed counterparts.

Table 15 Average net irrigation and tree performance of mangoes at Nelspruit over six consecutive years

Treatments	Irrigation applied (mm yr^{-1})	Total water*[1] use (mm yr^{-1})	Fruit yield (t ha^{-1} yr^{-1})	Fruit size (g/fruit)	WUE (kg/fruit/ mm water)
Dryland	0	494	23,3 a	316,3	47,2
-60 kPa	249	743	26,0 ab	338,2	35,0
-30 kPa	463	957	29,0 b	324,3	30,3
LSD ($P \leq 0,05$)			5,6	n.s.	

*[1] Net irrigation includes effective rainfall = 70 % of total rainfall

a,b Figures not followed by the same letter(s) differ significantly

n.s. Statistically not significantly different

LSD Least significant difference

The total yield of mangoes increased significantly in response to increased net irrigation (**Table 15**). Fruit size was, however, not significantly affected by any of the treatments.

Avocados

Alternate bearing is a serious industry problem in avocados and this phenomenon occurred on both cultivars (Hass and Fuerte) used in the irrigation trial. However, the fact that yield data were obtained for three seasons evened out the effect of alternate bearing.

The Fuerte orchard produced low yields (4,4 t ha^{-1} yr^{-1}) on average with no difference among irrigation treatments (data not shown). Hass gave better yields (5,7 t ha^{-1}). A comparison of the driest and wettest treatments (**Table 16**) showed a yield response.

Table 16 Average yield and net irrigation of Hass avocado over the duration of an irrigation experiment at Burgershall

Treatment	Average yield (94-96) (t ha^{-1} yr^{-1})	Irrigation applied (mm yr^{-1})	Total net irrigation (mm yr^{-1})	WUE (kg fruit/mm water)
-30 kPa	8,17	634	1115	7,3
-60 kPa	5,63	502	983	5,7

The two treatments in Table 5 had no effect on fruit size (Hoffman, Snijder and Botha, 1997).

Bananas

The plant crop (P), first ratoon (R1) and second ratoon (R2) yield results as well as net irrigation figures are presented in **Table 17**. Compared with the plant crop which coincided with a hot dry year with only 562 mm rainfall, the R1 vegetative cycle occurred during cooler, wetter, conditions (939 mm rainfall) Rainfall played a greater role in satisfying the water requirements of the banana crop during the R1 and R2 cycles. Water stress was consequently relieved more regularly in the lower crop factor treatments. Due to more rain, differences in yield response to different levels of irrigations in the ratoon cycles were reduced compared with those in the P cycle.

In the plant crop, an applied crop factor of 1,0 was the best treatment. For this treatment, the estimated effective rainfall was 210 mm giving a total consumptive net irrigation of 1489 mm per annum. A crop factor of 0,6 gave insufficient water (irrigation plus effective rainfall = 991 mm/annum) as shown by the 20 % yield reduction (**Table 16**). Average soil water potential in the 0.6 treatment plots before irrigation was -38 kPa when it was -4 kPa in the 1.0 treatment.

A crop factor of 0.3 (606 mm water/annum) was totally inadequate for bananas as was shown by the thin stunted plants, small bunches and short fingers. Average summer soil water potential in this treatment was -64 kPa, indicating highly stressed conditions.

In the R1 and R2 cycles, an estimated effective rainfall of 274 mm and 251 mm respectively, increased the total quantity of water available to all treatments. Even the 0,6 crop factor treatment received adequate water. Stress did, however, occur on the 0,3 crop factor plots and its yield was reduced during all three crop cycles. A greater proportion of cooler, on overcast days in the R1 and R2 helped to alleviate stress in the lower crop factors.

Table 17 Yield response of Williams banana at Levubu to different microjet irrigation treatments

Treatment (Crop factor)	Irrigation (mm/year)	Total water use (mm/year)	Yield (t ha^{-1} /year)	**WUE (kg fruit m^{-3} water)
Plant crop cycle (P) (dry year = 562 mm rainfall)				
0,30	396	606	12,9	21,3
0,60	781	991	27,6	27,9
1,00	1 279	1 489	34,8	23,4
*LSD (P≤0,05)				
First ratoon cycle (R1) (wet year = 939 mm rainfall)				
0,30	380	654	31,2	47,7
0,60	763	1 037	36,0	34,7
1,00	1 251	1 525	36,1	23,7
LSD (P≤ 0,05)			5,4	
Second ratoon (R2) (wet year; total rainfall = 670 mm)				
0,30	285	536	20,7	38,6
0,60	551	802	28,4	35,4
1,00	938	1 189	27,6	23,2
LSD (P≤0,05)			5,0	
Averages (P+R1+R2)				
0,30	354	599	20,2	33,7
0,60	698	943	30,4	32,2
1,00	1 156	1 401	32,7	23,3
LSD (P≤0,05)			3,6	

*LSD = Least significant difference
**WUE = Net irrigation efficiency

5.3.4 Net irrigation efficiency (WUE)

Net irrigation efficiencies for the best treatments in the different irrigation trials are presented in **Table 18**. Avocados had the lowest WUE by far while that of grapefruit is almost double that of its nearest rival, namely Valencias. The good WUE of grapefruit is primarily the result of very high yields which varied between 80 and 117 t ha^{-1} per year.

Table 18 Net irrigation efficiencies of various fruit crops determined for best treatments on the irrigation trials

Crop	Treatment	Nett irrigation applied (mm yr^{-1})	Fruit yield (kg ha^{-1} yr^{-1})	WUE (kg fruit/mm water)
Grapefruit	Tensiometers (-55kPa)	818	95 300	81,4
Valencias	Tensiometers (-30kPa)	627	52 040	46,5
Mangoes	Tensiometers (-30kPa)	463	29 000	30,3
Avocados	Tensiometers (-30kPa)	634	8 170	7,3
Bananas	Crop factor = 1,0	1 156	32 700	23,3

5.3.5 Representativeness of the data

Although the yield and net irrigation data cited in the above chapter were obtained under experimental conditions, these are considered not that different from best farmer yields (Du Plessis pers comm[1]).

The banana data set was the only data used above that was drawn from outside the Crocodile River Catchment. These data were drawn from an experimental station at Levubu. Both the net irrigation and yields of bananas are expected to be higher within the Crocodile catchment (Du Plessis pers comm). It is expected that the best economical yields in the Malelane area will be derived using 25% more irrigation than for the equivalent treatment at Levubu, which should result in yields of approximately 36.5 tonnes per hectare per year. This suggests that the NTV results presented for bananas in Chapter 6 will be conservative.

5.3.6 Conclusions

Net irrigation of four fruit crops (citrus, mangoes, avocados and bananas) of major importance in the Crocodile River Catchment area, has been determined over the past decade. A number of these trials were conducted at sites within the catchment, but the avocado and banana experiments were carried out at distant locations. Similar trials inside the study area are needed in future. The net irrigation results were, however, obtained through well-recognised scientific methods and can be considered as reliable and fairly applicable for calculating water balances in the Crocodile River Catchment area.

Most of the data are for microjet irrigation. Experimental data (not shown here) exists for banana and citrus that show a significant saving of water when drippers were compared to microjets. This can be

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[1] Dr. S. du Plessis, Institute for Tropical and Sub-tropical Crops, Nelspruit

Most of the data are for microjet irrigation. Experimental data (not shown here) exists for banana and citrus that show a significant saving of water when drippers were compared to microjets. This can be done without yield reduction. Further work on tree crops with regard to water saving with drip irrigation should be done in a new research project.

Data on the net irrigation of tree crops between planting and bearing age are scarce and are available for citrus only. Most irrigation trials only commenced when orchards or plantations were in full bearing. This information gap should be rectified since large areas are planted to young trees, while maximum net irrigation of the crops will probably only be reached six to seven years after planting.

The relationship between net irrigation and yields of fruit crop is not a simple one. Factors such as irrigation frequency, phenological stage at which water stress occurs, carry over effect from one season to the next and cultivars, also affect yields and complicates the development of reliable water production functions. In addition, not only is total yield important, but also fruit size when financial returns are to be calculated. Nevertheless, the best available data were presented to establish water quantity/yield relationships.

CHAPTER 6

COMPARATIVE ANALYSIS OF THE ECONOMIC EFFICIENCY OF WATER USE

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6.1 OBJECTIVES OF THE ECONOMIC ANALYSIS

The main objective of this section is to consolidate the information presented in the previous chapters, and combine it with economic data to analyse the economic efficiency of water use by plantation forestry, irrigated sub-tropical fruit and sugarcane. The following specific objectives are pursued within this overall goal:

1. Estimate the direct economic returns to water use in various irrigated crops
2. Derive the direct economic returns to water use in commercial forest plantations
3. Compare the economic costs and benefits of water use and rank the considered options in terms of economic efficiency based on net economic returns to water
4. Generate information that will assist water resources management and policy design and help evaluate water pricing and allocation policy questions.

6.2 DATA SOURCES USED IN THE ECONOMIC ANALYSES

Two data sets were eventually constructed for each of the crops investigated. In the first case data on water use and crop yields were based on scientific research studies. This situation, we believe, equates to 'optimally' managed crops, and these results are called 'best-practice' or potential data. The second data set on yield and water use was drawn from a wider range of sources in an effort to represent common 'average practice'.

6.2.1 Research Data

These represent the potential best practice. Water use data were obtained from the following sources:

- i Streamflow reduction by forest plantations (as presented in Chapter 3)
- ii Data on net irrigation by irrigated crops (obtained from various sources as discussed in Chapters 4 and 5).
- iii Crop yield in units of output per unit water or land was derived by type of product, e.g. pine, eucalyptus, mangos, sugarcane, etc. Calculation of mean annual increment (MAI) in volume, which is used as the measure of wood yield in plantation forestry, was described in Chapter 3. Yield data for irrigated crops was discussed in Chapters 4 and 5.

6.2.2 Average Practice Data

Data on yield levels achieved under common, average practice for the different enterprises were obtained from the following sources:

- i Forestry costs in SA (FOA-various issues) and unpublished statistics from Forestry Economic Services (FES)
- ii COMBUD Enterprise budgets from the Department of Agriculture (1994).
- iii Growers Associations of respective industries (e.g. Cane, Mango, Citrus, timber, etc.), personal communications.

These were compared with best practice data and used for various analytical purposes as described in subsequent sections.

6.2.3 Economic data

Economic data such as prices, input and production costs, labour use, interest rates, inflation rate, etc. in various units were compiled from the following sources (Appendix 4):

- i Forestry costs in SA (FOA-various issues) and unpublished statistics from FES.
- ii COMBUD Enterprise budgets from the Department of Agriculture (1994).
- iii Agricultural Growers Association (Cane, Mango, Citrus), personal communications.
- iv Abstract of Agricultural Statistics (AAS, 1998).

Table 19 summarises the basic features of the forest plantation systems considered in the analysis. Data were obtained for two pine species (*P. elliottii* and *P. patula*) and *E. grandis* under two timber production systems: pulpwood and sawlog rotations. Pulpwood is harvested once (at clear felling age), whereas a number of thinnings are carried out during sawlog rotations. The main components of the production cost structure associated with plantation systems and roundwood prices for 1994 are summarised in **Table 19**.

Similarly, the basic parameters of the sugarcane production system are summarised in **Table 20** as derived from experimental data described in Chapter 3 and average practice data, production costs and prices from the SACGA and COMBUD enterprise budgets. The production and net irrigation applied to the irrigated sub-tropical fruit crops are presented in **Table 21**.

The initial intention was to examine two scenarios in the research-based data. Scenario 1 described the irrigation regime which achieves the maximum crop yield *per hectare,* while Scenario 2 represented the irrigation regime resulting in the maximum crop yield *per unit irrigation.* While these data are presented in the remainder of this chapter, this comparison, was however, a little meaningless as there was only a difference between the two scenarios for mangos.

In cases where the difference in yields achieved by the various alternative irrigation regimes for a crop was less than 1%, they were considered not significantly different, and the regime giving the maximum yield was used in further analyses.

Table 19 A sample table illustrating the forest plantation activities included in the economic analyses.

	PULPWOOD ROTATION		SAWLOG ROTATION	
	PINE	**EUCALYPTUS**	**PINE**	**EUCALYPTUS**
Species	*P. elliottii* & *P. patula*	*E. grandis*	*P. elliottii* & *P. patula*	*E. grandis*
Rotation (years)	18	10	30	25
Yield (m^3 ha^{-1} yr^{-1})[a]				
Best practice	25.5 (18 - 34)	53 (37.6 - 67.4)	12.4 (8.1 - 17.9)	42.7 (30.6 - 54)
Average Practice	15.46	20.47	12.1	33.1
Runoff reduction (m^3 ha^{-1} /year)[a]	1071.1 (634 - 1538)	894.8 (636 - 1139)	1271.8 (768 - 1817)	1284.3 (921 - 1625)
Production costs				
Establishment (R ha^{-1})	1194.6	1090.9	1194.6	1090.9
Pre-harvest (R ha^{-1})[b]				
Weeding	186.2	150.3	186.2	150.3
Pruning	265.9	66.4	265.9	66.4
Thinning	148.9	83.8	148.9	83.8
Other	71.2	229.7	71.2	229.7
Harvesting and post-harvest (R/t)	45.4	61.6	45.4	61.6
Round wood price (1994)	62.75	66.5	77.86	77.86

Source: Chapter 3 for best practice (research) data. Average practice yields. Production costs and product prices were obtained from the FES of SATGA (1996).

a. Average of all productivity classes and species. Figures in brackets denote the range of averaged values.

b. Best practice data reflect weeding in the first three years for all rotations; three prunings (at 4, 7 and 10 years) and two thinnings (at 7 and 15) for pine sawlog rotations; and two prunnings (at 2 and 3) and four thinnings (at 4, 6, 8 and 12) for eucalypts in the sawlog rotation.

Table 20 Sugarcane production and net irrigation scenarios.

	ZONE 2 (400-600 mm)		ZONE 3 (600-800 mm)	
	Shortlands (High)	**Westleigh (Low)**	**Hutton (High)**	**Glenrosa (Low)**
Rainfall (m^3 ha^{-1} yr^{-1})	5799	5799	6247	6247
Scenario 1 (best practice)[a]				
Net Irrigation (m^3 ha^{-1} yr^{-1})	9 371	9 854	9 855	10 266
Sucrose yield (t ha^{-1} yr^{-1})	18.8	19.4	19.3	19.2
Scenario 2 (best practice)[b]				
Net Irrigation (m^3 ha^{-1} yr^{-1})	9 371	9 854	7 598	8 225
Sucrose yield (t ha^{-1} yr^{-1})	18.8	19.4	17.2	15.8
Sucrose price (R/t)[c]				
A Pool (70% of total)	833.5	833.5	833.5	833.5
B Pool sucrose	639.73	639.73	639.73	639.73
Sucrose (%)	13.5%	13.5%	13.5%	13.5%
Average practice yield (t ha^{-1} yr^{-1})[d]	14.1	14.1	14.1	14.1
Production costs(1994)[d]				
Establishment (R ha^{-1})	3971	3971	3971	3971
Pre-harvest (Rt^{-1} sucrose)	263	263	263	263
Harvest and post (R t^{-1} sucrose)	100	100	100	100
Rotation length (years)	6	6	6	6

Source: Calculated from data described in Chapter 4.

a. Scenario 1 = the irrigation regime resulting in the maximum crop yield (yield ha^{-1})

b. Scenario 2 = the irrigation regime resulting in the maximum crop yield per unit irrigation (yield ha^{-1} m^{-3})

c. From South Africa Cane Growers Association (SACGA)(1994/95 season- personal communications)

d. Average practice yield and production costs extracted from the SACGA data (1995)

Table 21 Horticultural Crops Production and Irrigation Water applied (Zone 2: 400-600mm)

	Orange	Grapefruit	Mango	Banana	Avocado
Rainfall (m^3 ha^{-1} yr^{-1})	5 382	3 527	2 940	2 450	6 569
Scenario 1 (best practice)[a]					
Net Irrigation (m^3 ha^{-1} yr^{-1})	6 270	8 182	4 630	11 560	6 340
Fruit yield at maturity (t ha^{-1} yr^{-1})	52	95.3	29	32.7	8.17
Scenario 2 (best practice)[b]					
Net Irrigation (m^3 ha^{-1} yr^{-1})	*6 270*	*8 182*	*2 490*	*11 560*	*6 340*
Fruit yield at maturity (t ha^{-1} yr^{-1})	52	95.3	26	32.7	8.17
Fruit price (R/t)[c]					
Export	1120	1347	1 829 [d]	Not exported	2230
Local market	599	642	1 217 [d]	950	2203
Percent exported (average 1980-1994)	60%	60%	50% [d]	0%	60%
Average practice yield (t $ha^{-1}yr^{-1}$)[e]	39.0	53.8	14.1	23.0	12.0
Production costs (1994)[e]					
Establishment (R ha^{-1})	11948	15312.1	14943.9	9086.8	21233.4
Pre-harvest (R ha^{-1})	192.9	128.6	395.0	238.9	347.3
Harvest and post (R t^{-1})	147.0	284.8	450.1	27.6	163.5
Rotation Length (years of total life)	20	12	16	10	25

Source: Calculated from data described in Chapter 5.

a. Scenario 1 = the irrigation regime resulting in the maximum crop yield (yield ha^{-1})

b. *Scenario 2 = the irrigation regime resulting in the maximum crop yield per unit irrigation (yield ha^{-1} m^{-3})*

c. COMBUD (1994); Outspan Citrus Centre ; South Africa Mango Growers Association. (1994/95 season-personal communications) and Department of Agriculture (1997).

d. SA Mango Growers Association (personal communication). AAS average price for mango was R 2179/t in 1994 (see Appendix 4).

e. COMBUD (1994); Outspan Citrus Centre ; South Africa Mango Growers Association. (1994/95 season-personal communications) and Department of Agriculture (1997).

6.3 RESULTS OF THE ECONOMIC ANALYSES

This section presents estimates of the various economic measures of water use efficiency for forest plantations and the selected irrigated agricultural crops. The following measures were derived and used to compare the two sectors:

a. Average crop yield per unit of irrigation water applied or volume streamflow reduction in forest plantations.
b. Annualised average net economic returns (ANR).
c. Net terminal value (NTV) per unit of irrigation water applied (or volume streamflow reduction in forest plantations) . In this method, the time value of expenditures (cash outflows) and revenue (cash inflows) occurring in the past are accounted for through compounding streams of cash flow into the present (1994) over the life cycle of the enterprise in question.

6.3.1 Average Physical Productivity of Water

Table 22 presents a summary of the average physical productivity of water. This parameter measures water productivity as the yield in tonnes per m^3 of irrigation water applied in the case of the irrigated crops, or per m^3 streamflow reduction in the case of forestry. The results were derived from the total production over the entire crop rotation divided by the total irrigation water or streamflow reduction (as appropriate) over the entire rotation. This was necessary to correct estimates for variations in yield over the crop cycle. Detailed results are presented in **Appendix 4**. Data on yield over the entire production cycle, obtained from growers' associations and the COMBUD, were used to present the average current practice situation. Net irrigation levels were, however, not adjusted but considered to be the same as those provided by research results (e.g. best practice). This is why results of the two cases (average and best practice) were similar.

A better measure of this physical parameter would have been the optimal rate of net irrigation (which maximises physical output) obtained from yield response or water production functions. Due to inadequacies of the data on continuous yield response curves for most crops, it was not possible to follow the optimization approach.

The results show that the pulp rotations produce higher physical output per m^3 of water than the sawlog rotations for all tree species in all zones and productivity classes **(Table 22)**. As expected, higher wood yields are generally attained in higher productivity classes and higher rainfall zones. However, the highest *water productivity* was achieved by eucalypts for pulp, with the high productivity class giving the highest yield per unit water (0.059 t m^{-3}) of all forest plantation regimes. Although, forest plantations in general outperform irrigated crops, these results are not comparable as physical production units are different (e.g. tonnes of timber, fruit and succrose). However, within irrigated crops, bananas, avocados and sugarcane showed the lowest yield per m^3. This is consistent with expectation as wood in the case of forestry is structural fibre, whereas the fruit from most of the irrigated crops is reproductive tissue. It is important to emphasise that the measure of water productivity is of little value in comparing these two sectors, as higher physical yields may not necessarily mean higher economic returns when values of inputs and products are considered as in the following sections. It is also important to consider the quality of the product rather than only the yield.

Table 22 A summary of water productivity estimated for the various crops investigated in this study.

Range of Values (ton m^{-3} water)	Average (Typical) practice	Best practice
0.050 - 0.060	*E. grandis* for pulp	*E. grandis* for pulp (all zones)
0.020 - 0.050	*E. grandis* for sawlog Pine for pulp	*E. grandis* for sawlog (all zones); *P. elliottii* for pulp (all zones); *P. patula* for pulp (all zones)
0.010 - 0.020	Pine for sawlog	*P. elliottii* for sawlog (except high rain); *P. patula* for sawlog (all zones); Grapefruit
0.005 - 0.010	Mango; Orange; Grapefruit	Mango; *P. elliottii* for sawlog (high rain); Orange
0.001 - 0.005	Banana; Avocados; Sugar Cane	Banana; Sugarcane; Avocados
Highest value **Lowest value**	0.059 (*E. grandis* for pulp) 0.0016 (Sugar cane)	0.059 (*E. grandis* for pulp) 0.0011 (Avocados)

6.3.2 Annualised Average Net Returns (ANR)

The ANR measures the average net returns per unit water used (ANR) based on output value and variable production costs estimates for the current year (1994). It is important to emphasise that this measure incorporates all outputs and production costs incurred over the entire crop cycle, but does not account for the fact that some costs and returns are paid and received at earlier dates that can be as far back as 18 to 30 years ago, e.g. at establishment of plantation or tree crops. However, as in the case of the above physical efficiency measure, average yield per ha was calculated over the entire production cycle, and not at maturity, again to account for yield variability at ages other than full maturity. Detailed estimates of annualised net returns are presented in **Appendix 2** with a summary provided in **Table23**. The summary indicates that the relative ranking of the crops changes dramatically when economic variables (e.g. prices) are taken into account in addition to physical production measures. Horticultural crops rank highest, followed by sugarcane and last come all forest rotations. While both scenarios generate a similar ranking, the average practice value estimates were much lower, especially for mangos. Nevertheless, average practice estimate for mangos was comparable to the best practice estimate for the mango treatment producing highest yield per ha (Appendices 2A and 2B). Avocados, also rank higher than bananas under average practice.

The biggest limitation of this method is that it does not account for the fact that some costs and returns are paid and received at earlier dates that can be as far back as 18 to 30 years ago, e.g. at establishment of plantations or tree crops. Therefore, this method assumes that timing of cost payments and receipts of revenue make no difference to resource allocation decisions. This is certainly a deficiency, given the importance of time preferences to economic investment and resource allocation choices. To address this, measures that account for the time factor in economic decisions are derived in the next section.

Table 23 A summary of the ranking of Annualised Net Returns (ANR) in Rand per m^3 of water for plantations and irrigated crops in the Crocodile Catchment. The crops are also listed in order of their returns within each of the classes.

Range of Values (Rand per m^3 water)	Average practice		Best practice	
	Crop	Rank	Crop	Rank
> 10			Mango	1
5 - 10	Mango	1	Grapefruit	2
3 - 5	Grapefruit; Orange; Avocados	2	Orange; Banana	3
1 - 3	Banana	3	Avocados	4
0.05 - 1	Sugar Cane	4	Sugar Cane	5
< 0.05	*All forest rotations*	5	*All forest rotations*	6
Highest Value **Lowest Value**	7.15 for Mango; -0.914 for E. grandis for pulp		11.78 for Mango - 0.365 for *E. grandis* for sawlog	

6.3.3 Measures Accounting for the time value of money

Among the methods used to account for the timing of expenditures and returns over the life cycle of the enterprise, two are commonly employed: The net present value (NPV) and net terminal value (NTV) measures. The two methods are defined below:

$$NPV = \sum_{t=1}^{T} [P_t Q_t - C_t Q_t] / (1+r)^t \quad (1)$$

Where:

- NPV Present worth at the beginning of the stream of net benefits, e.g. gross returns minus variable costs, expected from the project or investment
- P_t Price per unit of output
- Q_t Quantity or units of output produced
- C_t Variable cost per unit of output
- r The discount rate
- t Time in years
- T The last (terminal) year (end of project or life cycle, e.g. rotation length)

Equation 1 discounts the stream of benefits from the project or activity to be realized in future years to its present worth (time when investment is made). Alternatively, one can also use a modified version of equation 1 to derive the present worth at terminal time T (future or net terminal value-NTV) of the stream of net benefits occurring in the past. In this case costs and returns earned in past years are compounded to their future (terminal) value using the social discount rate r:

$$NTV = \sum_{t=1}^{T} [P_t Q_t - C_t Q_t] * (1+r)^t \quad (2)$$

Where:

NTV represents the present worth at the end of cycle or rotation of the stream of net benefits generated in future years.

Typical NPV and NTV calculations use either constant or nominal prices and either actual prices and costs over the entire production cycle (rotation length) or projections of future price and cost trends based on their observed past behaviour. This last mentioned approach is mainly due to lack of information about the future. Both approximations have limitations. While computationally convenient, the constant prices method assumes that prices and costs (e.g. prices of products and inputs) remain unchanged over the entire production cycle. Similarly, the price trends forecasting method assumes that future prices and costs will follow the same patterns of the past. These are considered very strong assumptions given the fact that results of NPV analyses are highly sensitive to movements in relative prices and shifts in production costs. This is of particular importance to our study considering the long rotation cycle of some of the enterprises under study (e.g. 30 years for pine to mature for sawlog purposes).

To avoid biases due to prediction errors and hedge against large deviations from present trends, the present study adopted the NTV method to derive and compare present values of streams of net benefits from forest plantation and irrigated crop production rotations in the Crocodile River catchment. The main reason was the fact that we have perfect knowledge today about the past from observed actual price and cost series, compared to our high uncertainty about the distant future. Accordingly, actual cost and price series reported over past years of production cycles were used to derive NTV measures. However, sensitivity analysis was used to provide for possible departures in the future from past trends and the implications of such deviations for our results and conclusions.

The year 1994 was used as the reference terminal year T. Since the alternative forest and irrigated agriculture activities compared here have different rotation cycles, the length of the longest rotation was adopted as the study period. Accordingly, enterprises with shorter rotations that complete before the end of the study period T were repeated until T was reached. Pine sawlog plantations had the longest rotation (30 years) and this was therefore used as the study period length. All other activities were continued over the 30 years' span with establishment costs and total output allocated annually in proportion to the ratio of years completed of the total cycle. This means that eucalypts for pulp rotation which has a 10 years cycle (**Table 23**) is repeated in full three times during the study period. On the other hand, the 12 year rotation of grapefruits is repeated 2.5 times with half the establishment (i. e. non-annual) costs reduced from the benefits of the last half cycle.

Price series were available for all crops for the 1964/65 -1994/95 period. Since no similar cost series were available, cost estimates for all crops for the terminal year (1994/95) were deflated over the study period back to 1964/65 using the *all farming requisites index* series (AAS, 1998). The price series and cost data used in the final analysis together with yield levels are presented in **Appendix 4**. In the analysis it was also necessary to compound net cash flows to the present (1994/95) using a nominal social discounting rate of 16%[2]. To test the robustness of the results and their sensitivity to time variations in the discount rate, NTV measures were recalculated at 18% and 20% discount rates.

NTV per m^3 of water was calculated considering total water used by the compared enterprises over the entire cycle of 30 years. Estimates were calculated for both current average practice and potential (best practice). Details of the NTV calculations are reported in Appendix 3 and a summary presented in **Table 24**.

The calculated NTV's ranged from 0.165 to 10.9 in the case of average practice and -0.052 to 19.04 for the potential best practice scenarios. In general, horticultural crops dominated sugarcane and forestry, while sugarcane dominated all timber rotations except eucalypts for pulp and sawlog rotations **(Table 24, Appendix 3)**. The average practice results were slightly different, with Sugar cane being superior to all forest rotations except eucalypts for sawlog.

In general the value estimates for the average practice situation were much lower, again especially for mangos. NTV for mango under average practice was, however, comparable to the best practice treatment giving the highest mango yields (Appendices 3A and 3B). Certain changes were observed in the NTV rankings relative to the ANR rankings: Eucalypts improved competitiveness and dominated sugar cane and avocados switched position to dominate oranges and bananas under average practice. This indicates that, while oranges and banana are currently less competitive, they have a better potential to achieve than avocados. Although all timber rotations, especially in low potential areas had low competitiveness in general, eucalypts for pulp and sawlog showed the highest potential, whereas the pine rotations gave the lowest NTV per unit streamflow reduction.

[2] Given the average inflation rate of 12% over the study period, this represents a 4% real social discount rate.

Table 24 A summary of the net terminal value (NTV) ranges, and the ranking of plantations and irrigated crops in the Crocodile Catchment.

Range of Values (Rand per m³ water)	Average practice		Best practice	
	Crop	Rank	Crop	Rank
> 10	Mango	1	Mango; Grapefruit	1
7 - 10	Grapefruit	2	Orange	2
4 - 7	Avocados; Orange; Banana	3	Banana; Avocados	3
2 - 4	E. grandis for sawlog	4	E. grandis for pulp (medium and high productivity sites)	4
1 - 2	Sugar Cane	5	*E. grandis* for sawlog (all sites) E. grandis for pulp (low productivity sites) *Sugarcane*	5
< 1	E. grandis for pulp; Pine for pulp; Pine for sawlog	6	*P. elliottii* for pulp *P. patula* for pulp *P. elliottii* and *P. patula* for sawlog	6
Highest Value Lowest Value	10.9 for Mango 0.165 for Pine sawlogs		19.04 for Mango -0.052 for P. Ellioti sawlogs on low productivity sites	

6.3.4 Sensitivity analysis

A sensitivity analysis was performed to test the robustness of the NTV results over ranges of fluctuations in key parameters.

6.3.4.1 Social Discount Rates

The social discount rate r represents the degree of impatience or pure time preference of people (wanting their benefits now rather than later) or the opportunity cost of capital. Several methods have been suggested to estimate a social rate of return on investment and the use of the appropriate social discount rate (Pearce and Ulph, 1995). Estimates of real social discount rates ranged from as low as 2% to more than 8%. The validity of our NTV analysis results were tested at the higher real discount rates of 6% and 8%. In general, higher NTV levels were obtained at higher discount rates (compounding in the case of NTV). However, the NTV of crops with shorter production cycles had larger increments than those with longer rotations. Nevertheless, the results showed very low sensitivity to discount rate variations as the same ranking was maintained at all rates used. This confirms the validity of our NTV results over a wide range of discount rate variations.

6.3.4.2 Threshhold Yields and Prices for efficiency

The results presented above reflect the current average practice as well as potential or best practice for all enterprises. Yield levels achieved under average practice common to most farmers are usually lower than research yields. Data compiled from the various growers associations (Tables 19, 20 and 21) showed that average practice yields are, on average, lower than best practice yields, except for the case of avocados, where average practice yield levels are higher. While this may mean that some enterprises are not at their optimum, it also indicates that those very same *non-achievers* have a potential to improve efficiency. Nevertheless, sensitivity of the results of the NTV analysis was evaluated under various yield and policy shifts scenarios. This was used to establish threshold yield and price levels for the various enterprises as reference ranges for the improvements required to become competitive with the most highly ranked crops.

A threshold yield level for an enterprise is therefore defined as the yield level to be achieved to dominate all other options (ie. in this case, to attain the mango position which is the highest). This provides useful information for crop management and breeding researchers and policy makers on the feasibility and potential for achieving yield gains towards economic efficiency, for example, by investing in technological innovations. To perform this analysis, yield levels for the various enterprises dominated by mango were increased until the mango position was reached. The same analysis was performed to determine threshold price levels that would be required to achieve an efficiency position equal to that calculated for mango. To provide for precision (data and estimation errors), the required level of NTV per m^3 of water used was specified to exceed R 10 (the current average practice of mango -**Table 25**). Results of the sensitivity analysis are summarised in **Table 25**.

Table 25 shows that, except for the citrus crops (grapefruit and oranges), all other enterprises need to improve their current research yield levels by more than 100% to become competitive to mangos. Similarly, prices need to have been higher by more than 100% for all crops except citrus fruits to exceed R 10 NTV per m^3 in 1994. Also, although it was felt that the net irrigation and yield data for bananas were conservative, the adjustment of the Levubu data to Malelane conditions would not result in a change in the observed rankings below.

Table 25 Percent increase in current average practice yield and price levels to achieve an economic efficiency of water use of more than R 10 per m^3.

Enterprise	Required % increase in yield	Required % increase in price
Mango	0.0	0.0
Grapefruit	30	20
Orange	75	50
Banana	120	98
Avocados	60	43
E. grandis for sawlog	350	150
E. grandis for pulp	750	450
Other timber rotations	>1000	>1000

CHAPTER 7

CONCLUSIONS, POLICY IMPLICATIONS AND LIMITATIONS OF THE STUDY

7.1 OVERVIEW AND SUMMARY OF STUDY FINDINGS

A new policy environment has been unfolding in the water sector in South Africa in response to its evident scarcity, escalating costs of developing new supply sources and growing competition for its use by an ever expanding sectoral, regional and national demand. The new Water Act is an example of recent initiatives proposing radical shifts in the definition of water rights and management of its allocation and use. This has sent strong signals to main water users and managers to begin a serious search for more efficient means and improved methods of utilising existing water resources. Proper understanding and analysis of current efficiencies in water use and allocation is an essential first step toward improved water policy design and effective management of its scarce supply. This provides valuable information about required adjustments in current patterns of water use and future development in response to the emerging policy changes. To contribute to this goal, the present study analysed and compared the efficiency of water use by irrigation agriculture and plantation forestry in the Crocodile river catchment. The fact that irrigation agriculture uses approximately 53% of total water resources in the country in general, and in the study area in particular prompted the focus of this study. Also, plantation forestry represents a major economic activity in the catchment that competes indirectly for water with down stream users through abstraction of soil water which depletes streamflow. This sector is accordingly expected to be influenced by evolving water policy changes.

Levels of water use in terms of net irrigation applied to sugarcane and horticultural crops and yield levels achieved under different irrigation regimes were analysed and compared with the impacts of plantation forestry on runoff under various commercial timber production rotations. The efficiency of water use by the two sectors was evaluated using measures of physical productivity and net economic returns under both current practice and research potential, or best practice. Results showed that forest plantations achieve higher physical productivity levels in terms of timber yields per unit reduction in runoff than yields realised per unit irrigation water applied to sugar cane and horticultural crops. However, when economic variables (e.g. prices and costs) were accounted for, high-value horticultural crops dominated forest rotations in terms of net economic returns. Two monetary measures of economic efficiency were derived: the annualised net returns and net terminal value (NTV). Unlike NTV, the former measure (ANR) does not control for the timing of expenditure outlays and cash inflows. The NTV, on the other hand, calculated the terminal worth of the sum of the past stream of net cash flows (revenue minus establishment and operating costs) per unit water used in the compared production alternatives. NTV was calculated for the full length of the longest production cycle of 30 years of pine in sawlog rotations.

Mangos achieved the highest NTV of R 10.9 m^{-3} of net irrigation water under current average practice, followed by grapefruit, avocados, oranges and bananas. The only forest rotation dominating sugar cane under current practice was eucalypts for sawlog, achieving R 2.99 m^{-3} compared to

R 1.02 m^{-3} for sugar cane. A similar ranking of crops was produced using research data representing the potential (best practice) for the studied crops. As expected, the average values under best practices were, however, much higher. The highest NTV under best practice was again achieved by mangos generating R 19.04 m^{-3}. While avocados dominated oranges and bananas under current practice, research data showed a higher potential for the latter crops to become more competitive than avocados. Also, best practice results revealed a similar superiority in the competitiveness of all eucalypts regimes over sugar cane, while sugar cane dominated the remaining forest regimes.

It is clear that irrigated subtropical fruit crops are more efficient in economic terms than forest plantations in using water resources in the Crocodile catchment. In general, forestry in low productivity classes and low rainfall zones generate lower direct economic gains and hence has a weaker competitive advantage. Nevertheless, eucalypts for pulp and sawlogs dominated sugarcane in terms of economic efficiency. Also, the comparison of best practice results with common practice results suggests there is considerable potential for increasing the economic efficiency particularly in the irrigated crops beyond the R 10 m^{-3} achieved under current practice (mango and grapefruit).

The opportunity costs (net returns foregone) per unit of reduction in runoff water caused by forest plantations can be as high as the R 10.90 of NTV achieved with mangos under current average practice (at 4% real social discount rate). This estimate represents only gross margins minus establishment costs, i.e. it includes fixed costs (i.e. depreciation, permanent labour, etc.) as well as returns to land, management and capital. If one considers only 50% of the gross margins' returns realised with irrigation agriculture to be net farm profits (e.g. 50% cost of fixed inputs), this suggests that net economic returns to water, land, management and capital in the Crocodile catchment was about R 5.05 m^{-3} in 1994. This suggests that a considerable margin of economic rent is generated from irrigation in excess of current water charges. On the other hand, the opportunity cost of reducing plantations area to yield an extra unit of water for further expansions in irrigation agriculture downstream can be as high as R 1.50 m^{-3} (50% of NTV of eucalypts for sawlog at 4% real discount rate). The opportunity cost of shrinking the area under plantations for larger stream flows is much lower in medium to low rainfall zones, given their low competitiveness in those zones.

This study could, however, not establish an estimate of residual returns to water over and above the shares of land, capital and management. This was mainly due to lack of data decomposing net farm income by factor resources. Nevertheless, it is reasonable to assume that the opportunity cost of land, capital and management is at least similar in all compared enterprises, and hence the validity of using the derived value estimates for relative ranking still holds. On the other hand, using the absolute value of derived estimates as the economic value of water represents an overestimation as this value contains returns to the said resources. While forest plantations and irrigation agriculture do not compete directly for land, trading between the two sectors can take place indirectly through water markets if created. Therefore, the trade-off between development strategies based on increased afforestation upstream, and expanded food or fibre production under irrigation downstream, can be guided by water allocations either through private trading in water or through quantitative measures (e.g. quota systems for physical allocations) or regulated markets.

7.2 LIMITATIONS OF THE STUDY AND AGENDA FOR FURTHER RESEARCH

It is important to bear in mind the limitations of the present analysis, and we wish to elaborate on the five deficiencies of the present analysis below. While these are limitations of the current investigation, they are research opportunities that ought to receive attention should it be necessary to expand this analysis to be of more substantial value to water policy considerations.

7.2.1 Limitations in the available data.

The analyses presented in this report consolidate available information for the selected crops and apply this to the situation in the Crocodile River Catchment. It was necessary to combine data from a wide variety of sources including the output of simulation models (streamflow reduction by forestry and net irrigation applied to sugarcane), data from research trials (eg. for the irrigated subtropical fruit crops), and direct yield measurements (eg. forestry, and irrigated crops). Because of limited source data the analysis presented was more comprehensive in some areas (such as forestry and sugarcane) than was the case with the irrigated crops for example. As a consequence the final data could be a little misleading in that only the irrigation regimes deriving the highest returns are presented while all the data are presented for forestry.

A further limitation of the irrigation trial data was that it was not possible to accurately extrapolate from the irrigation trials to other areas with different growing conditions. Also, rather than using net irrigation data for the irrigated crops it would be necessary to quantify transmission losses (evaporation from dams, leakage from pipes etc.) and the degree to which these are balanced by return flows. In this way it would be possible to strictly compare the economic returns to water from both forestry and irrigated agriculture as the 'water use' would in both cases be based on production per unit streamflow reduction.

Should a comprehensive catchment-based comparison be required, these limitations would have to be addressed.

7.2.2 Indirect economic effects

This analysis does not cover the total economic benefits, rather, it calculates the direct returns (gross margins minus establishment costs) as estimated at 'farm gate'. Estimating the total economic benefit would require accounting for indirect economic and hydrological impacts. Each of the analysed activities generate indirect economic benefits through their linkages with other sectors of the economy, which either supply input or use the outputs of these sectors for further processing, e.g. food processing, pulp manufacturing, trade, etc. Often the indirect impacts of an economic activity are larger than its direct benefits.

The total (direct+indirect) economic benefits from a particular activity may therefore be larger than rival alternatives considered even though its direct economic contribution is smaller. It is therefore very important to consider indirect impacts through economic multipliers. Forward (using output) and backward (supplying inputs or services) indirect impacts are commonly measured in terms of output and job multipliers. This means the extra units of output or number of jobs generated in other sectors as a result of increased output or employment in the sector in question. It is recommended that this extension of the present analysis should be conducted to evaluate the full chain of economic activities linked to forestry, and irrigated sub-tropical fruit and sugarcane and the costs associated with achieving this.

7.2.3 Environmental costs and benefits

The economic activities compared in this study have different impacts on the environment and the natural resource base. These were not taken into consideration in this analysis. This is relevant because an option that generates higher economic benefits may involve larger environmental risks through degradation of environmental quality or resource stocks. Health hazards to humans, degradation of water quality, fauna and flora resulting from pollution caused by the use of chemicals in agriculture are examples of such factors that should also be accounted for. Further examples include cultivation practices such as ploughing and harvesting which can cause soil erosion and sedimentation.

On the benefits side, forest plantations have larger carbon storage density and hence act as a sink of carbon mitigating against greenhouse gasses. The environmental costs and benefits of the compared options also extend to the processing phases of their production, e.g. environmental externalities caused by storage and transport activities (greenhouse gases). The present research did not account for the costs and benefits associated with the environmental impacts of the alternative economic uses of water resources in the Crocodile catchment. As the magnitude and economic value of such environmental externalities may outweigh direct and indirect economic benefits of alternative options, it is important to extend the present analysis to include environmental costs and benefits.

In the broader environmental context, the impact on people and job creation should also be assessed. For adequate and proper assessment of the net impact on social welfare one needs to account for such effects.

7.2.4 Risk management

Another important caution against misinterpreting the implications of the above results to mean switching of all land in the study area to the production of the crop yielding the highest NTV (e.g. mango) relates to the limitations on such an option. Among other things, factors such as diversification to hedge against the production and market risks associated with monocropping must be taken into account in land use planning.

While the analytical results generated by this study will provide valuable information as guidelines for evaluation of alternative water pricing policy and allocation strategies, it is also imperative to consider the limitations under which this analysis was conducted.

7.2.5 Better estimates of the marginal value of water

As discussed earlier, a more appropriate way of measuring the direct economic value of water would be to use continuous yield response surfaces to estimate marginal product curves for water. Research to generate or collate such type of data is crucial for the purpose of measuring water productivity and economic value.

APPENDICES

Appendix 1A. The ratio of water use to productivity of plantations and irrigated crops in the Crocodile catchment: ***Average practice.***

	tonnes $_{yield}$ **m**$^{-3}$ $_{water\ use}$
Average Forest plantations	
Pine -Pulpwood rotation	0.023
E. grandis -Pulpwood rotation	0.059
Pine - Sawlog rotation	0.011
E. grandis- Sawlog rotation	0.033
IRRIGATED CROPS [a]	
Sugarcane	0.0016
Orange	0.0062
Grapefruit	0.0057
Mango	0.0066
Banana	0.002
Avocados	0.0019

a. Net irrigation equals only the amount of irrigation water applied for the option/treatment with the highest average yield m^{-3} ha^{-1}

Appendix 1B. The ratio of water use to productivity for plantations and irrigated crops in the Crocodile catchment: ***Best practice: crop yield in tonnes per m³ of water.***

	ZONE2 400-600 mm	ZONE3 600-800 mm	ZONE4 800-1000 mm	ZONE5 >1000 mm
PRODUCTION CLASS 1[a]				
P. elliottii -Pulpwood rotation		0.028	0.029	0.023
P. patula -Pulpwood rotation			0.021	0.021
E. grandis -Pulpwood rotation				0.059
P. elliottii - Sawlog rotation		0.011	0.011	.008
P. patula- Sawlog rotation			0.01	0.01
E. grandis- Sawlog rotation				0.033
PRODUCTION CLASS 2[a]				
P. elliottii -Pulpwood rotation		0.028	0.029	0.023
P. patula-Pulpwood rotation			0.021	0.021
E. grandis-Pulpwood rotation				0.059
P. elliottii - Sawlog rotation		0.011	0.011	0.008
P. patula- Sawlog rotation			0.01	0.01
E. grandis- Sawlog rotation				0.033
PRODUCTION CLASS 3[a]				
P. elliottii-Pulpwood rotation		0.028	0.029	0.023
P. patula-Pulpwood rotation			0.021	0.021
E. grandis-Pulpwood rotation				0.059
P. elliottii- Sawlog rotation		0.011	0.011	0.008
P. patula- Sawlog rotation			0.01	0.01
E. grandis- Sawlog rotation				0.033
IRRIGATED CROPS[b]				
Sugarcane	0.0016	0.0017		
Orange		0.0075		
Grapefruit		0.0107		
Mango		.009 (.0055)[c]		
Banana		0.0025		
Avocados		0.0011		

a. Productivity classes 1, 2 and 3 refer to low, medium and high, respectively.

b. Net irrigation equals only the amount of irrigation water applied for the option/treatment with the highest average yield m^{-3} ha^{-1}

c. The figure in brackets refers to the treatment producing highest yield per ha.

Appendix 2A. The annualised net returns in Rand per m^3 of water for plantations and irrigated crops in the Crocodile River Catchment: **Average practice - 1994 prices.**

	Average	RANK
Average Forest plantations		
Pine-Pulpwood rotation	0.082	9
E. grandis-Pulpwood rotation	(0.914)	10
Pine - Sawlog rotation	0.207	7
E. grandis - Sawlog rotation	0.165	8
IRRIGATED CROPS [b]		
Sugarcane	0.62	6
Orange	3.39	3
Grapefruit	4.16	2
Mango	7.15	1
Banana	2.70	5
Avocados	3.07	4

Figures in brackets denote negative values, e.g. net economic loss.

a. *Productivity classes 1, 2 and 3 refer to low, medium and high, respectively.*

b. Net irrigation equals only the amount of irrigation water applied for the option/treatment with the highest average yield m^{-3} ha^{-1}

Appendix 2B. The annualised net returns in Rand per m^3 of water for plantations and irrigated crops in the Crocodile River Catchment: **Best practice - 1994 prices.**

	ZONE2 400-600 mm	ZONE3 600-800 mm	ZONE4 800-1000 mm	ZONE5 >1000 mm	RANK
PRODUCTION CLASS 1 [a]					
P. elliottii-Pulpwood rotation		0.158	0.165	0.147	>7
P. patula-Pulpwood rotation			0.151	0.150	>7
E. grandis-Pulpwood rotation				(0.365)	>7
P. elliottii - Sawlog rotation		0.114	0.118	0.104	>7
P. patula - Sawlog rotation			0.168	0.167	>7
E. grandis - Sawlog rotation				0.134	>7
PRODUCTION CLASS 2 [a]					
P. elliottii - Pulpwood rotation		0.238	0.246	0.202	>7
P. patula - Pulpwood rotation			0.191	0.192	>7
E. grandis - Pulpwood rotation				(0.167)	>7
P. elliottii - Sawlog rotation		0.166	0.172	0.141	>7
P. patula - Sawlog rotation			0.196	0.197	>7
E. grandis - Sawlog rotation				0.254	>7
PRODUCTION CLASS 3 [a]					
P. elliottii - Pulpwood rotation		0.294	0.306	0.250	>7
P. patula - Pulpwood rotation			0.229	0.227	>7
E. grandis - Pulpwood rotation				(0.075)	>7
P. elliottii - Sawlog rotation		0.204	0.211	0.173	>7
P. patula - Sawlog rotation			0.224	0.222	>7
E. grandis - Sawlog rotation				0.310	7
IRRIGATED CROPS [b]					
Sugarcane	0.638	0.659			6
Orange		4.11			3
Grapefruit		6.83			2
Mango		11.8 (7.09)[c]			1
Banana		3.49			4
Avocados		1.78			5

Figures in brackets denote negative values, e.g. net economic loss.

a. Productivity classes 1, 2 and 3 refer to low, medium and high, respectively.

b. Net irrigation equals only the amount of irrigation water applied for the option/treatment with the highest average yield m^{-3} ha^{-1}

c. Figure in bracket refer to treatment producing highest yield per ha.

Appendix 3A. *Net terminal value* (NTV) *in* Rand per m^3 of water for plantations and irrigated crops in the Crocodile Catchment.
Average practice - 1994 data

		NTV per m^3 water	Rank
AVERAGE FOREST PLANTATIONS	*Pine* - Pulpwood rotation	0.271	9
	E. grandis-Pulpwood rotation	0.817	8
	Pine - Sawlog rotation	0.165	10
	E. grandis - Sawlog rotation	2.990	6
IRRIGATED CROPS [b]	*Sugarcane*	1.020	7
	Orange	5.67	4
	Grapefruit	7.74	2
	Mango	10.9	1
	Banana	4.51	5
	Avocados	6.08	3

Figures in table represent results under the 8% social discount rate.

Appendix 3B. Net terminal value (NTV) in Rand per m³ of water for plantations and irrigated crops in the Crocodile Catchment. Best practice data based on the treatment resulting in the highest yield per m³ of water:

		ZONE2		ZONE3		ZONE4		ZONE5	
		NTV	Rank	NTV	Rank	NTV	Rank	NTV	Rank
FORESTRY PRODUCTION CLASS 1 [a]	*P. elliottii* - Pulpwood rotation			0.435	24	0.446	23	0.381	25
	P. patula - Pulpwood rotation					0.381	27	0.378	26
	E. grandis-Pulpwood rotation							1.722	10
	P. elliottii - Sawlog rotation			-0.052	41	-0.043	40	-0.010	39
	P. patula - Sawlog rotation					0.175	33	0.173	32
	E. grandis - Sawlog rotation							1.544	11
FORESTRY PRODUCTION CLASS 2 [a]	*P. elliottii* - Pulpwood rotation			0.570	17	0.584	16	0.476	20
	P. patula - Pulpwood rotation					0.448	22	0.449	21
	E. grandis - Pulpwood rotation							2.047	7
	P. elliottii - Sawlog rotation			0.067	39	0.079	37	0.073	38
	P. patula - Sawlog rotation					0.236	32	0.237	31
	E. grandis - Sawlog rotation							1.795	9
FORESTRY PRODUCTION CLASS 3 [a]	*P. elliottii* - Pulpwood rotation			0.666	15	0.686	14	0.558	18
	P. patula - Pulpwood rotation					0.514	19	0.509	15
	E. grandis-Pulpwood rotation							2.198	6
	P. elliottii - Sawlog rotation			0.153	35	0.171	34	0.148	36
	P. patula - Sawlog rotation					0.295	28	0.291	29
	E. grandis - Sawlog rotation							1.923	8
IRRIGATED CROPS [b]	*Sugarcane*	1.04	13	1.07	12				
	Orange			8.47	3				
	Grapefruit			14.52	2				
	Mango			19.04 (11.48)[c]	1				
	Banana			5.79	4				
	Avocados			3.79	5				

Figures in table represent results under the 8% social discount rate.

a. Productivity classes 1,2 and 3 refer to low, medium and high respectively
b. Only Net irrigation data used for the treatment with the highest yield m^{-3} ha^{-1}
c. Figure in brackets refers to the treatment producing highest yield per ha.

Appendix 4A. *The price series (Rand per tonne) used for the crops in the economic analyses.*

	Products' Price Series 1965 - 1994 (AAS1997)														
Year	Mango	Orange			Grapefruit			Sugar cane	Banana	Avocados			Hard-PLP	Soft-plp	Sawn logs
		Local	Export	Average	Local	Export	Average			Local	Export	Average			
1965	101	41.00	74	60.8	47	82	68	33.48	117	178	151	161.8	6.13	5.84	6.42
1966	126	47.00	64	57.2	54	69	63	37.33	104	179	152	162.8	6.13	5.84	6.42
1967	90	41.00	66	56	54	89	75	34.59	109	169	143	153.4	6.13	5.84	6.42
1968	120	47.00	74	63.2	60	56	57.6	37.63	109	165	127	142.2	6.37	6.07	6.68
1969	122	54.00	87	73.8	73	119	100.6	41.78	77	192	163	174.6	6.37	6.07	6.68
1970	183	54.00	68	62.4	94	112	104.8	47.04	100	214	242	230.8	6.37	6.07	6.68
1971	116	46.00	83	68.2	82	166	132.4	42.30	69	211	249	233.8	6.93	6.6	7.26
1972	160	51.00	86	72	78	100	91.2	45.33	81	202	172	184	6.93	6.6	7.26
1973	178	70.00	89	81.4	81	111	99	66.00	95	231	198	211.2	7.99	7.61	8.37
1974	317	71.00	107	92.6	84	132	112.8	74.89	136	262	223	238.6	10.25	9.76	10.74
1975	229	75.00	122	103.2	71	180	136.4	102.30	187	269	229	245	10.25	9.76	10.74
1976	302	97.00	112	106	90	112	103.2	96.67	220	309	263	281.4	11.26	10.72	11.79
1977	236	120.00	199	167.4	142	164	155.2	102.74	273	329	501	432.2	11.26	10.72	11.79
1978	291	120.00	196	165.6	140	186	167.6	113.04	273	364	657	539.8	11.26	10.72	11.79
1979	386	147.00	237	201	163	256	218.8	134.44	301	473	730	627.2	12.95	12.33	13.56
1980	366	167.00	182	176	173	238	212	183.11	351	593	769	698.6	12.33	15.22	16.50
1981	667	186.00	233	214.2	145	164	156.4	168.74	386	623	907	793.4	19.1	17.9	17.47
1982	574	226.00	265	249.4	186	222	207.6	187.33	388	660	960	840	20.2	19.2	22.20
1983	543	254.00	266	261.2	243	231	235.8	248.59	558	781	880	840.4	23.41	22.4	24.80
1984	680	286.00	434	374.8	272	269	270.2	202.44	539	837	1097	993	25.1	25.2	26.60
1985	664	345.00	580	486	295	485	409	227.85	559	839	1228	1072.4	29	26.5	28.73
1986	713	384.00	538	476.4	358	625	518.2	266.59	595	926	1246	1118	34.2	31.4	31.60
1987	863	405.00	491	456.6	320	441	392.6	241.63	694	990	1289	1169.4	40.7	36.25	31.60
1988	1095	437.00	669	576.2	446	542	503.6	304.52	768	1249	1440	1363.6	45.75	41	35.55
1989	1152	542.00	710	642.8	483	883	723	374.67	774	1237	1477	1381	51.6	47.5	41.77
1990	1355	513.00	850	715.2	460	1097	842.2	410.30	937	1494	1510	1503.6	58.7	54.15	48.66
1991	1601	553.00	988	814	493	1337	999.4	420.74	945	1675	1700	1690	58.7	54.15	58.36
1992	1819	605.00	895	779	608	1405	1086.2	701.19	1520	1995	1891	1932.6	58.7	54.15	67.00
1993	1699	544.00	1193	933.4	544	1113	885.4	739.93	1128	2026	2066	2050	61.6	58	72.77
1994	2179	599	1120	911.6	642	1347	1065	768.07	1672	2203	2230	2219.2	66.5	62.75	77.86

Appendix 4B.1. All Farming Requisite Index and yield levels for best and average practice for the Irrigated crops rotations analysed.

Year	All farming requisites Index	Avocados		Banana		Grapefruit		Orange		Mango		Sugar Cane	
		Best	Average	Best	Average	Best	Average	Best	Average	Best	Average	Best	Average
1965	6.5	0	0	0	0	0	0	0	0	0	0	0	0
1966	6.7	0	0	32.7	14.6	95.3	13.6	0	0	0	0	19.2	14.9
1967	6.7	0	0	32.7	33.6	95.3	13.6	52	3.6	26	4.17	19.2	16.9
1968	6.8	8.17	2.4	32.7	33.6	95.3	52.7	52	9.6	26	8.33	19.2	17.6
1969	6.9	8.17	4.2	32.7	26.9	95.3	52.7	52	16	26	10	19.2	17.6
1970	7.2	8.17	7.5	32.7	25.8	95.3	52.7	52	22	26	12.5	19.2	17.6
1971	7.6	8.17	10.3	32.7	24.6	95.3	76.8	52	32.4	26	13.33		
1972	8.1	8.17	7.5	32.7	24.6	95.3	76.8	52	35.6	26	15		
1973	9	8.17	13	32.7	23.5	95.3	76.8	52	39.2	26	16.67		
1974	10.6	8.17	17.8	32.7	22.4	95.3	76.8	52	43.2	26	20.83		
1975	12.8	8.17	19.4			95.3	76.8	52	47.5	26	20.83		
1976	14.8	8.17	13			95.3	76.8	52	52.3	26	20.83		
1977	16.7	8.17	15					52	57.5	26	20.83		
1978	18.8	8.17	17					52	63.3	26	20.83		
1979	22.7	8.17	17					52	70	26	20.83		
1980	26.8	8.17	17					52	70	26	20.83		
1981	29.7	8.17	17					52	63				
1982	34.6	8.17	17					52	57				
1983	39.4	8.17	17					52	52				
1984	42.5	8.17	17					52	46				
1985	50.6	8.17	17										
1986	60.4	8.17	17										
1987	66	8.17	15										
1988	74.5	8.17	12										
1989	89.4	8.17	10										
1990	100												
1991	111.8												
1992	118.9												
1993	130.2												
1994	140												
1995	152.4												
Net irrigation ($m^3\ ha^{-1}\ yr^{-1}$)		6340	6340	11560	11560	8182	8182	6270	6270	2490	2490	9836.5	8762

Appendix 4B.2. Yield Levels and streamflow reduction for Pulp Rotations analysed.

	P. elliotti for Pulp - (< 800 mm zone)			P. elliotti for Pulp - (800-1000 mm)			P. elliotti for Pulp - (> 1000 mm zone)			P. patula for Pulp (800-1000 mm)			P. patula for Pulp - (>1000 mm zone)			E. grandis for pulp (> 100mm zone)		
Year	Low	Medium	High	Low	Medium	High	Low	Medium	High	Low	Medium	High	Low	Medium	High	Low	Medium	High
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	376.4	539.2	674.2
11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0			
12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0			
13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0			
14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0			
15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0			
16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0			
17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0			
18	324.33	424.95	544.98	330.6	438.6	578.6	352.6	455.8	612.4	374.3	457.5	586.5	371.8	460.1	575.2			
Streamflow reduction (m^3 ha^{-1} yr^{-1})	633.5	830	1064	633.5	830	1064	868.4	1122	1508	981.300	1199	1538	974.7	1206	1508	635.5	910.4	1139

Appendix 4B.3. Yield Levels and streamflow reduction for Sawlog Rotations analysed.

Year	P. elliotti for Sawlog - (< 800 mm zone)			P. elliotti for sawlog - (800 - 1000 mm zone)			P. elliotti for Sawlog - (> 1000 mm zone)			P. patula for Sawlog (800-1000 mm zone)			P. patula for Sawlog- (>1000 mm zone)			*E. grandis for sawlog (> 100mm)*		
	Low	Medium	High	Low	Medium	High	Low	Medium	High	Low	Medium	High	Low	Medium	High	Low	Medium	High
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	48.76	73.81	95.53
5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	59.1	86.76	110.16
7	6.32	8.73	11.76	6.46	9.07	12.63	6.98	9.49	13.53	13.141	15.876	20.063	13.1	15.964	19.7	0	0	0
8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	57.57	83.22	104.67
9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	87.47	124.53	155.14
13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
15	14.83	19.2	24.34	15.1	19.78	25.75	16.06	20.52	27.19	44.738	54.601	69.866	44.44	54.916	68.533	0	0	0
16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	512.1	717.48	885.1
26	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0			
27	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0			
28	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0			
29	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0			
30	221.85	286.67	363.1	225.84	295.45	384.12	240.16	306.39	405.6	283.82	347.92	447.67	281.9	349.92	438.87			
Streamflow reduction (m^3 ha^{-1} yr^{-1})	767.5	993.9	1261	781.5	1024	1335	1051	1343	1782	1155	1414	1817	1147	1423	1782	920.7	1307	1625

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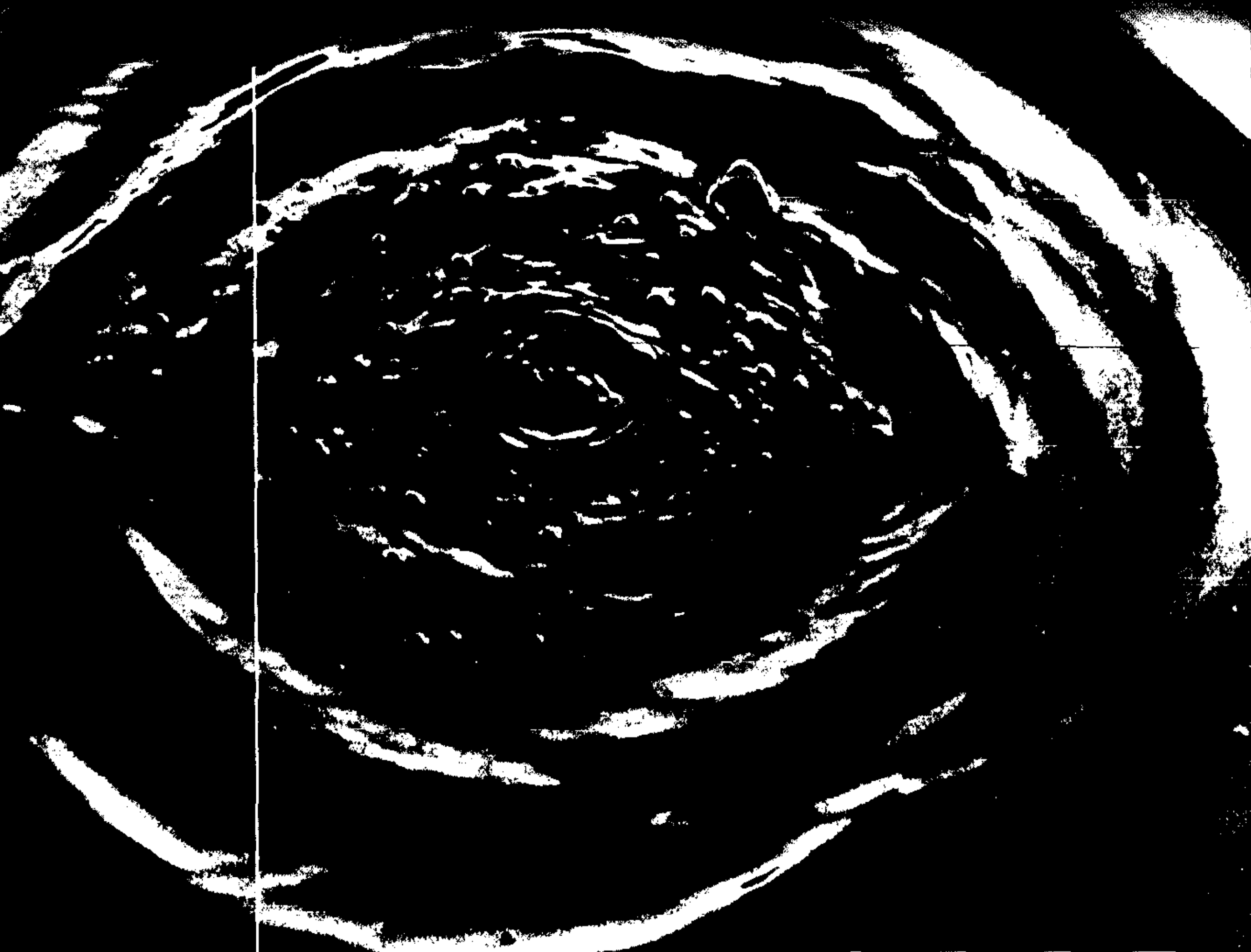

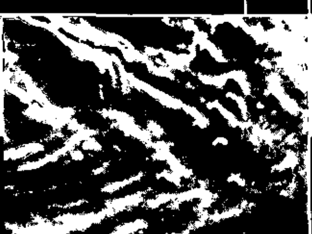

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