THE DEVELOPMENT AND TESTING OF AN INTEGRATED HYDRO-ECONOMIC MODEL TO EVALUATE THE FINANCIAL IMPACT OF CURTAILMENT DECISIONS ON A FARM CASE STUDY IN THE CROCODILE CATCHMENT

Report to the
WATER RESEARCH COMMISSION

BY

B GROVÉ
DEPARTMENT OF AGRICULTURAL ECONOMICS
UNIVERSITY OF THE FREE STATE

M FREZGHI AND A POTT
DANISH HYDROLOGY INSTITUTE (DHI) SOUTH AFRICA
JOHANNESBURG

N LECLER
ZIMBABWE SUGAR ASSOCIATION EXPERIMENT STATION
ZIMBABWE

WRC Report No. 1805/1/12
ISBN 978-1-4312-0385-7

DECEMBER 2012

Obtainable from

Water Research Commission
Private Bag X03
GEZINA, 0031

orders@wrc.org.za or download from www.wrc.org.za

ACKNOWLEDGEMENTS

The following reference group members supervised the project:

Dr G.R. Backeberg	Water Research Commission (Chairperson)
Dr N. Benadé	NB Systems
Dr M. Dent	University of KwaZulu-Natal
Mr J. Hallowes	Danish Hydrology Institute (DHI) South Africa
Mr B. Jackson	Inkomati Catchment Management Agency
Mr A. Jumman	South African Sugarcane Research Institute
Mr J. Fourie/Mr T Masike	Department of Water Affairs
Mr J. Murray	Mpumalanga Cane Growers Association
Dr A.J. Sanewe	Water Research Commission
Mr M. Slabbert	Crocodile Major Irrigation Board
Mr D. van Rooy	Crocodile Major Irrigation Board

The research team would like to sincerely thank the reference group members for the guidance and valuable input provided and the project chairman (Dr Backeberg) for always being available to provide guidance and support when required.

The project team would like to thank the following persons and organisations that facilitated the research:

- Personnel from TSB for providing valuable insight and information to complete the project. Specifically the following people need to be mentioned: Dawie van Rooy, Martin Slabbert and Hennie Greyling.

- SA Canegrowers for making available their average producer budgets for the Malelane region.

A special word of thanks and acknowledgment is made to Dr Neil Lecler, who was part of the research team for two years, but who moved to another country during the course of the project. Dr Lecler made a significant contribution towards this research project.

LIST OF ACRONYMS

BHN	Basic Human Needs (for water)
CMA	Catchment Management Agency
CMS	Catchment Management Strategy
DSS	Decision Support System
DWA	Department of Water Affairs
ELU	Existing Lawful Use (of water)
EWR	Ecological Water Requirement
GA	Genetic Algorithm
HE	Hydro-Economic
IIMA	Interim Inco-Maputo Accord
LP	Linear Programming model
MBIM	MIKE BASIN Irrigation Model
NWA	National Water Act
NWRS	National Water Resources Strategy
PRIMA	Progressive Realisation of the Inco-Maputo Accord
RDM	Resource Directed Measures (water)
STOMSA	Stochastic Model of South Africa
WC & WDM	Water Conservation and Water Demand Management
WUA	Water User Association

EXECUTIVE SUMMARY

Background, motivation and objectives

Globally, South Africa is classified as a water scarce country – due to below world average rainfall and comparatively high evaporation with significant spatial variability. Despite South Africa's classification as being water scarce, the potential water supply of the country is enough to satisfy demand (DWA, 2012). The problem is that the National Water Act (Act No. 36 of 1998) stipulates that water must be allocated to sustain an Ecological Water Requirement (EWR), described in the National Water Act as the Ecological component of the "Reserve". After considering the Ecological Water Requirements (EWRs), the catchment water balances published in the First Edition of the National Water Resources Strategy (NWRS-1) show that half of the water management areas (WMAs) are over-allocated. The water balances give consideration to multi-year wet and dry cycles; and consider the assurance of water supply required by various water users. A water balance showing over-allocation indicates that, during dry years, or sequences of dry years, water users will not get the assurance of water supply that they require. Water managers will try to address the over-allocation so as to meet the assurances of water supply required by the various water-user and water-use sectors in the catchment.

The over-allocation problem is not easily solved, because it is often neither practical nor economically feasible to transfer water from surplus areas to deficit areas (DWAF, 2004). Therefore localised water scarcities exist in many catchments. Thus, the traditional water management model that purely relies on an engineering (i.e. supply-side) approach through infrastructure development to reconcile imbalances, fails. The Second Edition of the National Water resources Strategy (NWRS-2) emphasises the need for "**smart water management**" (DWA, 2012:50) to complement the engineering and technologically based approaches to water management. "Smart water management" entails, amongst others, the inclusion of business principles and sustainability into water management – with strong stakeholder involvement in the planning and managing of water resources.

An important stakeholder group in the water sector is irrigated agriculture, which accounts for 62% of all surface- and groundwater use in the country. Its water use is, in some cases, is characterised by high inefficiencies (DWAF, 2004). In many instances, irrigated agriculture is seen as a potential source of water for reallocation to other water-use sectors due to the perceived inefficiencies and potential to achieve water savings. As a result, irrigated agriculture, after improving its water use efficiency could play an important role in reconciling water imbalances in some of the over-allocated catchments. Currently, the Mhlathuze catchment is undergoing compulsory licensing to reconcile imbalances in that catchment. Based on information contained in the NWRS-1, the Mhlathuze catchment has water requirements in excess of 28% of the available water (DWAF, 2004:D6.4), i.e. a deficit of 28%. However, to reconcile the 28% imbalance, the proposal that is gazetted for approval is to curtail irrigators' water rights by 40% (RSA, 2012). It is not clear from the gazette if higher assurances of water supply are associated with this curtailment or not. If the assurance of supply to the irrigation sector in the Mhlathuze is to remain the same, the extent of the curtailment may have a devastating impact on the financial feasibility of the farming operations, with a direct impact on the local economy. If the assurance of water supply are increased (i.e. although the annual allocation is reduced, the assurance of water supply is increased), hydro-economic modelling will be needed to assess the likely impact of this action on the long term financial viability of the irrigation sector.

The NWRS-2 highlights the need for a more sophisticated approach through **decentralisation and stakeholder participation** to optimise operational management of infrastructure to address sometimes conflicting water requirements (DWA, 2012). The research reported in this report contributes towards improved decision-making and operational management at both catchment and water user association level, through the development of an integrated hydro-economic modelling framework. The hydro-economic modelling framework allows water managers to test various catchment-scale water management scenarios (e.g. the building of new dams; the adjustment of dam operating rules for existing dams; the changing of EWRs; and combinations of the afore-mentioned) on irrigators' security of water supply and the resulting impact on irrigation farming profitability and livelihoods. Key to the development of the integrated framework was multi-stakeholder participation at catchment and water user association levels.

The following key objectives guided the development of the integrated modelling framework:

1. To link the output of a hydrological systems model (ACRU linked with MIKE BASIN) with the whole-farm economic model (the skeleton model) in order to evaluate the impact of curtailment decisions on a number of farm case study participants in the Crocodile Catchment.
2. To interact with the stakeholders and water resource managers (i.e. the CMA and DWA) in the Crocodile Catchment (in the form of workshops), in order to (i) ensure that the research team tests curtailment decisions in an appropriate manner and (ii) to share the findings of the research with the stakeholders.
3. To further test and refine the MIKE BASIN irrigation module (to ensure that the simulation of crop yields and return flows is reasonable in the participant farm case study areas).
4. To further develop the whole-farm skeleton model in order to accommodate assurance of water supply.

Research area

The research was conducted in the Crocodile East sub-area, which falls within the Inkomati Water Management Area (WMA) in the north-eastern part of South Africa. All the rivers in the catchment flow through Mozambique to the ocean and there exists an international flow obligation. The Kwena Dam, which is situated in the Upper Crocodile Catchment, is the only major storage dam in the catchment. The study area falls entirely within the Mpumalanga province and includes the capital city of Nelspruit and regional centres White River, Barberton and Ka-Nyamazane. Smaller urban centres include Dullstroom, Waterval Boven, Machadodorp, Malelane, Matsulu and Hectorspruit. There are no large mines in this catchment presently and the only major industries are Sappi, with a wood mill in the Elands catchment; and the TSB sugar mill in the Lower Crocodile. The southern portion of the Kruger National Park is located on the northern bank of the Lower Crocodile River in the east of the catchment. Annual rainfall varies significantly over the catchment area: from 400 mm in the lower lying areas (i.e. close to the border with Mozambique) to close to 1500 mm in the mountains.

The farm case study selected for the research was one of TSB's farms, which is situated in the lower Crocodile River. The farm has diverse soil types with sugarcane irrigated with drip, sprinkler and centre pivot irrigation systems.

Methodology

The project team consisted of researchers from different disciplines: such as agricultural economics, agricultural engineering, hydrology and computer programming. Furthermore, the importance of stakeholder involvement in developing the hydro-economic (HE) decision-making framework was acknowledged from the onset of the project. Before any progress was possible, it was important to harmonise the interpretations of terms used by different disciplines and to make sure that the stakeholders understood these terms. Several workshops were organised to ensure a common understanding of the main objectives of the project and the proposed methodology that was employed to achieve the objectives.

The outputs from three different computer-based models were loosely integrated to develop the HE framework. Firstly, the catchment rainfall-runoff of the various Crocodile River Catchment tributaries and main river stem was modelled with the ACRU process-based hydrological model. Secondly, the hydrological information was integrated into a catchment-scale water allocation model (MIKE BASIN) to reconcile water supply (dams and rivers) and demand (domestic, industrial, irrigation, environment and international) according to the water apportionment rules that exist in the catchment, including a consideration of water related infrastructure and associated operating rules.

A drawback of the MIKE BASIN Irrigation Model in its current form is that it is not possible for the model to restrict total irrigation water use of an abstraction node to be equal or less than the annual water allocation. In other words, the irrigation demands are calculated dynamically in the model and are a function of the crop area, crop type and weather conditions. Although the MIKE BASIN model is able to accommodate water restriction rules based on dam levels, it was necessary to ensure that that an irrigator did not exceed his/her annual water allocation. The research team managed to address this short-coming via an iterative process, whereby an economic optimisation model (which is able to constrain water use to the annual maximum allowed) was loosely coupled with MIKE BASIN to model the impact of various catchment-scale water management scenarios on the profitability and livelihoods of four alternative case study farms.

After the first round of discussions with stakeholders, it was decided to replace the ACRU hydrological simulations with the Inkomati Water Availability Assessment Study (IWAAS) dataset. The IWAAS dataset is currently used for decision-making in the catchment and changing to the dataset would help to ensure a common ground for enhanced discussions. Meetings with water resource managers and water users took place to help identify meaningful catchment scale scenarios. The water intervention scenarios identified by the stakeholders included:

- The building of new dams (Montrose &/or Mountain View Dam)
- Changes to the EWR
- Changes to the International Flow Requirement
- Combinations of the items above.

Once the scenarios were identified, the research team used the integrated HE decision-making framework to simulate the impact of each scenario on the farm case study, with the optimisation model determining the most optimal response option for the farm case study, from a profitability and livelihood perspective. A farm was deemed financially feasible if the return on equity was greater than the return on assets, which indicated profitable employment of foreign capital. On the other hand, a livelihood was provided if the farm was able to generate sufficient cash flows to cover living expenses. The results were discussed and validated with the stakeholders, and adjustments were made to model input parameters where required.

Results and conclusions

The application of the HE modelling framework demonstrated the ability of the framework to appropriately assess the impact that changes in catchment water management scenarios would have on the financial feasibility of irrigation farming. The following represents a summary of the results – and the conclusions reached:

- Results for the baseline (i.e. the baseline simulation including the existing Kwena Dam and the international flow requirement of 0.9 m^3/s, but with no EWR) showed that the irrigated farms do not have secure reliability of water supply. On average, the farms will not be able to achieve their potential production levels 40% of the time. Achieving a positive financial leverage (Return on equity >Return on assets) for the larger farms (150 ha), was closely linked to the ability to produce according to potential. The small farm, with relatively higher water application efficiencies, was barely financially feasible, while the other farm, with lower efficiencies, was not financially feasible. All the farms may provide a livelihood more than 70% of the time. The conclusion is that irrigated farming in the area is risky, which emphasises the importance of conducting risk analyses to determine the potential impact of catchment scale water management scenarios on irrigation farming profitability and their livelihoods. Furthermore, small farms will be under severe pressure to handle any water curtailments.

- Increasing the international flow requirement to 1.2 m^3/s has a negative impact on both the profitability and livelihoods (potential to generate cash surpluses) of the irrigated farms. Results showed that the potential to achieve a positive financial leverage was affected most, while the probability of a negative return was only slightly increased. The potential to provide a livelihood was affected only marginally. The conclusion is that the irrigation farming may still be viable if the international flow requirement is increased.

- Implementing the Class C EWR was significantly detrimental to the profitability of all farms and none of the farming scenarios were financially feasible, or could provide a livelihood to irrigators. As an alternative to the Class C EWR, operating rules were developed to implement the EWR based on the present flow regime. Results showed that the impact on irrigation farming will be minimal when compared to the scenario with an international flow requirement of 1.2 m^3/s. The conclusion is that implementing the Class C EWR should be seriously reconsidered, since it would have a devastating impact on irrigation farming in the area. Alternatives, such as implementing the EWR based on the present flow regime, should be further investigated.

- Several scenarios, which included the development of new dams in the catchment, were investigated to determine whether it will be possible to allocate water to the environment while stabilising the flow in the catchment. Results showed that neither of the dam scenarios (Mountain View Dam and/or Montrose Dam) would improve the financial feasibility of irrigation farming enough to justify implementing the Class C EWR. However, building both dams would improve the ability to provide a livelihood. The conclusion is that implementing the Class C EWR is infeasible, even when building dams is considered. When considering the implementation of the EWR based on the present flow regime, the dam scenarios showed interesting results. Generally, the results showed that building Montrose Dam would increase the ability of the irrigated farms to achieve a positive financial leverage with only slight improvements in the livelihoods of farmers. Contrary to these results, building the Mountain View Dam would not improve the chance of achieving a positive financial leverage as much, but would increase the chance of generating cash flows to provide a livelihood significantly. The conclusion is that building dams will definitely improve the financial situation of farmers in the catchment if the EWR is implemented using the present flow regime. Cognisance should be taken of the fact that the cost of building the dams was not considered in the analysis.

- The impact of water curtailments was evaluated – also considering an international flow requirement of 1.2 m^3/s. Results showed the financial feasibility of irrigation farming will come under severe pressure, even with a curtailment of 10%. However, the livelihoods of the farmers will not be jeopardised. A water curtailment of 20% is detrimental to irrigation farming profitability and irrigation farming will be unable to provide a livelihood to farmers. The conclusion is that, of all the water management scenarios, the impact of water curtailments is the most profound and that the magnitude of water curtailments needs careful consideration before it is implemented.

Overall, the results showed that small farms will come under severe pressure to provide a livelihood to farmers and to be financially feasible. Farms with higher application efficiencies will also be in a better position to handle any changes in their water allocation or decreased security of supply.

Achievement of objectives and value of the decision-making framework

A major modelling achievement is the linkage of MIKE BASIN with the economic optimisation model to quantify possible impacts of changes in catchment water management scenarios on irrigation farming profitability and livelihoods (Objective 1). Through the development of the integrated HE decision-making framework, the research showed that it is possible to replicate the decision-making framework used by DWA to manage water in the Crocodile East catchment. The developed framework proved to be flexible and the researchers were able to incorporate operating rules that were practised in the catchment, but which are not currently included in the DWA decision-making framework. Accommodating these operating rules increased the creditability of the results, which enhanced participation and discussions about alternative water management scenarios. Strong participation of stakeholders (Objective 2) definitely resulted in an improved modelling framework and better understanding of the issues surrounding catchment water management and the implications thereof for water users.

The integrated modelling framework hinges strongly on the outputs from the irrigation module to optimise agricultural water use. Objective 3 was achieved through the development of an FAO 56 based irrigation model that is integrated with MIKE BASIN. This model runs on a daily time-step. The irrigation model was used to provide the inputs for the optimisation model to optimise water use. Objective 4 was achieved through the development of state-contingent response functions that are able to more accurately model the impact of different levels of assurance of water supply. Important to note is that the state-contingent approach increased the dimensionality of the programming model to such an extent that it was collapsed into a single annual time period. Thus, the modelling framework does not allow for dynamic changes in irrigators' response to changes in catchment management over the long-run.

Overall, the objectives of the research were achieved to a satisfactory extent given the assumptions that were made. However, the knowledge that was gained through the development of the integrated decision support system paves the way for more sophisticated developments to model the impact of changes in water management on irrigation farming profitability in the long-run.

Recommendations for future research

- The research was successful in determining the impact of changes in water management intervention scenarios, which are aimed at addressing the over-allocation, on different irrigation farms within a specific location of the catchment. The implication is that changes in all irrigators' reactions to changes in water management are not incorporated into the modelling framework. More research is necessary to extend the research to catchment level.

  Specific issues that need further consideration in future research projects are the following:

  - Currently the HE frame allows for the modelling of one irrigation node to represent the case study farms. The modelling framework should be extended to represent all the irrigation areas in the catchment.
  - Modelling the impact of return flows on water availability of users. The current setup of the catchment scale hydrological model is not sensitive to return flows of irrigators, which will change in response to the manner in which these irrigators adapt to the various water management intervention scenarios. The existing hydrological model needs to be improved to better represent the manner in which all irrigators may adapt to the water intervention scenarios and consequent impact on return flows, which may have a significant impact on the flows available to downstream users.
  - Improving economic modelling procedures and hydrological model integration to model dynamic responses by irrigators to changes in water management rules in the long-run.
  - Developing economic decision rules that will enable the MBIM to allocate water economically between different irrigation fields. In this regard, the application of genetic algorithms should be further investigated.

- The economic modelling could be enhanced in various ways. The following provide directions for further developments and applications:
    - The application of the state contingent framework to modelling irrigators' responses to changes in water availability should be further researched to model long-term responses.
    - Procedures should be developed to reduce the dimensionality of states of nature that are used to represent the security of water supply over the long-run, within a state contingent framework.
    - Sources of risk other than the impact of insecure water availability on crop yield should be considered.
- The current operational rules should be optimised and other institutional arrangements such as water markets and capacity sharing should be investigated. Specifically, a water accounting and auditing framework needs to be developed to give effect to water markets and capacity sharing – and to help enforce compliance.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1: INTRODUCTION

1.1 BACKGROUND, MOTIVATION AND OBJECTIVES

Globally, South Africa is classified as a water scarce country due to below world average rainfall and comparatively high evaporation with significant spatial variability. Despite South Africa's classification as being water scarce, the potential water supply of the country is enough to satisfy demand (DWA, 2012). The problem is that the National Water Act (Act No. 36 of 1998) stipulates that water must be allocated to sustain Ecological Water Requirements (EWRs), which, together with Basic Human Needs (BHNs), are referred to as the "Reserve". After considering EWRs, the catchment water balances published in the First Edition of the National Water Resources Strategy (NWRS-1), published in 2004, show that half of the Water Management Areas (WMAs) are over-allocated. The water balances give consideration to wet and dry cycles and consider the assurance of water supply required by various water users. A water balance showing over-allocation indicates that, during dry years, or sequences of dry years, water users will not get the assurance of water supply that they require. Water managers will try to address the over-allocation so as to ensure the required assurance of water supplies to water users is met, as these levels of water reliability are often required for the water users to be sustainable.

The over-allocation problem is not easily solved because it is often not economically feasible to transfer water from surplus areas to deficit areas (DWAF, 2004). Therefore localised water scarcities exist in many catchments and, thus, the traditional water management model that purely relies on an engineering (i.e. supply-side) approach through infrastructure development to reconcile imbalances, fails.

The Second Edition of the National Water resources Strategy (NWRS-2) emphasises the need for "smart water management" (DWA, 2012:50) to complement the engineering and technological based approaches to water management. 'Smart water management' entails, amongst other things, the inclusion of business principles and sustainability into water management – with strong stakeholder involvement in the planning and managing of water resources.

An important stakeholder in the water sector is irrigated agriculture, which accounts for 62% of all water use in the country. Its water use is, in some cases, characterised by high inefficiencies (DWAF, 2004). In many instances, irrigated agriculture is seen as a source of irrigation water. As a result, irrigated agriculture will play an important role in reconciling water imbalances.

Currently, the Mhlathuze catchment is undergoing Compulsory Licensing (CL) to reconcile the over-allocated nature of the catchment. Based on information contained in the NWRS-1, the Mhlathuze catchment is 28% over-allocated (DWAF, 2004:D6.4). However, to reconcile the imbalance, the proposal that has recently been gazetted for approval is to curtail irrigators' water rights by 40% (RSA, 2012). The gazetted information relating to the curtailment does not make any mention of the assurance of water supply and associated water restriction rules. Assuming the restriction rules remain as before, the extent of the curtailment may have a devastating impact on the financial feasibility of the farming operations – with a direct impact on the local economy.

The NWRS-2 highlights the need for a more sophisticated approach, through decentralisation and stakeholder participation, to optimise the operational management of infrastructure to address sometimes conflicting water requirements (DWA, 2012). The research reported in this document has the potential to contribute towards improved decision-making and operational management at both catchment and Water User Association (WUA) levels through the development of an integrated Hydro-Economic (HE) modelling framework. The HE modelling framework allows water managers to test various catchment-scale water management intervention scenarios, which could help address the effects of over-allocation (e.g. the building of new dams; the adjustment of dam operating rules for existing dams,; the changing of EWRs; and combinations of the afore-mentioned) on irrigators' security of water supply and the resulting impact on irrigation farming profitability and livelihoods. Key to the development of the integrated framework was multi stakeholder participation at catchment and WUA levels. The close stakeholder interaction included combined discussions with water planners and operators at the ICMA, as well as with irrigators. Having this combination of people present in the discussions helped to ensure that:

1. The HE model could appropriately capture both the catchment-scale hydrological modelling functionality, as well as the farm-scale financial modelling functionality.
2. The catchment-scale hydrological data used in the models, as well as the farm-scale financial data used in the models, was appropriate.

The following key objectives guided the development of the integrated modelling framework:

1. To link the output of a hydrological systems model (ACRU linked with MIKE BASIN) with the whole-farm economic model (the skeleton model) in order to evaluate the financial impact of curtailment decisions on a number of farm case study participants in the Crocodile Catchment.
2. To interact with the stakeholders and water resource managers (i.e. the CMA and DWA) in the Crocodile Catchment (in the form of workshops), in order to (i) ensure that

the research team tests curtailment decisions in an appropriate manner, and (ii) to share the findings of the research with the stakeholders.

3. To further test and refine the MIKE BASIN irrigation module (to ensure that the simulation of crop yields and return flows is reasonable on the participant farm case study areas).
4. To further develop the skeleton model in order to accommodate assurance of water supply.

1.2 RESEARCH AREA

The Crocodile Catchment (East) study area falls within the Inkomati WMA and covers the entire X2 tertiary catchment. The total catchment area of the Crocodile East River catchment is 10 446 km2. The upper Crocodile (X21) tertiary catchment (at 3090 km²) is divided into 3 catchment areas: the Crocodile upstream of Kwena Dam, the Crocodile downstream of Kwena Dam and the Elands (1573 km²) catchment. The middle Crocodile (X22) tertiary catchment (at 2366 km²) and has 2 major tributaries: the Nels River and the White River catchments. The Kaap (X23) tertiary catchment (at 1640 km²) is the largest tributary and has 3 headwater catchments: the Noordkaap, Suidkaap and Queens Rivers. The lower Crocodile (X24) tertiary catchment (at 3349 km²) is the largest, but least significant – hydrologically, of the four tertiary catchments that make up the Crocodile Catchment. Kwena Dam, situated in the Upper Crocodile, is the only major dam in this catchment. The description of the catchment is shown in Figure 1.1

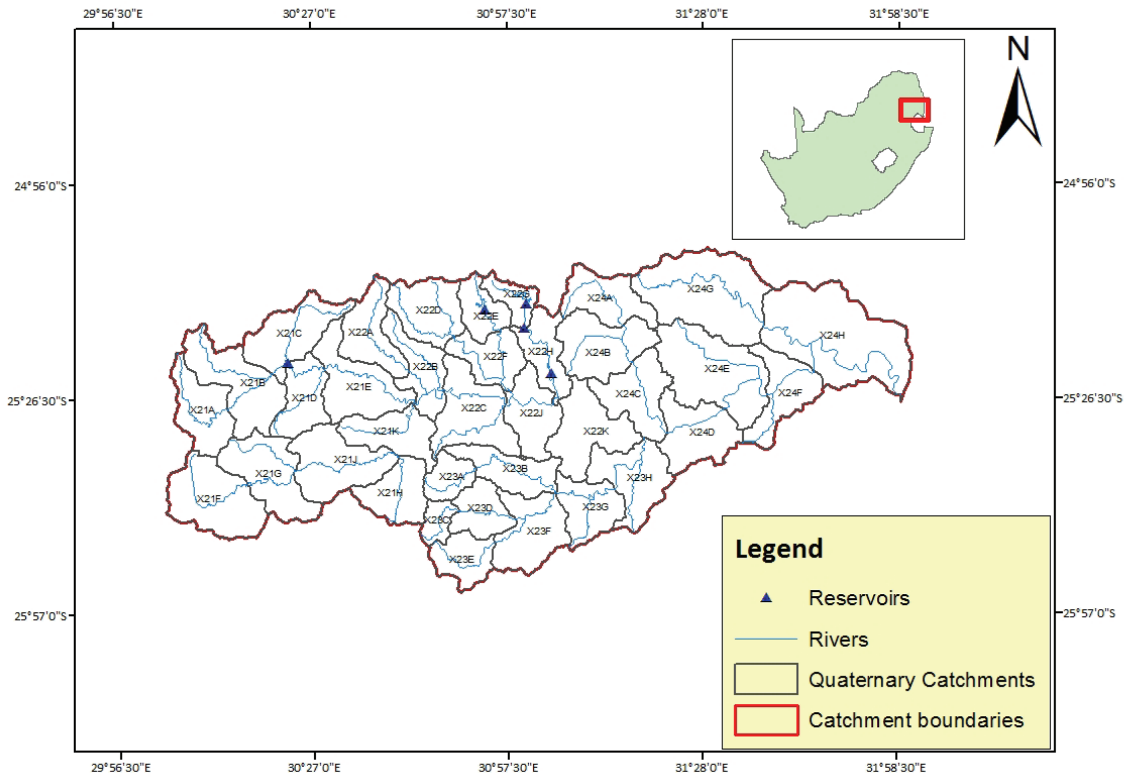


Figure 1. 1: Description of the Crocodile Catchment (East).

The study area falls entirely within the Mpumalanga province and includes the capital city of Nelspruit and regional centres White River, Barberton and Ka-Nyamazane. Smaller urban centres include Dullstroom, Waterval Boven, Machadodorp, Malelane, Matsulu and Hectorspruit. There are no large mines in this catchment and the only major industries are Sappi, with a wood mill in the Elands catchment; and the TSB sugar mill in the Lower Crocodile. The southern portion of the Kruger National Park is located on the northern bank of the Lower Crocodile River in the east of the catchment.

Topographically, the Crocodile River Catchment is very diverse, but can be divided into three areas: the western upper plateau (highveld) area, consisting of rolling grasslands, with moderate rainfall; the middle mountainous, or escarpment, area (middleveld), with higher rainfall; and the eastern bushveld sub-tropical region (lowveld), with lower rainfall. Elevations in the highveld and middleveld areas can range above 2000 m**.**

The Crocodile River Catchment lies within the summer rainfall region. The climatic conditions in the Catchment can generally be classified with the topography. The Highveld region has a cooler, dryer climate with a mean annual rainfall (MAP) of about 730 mm. The escarpment region that includes high altitude mountains and variable topography has a range of climatic conditions. The MAP ranges from 800 to 1270 mm, but can be as high as 1600 mm in the mountainous area. The Lowveld experiences a warm-to-hot and humid climate, with MAP in the range of 550 to 850 mm.

The farm called “Mhlati” was chosen as a case study to represent the irrigation water demand at farm scale. Mhlati farm is located near the main Crocodile River. The farm water supply is from naturally occurring flows in the Crocodile River whenever there is water; otherwise water is requested from Kwena Dam. Different irrigation systems/technologies are implemented in different fields of the farm as shown in Figure 1.2. Various soil types, with differing field-holding capacities occur, in the various farm fields. Sugarcane is the crop that is planted in the farm and it feeds the Malelane Sugar mill.

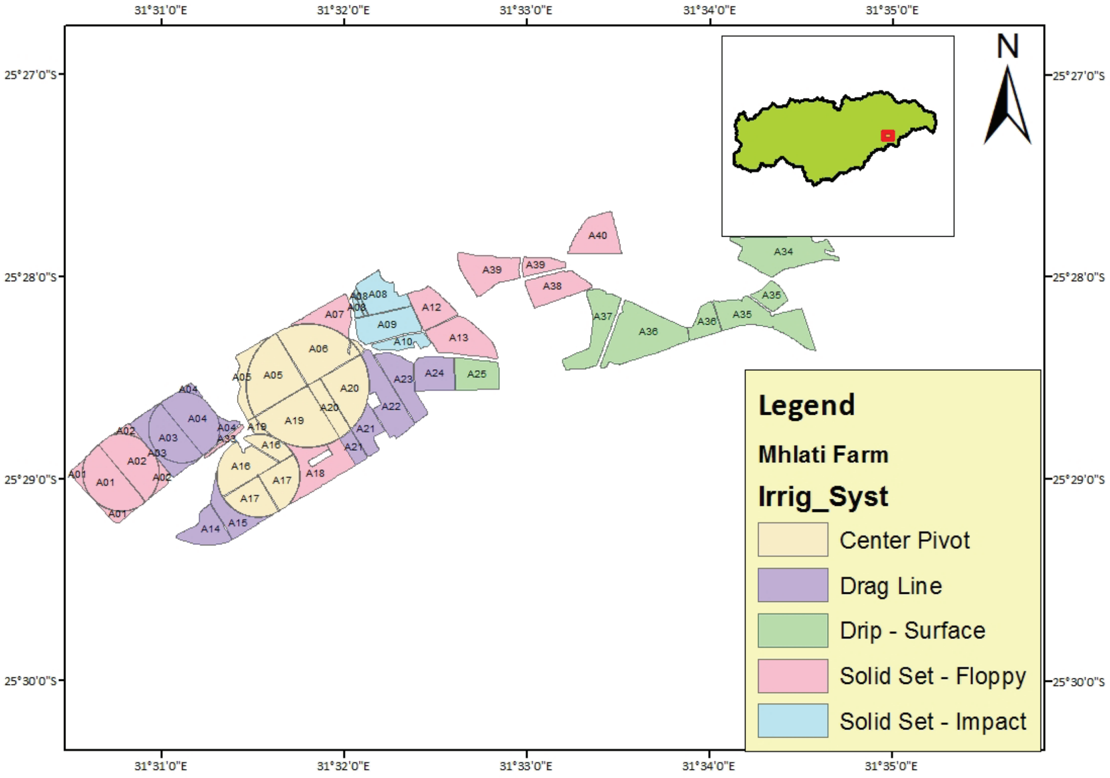


Figure 1. 2: Description of the Mhlati Irrigated Sugarcane Farm.

1.3 REPORT LAYOUT

Chapter 2 provides a literature review of integrated HE modelling. The modelling procedures that were adopted and further developed to model the impact of alternative catchment scale water management scenarios on the profitability of four alternative irrigation farming scenarios, are discussed in Chapter 3. This chapter also provides a description of the data used and the configuration of the different models that were used in the research. The results from the hydrological and farm-scale economic analyses are given in Chapter 4. The conclusions and recommendations for further research are discussed in Chapter 5.

CHAPTER 2:

LITERATURE REVIEW:

INTEGRATED HYDRO – ECONOMIC MODELLING

The chapter is structured into two parts. The first part gives a short review of modelling approaches used for hydro-economic modelling. The second part considers research efforts pertaining to water use optimisation in South Africa and internationally.

2.1 INTRODUCTION TO HYDRO-ECONOMIC MODELLING

To achieve the overall objective of the project an integrated hydro-economic modelling approach is necessary to meaningfully assess the impact that a curtailment of existing lawful water use may have on the economic and financial feasibility of an irrigator. Different levels of hydro-economic integration are possible. McKinney *et al.* (1999) reviewed alternative modelling approaches to combine hydrology and economics at the catchment level. Basically two broad types of integration approaches between hydrological and economic models were identified in the review. The two broad approaches are (i) holistic and (ii) compartment modelling.

A holistic modelling approach refers to a unified model where the economic and hydrologic model components are integrated in a unitary body of code (Bharati *et al.*, 2008). Many researchers (e.g. Cai, 2008; Puilido-Velazquez *et al.*, 2008) have chosen GAMS (Brooke *et al.*, 1998) as their preferred software to develop their unified models which is solved via external linkages to optimisation solvers. Due to the unification of the hydrological and economic components the hydrological components are usually simplified not to overburden the solvers that are used to solve the unified models (Bharati *et al.*, 2008). Cai (2008) argues that an advantage of the unified approach is that the inter-relationships between hydrologic and economic systems are modelled endogenously which allows for more effective combined environmental-economic analysis.

An advantage of the compartment modelling approach is that it couples detailed hydrological and economic modelling systems together through data transfer activities to study the hydro-economics of complex problems. McKinney *et al.* (1999) argue that the compartment modelling approach is likely to be more realistic and hence suitable for application. However, more research is necessary to realistically integrate hydrological and economic modelling systems in a dynamic interactive manner. Specifically research efforts should emphasise better characterisation of the interrelationships between models that govern their behaviour. Figure 2.1

provides an example of a dynamically linked hydrologic economic modelling system which is based on compartment modelling.

A detailed simulation of the hydrological system is done first to quantify the water availability in the river system while taking cognisance of the operation of the system. The simulated water yield is routed through a water allocation model to define the water availability for which water use is optimised. The outputs from the water use optimisation model are used as inputs in the hydrological simulation model to determine whether the optimisation model output is hydrologically feasible. If the optimised water use is hydrologically feasible, policy recommendations are made, however, when it is infeasible a correction is made via the water allocation model whereby water availability is reduced. The process repeats itself until the optimised water use is hydrologically feasible or the “red line” hydrological constraint is met. An example of a “red line” constraint is an instream flow requirement that must be met. In essence such an approach can be used to optimise the water allocation of the whole catchment through the backwards and forward linkages that consists when the framework is applied to a catchment with multiple agricultural water demand nodes (crop water use optimisation model).

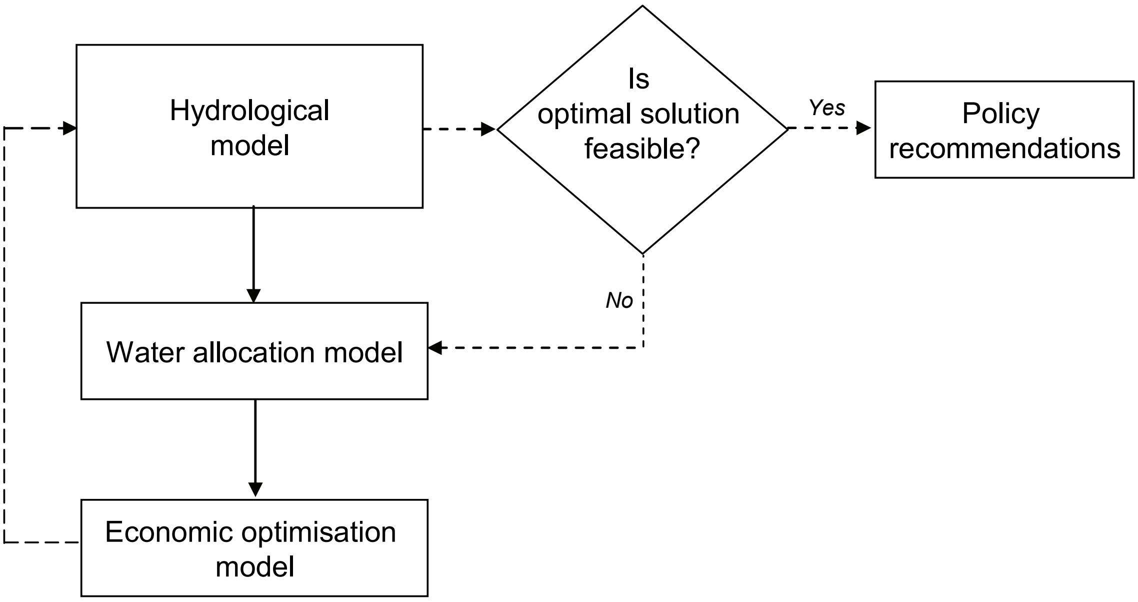


Figure2. 1: Sequential optimization and simulation model application to derive feasible and optimal policy alternatives (Adapted from McKinney et al., 1999:23)

Important to note is that the whole idea with dynamic compartment modelling is that the hydrological models are detailed models used to evaluate the hydrology, whereas the economic models are detailed economic models that are used to answer the questions regarding financial feasibility hand. However, only through the combined application of the hydrological and economic models is one able to answer hydro-economic questions relating to the interaction between hydrology and economics. Applications of such a dynamic interactive coupling of hydrological and economic models include the work done by Ahrends *et al.* (2008) and Bharati *et al.* (2008) in the Volta basin.

2.2 KEY ISSUES IN HYDRO-ECONOMIC MODELLING

Several hydro-economic modelling issues were identified from the literature and are discussed in some detail below.

2.2.1 SPATIAL SCALES

Hydrological models use a nodal network setup to link different scales in a top-down structure from the river catchment to the crop land (Cai, 2008). By implication hydrological models are associated with larger decision-making units and the management of larger scales. On the other hand agricultural water use decisions are associated with the management of available water at the farm-level or Water User Association (WUA) level and therefore smaller spatial scales. However, it should be noted that the decisions made by decision-makers at the small spatial scales (farms) may have significant impacts on the overall hydrology of the system via the externalities that they cause. Therefore it is important to satisfactory represent smaller decision-making units in the overall framework that is used.

Holistic (unified) modelling approaches have an overall objective of improving the economic benefits for the whole catchment. Thus, holistic models are typically also associated with larger spatial scales and therefore with larger decision-making units. Less attention is given to providing decision-support at smaller scales. Compartment modelling is more suited for providing decision support at smaller spatial scales while at the same time adhering to the hydrological realities of the river catchment. Depending on the exact dynamic linkages it is possible to link optimisation models at WUA or farm-level to hydrological models via the compartment modelling framework to assist decision-support at the smaller spatial scales.

2.2.2 MATCHING TEMPORAL SCALES OF HYDROLOGIC AND ECONOMIC MODELS

Hydrologic models simulate hydrological flows on fine time-steps such as days. Whereas economic models uses monthly, seasonal or annual time steps. A small time-step for hydrologic models is justified by the fact that small time-steps are necessary to reflect the real world processes and to compute the transition change of the physical system (Cai, 2008). Modelling the hydrology correctly is of utmost importance since it will provide the boundary conditions within which decision-makers will make their economic decision. Economic models use larger time-steps as a result of the time intervals associated with their decision that may impact on their profitability. Care should thus, be taken when integrating hydrologic and economic models due to the different time scales.

2.2.3 INSTITUTIONAL REPRESENTATION

The institutional setting provides the rules for using and developing a water resource within a basin. The challenge for integrating hydrologic economic models at the catchment level is to deal with institutions of stakeholders at multiple levels from national to catchment management agencies and to water user associations (Cai, 2008). Examples of the institutional rules that need to be adhered to are water allocation mechanisms, water rights, water trade, instream flow requirements, international obligations, etc.

Currently uncertainty exists within the national authorities on how to define water curtailments. Uncertainty also exists on how to formulate operational rules that will determine the amount, timing and the resulting security of supply of the water use entitlement.

2.2.4 SIMULATION VS. OPTIMISATION

Simulation models are pre-eminently suitable for assessing the performance of water resource systems over the long-run under predefined rules governing water allocations and infrastructure operations (McKinney *et al.*, 1999, Pulido-Velasquez *et al.*, 2008). Typically these models are used to assess the impact of alternative management rules on the performance of the hydrological system through detailed simulations.

A distinct advantage of optimisation models over simulation models is their ability to incorporate social value systems in the allocation of water resources (McKinney *et al.*, 1999) thorough a multi-objective framework of analysis. Optimisation models are well suited to predict the response of water users based on a defined objective function. Thus, optimisation can be used to identify or suggest possible actions that should be explored in an operational sense to improve the management of the overall hydrological system.

2.2.5 CONCLUSION

Both the holistic (unified) and compartment modelling approaches have merit for application to water resource management problems. Cognisance should be taken of the specific problem at hand when deciding upon a specific modelling framework. Specifically this research project is concerned with assessing the potential financial impact that curtailment of existing lawful water use may have on the irrigation case study participants. A detailed spatial representation of the catchment hydrology is necessary to capture the impact of alternative operating rules in the catchment. At farm-level a detailed analysis of agricultural water use optimisation is necessary to evaluate irrigation farming profitability in light of changing catchment operating rules and water curtailments. Thus an integrated compartment modelling approach is proposed in this research.

In the following section farm-level agricultural water use optimisation is reviewed,

2.3 AGRICULTURAL WATER USE OPTIMISATION

Numerous research studies have been done in the area of water use optimisation and the review in this section is by no means exhaustive. Rather, the review concentrates on selected studies which influenced the methodology used in this research to optimise water use taking deficit irrigation into account. The review of the South African literature is, however, thoroughly done.

English *et al.* (2002) argue that modelling deficit irrigation realistically is critical in efforts to optimise agricultural water use. Some of the issues in agricultural water use optimisation that need to be considered are the following: (i) non-linear relationship between applied water and crop yield, (ii) interdependencies between water use in different crop growth stages and (iii) production risk.

2.3.1 NON-LINEAR RELATIONSHIP BETWEEN APPLIED WATER AND CROP YIELD

Modelling the non-linear relationship between applied water and crop yield is very important since the non-linear relationship gives rise to declining marginal productivity of applied water, which is a necessary condition to maximise profits. The existence of a non-linear relationship between applied water and crop yield and a linear relationship between ET and crop yield are discussed at the beginning of this chapter. Therefore, the specific objective of this section is to evaluate alternative procedures to quantify the relationship between applied water and crop yield and to evaluate how researchers have incorporated the relationship in their analyses.

2.3.1.1 International research

Recent international research has emphasised the importance of non-uniform water applications on crop yields. Two alternatives exist to model the non-linear relationship as a result of non-uniform water applications. The first approach simulates spatial variability in soil depths, water holding capacities, infiltration characteristics, and distribution of applied water by dividing irrigated fields into sectors and using Monte Carlo simulation to assign variable values randomly to each sector (Hamilton *et al.*, 1999). As a result some portion of the irrigated field will be over-irrigated and some portion under-irrigated, which gives rise to a non-linear relationship between applied water and crop yield. Hamilton *et al.* (1999) used the stochastic simulation approach with CropSyst (Cropping Systems Simulation model) to estimate crop water production functions for different crops under various irrigation technologies. These crop water production functions were then utilised in a mathematical programming model to evaluate water reallocation possibilities in the Snake River.

The second approach assumes a statistical distribution for the non-uniform applications to calculate the average area that is respectively under-irrigated and over-irrigated. The second approach is used extensively in recent agricultural water use optimisation literature to characterise the relationship between applied water and crop yield (Mantovani *et al.*, 1995; De Juan *et al.*, 1996; Reca, Roldán, Alcaide, López and Camacho, 2001; Ortega, de Juan, Tarjuelo and López, 2004; Sepaskhah and Ghahraman, 2004; Ortega, de Juan and Tarjuelo, 2005). The overall procedure is based on the integration of an estimate of the average water deficit due to non-uniform applications and a relative ET formula to calculate crop yield. Relative ET formulae calculate crop yield by relating relative yield percentage (Y_a/Y_m) to relative evapotranspiration percentage (ET_a/ET_m) by means of a crop yield response factor which indicates the sensitivity of the crop to water deficits (Doorenbas and Kassam, 1979). Most of the researchers that have adopted the procedure use the Stewart multiplicative relative ET formula to calculate crop yield because it takes into account the impact of water deficits in different crop growth stages on crop yield. The most frequently used distributional assumptions for water applications are the normal and uniform distributions. Information regarding the non-linear relationship between applied water due to non-uniform water applications is then used in some kind of an optimisation procedure to optimise water use.

2.3.1.2 South African research

Various South African researchers optimised agricultural water use by means of linear programming (LP) (Hancke and Groenewald, 1972; Van Rooyen, 1979; Brotherton and Groenewald, 1982) or dynamic linear programming (DLP) (Backeberg, 1984a; Oosthuizen, 1995; Maré, 1995; Louw and Van Schalkwyk, 1997; Haile, *et al.*, 2003). Typically, these researchers use one point estimate on a crop water production function to represent the relationship between applied water and crop yield. Although the crop yield estimates correspond to actual crop yields, the water use is typically derived for conditions of no water deficits. These research efforts are not reviewed in this section since the main objective of this section is to review the South African literature that considers the economics of allowing the crop to sustain some level of water stress commonly referred to as deficit irrigation.

Viljoen, Symmington, Botha and Du Plessis (1993) used a crop growth simulation model to simulate the impact of alternative deficit irrigation scheduling strategies on water use and crop yield. The outputs of the model were used to estimate polynomial crop water production functions to represent the non-linear relationship between applied water and crop yield. Point estimates on these functions were then included in a DLP model to evaluate the impact of alternative canal capacities on agricultural water use in Vaalharts. By implication, these researchers are implicitly assuming that water applications are distributed optimally over the growing season. However, theory suggests that the assumption will be violated if intraseasonal water allocations are limited by canal capacities when multiple crops compete for water.

Mottram *et al.* (1995) adopted a procedure that will correctly optimise water use between multiple crops when intra-seasonal water allocations are limiting but assumed a linear relationship between applied water and crop yield. The procedure relies on the inclusion of different activities consisting of different combinations of 10 mm deficits in each of the growth stages in their programming model. Crop yield was estimated for each combination using an additive law of calculating crop yield as a function of ET deficits. Two critical assumptions were made by these researchers. Firstly, they assumed that water use in any of the crop growth stages is independent of the other. Thus, the influence of irrigation decisions early in the season have no influence on decisions made later in the season. Secondly, they assumed that reductions in ET are proportional to reductions in applied water. Thus, these researchers did not account for the non-linear relationship between applied water and crop yield and therefore the increasing water use efficiencies as the crop is deficit irrigated. Results from their analyses indicated that deficit irrigation is not viable and that the areas planted should be reduced and fully irrigated. These results may be the direct result of the inability of these researchers' procedures to account for increasing irrigation efficiencies when the crop is deficit irrigated.

Grové and Oosthuizen (2002) optimised agricultural water use while quantifying economic environmental tradeoffs of maintaining instream flow requirements. Rather than generating discrete activities of alternative deficit irrigation schedules these researchers optimised a continuous function that relates ET to crop yield. The Stewart multiplicative function has the property of modelling more than proportional yield reductions if the crop is stressed in more than one crop growth stage. Increasing water use efficiencies as the crop is deficit irrigated were modelled using procedures developed by Willis (1993) whereby efficiencies are assumed to increase linearly between maximum water application and a given maximum allowed deficit. The results of the analyses indicated that it is profitable to practise deficit irrigation while spreading available water over larger irrigation areas. Although these researchers were able to model increasing irrigation efficiencies as the crop was deficit irrigated no link exists between the water budgets in different crop growth stages. Furthermore, these researchers did not account for any changes in yield variability as the crop is increasingly deficit irrigated.

The work done by Lecler (2004) is not specifically aimed at optimising water use but provides an important simulation application that acknowledges the importance of the uniformity with which irrigation technology applies water to the relationship between applied water and crop yield. The water use efficiency of alternative irrigation schedules and irrigation technologies was evaluated by simulating multiple water budgets with ZIMsched (Zimbabwe Irrigation Scheduling model) to incorporate the impact of non-uniform water applications of alternative irrigation technologies on sugarcane yields. Recently Grové (2006a) used a simulation model that incorporates the impact of non-uniform water applications on crop yield to generate activities for a linear programming model to optimise water use.

2.3.1.3 Conclusions

At the international level researchers are increasingly focussing on modelling the non-linear relationship between applied water and crop yield using the non-uniformity with which irrigation systems apply water linked to the Stewart multiplicative relative ET formula. Modelling procedures to simulate the impact of non-uniform applications on crop yields have only recently being adopted by South African researchers.

The review of the South African research indicated that a large number of optimisation studies have followed the old paradigm of allocating water to achieve maximum yield. The difference in the results of the research by Mottram *et al.* (1995), which assumed constant irrigation efficiencies, and the research by Grové and Oosthuizen (2002), who modelled increasing efficiencies as the crop is deficit irrigated, emphasises the importance of modelling the non-linear relationship between crop yield and applied water. The conclusion is that failure to model the non-linear relationship between applied water and crop yield will result in an under estimation of the potential benefits of deficit irrigation if it is profitable to deficit irrigate the crop.

2.3.2 INTERDEPENDENCY BETWEEN WATER USE IN DIFFERENT CROP GROWTH STAGES

Optimising agricultural water use is difficult because irrigation water differs from other production inputs since it can be dynamically adjusted as the growing season progresses (Peterson and Ding, 2005). A further complicating factor is that water deficits in different crop growth stages will impact differently on final crop yield (Doorenbos and Kassam, 1979). In order to model deficit irrigation satisfactorily the modelling procedure should be able to model the interdependency of sequential irrigation decisions on crop yield. Modelling these interdependencies is especially important in systems where multiple crops compete for limited water supplies.

2.3.2.1 International research

Dynamic programming (DP) is frequently used by researchers to optimise water use within a growing season. One of the problems with DP is that many simplifying assumptions are necessary to cope with the problem of dimensionality (Schütze, de Paly, Wöhling and Schmitz, 2005). Typically, water use optimisation between multiple crops is achieved by a multi-tier approach.

Reca *et al.* (2001) used DP to derive optimal seasonal production functions. The relationship between applied water and crop yield is based on normally distributed water applications and the Stewart multiplicative relative ET formula to account for the impact of ET deficit in different crop growth stages. DP is used to allocate a limited amount of irrigation water optimally over the growing season. Repeating the optimisation for different levels of water availability yields the necessary information to estimate a crop water production function based on optimally distributed irrigation quantities over the growing season. The optimal crop water production functions of different crops are used in a second optimisation model to optimise water use between multiple crops. Since the production functions of the individual crops are non-linear Reca *et al.* (2001) transformed it into a linear problem by approximating the benefit function to a discrete function. Shangguan, Shao, Horton, Lei, Qin and Ma (2002) adopted a similar procedure to optimise water use between multiple crops. In the first stage, DP is used to distribute alternative limited amounts of water optimally over the growing season. Regression analysis is used to estimate m-order polynomial crop water production functions. These functions are used in a second DP optimisation model to optimise water use between competing crops given a limited amount of water is available. A problem with using optimal production functions to optimise water use between multiple crops is that the solutions may not be optimal if intra-seasonal water allocations are limiting.

Ortega *et al.* (2004) developed a comprehensive water use optimisation model, which forms the basis of the irrigation advisory service provided to farmers in Castilla-La Mancha (Ortega *et al.*, 2005). Rather than developing optimal production functions to generate the necessary information for a second optimisation model, the model utilises a genetic algorithm (GA) to optimise the whole system. Crop yields are estimated using the Stewart multiplicative relative ET formula while the non-linear relationship between applied water and crop yield was modelled assuming normally distributed water applications over the entire field. Historical weather data is used to drive the system where ET is calculated using Penman-FAO and Penman-Monteith procedures. The cropping pattern and corresponding irrigation schedule are optimised for each year with the GA. The recommended strategy is chosen based on the lowest accumulative measure of risk. The cumulative risk associated with a specific alternative corresponds to the sum of deviations from a reference gross margin, determined for each year, as a consequence of the application of this crop rotation throughout the climatic series (Ortega *et al.*, 2004:67).

Bernardo, Whittlesey, Saxton and Bassett (1987) developed a procedure to approximate the dynamic problem of optimising water use between multiple crops with LP. The approximation is based on the inclusion of a large number of discrete activities representing alternative ways of distributing water over the growing season. Information for the activities is simulated with a crop growth simulation model. The methodology is appealing since it uses procedures that are easily understandable by a large community and does not require highly specialised software or modelling expertise. The procedure has recently been applied by Scheierling, Young and Cardon (2004) to determine the price responsiveness of demands for irrigation water deliveries and consumptive use.

2.3.2.2 South African research

The most sophisticated example of crop water use optimisation is the work done by Botes, Bosch and Oosthuizen (1996). These researchers linked a crop growth simulation model to an optimisation procedure to optimise different irrigation scheduling strategies for maize under dynamic plant growth conditions in order to estimate the value of information for irrigation scheduling for different soils. Results indicated that the value of irrigation information is sensitive to the plant extractable soil water of the soils and water availability.

As an alternative to the highly specialised applications of water use optimisation above Grové (2006a) used a more robust procedure to optimise water between competing crops that can be applied within a whole farm setup. The procedure is based on simulating the effect of multiple irrigation quantity combinations on crop yield. Information on water applications in different time periods and crop yields are then used in a mathematical programming model to optimise water use (Bernardo *et al.,* 1987).

Although not specifically aimed at deficit irrigation[1] the research by Viljoen, Dudley, Gakpo and Mahlaha (2004) needs mentioning because theirs is one of the few South Africa African studies that employed LP and stochastic dynamic programming (SDP[2]) to optimise water use. A rather simple LP model in terms of water use optimisation was used to derive gross margin as a function of the total amount of water allocated to the farm. The first derivatives of these functions provide estimates of the MVP of water allocated to a specific farm under consideration. These values were used in the SDP model to optimise the water allocation for different capacity shares in the Vanderkloof dam. Linking the results of the LP with the SDP model clearly demonstrates the inability of SDP approaches to handle more complex problems due to the curse of dimensionality.

2.3.2.3 Conclusions

DP procedures are typically preferred to optimise crop water use within a growing season to derive optimal crop water yield production functions. Simplifying assumptions are, however, necessary to keep the model tractable because adding more detail quickly results in too large a

---

[1] These researchers pre-assumed irrigation requirements consistent with maximum yield.

[2] Stochastic dynamic programming incorporates stochastic elements into a dynamic programming model.

model. Incorporating information regarding optimal production functions in a second tier optimisation model to allocate water optimally between competing crops will violate optimality conditions if intra-seasonal water availability is limiting. Use of GA to optimise complex systems seems to be a practical alternative to DP and should be further investigated.

South African research that focused on optimising the interdependency between water usage in different crop growth stages is scant. Botes *et al.* (1996) treated the problem comprehensively. However, application of the methodology requires computer-programming skills and is time consuming to implement. Furthermore, application of such a methodology will be highly complicated if water use needs to be optimised between competing uses where the decision-makers have to decide upon areas planted and irrigation quantities. Grové (2006a) adopted the procedures developed by Bernardo *et al.* (1987) to optimise water use with standard mathematical programming procedures while adhering to the theory of water use optimisation. The same procedure was recently applied by Scheierling *et al.* (2004). The simplicity of the approach is appealing because incorporating the non-linear relationship between applied water and crop yield, while taking cognisance of the impact of water deficits in different crop growth stages, production risk and other farm level constraints, is straightforward. The conclusion is that less complicated procedures that conform to economic theory may provide a framework for optimising water use between multiple crops within a whole-farm setup while taking cognisance of production risk.

2.3.3 PRODUCTION RISK

To evaluate deficit irrigation thoroughly production risk needs to be taken into account because adjusting irrigation amounts during the growing season is viewed as the producer's primary tool for managing production risk (Peterson and Ding, 2005). English *et al.* (2002:272) furthermore argue that when the opportunity cost of water is taken into account and it is optimal to reduce water applications and at the same time increase the area irrigated, any losses that may incur will be amplified by the increased area under irrigation. The need to take production risk into account is accentuated by the fact that irrigation farmers in South Africa are found to be risk averse (Botes, 1994; Meiring, 1993). The main objective of this section is to review the impact of deficit irrigation on production risk.

2.3.3.1 International research

Reca *et al.* (2001) used optimal production functions derived from DP models to demonstrate the impact of climate variability on income. Analyses were conducted for both winter and summer crops. Results indicated that higher climatic variability causes the overall income variability between crops to increase while increased levels of deficit irrigation cause increased levels of income variability.

Peterson and Ding (2005) developed a risk programming model to quantify the effect of irrigation efficiency on water use in the High Plains of America taking account of the impact of irrigation timing on production risk. Data simulated with a crop growth simulation model is used to estimate a Just-Pope production function to determine the impact of irrigation timing on expected crop yields and the variability thereof. Results indicated that irrigation water applications are risk reducing in some crop growth stages and in others it is risk increasing. These results were explained by differences in crop growth development resulting from different irrigation scheduling practices during the season.

2.3.3.2 South African research

Botes (1990) evaluated the risk efficiency of alternative wheat irrigation strategies taking plant extractable soil water-holding capacities of different soils into account. Only one deficit irrigation strategy was simulated by allowing the crop to sustain 20% crop water stress before triggering the next irrigation. Simulated crop yields for the deficit irrigation strategy showed increased variability in crop yields over the other irrigation strategies. Stochastic dominance with respect to a function (SDRF) (Meyer, 1977) was used to show that risk averse irrigators will not choose to deficit irrigate their crop. Unfortunately, Botes (1990) did not include alternative levels of deficit irrigation in his analysis.

Grové *et al.* (2006a) extended the research by Botes (1990) by including increasing levels of deficit irrigation for wheat and maize in their risk efficiency analyses. A more robust alternative to SDRF, called stochastic efficiency with respect to a function (SERF) (Hardaker, Richardson, Lien and Schumann, 2004) was used to rank alternative water use strategies for decision-makers with varying degrees of risk aversion. Results of the analyses indicated that gross margins of both crops are more variable under deficit irrigation. In contrast with the findings of Botes (1990) results also indicated that there might be some level of maize deficit irrigation that will be preferred by risk averse irrigators under limited water supply conditions whereas full irrigation is preferred for wheat. These results highlight the importance of weather on the risk efficiency of deficit irrigation since maize is produced during periods of relatively higher expected rainfall while wheat is produced during periods of lower expected rainfall conditions.

The research efforts discussed above used simulation procedures to determine the risk efficiency of alternative deficit irrigation schedules. A shortcoming of simulation is that it shows the impact of predefined alternatives which ignore the opportunity cost of water. Botes *et al.* (1996) enhanced their previous efforts (Botes, Bosch and Oosthuizen, 1995) to quantify the value of irrigation information for risk averse decision-makers. However, these researchers did not allow changes in the area planted while optimising limited water availabilities. Grové (2006a) incorporated risk into his analysis to evaluate the potential of deficit irrigation to conserve irrigation water. Results indicated that it is profitable to use the water that is saved through deficit irrigation to irrigate larger areas.

2.3.3.3 Conclusions

The international studies show some important aspects that need to be taken into account when evaluating deficit irrigation. Firstly, deficit irrigation will decrease expected crop yield and most likely increase yield variability as the crop is deficit irrigated. Secondly, the importance of using appropriate crop growth simulation models to quantify the impact of deficit irrigation on crop yield is highlighted by the fact that water applications might be risk reducing or risk increasing in some crop growth stage.

The South African studies emphasise the importance of weather conditions on the profitability of deficit irrigation. The conclusion is made that the potential to use rainfall more efficiently has a significant impact on the adoption of deficit irrigation strategies by risk-averse decision makers. Any information that will increase the potential to use rainfall more efficiently, such as improved localised weather forecasts, will improve the adoption of deficit irrigation strategies. However, use of deficit irrigation in areas where rainfall is minimal may cause risk averse farmers to adopt full irrigation. The overall conclusion is that the risk aversion will impact significantly on the adoption of deficit irrigation in different regions because the impact of deficit irrigation is highly dependent on prevailing weather conditions.

CHAPTER 3:
MODELLING PROCEDURES

3.1 CATCHMENT SCALE WATER RESOURCES MANAGEMENT

3.1.1 MODELLING APPROACHES

Currently, water resources in South Africa are proactively managed in order to supply water for human needs as well as the needs of other water-use sectors (e.g. mining, domestic, industrial, irrigation) and, where applicable, also international flow requirements. In certain catchments EWRs are being managed, largely via controlled releases from dams. However, in many run-of-river dominated catchments, water managers have yet to operationalise (give effect to) EWRs. The draft NWRS-2 acknowledges this fact, and stresses the need for the EWRs to be upheld, as they together with Basic Human Needs are the only "right" to water recognised by the National Water Act of 1998 (Act 36 of 1998).

In a global context South Africa has a very high variability of rainfall and runoff. The result is that, without dams (reservoirs), there are often times of more than enough (and sometimes too much) water and times of too little water. Water resource managers have had to develop sound water resource planning techniques to carefully work out how to cater for growing water demand in the face of the high variability of rainfall and runoff. Water managers in South Africa have, over the past 20-odd years, developed and refined the Water Resource Yield Model (WRYM) and Water Resource Planning Model (WRPM) which are used by water resource planners to help determine the water availability of catchments and how best to meet growing demands. These planning models replicate water resources, water users and the water apportionment rules that exist, which help govern assurance of water supply levels to various categories of water users. The planning models can be used to assess current levels of water availability (for current water use patterns, but can also be used to project into the future with consideration being given to changes in water-use patterns and flows (which may change due to climate change).

When undertaking water resource planning studies, two similar yet slightly differing approaches are often adopted. In the first option, the water planners only make use of historical river flow and weather information in their evaluation. This information is based on observed data, which may be processed (naturalised) to account for water abstractions and discharges that took place in the past. The second approach is to generate stochastic hydrological sequences (i.e. synthetically generated hydrological sequences), which are based on the naturalised historical sequence. The two approaches are explained in more details below. The second approach, which makes use of multiple flow sequences (i.e. a combination of the historical naturalised flow sequence as well as numerous synthetically generated stochastic flow sequences), enables water resource managers to undertake a more thorough probabilistic (risk-based) overview of water availability. This is explained in more detail below.

3.1.1.1 Assessment of water resources using naturalised observed historical data

The assessment of water resources using historical flows is performed to gain an understanding of the historical yield potential of a catchment with the current water resource infrastructure in place (e.g. dams &/or inter-basin transfer infrastructure, desalination & water reuse plants, etc.). Catchment historical firm yields are determined based on historically observed hydrological data sets. A shortcoming of this approach is that the accuracy of the assessment is highly dependent on the record length and the spatial coverage of the observed hydrological data. The hydrological data required for historical assessment of catchment resources is streamflow, rainfall, evaporation and historical water-use data. This data is mainly highly dispersed spatially and, where there is a record, the length of the documented data is often short. A typical output, which is a draft-yield curve, from the historical assessment of a catchment or water resource unit is shown in Figure 3.1.

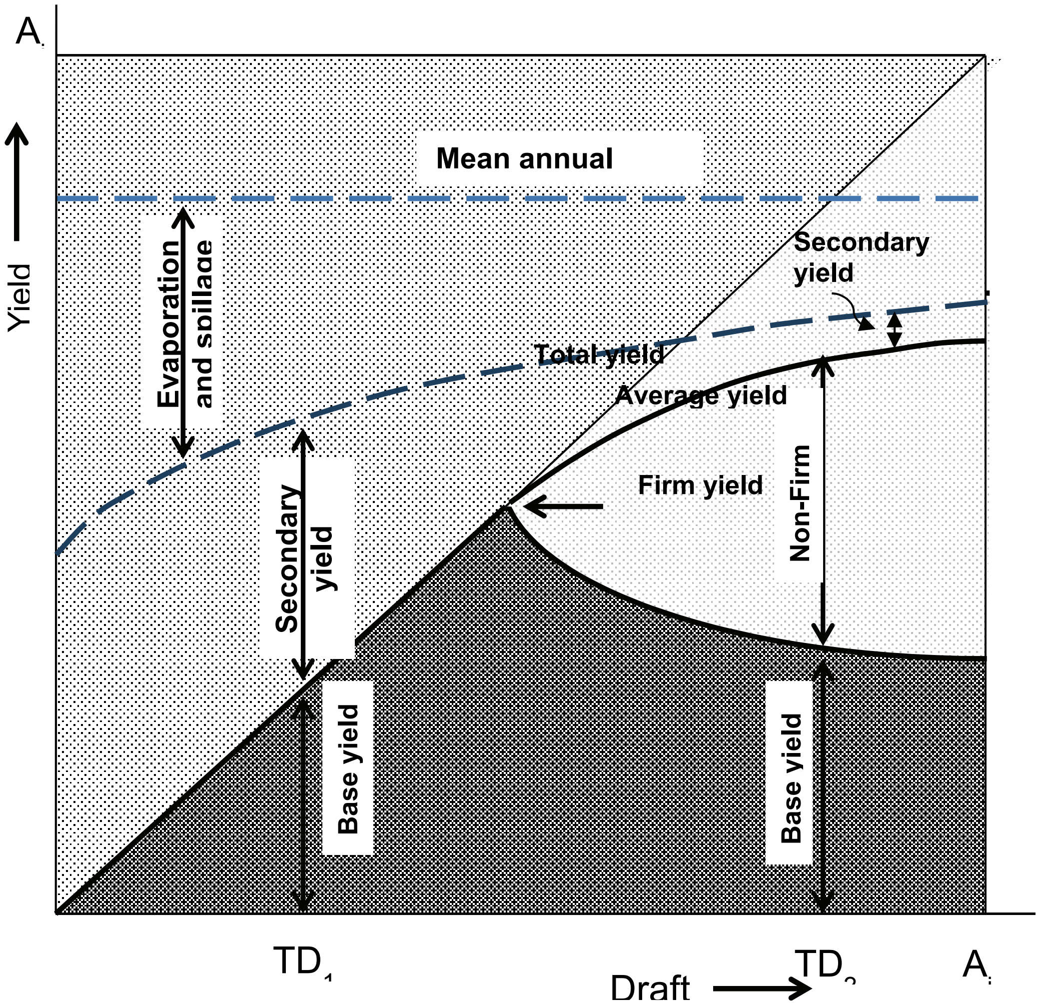


Figure 3. 1: Historical Draft Yield Graph (Basson *et al.,* 1994)

The total mean annual runoff is a combination of base yield, secondary yield, non-firm yield and the water lost due to evaporation and spillage from dams when they are over-full. A base yield is an amount that can be supplied with 100 % reliability, while secondary and non-firm yield are yields that could be supplied at lesser percentages of reliability. The historical firm yield is the maximum yield that the catchment/ water resource unit can produce with 100 % reliability based on historically observed data.

3.1.1.2 Assessment of water resources using historically observed and synthetically generated data

The assumption made in historical catchment water resources assessments is that the future hydrological annual or monthly series/sequence will be identical to the historical hydrological sequence. However, it is highly unlikely that historical hydrological series will be repeated in precisely the same sequence in the future. The sequencing of wet and dry cycles has an impact on the yield of catchments. A probabilistic risk-assessment approach has been adopted in South Africa, where the probabilistic approach uses stochastically generated (synthetically generated) streamflow values – with all the possible hydrological sequences (i.e. historical and stochastically-generated sequences) used as an input into the water allocation network models to assess all possible risk scenarios. The stochastic approach generates different flow sequences, but keeps statistical properties, such as the mean constant (i.e. the mean of the historical time series). Changing the flow sequences, changes the sequencing of wet and dry cycles. By using a number of separate flow sequences, water resource planners can plot out probabilities of exceedence (or non-exceedence).

The stochastic streamflow values are generated on the assumption that the historical annual/monthly streamflow series is stationary. The Stochastic Model of South Africa (STOMSA) is the stochastic generator software that was used in this project to generate stochastic streamflow values. STOMSA uses the Auto-Regressive Moving Average (ARMA) method, which simulates new total annual values that preserve the co-variance structure with the historical time series and is statistically similar to the original historical time series (Basson *et al.*, 1994). The software follows three steps when generating stochastic values –namely:

(i) Describes the characteristics of the marginal distribution of the annual flows,
(ii) Presents a time distribution that best represents the serial correlation exhibited by the normalise annual flows
(iii) Establishes cross-correlation between the normalised annual flows.

Besides from STOMSA, there are a number of other stochastic models that are used to generate synthetic streamflow values in South Africa. One of these models is a stochastic model developed by Mallory. The stochastic model determines the probability of future short-term flows based on the catchment's antecedent conditions. The model is being applied in the Crocodile Catchment (East) to determine the yield of the catchment.

The probable risk assessment approach to water resources allows water managers to manage resources at an informed risk level. The probabilistic risk-assessment framework to catchment water resource management is described in Figure 3.2.

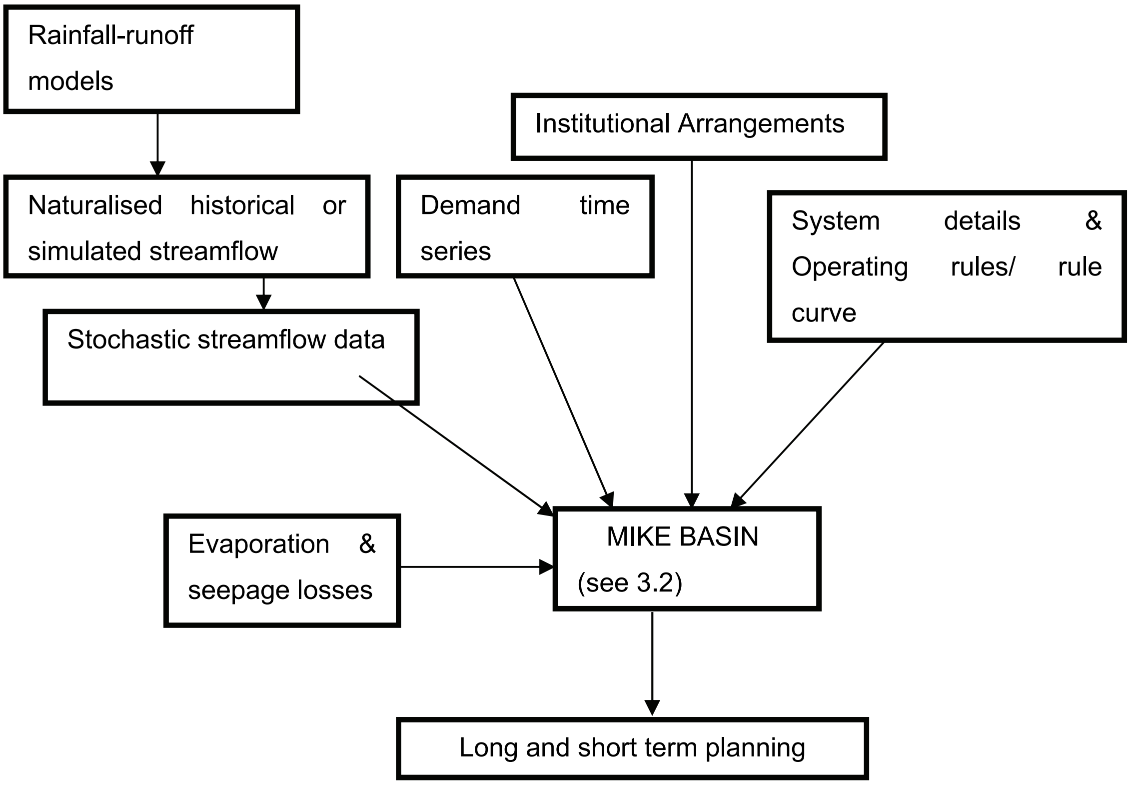


Figure 3. 2: Water resource modelling framework

Within the water resource modelling framework, a number of inputs are required for the network water-allocation model. These inputs are system details and operating rules; water institutional arrangements on how water shall be allocated; and evaporation and other water losses from the system and stochastic streamflow data. Each of the input elements to the water-allocation model is discussed below:

Institutional arrangements

A "water right" is defined as "the right to take and use water subject to terms and conditions of the grant" (Burchi and D'Andrea, 2003). An institutional arrangement [3]is where water rights of

---

[3] Institutional arrangement is legal framework, tools and mechanism with which catchments are operated.

different water sectors are defined and, in South Africa's case, how water is allocated or distributed based on some priority water right (National Water Act, 1998). Ecological Water Requirements (EWR) and Basic Human Needs (BHN) are allocated first priority, where other legitimate water claims are allocated on a sector priority basis. Domestic and industrial water claims have higher priority than irrigation. The water allocation framework distributes water according to the institutional arrangement of the country.

System details and operating rules

In the water-allocation modelling framework, the system details are configured to represent the system ground truth. Catchments, reservoirs, rivers, channels and water users are configured and a relationship or link is created where a link exists on the ground. Reservoirs, rivers and channel operating rules are configured or detailed in the water-allocation modelling setup to realistically represent the operation of the catchment in the modelling framework.

Stochastic streamflow

Stochastic streamflow values are generated using a stochastic streamflow generator (e.g. STOMSA) from naturalised streamflow data/values. Naturalised streamflow refers to flows that would have occurred without an anthropogenic effect. The naturalised flows are estimated by subtracting the anthropogenic effect from the historical or simulated streamflow data. The anthropogenic effect could be summarised as past human activities in the catchment (e.g. past water use for economic and social benefits).

Traditionally, in South Africa, the anthropogenic effects are estimated using different models (e.g. past irrigation water use is determined using the WQT model). However, another approach to determine natural flows could be to use a suitable physical process based rainfall-runoff. The naturalised flows are simulated by using historically observed rainfall and natural past landuse (e.g. Acocks Landover).

Demand time series

Demand time series are monthly/daily time series that are legitimate claims of the water users. In areas where the legitimate claim figure is available from a relevant authority (e.g. Irrigation board), the water allocation figure is used. However, as the licensing process is still in progress, the demand time series are estimated using different models (e.g. irrigation water demand is determined using WQT model). International Trans-boundary flows are also included as demand time series in the modelling framework.

Evaporation and Seepage losses

Significant water is lost from reservoirs, rivers and channels through evaporation and seepage. It is important to account for the water lost from the system in the modelling framework. The losses are represented as time series in the modelling framework and, in arid and sub-arid climate areas, evaporation losses have a big impact on catchment yield.

Framework outputs

The outputs from the probabilistic approaches are stochastic yield-target draft graphs and short or long term yield curves, as shown in Figure 3.3 and Figure 3.4.

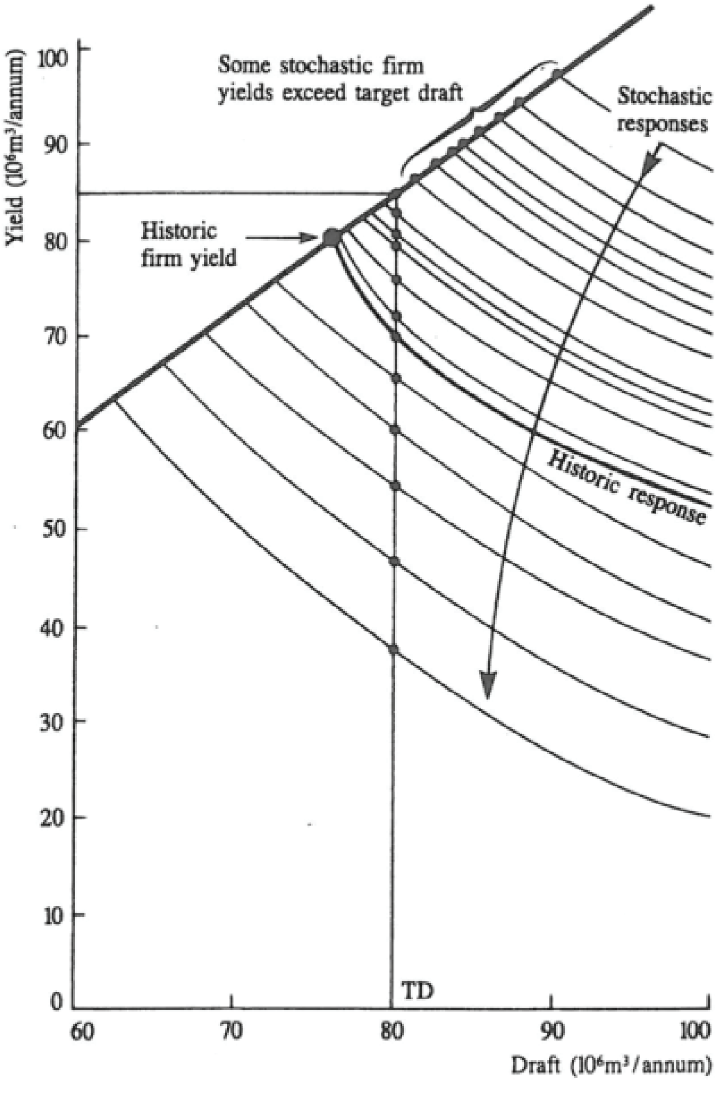


Figure 3. 3: Stochastic Draft-yield curve (Basson *et al.,* 1994)

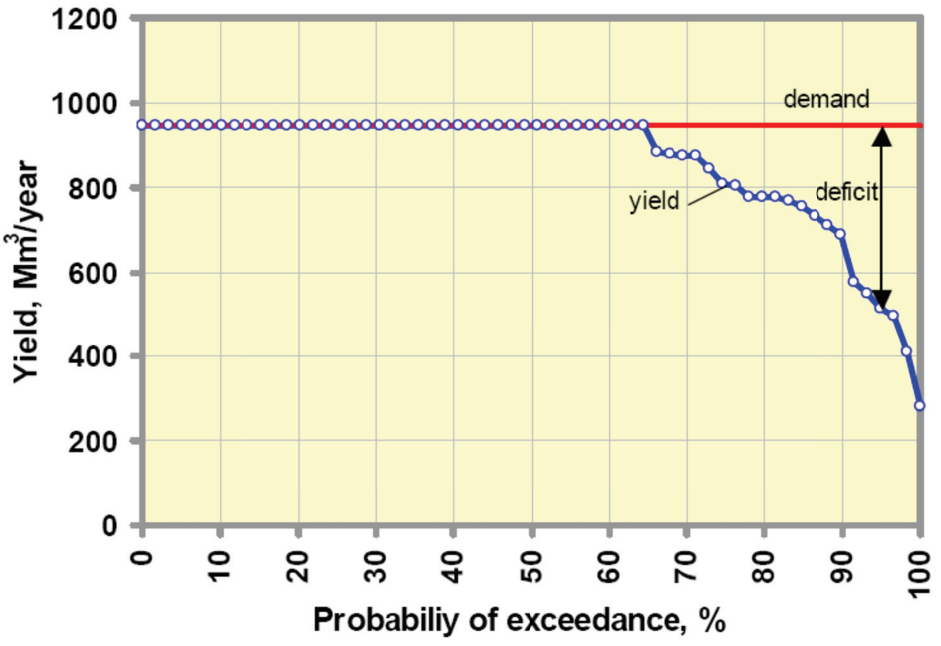


Figure 3. 4: Probability of exceedence of a system/catchment (Findikakis *et al.,* 2003)

3.1.2 MODEL DEVELOPMENTS FOR APPLYING THE CATCHMENT WATER RESOURCE MODELLING FRAMEWORK

It was necessary to develop a catchment-scale modelling framework which could be used to test various scenarios to deal with the over-allocation. Scenarios include options such as building one or more dam/s, changing dam-operating rules, or imposing curtailments on water users. As a probabilistic approach is used by Water Resource Planners in South Africa to determine the extent to which catchments are over or under-allocated, and these planning approaches are not formally included in MIKE BASIN, certain new routines were developed to enable MIKE BASIN to perform the functionality required to successfully complete probabilistic evaluations.

3.1.2.1 In-stream Ecological Water Requirement Implementation

The 1998 National Water Act has recognised the importance of "Reserving" an amount of water to sustain ecological process (NWA, 1998). This is known as the Ecological Water Requirement. The Riparian Rights system which preceded the 1998 NWA did not make specific provision for EWRs. The inclusion of EWRs to the water balances of catchments throughout South Africa has led to some of the catchments becoming over-allocated. The compulsory licensing process is the process whereby water may be re-allocated from existing water users to the environment and/or other users which should be granted water according to the letter of the new National Water Act.

Human activity in a catchment to utilise the resource for economic and social benefits affects the balance of river ecology. Various water-related infrastructure to store water, or to divert water from its natural course, are typical human interventions in a catchment and such activities impact heavily on the ecological health of a river. In the Crocodile Catchment there is one major dam(the Kwena Dam) and four sub-catchment supply dams, where their main purpose is to supply water to water-users. According to the National Water Act (1998), the Ecological Water Requirements (EWRs) and Basic Human Needs (BHNs) have a first priority call on water resources, though the exact amount of water required for the EWR has been controversial. A number of EWR sites have been identified in the Crocodile Catchment. In each of the EWR sites, a Class of Instream EWR is recommended to maintain the ecology of the river. Where a flow duration curve is developed for each ecological class – and this can be translated to a demand time series for environmental use, where it can be input as demand time series as shown in Figure 3.5.

A general modelling framework has been developed to implement the In-stream ecological water requirement at these different EWR sites of the Crocodile catchment. A script (macro) was written in the Vb.net platform to run a MIKE BASIN Crocodile setup and produce the flow required at each of the sites, based on flow duration curve recommended for each sites. The conceptual description of the framework is shown in schematic diagrams as shown in Figure 3.5. The first step in implementing EWRs at the EWR sites, or minimum flow at an outlet, is to simulate naturalised streamflow for the sub-catchments of the Crocodile Catchment. Natural vegetation is used as the land-use to simulate naturalised flows. Use was made of the *ACRU* process-based rainfall-runoff model.

In implementing the new Reserve, monthly flow duration curves of EWR sites are translated into daily minimum flow requirements at each EWR site. A daily minimum flow requirement from each sub-catchment is calculated proportional to the naturalised flow of each sub-catchment, respectively. The daily minimum flow requirement from sub-catchments is translated into daily minimum flow requirements at each water-user intake. Therefore, whenever the daily flow at water-user intake is lower than the daily minimum flow EWR at that respective node, the MIKE BASIN algorithm restricts water user/s on based on priority operating rules, with the EWR receiving water before the water users.

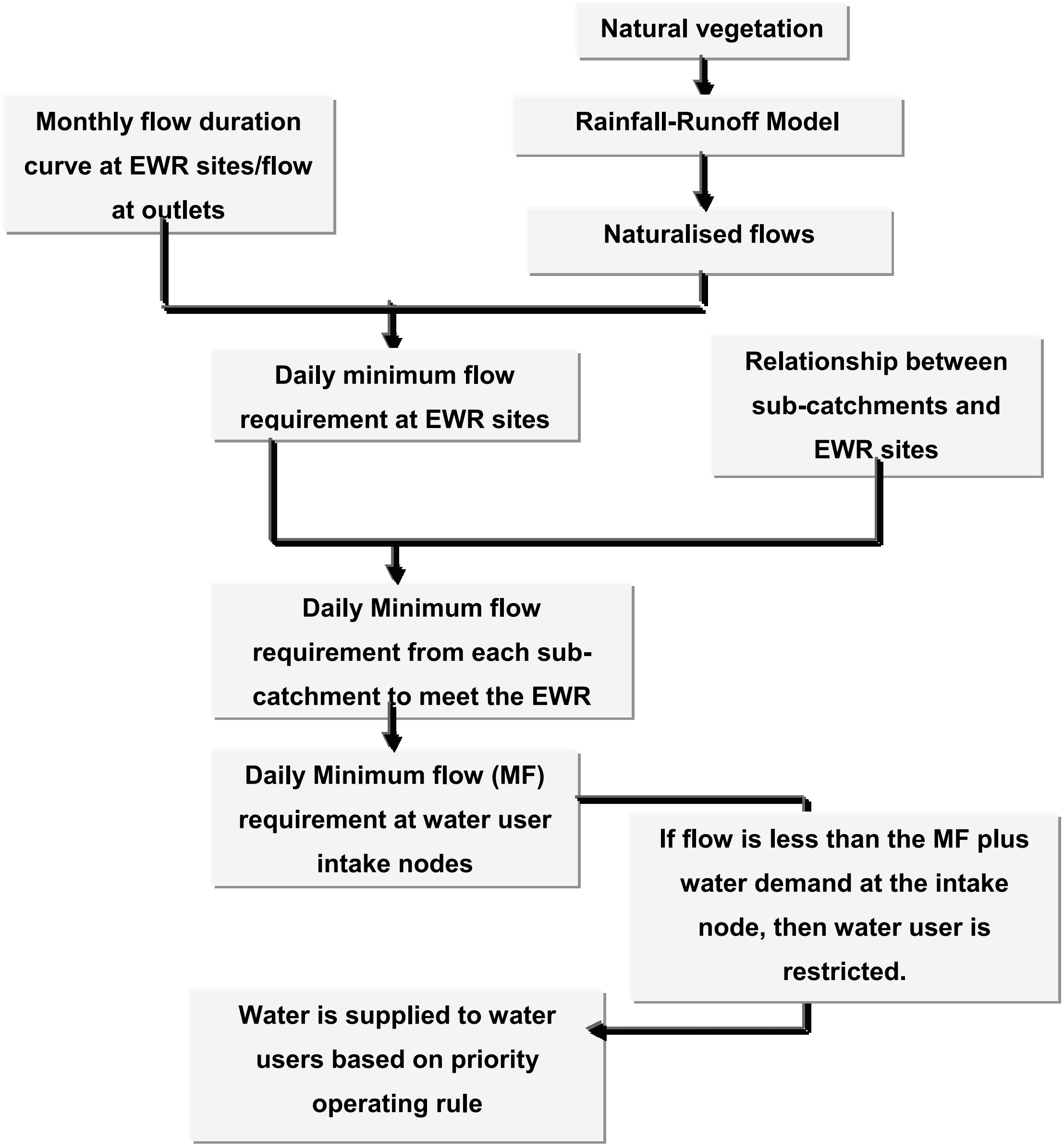
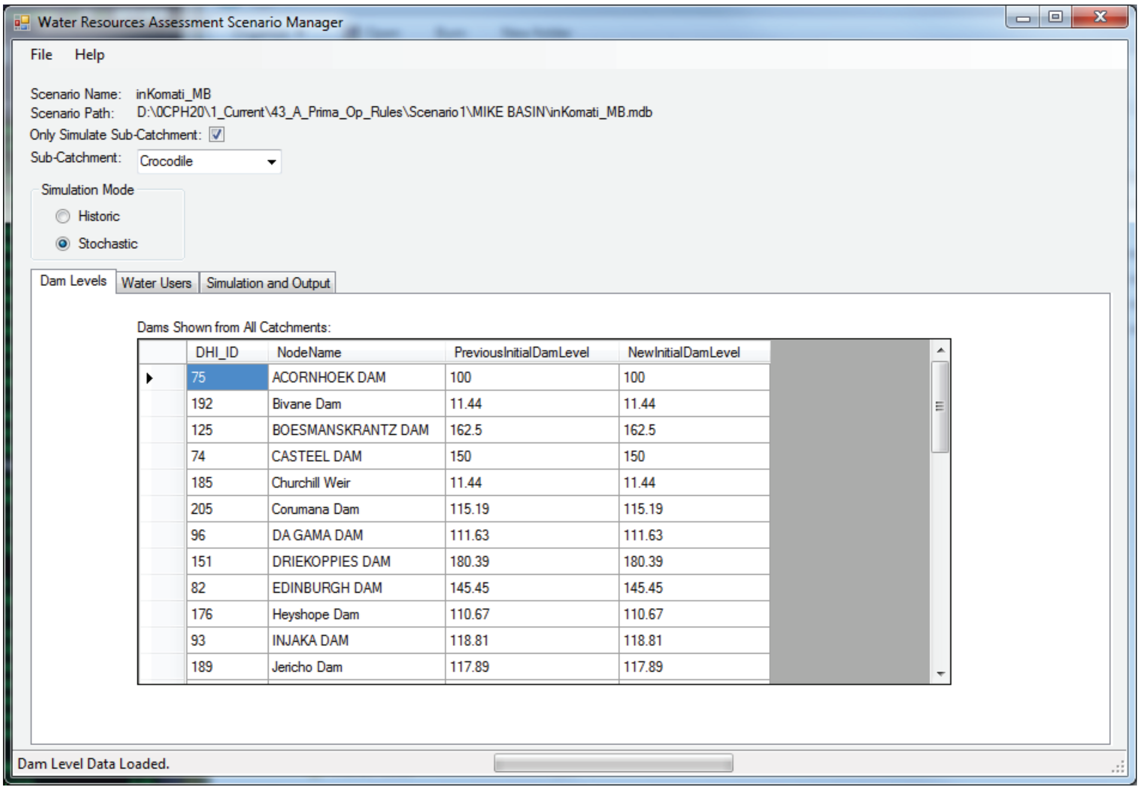


Figure 3. 5: **Schematic diagram of the modelling framework developed to implement the EWR**

The relationship described in Figure 3.5, i.e. between the sub-catchment/s and the EWR sites, refers to the contribution of the sub-catchment towards the EWR at the site. If the sub-catchment is expected to contribute a share of the flow at the EWR site, then there is a relationship and the contribution from the sub-catchment is calculated in the framework.

3.1.2.2 *Simplified Graphical user interface to enable the running of a probabilistic risk based assessment in MIKE BASIN*

The probabilistic risk-assessment approach to catchment water resources is performed using a number of stochastically generated streamflow sequences as model inputs – which are then processed to develop meaningful indicators that show the status and future risk levels of the catchment for a particular scenario. The probabilistic approach is not currently an in-built feature of the MIKE BASIN model. There was thus a need to add the probabilistic approach to MIKE BASIN. In this project, a simplified Graphical user interface for MIKE BASIN, Water Resource Assessment Scenario Manager (WRASM) as shown in Figure 3.6, was developed to perform the probabilistic risk assessment for different scenarios and to view the processed/developed outputs of the Scenarios. The simplified graphical user interface is built in the Vb.net Interface, which allows users to access the Crocodile Catchment MIKE BASIN setup. Users can change initial dam levels, amount and distribution of water requested by water user/s make historical or stochastic simulation runs through the graphical interface. In the WRASM, there is a functionality which allows users to see processed statistical outputs in an Excel framework, both for the historical or stochastic simulations.



Scenario Name: inKomati_MB
Scenario Path: D:\0CPH20\1_Current\43_A_Prima_Op_Rules\Scenario1\MIKE BASIN\inKomati_MB.mdb
Only Simulate Sub-Catchment: ☑
Sub-Catchment: Crocodile

Simulation Mode
○ Historic
● Stochastic

Dams Shown from All Catchments:

DHI_ID	NodeName	PreviousInitialDamLevel	NewInitialDamLevel
75	ACORNHOEK DAM	100	100
192	Bivane Dam	11.44	11.44
125	BOESMANSKRANTZ DAM	162.5	162.5
74	CASTEEL DAM	150	150
185	Churchill Weir	11.44	11.44
205	Corumana Dam	115.19	115.19
96	DA GAMA DAM	111.63	111.63
151	DRIEKOPPIES DAM	180.39	180.39
82	EDINBURGH DAM	145.45	145.45
176	Heyshope Dam	110.67	110.67
93	INJAKA DAM	118.81	118.81
189	Jericho Dam	117.89	117.89

Dam Level Data Loaded.

Figure 3. 6: Simplified graphical user interface for MIKE Basin

3.2 INTEGRATED FARM SCALE MODELLING

A key focus of the research project was to determine the impact of changes in catchment operating rules or the imposition of curtailments on irrigation farming profitability and livelihoods. This objective was achieved through the application of an integrated hydro-economic modelling framework that uses compartment modelling. The previous section described how MIKE BASIN was used to quantify the impact of changes to the operating rules on water availability. The main emphasis of this section is to explain the procedures that were used to translate these changes in water availability to changes in irrigation farming profitability and the irrigators' livelihoods through the application of the integrated hydro-economic modelling framework.

An overview of the integrated modelling framework is given next, followed by a more detailed description of the specific models used to model the impact of changes in water availability on irrigation farming profitability.

3.2.1 INTEGRATED HYDRO-ECONOMIC MODELLING FRAMEWORK

The MIKE BASIN model is referred to as a node-and-channel network model. There are different types of nodes, including nodes to represent catchments, nodes to dams and nodes to represent water uses. The channels represent rivers, pipes, canals and other links between water sources and water users. The MIKE BASIN model requires time-series of river flows, details of dams (e.g. the height, volume area relationship of dams), and a time series of water demands by water users. There are two options with which a time series of water demands can be specified in MIKE BASIN. The first option can be referred to as a pre-determined time series of water demands. The second includes a model which dynamically calculates demands specifically for crops. The model considers the type of crop, the area of the crop, weather and soil moisture conditions. This MIKE BASIN Irrigation Model (MBIM) is dynamic water demand calculating model which can be described as a soil water balance model, which computes crop water requirements under given climatic and field conditions/constraints. It is built as an optional module in MIKE BASIN, where the MIKE BASIN catchment model handles the allocation of the available water to different users according to the operating rules and local/global priority institutional arrangement of the catchment. The MBIM computes the crop water requirement and requests water accordingly and it computes the crop yield from field/s, although it doesn't translate the crop yields from the field/s into monetary value, or doesn't advise the optimal approach for maximum profit under giving constraints. The economic water use optimisation (WUO) model factors in all the constraints of the farm and prescribes irrigation schedules that will maximise total farm gross margin.

The WUO model includes a simplistic farm-scale soil water budget. It assumes the water demand calculated, or the water allocation of the farm is available at the time it is requested, considering pump capacity and other farm constraints. It has no knowledge of the dynamics of the catchment water availability, whereas the MBIM simulates the catchment and farm hydrological dynamics, but has little or no knowledge on the economics or financial aspect of the farm. A farmer manages a farm as an entity with consideration of water availability, financial capacities and hydrological dynamics of the farm. Therefore, a farmer requires catchment water availability information, soil water budget knowledge of the farm and financial constraints and opportunity to make informed and profitable decisions.

Kirda and Kanber (1999) believe that there is a shift in irrigation management practices. They point out that the ever increasing competition for water, economic pressure and negative effect of irrigation on the environment will motivate the economic efficiency, rather than crop water demand. Hence, in order to help a farmer to make informed and profitable decisions based on scientific findings, it is imperative to integrate the best of the two disciplines, namely hydrology and economics. One of the main objectives of this project is to integrate the MBIM with the WUO model to show the impact of different future scenarios on farmer finances. As explained above, the MBIM is built to be accessible through the COM interface, while the WUO model is built using the General Algebraic Modelling System (GAMS), which could be called using command text in the COM interface. Therefore, a logical flow of information between the MIKE BASIN *irrigation model* and GAMS WUO model was designed as shown in Figure 3.7.

The WUO model optimises financial opportunities by allocating water between different irrigation fields, and takes into consideration the different irrigation technologies used on each field. There are two ways of checking if the optimised response is hydrologically feasible; that is whether the water demand required for the optimised response could be supplied from the catchment hydrological system. The first option is to correct the changed parameters in the MBIM and run the MIKE BASIN Irrigation model to establish that the total water demand of the farm is not above the water allocation amount of the farm; and that the daily water demand profile of the farm can be supplied with little or no restrictions. The second option is to represent the farm using a demand node with a pre-determined demand profile, or time series, outputted by the optimisation model and to evaluate the feasibility of supplying the required amount from the different sources in the catchment. It shall be noted that the second option will not cater for the return flow from the irrigation farm.

If the required daily amount of water by the farm is not available from the different sources in the catchment to the farm, then weekly available water to the farm is fed back to the optimisation model to optimise the financial opportunity with added constraints.

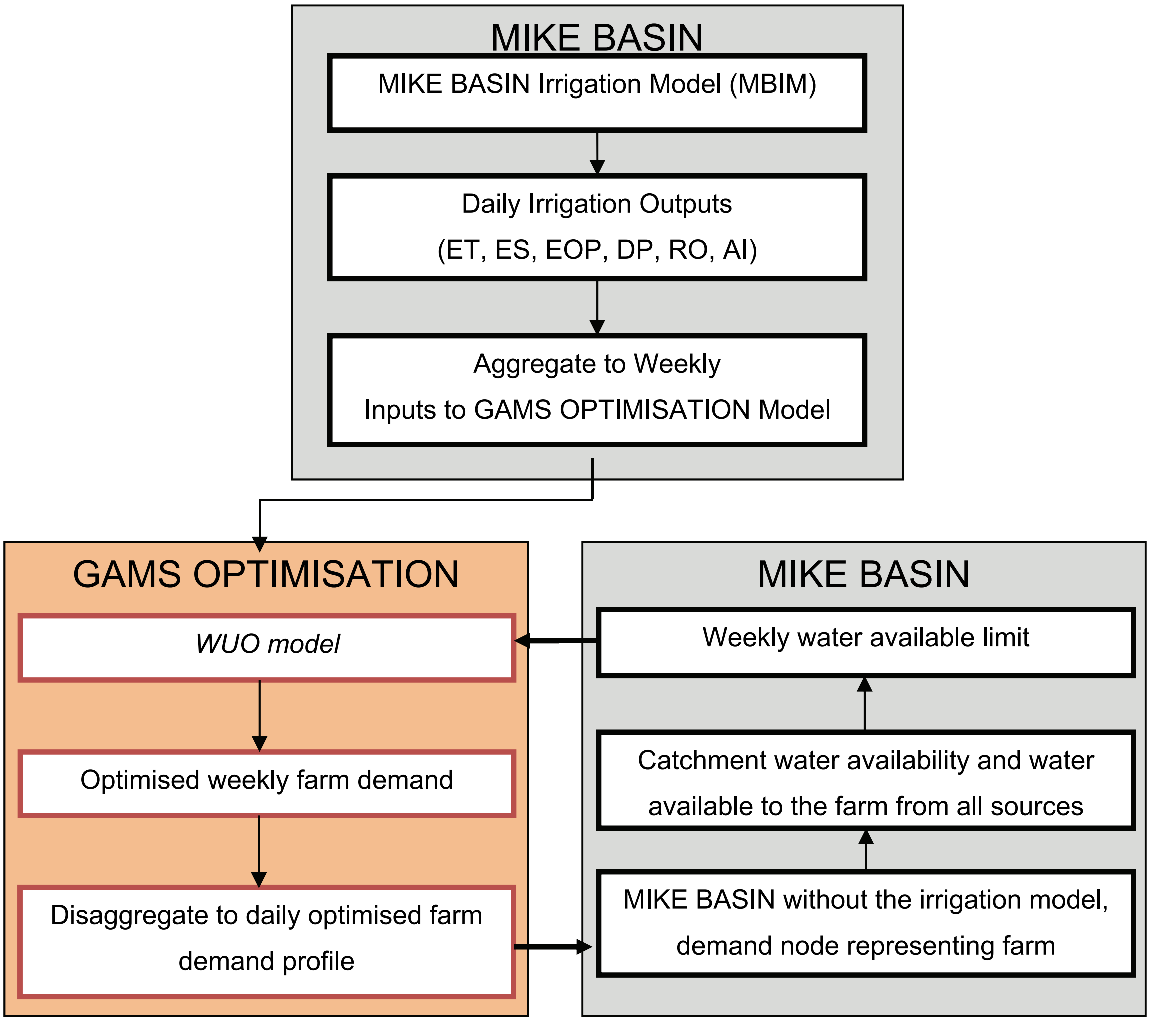


Figure 3. 7: **Description of MIKE BASIN Irrigation Model and Water Use Optimisation Model Integration**

In the next sections the MBIM and the water use optimisation model are discussed in more detail.

3.2.2 MIKE BASIN IRRIGATION MODEL (SCS SOIL WATER BALANCE MODEL)

Irrigated agriculture often exerts a major influence on the water balance of a catchment. The impacts of irrigated agriculture on available water supplies and *vice versa* are, therefore, key aspects of any proposed changes to water resources management and allocation. However, existing water resources planning tools and methods used by the Department of Water and Environmental Affairs (DWAE) have a very coarse temporal and spatial representation of the irrigation water balance. For example, in the Water Quality TDS WQT irrigation model (Allan and Herold, 1988) – a simulation software system developed to assist in the evaluation of salinity related management measures – is used to represent irrigation in Vaal River System and other water resources systems in South Africa. In the model, there are so-called ‘return flow factors', 'rainfall efficiency factors' and 'irrigation efficiency percentages'. These 'factors' can have independent values ranging from 0 to 1 (or 0 to 100 for the percentage) and are reported to be set by so-called 'fundi's', rather than related to physical characteristics of the environment, the type of irrigation and its management.

To undertake scenario analyses for water resources planning and operations with fixed/calibrated and independent 'factor values' (for example, for irrigation return flows), is of dubious value. Irrigation efficiency, uniformity and return flows are inter-dependent. They also depend on, amongst other things, catchment water supply constraints and water management/scheduling approaches. Furthermore, to assess potential impacts of water supply constraints as may occur with water-allocation reform, or the implementation of different levels of the reserve, associated crop yield and economic impacts should be assessed.

DHI have developed a very powerful network analysis tool for water-resources planning and management. Amongst other things, the tool, MIKE BASIN, has unique capabilities in terms of being able to represent the fractional water-allocation and capacity sharing institutional arrangement. However, the standard irrigation module in MIKE BASIN was relatively simple and did not adequately represent either the inter-dependence of irrigation efficiency, uniformity and return flows or the dependence of these on water management approaches. Furthermore, crop yield impacts were not represented so the economic consequences of, for example, various water supply options/allocations or mitigating management strategies were difficult to assess.

The *ACRU* agro-hydrological model is well-proven and very capable of representing irrigation water supply and demand and associated crop-yield impacts in an integrated fashion. However, a limitation of the *ACRU* model is that it cannot represent complex catchment operating rules and constraints; and only a limited number of crops are represented in the crop yield predictions.

To overcome constraints in representing irrigation and crop-yield impacts in water resources planning studies, a new irrigation module was developed and linked to the MIKE BASIN model. In the new integrated modelling system, the *ACRU* or NAM or MIKE SHE model is used to simulate the catchment rainfall / runoff response. The runoff information generated from the hydrological model is used as an input to the MIKE BASIN model. The new irrigation module is used to simulate irrigation crop water demands on a daily basis based on the crop, growing environment, type of irrigation system and irrigation management approach. The irrigation crop water demands are sent to MIKE BASIN as a demand node request. Depending on the operating rules governing water supply, and the runoff generated during a particular time period, the MIKE BASIN model determines how much water is available to meet the irrigation crop water demand request. The application of available irrigation water is then simulated in the new irrigation module, and any return flows generated are then fed back to MIKE BASIN and potentially become available for downstream, or ground-water, abstraction. It is important to note in this study, a return flow from Mhlati Farm is simulated, but it wasn't made available to downstream or groundwater. The new irrigation module can also be used to predict the crop yield response to the simulated water supply and demand scenarios. A schematic of the integrated modelling system is shown in Figure 3.8.

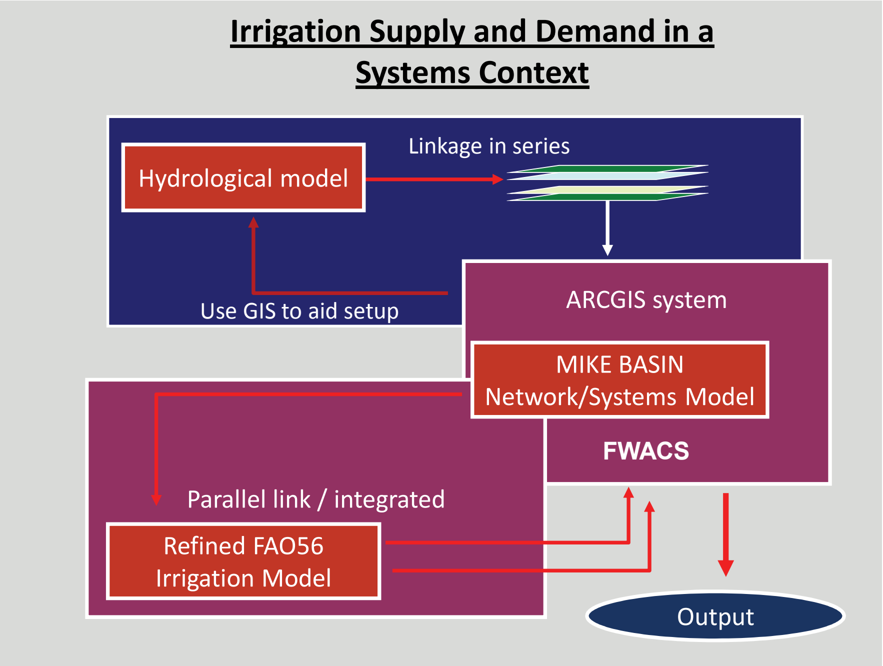


Figure 3. 8: An integrated modelling system for scenario analysis in water resources planning and operations (after Hallowes and Lecler, 2005)

The MBIM is an optional sub-model in MIKE BASIN, which when selected will determine the water demands of the irrigated crop/s dynamically. This is important when one is working on scenario cases or optimisation. For example, if one is looking at how to optimise crop yield during drought season, this can be achieved by assessing different scenarios of area irrigated, field water supply priority or irrigation scheduling strategy. The water balance and crop yield algorithms are described as well as the irrigation scheduling options and water supply constraints.

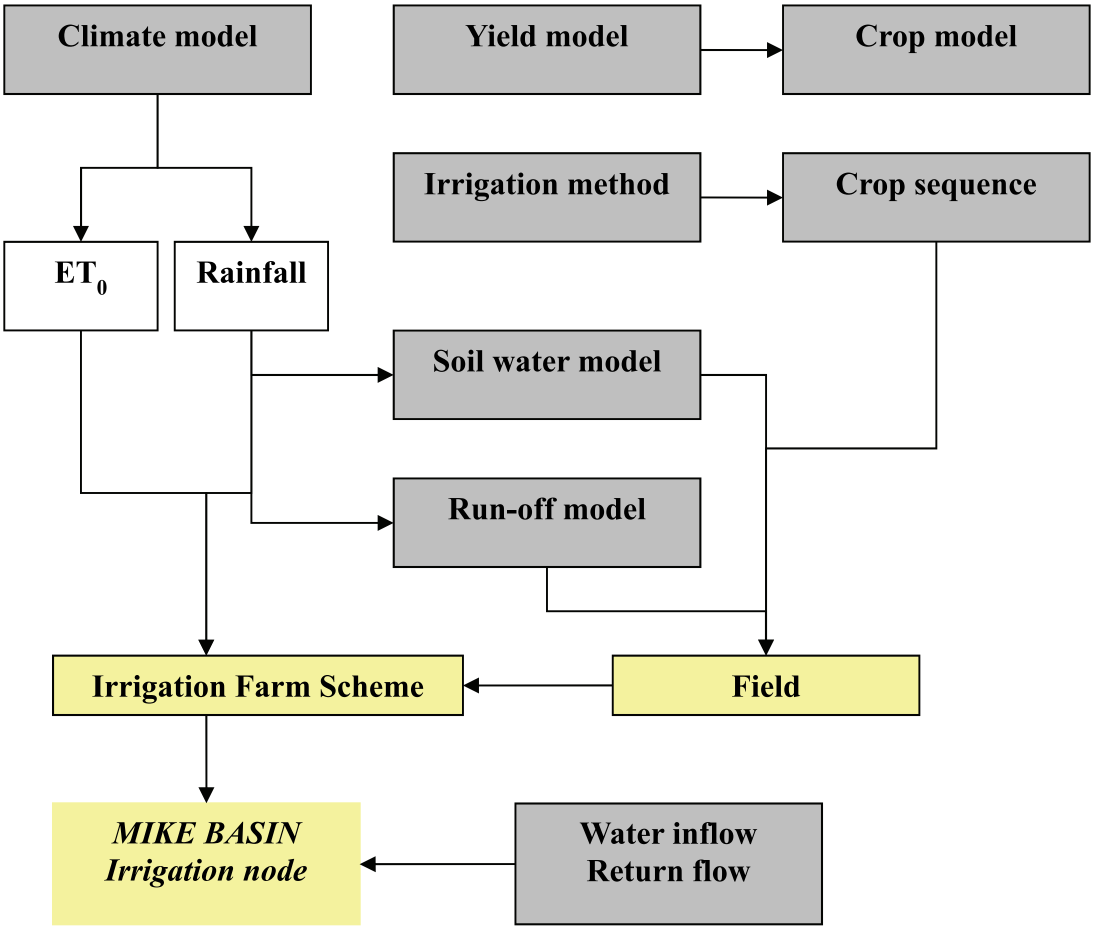


Figure 3. 9: **Schematic diagram of the MBIM flow of process**

The complexities of water budgeting (Figure 3.10) were integrated in the form of robust algorithms based on leading research reported in, *inter alia*, the Food and Agricultural Organisation Irrigation and Drainage Paper No. 56 (FAO 56, Allen *et al.,* 1998) the *ACRU* 3.00 Theory Manual, Schulze (1995) and the *ZIMsched* 2.0 irrigation and crop yield model developed by Lecler (2004). The following processes are represented in the new irrigation module, named MIKE BASIN *Irrigation model (MBIM):*

- Evaporation from the soil surface and transpiration in relation to:
    - Atmospheric evaporative demand
    - Available soil water, including excess and/or deficient conditions
    - Crop and rooting characteristics of different crops,
    - Irrigation system type, for example, sub-surface drip irrigation versus overhead sprinkler irrigation
    - Irrigation scheduling approaches
- Stormflow (surface runoff)
- Deep percolation.

The processes listed above have a bearing on:

- Irrigation efficiency
- Rainfall effectiveness
- Irrigation return flows

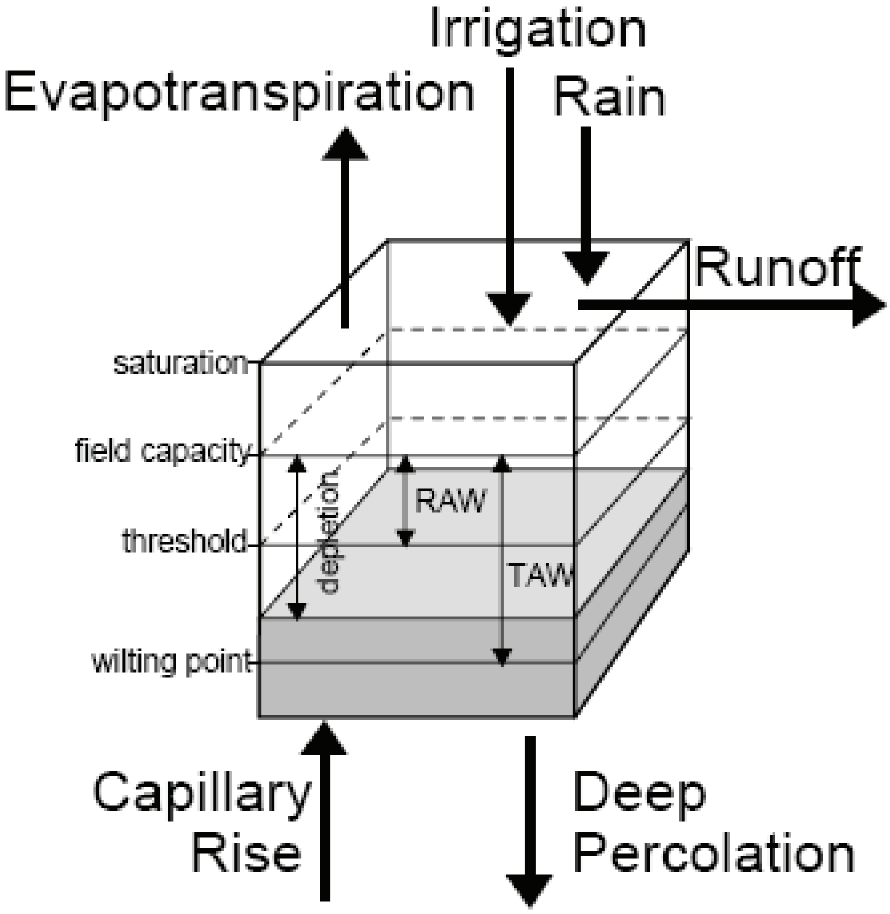


Figure 3. 10: Irrigation Water Balance

A summary of the algorithms used in the MBIM and a discussion on their validity follows.

3.2.2.1 *Evaporation*

In the MBIM, evaporation from the soil and the crop are determined separately, based largely on the algorithms described in the FAO Irrigation and Drainage Paper No. 56 (FAO 56, Allen *et al.,* 1998). It was very important to separate these processes because, prior to the development of significant canopy cover, water losses are dominated by evaporation from the soil surface. This evaporative loss can be very variable because different types of irrigation systems wet different fractions of the soil and there are also variations in wetting frequencies. Effective early season water losses and associated crop coefficients can thus vary significantly, depending on the type of irrigation system and its operation.

The main modification to the algorithms given in FAO 56 (Allen *et al*., 1998) involved small refinements to the procedures used to calculate the soil surface water evaporation coefficient (K_e). The calculation of the soil surface water evaporation coefficient, K_e, is simplified in FAO 56 calculations, where it is assumed that all water infiltrates – i.e. zero runoff and that transpiration from the surface layer that contributes to the accumulated 'Stage 1'evaporation losses from the soil surface, (E_i) is negligible (Allen *et al*., 1998). In the MBIM, stormflow/runoff is not assumed to be zero, but is calculated using the modified SCS stormflow equation (Schulze, 1995). Transpiration from the soil layer contributing to E_i is also not assumed to be zero. The proportion of the actual transpiration for a day, that is extracted from the topsoil layer and added to the accumulated 'Stage 1' $E_{i,}$ is related to the total rooting depth and the soil water content in this layer as described by Lecler (2004).

The effects on water-uptake and crop-yield caused by either too much, or too little. water are based on algorithms used in the *ACRU* model, following research by Dijkhuis and Berliner (1988), Slabbers, (1980) and also FAO 56 Allen *et al*. (1998). Details of these algorithms are given in Lecler (2004). The relationships account for the fact that, under very hot and dry conditions, a crop will experience stress at relatively higher soil water content compared to when conditions are more cold and humid, where, even with a relatively dryer soil, the crop may not be experiencing water stress. The algorithms also account for the fact that it is harder to withdraw water from a clay soil than from a sandy soil, even if they are both at the same volumetric water content.

The MBIM has one option for representing the atmospheric evaporative demand (AED): the evaporation from a hypothetical short grass crop as described in FAO 56 (Allen *et al*., 1998). This method has become an international standard.

3.2.2.2 Runoff/Stormflow, deep percolation and return flows

Three different options of soil water model are available in MBIM. A soil water model tracks the water flow in the different soil profiles and calculates return flow/runoff from the irrigation field, deep percolation. Lecler (2004) describes one of the stormflow/runoff and deep percolation/drainage algorithms, *ZIMsched,* which has been used in MBIM. The runoff/storm flow, deep percolation and return flow algorithms are based on relationships well proven in the *ACRU* agro-hydrological model (Schulze, 1995), including verification studies on sugarcane catchments (Smithers, *et al*., 1997). A major difference between the SCS equation modified by Schulze (1995) and the original, 'Curve Number (CN) based', SCS stormflow equation (USDA, 1985), is that the potential maximum water-retention capability of the soil is a soil water-deficit calculated by daily water budgeting techniques. The soil water deficit is taken as the difference between water retention at porosity and the actual soil water content just prior to a rainfall event. This represents a substantial refinement to the 'curve number' approach to account for, amongst other things, antecedent soil water conditions and is discussed in detail in Schulze (1995).

In the *ZIMsched* option of soil water model of the MBIM, drainage due to deep percolation can take place over a number of days – during which the plant can extract water, but at a slightly reduced rate due to poor aeration. The amount of drainage and the duration of drainage are dynamic dependent on soil characteristics, antecedent soil water and the magnitude of the rainfall or irrigation event resulting in excessive soil water. Thus when compared to many other water budgeting algorithms, which assume a fixed drainage time -often of only one day – the time for the soil to drain to field capacity (or the drained upper limit), as determined in the *ZIMSched* option (the soil water model of the MBIM), is highly variable. This is a very important aspect, as the tendency to over-simplify drainage assumptions and assume drainage to field capacity in a fixed time period, which is often too short, can result in grossly inaccurate water budgets and lead to a snowballing cycle of over-irrigation and poor root aeration, with large differences between the theoretical budget and actual field conditions. Often the over-simplified water budget calculations can indicate a substantial soil water deficit when, in fact, field observations would show that soils are still close to the drained upper limit (field capacity). This discrepancy is especially prevalent with furrow irrigation, where irrigation water applications are typically excessive and 'time-to-drain' is underestimated (Lecler, 2004).

The water budget presented in FAO 56 (Allen *et al*., 1998) does not specifically account for runoff or deep percolation/drainage, but both of these processes are of great importance in a water budget when rainfall can provide a significant portion of the crop's water requirements, as is often the case in South Africa and in a catchment context where the impact of return flows on the catchment water balance can be substantial. Therefore, the incorporation of algorithms for runoff and deep percolation, as described by Lecler (2004) and incorporated into the ZIMSched option of the soil water model of the *MBIM*, was considered to be a very important refinement to the water budget described in FAO 56.

The runoff/stormflow generated in the ZIMSched option of the soil water model of the MBIM returns directly to the stream. The deep percolation can either be added to the ground water store in MIKE BASIN or returned to the stream. It will be added to the stream if the groundwater option in MIKE BASIN is not activated. However, the deep percolation enters a so-called baseflow store and a portion of the baseflow store returns to the stream according to algorithms described in the *ACRU* agro-hydrological model (Schulze, 1995). The magnitude and timing of the return flows will depend on the type of irrigation system, its management, the crop and the environment/climate where the crop is grown.

3.2.2.3 Rooting characteristics

In the *ZIMSched* option of the soil water model of the MBIM*,* the root zone which delimits the depth of soil from which water is available to the crop is dynamic – in order to account for root growth and associated soil water stress effects. The depth of the zone from which water uptake can occur, $R_{z,}$ was calculated by assuming that maximum rooting depth coincides with the development of full canopy (Jensen *et al.*, 1990) as described by Lecler (2004).

3.2.2.4 Irrigation scheduling options

The mode of irrigation scheduling can have a substantial impact on the agro-hydrology of a catchment, impacting on the water supply and demand interactions, return flows and crop yields. There are three primary options for representing irrigation scheduling in MBIM. Within these three options there are, however, an almost unlimited number of permutations – such that any irrigation scheduling mode and system likely to be used in practice can be represented. In all the scheduling options described below, the amount of water actually applied to the field and crop is limited by water-availability from the supply source, as determined by the MIKE BASIN model.

3.2.2.4.1 Irrigation with a specified cycle and fixed application amount

In this mode of irrigation scheduling, a specified amount of water is applied in a specified cycle. The amount of water applied and the irrigation cycle time (i.e. the time period in days between successive irrigation water applications), can be varied on a month-by-month basis. This allows, for example, the simulation of a typical farmer irrigation strategy where fixed irrigation applications are applied with different summer and winter cycle times. In MBIM, the irrigation cycle can be stalled for a period of time if rainfall on a particular day in the cycle exceeds a threshold amount. The delay, or stall period, is equivalent to the rainfall amount divided by the average crop evapotranspiration for the month and has a maximum value of the fixed irrigation cycle time in days. The fixed cycle / fixed amount mode of irrigation scheduling would typically represent poorly managed irrigation systems and result in excessive runoff and/or deep percolation, as well as some reduction in crop yield due to too much and/or too little water at different times in the growing season.

3.2.2.4.2 Demand mode scheduling according to a specified soil water depletion using a specified application amount

In this mode of scheduling, the user specifies a soil water depletion level below Field Capacity or the Drained Upper Limit (DUL) at which an irrigation application of a specified amount is to take place – provided a minimum number of days since a previous irrigation application has passed.

This option allows a user to assess the impacts of different irrigation system capacities and various deficit irrigation strategies. For example, compare a dragline irrigation system with the capacity to apply 42 mm in 10 days with a dragline system with capacity to apply 42 mm in 15 days. In this example, the dragline system, which can apply water every 10 days, will cost more than the system, which can only apply water every 15 days. However, the ability to apply water every 10 days, if needed, may result in much better crop yields. A user can also use this mode of scheduling to simulate different watering strategies at different months in the year. Thus, strategies which stress the crop to different levels at various times in the year can be represented and assessed.

This mode of irrigation scheduling is also useful for simulating different types of irrigation system hardware. For example, a drip irrigation system would be configured to apply a small amount of water, say, 6 mm, at a certain depletion level. A furrow irrigation system would be configured to apply a relatively large amount of water, say, 70 mm, at a certain depletion level. The associated crop and water balance responses for these two different types of irrigation system could then be very different – dependent on, amongst other things, soil properties.

3.2.2.4.3 Irrigation with a specified amounts at specified times

In this mode of scheduling, the user can simulate a known watering regime, which is read into the model from a data file containing the date and corresponding irrigation application amount. This mode of watering is useful for model verification studies, where, for example, crop yield associated with a given watering regime of an experimental trial needs to be simulated and compared to observed data.

3.2.2.5 Crop yield simulation

The Land and Water Division of the Food and Agriculture Organization of the United Nations (FAO) initiated a study, reported on in 1979, to establish generalised crop yield and water use relationships for selected important irrigated crops. It was acknowledged that developments in crop growth modelling had met with some success, but that, for practical application, a method was required to measure yield response to water supply that was:

- Simple
- Required commonly available climatic, soil and crop information/data
- Was widely applicable with acceptable accuracy
- Allowed for easy verification through adaptive research (Doorenbos and Kassam, 1979).

These requirements have particular relevance to the South African situation. In South Africa, detailed input information on climate and soils is often limiting and crop genetic parameters for South African cultivars, which are required as input to the more complex crop growth models, such as the DSSAT v3. (Tsuji, Uehara and Balas, 1994) suite of models, have only been derived and tested for relatively few crops (*viz.* maize, wheat and sugarcane). Even when sufficient input information/data is available, the expertise required to configure, operate and analyse the outputs from these more complex crop growth models often limits their useful application. There appears, therefore, to be a need for more generalised crop yield: soil water stress relationships, which can be incorporated into operational soil-water-budgeting models such as MBIM. The rationale and development of such relationships is described in this Chapter.

In order to quantify the effects of soil water stress on crop yields, Doorenbos and Kassam (1979) utilised a function relating the relative yield decrease to the relative deficit of total evaporation (i.e. actual evapotranspiration). This relationship is given below as Equation 1.

$$1-Y_a/Y_p = K_y(1-ET/ET_m) \qquad (1)$$

Where:

Y_a = actual harvested yield of a given crop (t/ha)

Y_p = potential non-water-stressed harvested yield of a given crop, i.e. reference potential yield (t/ha)

ET = actual total evapotranspiration (i.e. $T_a + E_s$, mm)

ET_m = maximum potential evapotranspiration (i.e. $T_p + E_s$, mm)

E_s = evaporation from the soil surface (mm)

T_a = actual evaporation from the plant tissue, i.e. actual transpiration (mm)

T_p = maximum potential evaporation from the plant tissue, i.e. maximum potential transpiration (mm), i.e. assuming no soil water stress effects

K_y = growth stage specific yield response factor

The response of yield-to-water supply is quantified through the yield response factor, K_y, which relates the relative decrease in yield, $(1-Y_a/Y_p)$ to a relative deficit in total evaporation $(1-ET/ET_m)$. The K_y values for most crops were derived on the assumption that the relationship between relative yield (Y_a/Y_p) and relative total evaporation (ET/ET_m) is linear and is valid for water deficits of up to approximately 50%, i.e. $(1-ET/ET_m) = 0.5$. For water deficits greater than 50%, it is likely that feedbacks to canopy development, which are not incorporated in the Doorenbos and Kassam (1979) approach, could be significant.

Values for K_y, for a wide range of crops, were derived based on the analysis of experimental field data covering a range of different growing conditions. Details of the numerous experiments analysed to derive the K_y values are given in the Appendices of the publication by Doorenbos and Kassam (1979). In the analysis of these experiments, the magnitude and duration of water deficits, expressed as relative deficits of total evaporation, were made to correspond closely to individual crop growth periods. As a result, in most cases, 80 to 85 % of the yield variations due to different water treatments could be explained (Doorenbos and Kassam, 1979).

The relationships described in Equation 1, between relative yield deficits and the relative deficits in total evaporation are affected by factors other than water – *viz.* crop variety, pests, fertilizer applications, levels of soil salinity and diseases. Therefore, Doorenbos and Kassam (1979) advised that they be applied to high-producing varieties, growing in large fields where optimum agronomic practices, including adequate input supply, except for water, are provided.

The use of relative total evaporation rather than absolute total evaporation in Equation 1, is aimed at permitting some degree of transferability between sites, since site-specific variables, *viz.* climate, may produce different absolute total evaporation values for the same amount of growth. However, researchers, such as, Vaux and Pruitt (1983) who cited the work of Stewart, Cuenca, Pruitt, Hagan and Tosso (1977) and Hanks, Stewart and Riley (1977) reported that the relative yield: relative total evaporation functions could not be freely transferred from site-to-site. From research by De Jager (1994), it can be inferred that this is because attempts to remove accounting for climatic influences by normalising total evaporation in terms of pan evaporation or maximum evaporation (ET_m) are flawed. They have had limited success because both pan evaporation and ET_m adjust to climate in a manner which differs to that in which plant evaporation (T_a) does, as has been shown, for example, by Van Zyl and De Jager (1992).

According to De Jager (1994), concerns about the transferability of the yield function given in Equation 1 can, however, be eliminated through the use of transpiration ratios (i.e. T_a/T_p) in the place of total evaporation ratios (i.e. ET/ET_m). In Equation 3.2, the influences of atmospheric vapour pressure deficits and climate-crop architecture on ET/ET_m and hence Y_a/Y_p cancel out (De Jager, 1994). Hence the yield response factor, K_y, defined in Equation 2 becomes a purely plant physiological entity and is thus determined by crop genetics and not climate. The K_y factor should thus be neither site nor climate specific (De Jager, 1994).

$$Y_a/Y_b \quad = \quad \prod_{i=1}^{i=G} [\, 1 - K_{yi}(1 - T_a/T_p)] \qquad (2)$$

Where

i = i-th growth stage in a growing season with a total of G growth periods

K_{yi} = yield response factor for the i-th growth period

De Jager (1994) tested a range of wheat yield functions, including Equation 2, using the water budgeting algorithms of the PUTU model to calculate T_a and T_p. Results of these tests showed that using a yield function based on Equation 2 with values for K_{yi} for wheat taken from Doorenbos and Kassam (1979), was the most accurate of the various different yield functions tested and that the accuracy was very acceptable for use in decision support applications.

Based on research by, amongst others, Doorenbos and Kassam (1979); De Jager (1994), Matsebula (2008) and Lecler (2004), Equation 3.2 has been adopted as an option for estimating crop yields in *MBIM*. Lecler (2004) and Matsebula (2008) reported good correlations between simulated and observed sugarcane yields using a water budget based on algorithms described in Chapter 2 to simulate T_a and T_p together with the relationship described in Equation 2.

With this facility for estimating crop yields, it is possible to plan and design, amongst other things, irrigation projects, taking into account the effects of different water supply regimes and scheduling practices on crop production – and utilising commonly available data/information.

3.2.2.6 Water supply

The MIKE BASIN model can simulate a range of water supply options. The MBIM is linked to the MIKE BASIN model at a daily time-step and thus all the water supply options available in MIKE BASIN can be used to simulate the impact of different water supply constraints and operating rules on the crop yield and water balance of an irrigated area. Options include:

- Water supply directly from a river.
- Water supply directly from a dam.
- Water supply from an off-channel storage dam.
- Water supply from any combination of the above, with given operating rules and priorities.

A representation of an irrigation farm in MIKE BASIN is shown Figure 3.11. The farm can be connected to different water sources. The farm in the irrigation model is further divided into fields, where water is supplied to fields based on equal shortage or priority basis.

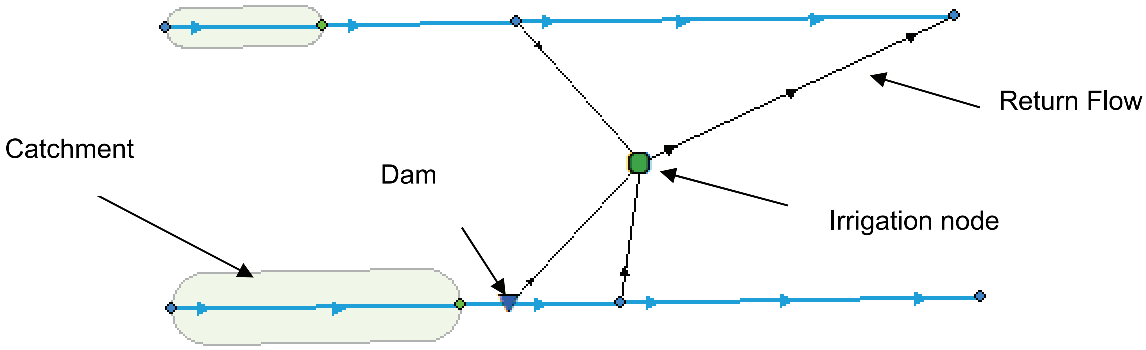


Figure 3. 11: Schematic Diagram of a MIKE BASIN setup with an Irrigation Node

A brief description of the supply options is provided together with how irrigation supply losses are accounted for.

3.2.2.6.1 *Unlimited water supply*

It is often required to simulate irrigation options assuming unlimited irrigation water supply. This can be done by configuring the MIKE BASIN model appropriately, so that excess water is available at an irrigation demand node. One way to do this is to make the irrigation area very small relative to the water supply source.

3.2.2.6.2 *Irrigation water supply from a reservoir or dam*

In this option, irrigation water supply is simulated in combination with a reservoir water balance taking into consideration associated reservoir operating rules. Irrigation requirements are abstracted from the reservoir/s provided it/they has/have sufficient water available and provided any operating rules do not enforce restrictions. The dams can be on the mainstreams or off-channel or a combination of mainstream and/or off-channel dams.

3.2.2.6.3 *Irrigation water supply from a river*

In this option, daily streamflow is abstracted at the irrigation demand mode according to the simulated irrigation demand and any associated operating rule restrictions (for example, EWRs). The streamflow remaining is reduced accordingly. In MIKE BASIN, irrigation requirements can be supplied from a combination of streams and dams.

3.2.2.7 Irrigation supply losses

The in-field water losses such as surface runoff/stormflow and deep percolation are simulated on a day-to-day basis, based on irrigation water balance. These depend on the interaction of the soil, climate, crop, type of irrigation system and the scheduling strategy adopted. Losses due to non-beneficial spray evaporation and wind drift and any conveyance losses, need to be specified by the user when configuring the model.

3.2.2.8 Sub-section summary

A key focus of the research project was to understand how an irrigation farm could, or should, respond to changes in catchment operating rules or the imposition of curtailments. A hydro-financial framework is needed to help model irrigation behaviour, as irrigators are influenced by financial considerations (and others) in their decision-making. Although an optimisation model would be used for the hydro-financial analysis, the optimisation model required meaningful inputs, which could only be generated from a physical process based model. Thus a process based crop modelling framework, based on FAO 56 and *Zimsched* 2.0, was built into the MIKE BASIN framework. Results are then taken from the MIKE BASIN Irrigation Model and fed into the economic optimisation model. Outputs from the GAMS water use optimisation model are then fed back into the MBIM.

3.2.3 GAMS WATER USE OPTIMISATION MODEL

The general structure of the SKELETON water use optimisation model is well-documented (Grové, 2006b). The main objective of this section is to describe the modifications that were necessary to model the impact of catchment-scale operating rules and water curtailments on the economic efficiency of irrigation farms. Since the modelling framework relies on an interactive linkage between MIKE BASIN and the optimisation model, a steady state was assumed. By implication no long-run adjustments to the farm structure was modelled. However, the model was setup for two different farm sizes with different irrigation technologies to demonstrate the impact of farms using more efficient irrigation technologies on water use and the resulting irrigation farming profitability.

3.2.3.1 Modelling gross margin variability

Water-use optimisation with the aim of achieving economic efficiency implies some form of deficit irrigation (English *et al*., 2002). The specific level of deficit irrigation is a function of the price of the output produced; the cost of irrigation water and the application thereof; and the productivity of water and whether water availability is constraining the optimal level of output that should be produced. A major problem with modelling the impact of irrigation water supply reliability on irrigation farming profitability is the fact that irrigation farmers' responses are dependent on the state of nature. By implication, irrigators will apply different degrees of deficit-irrigation, depending on the state of nature. State-contingent theory suggests that a production function exists for every state of nature (Quiggin and Chambers, 2006). The state of nature is picked by "nature" after, and independently of, the production decisions made by the decision maker. Therefore the responses of farmers are determined by the state of nature.

Following a state contingent approach, the gross margin of each field was calculated as follows:

$$GM_s = Y_s(AET_s(W_s|I))P_Y - W_s IC_w - Y_s(AET_s(W_s|I))VC_y - VC_a \tag{3}$$

Where:

$\mathrm{GM_s}$	Gross margin of state of nature s (R/ha)
$Y_s(AET_s(W_s\|I))$	Crop yield produced as a function of actual seasonal evapotranspiration in state of nature s (AET_s) where AET_s is again a function of the amount of water applied in state of nature s with a given irrigation technology ($W_s\|I$) (ton/ha)
AET_s	seasonal evapotranspiration (mm)
$\mathrm{P_Y}$	price of sugarcane (R/ton)
$\mathrm{W_s}$	applied irrigation water in state of nature s (mm)
IC_w	cost of applying irrigation water (R/mm)
$\mathrm{VC_a}$	area dependent cultivation cost (R/ha)
$\mathrm{VC_y}$	yield dependent cost (R/ton)

Gross income, represented by the term $Y_s(AET_s(W_s|I))P_Y$, is calculated by multiplying the sugarcane yield with the price per ton (P_Y). Important to note is that the sugarcane yield is estimated as a function of the level of actual evapotranspiration, while the actual evapotranspiration level is determined by the amount of irrigation water supplied. The gross margin is calculated by subtracting variable cost of production from gross income. Variable costs are divided into costs that are dependent on the amount water supplied to the crop ($W_s IC_w$) – costs that are dependent on the crop yield harvested ($Y_s(AET_s(W_s|I))VC_y$) and the costs that are dependent on the area irrigated.

The term $Y_s\big(AET_s(W_s|I)\big)$ represents the irrigation system specific crop water response function that is used to model sugarcane water use. Two separate functions are integrated to yield the irrigation specific crop water response function. Firstly, the Thompson (1976) sugarcane model is used to relate actual evapotranspiration to sugarcane yield. Important to note is that the literature review indicated that although the relationship between AET and crop yield may be linear, the relationship between applied water and crop yield is nonlinear. In this research, the uniformity with which an irrigation system applies water is used to approximate the non-linear relationship between applied water and actual water consumption. Next, the development of the irrigation system specific crop water response function is discussed in more detail.

3.2.3.1.1 Sugarcane yield as a function of actual evapotranspiration

The Thompson (1976) sugarcane yield function is somewhat different from other crop yield functions, since it relates crop yield directly to AET, whereas other crop-yield functions relate crop yield to a relative consumptive use deficit (De Jager, 1994). The Thompson (1976) sugarcane yield function is given by:

$$Y_s = 0.0953AET_s - 2.36 \qquad (4)$$

Application of the formula is straight forward given a good estimate of AET_s is used. AET_s is crop specific and a function of the atmospheric water demand. In the next section, it is shown how an estimate of AET_s is obtained in relation to the crop water requirements of the crop and the irrigation technology that is used to irrigate the crop.

3.2.2.1.1 Actual evapotranspiration as a function of applied water

Not all the water that is supplied to an irrigation field is consumptively used by a crop. The relationship between the uniformity with which water is applied and water deficits in the soil is discussed by Li (1998). Figure 3.12 will be used to describe the relationship in more detail.

Let us assume the irrigator needs to compensate for a soil water depletion or required depth (H_R). In normal practice, one will apply gross irrigation depth (H_G). Due to non-uniform applications, some portion of the field will receive more water; and some less with an average deficit of H_D. Assuming a uniform distribution, an irrigation system will apply water uniformly between a minimum (H_{min}) and maximum (H_{max}) level. The result is that triangle H_ROH_{max} represents areas where too much water is applied and triangle BOH_{min} or H_D areas, where too little water is applied. A deficit coefficient (C_D), which gives the percentage deficit is defined as: $C_D=H_D / H_R$. Multiplying (1- C_D) with H_R calculates the amount of water that is actually available to satisfy H_R.

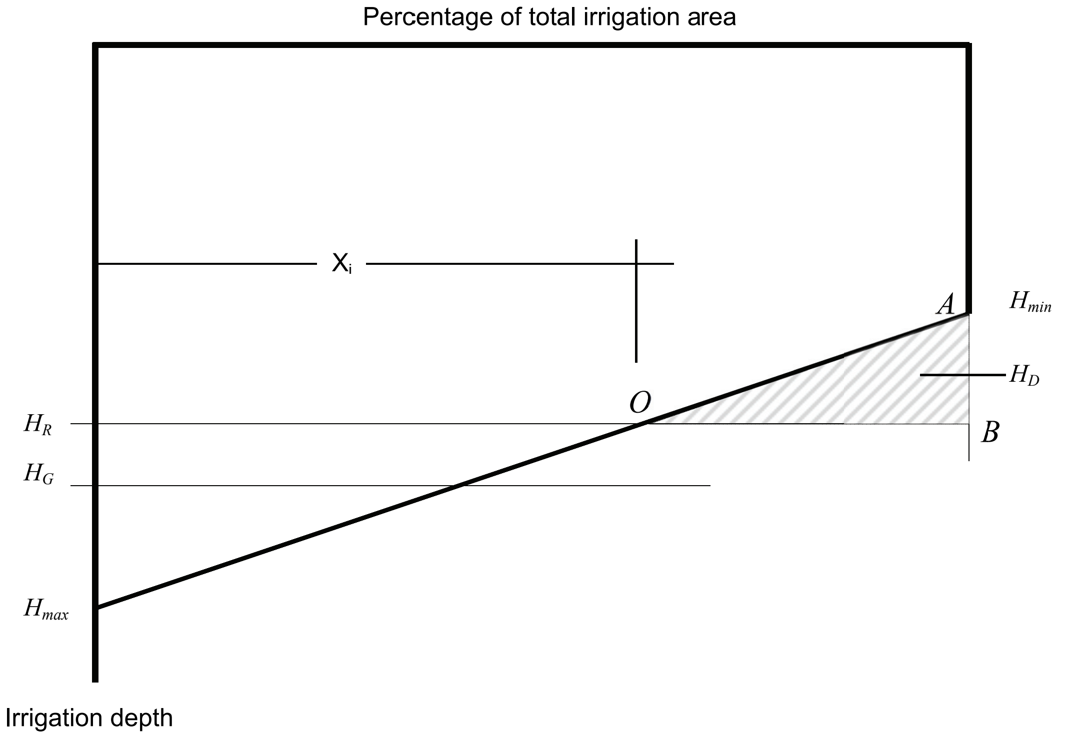


Figure 3. 12: Probability distribution of irrigation depths assuming a uniform distribution.

The relationship between the coefficient of uniformity (*CU*), H_{max} and H_G is given by:

$$CU = 1 - \frac{H_{\max} - H_G}{2H_G} \tag{5}$$

While the average amount of water applied is calculated as:

$$H_G = \frac{1}{2}\left(H_{\max} + H_{\min}\right) \tag{6}$$

For known values of *CU* and H_G it is possible to calculate H_{max} and H_{min} through manipulation of Equations (5) and (6). The relationship between C_D and *CU*, H_r and H_G is given by:

$$C_D = \left| \begin{array}{l} \dfrac{(1 - 2CU + H_R / H_G)[1 - H_G / H_R (2CU - 1)]}{8 - 8CU} \quad if \;\; H_{\max} \geq H_R \\ 1 - \dfrac{H_G}{H_R} \quad if \;\; H_{\max} < H_R \end{array} \right. \tag{7}$$

Equation (7) indicates that the relationship between H_G and C_D is linear if H_{max} is less than H_R and nonlinear if H_{max} is greater than H_R. Figure 3.12 shows the relationship between the fraction of H_R that is applied (H_G / H_R) and the fraction of H_R that is actually usable (1- C_D).

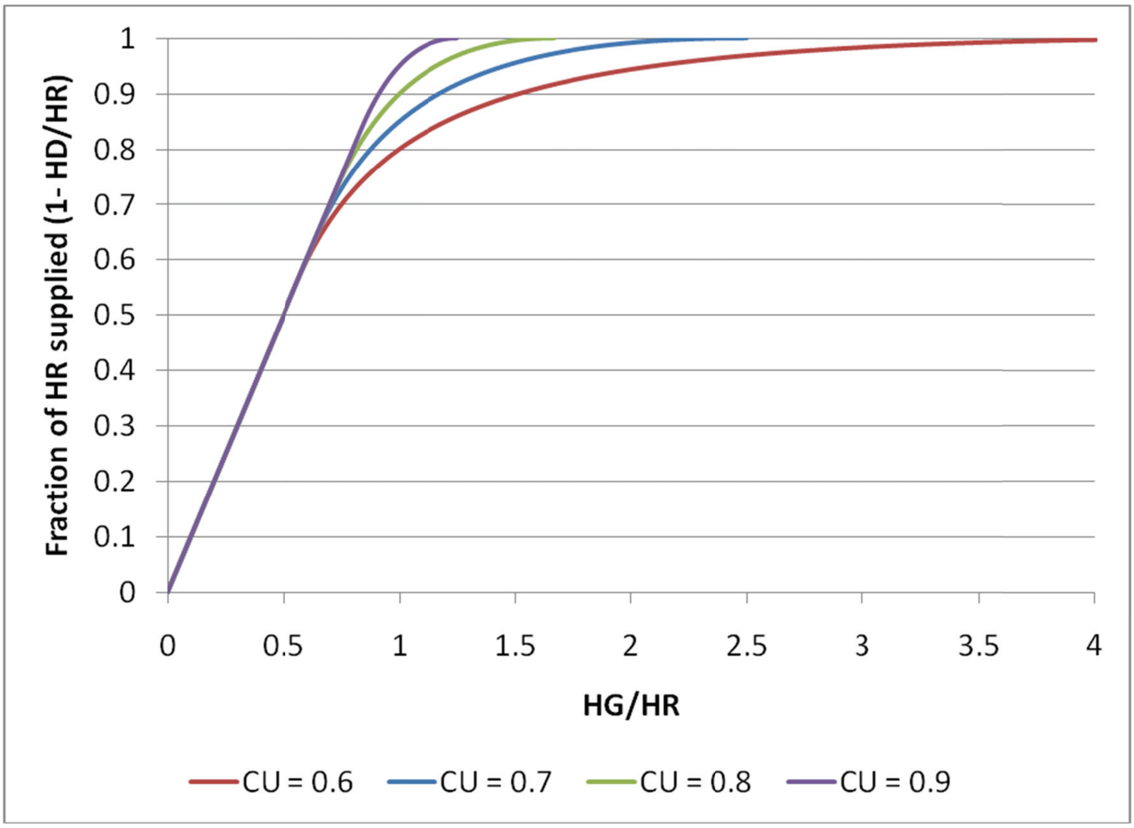


Figure 3. 13: Relationship between applied water fraction (H_G / H_R) and the usable water fraction.

The relationship portrayed in Figure 3.13 is generic since both axes are given as fractions. Thus, the usable portion of the applied water can be calculated for any amount of applied water if it is expressed as a fraction of the required amount. Application of the Equation (7) within a programming framework is not straight forward because of the “if” statement in the equation that makes it discontinuous.

Application of Equation (7) requires the assumption that the irrigation system applies water uniformly between an upper and lower bound which is a function of the uniformity of the system (CU), an estimation of the crop water requirement (H_R.) and the amount of water that is applied. An estimate of H_R. is obtained from the outputs generated with the MIKE BASIN irrigation module for each irrigation field.

3.2.3.2 Water resource constraints

The main purpose of the resource constraints is to ensure that the actual water use does not exceed the available irrigation water resulting from changes in the operating rules and local/global priority institutional arrangement of the catchment. Restrictions to maximum amount of water that can be utilised have two dimensions. Firstly, the weekly water use of the irrigation farm is restricted such that the total amount of water abstracted is less than what is available for a specific water supply scenario in a specific week. The weekly constraints ensure that the impact of changes in the distribution of water availability resulting from a specific water supply scenario on irrigation farming profitability is captured even though annual water supply security to the farm is not changed. Secondly, total annual water use is restricted to be less than the water quota of 13 000 m^3/ha. This constraint is used to model the impacts of water curtailments on irrigation farming profitability.

3.2.3.3 Calculating key performance indicators

Given the steady state nature of the optimisation model, the main objective of the optimisation model is to maximise the total farm gross margin by allocating irrigation water between multiple irrigation fields in each state of nature. The optimised total gross margin of the farm is then used to calculate key performance indicators to determine the impact of different catchment scale water management operating rules and water curtailments on the profitability of the irrigation farms; and to evaluate whether these farms will still be able to provide a decent way of living. A similar approach was used by Backeberg (1984b) to evaluate the financial feasibility of sugarcane irrigation farms in the Komati area.

3.2.3.3.1 Profitability

Key to evaluating the profitability of a farm is the calculation of the return on total assets managed (ROA) and the return on equity (ROE) (Van Zyl *et al.*, 1999).

The formulas to calculate ROA and ROE are as follows:

$$ROA = \frac{TGM-O-RM}{TA} \tag{8}$$

$$ROE = \frac{TGM-O-RM-I}{TA-L} \tag{9}$$

Where

TGM	Total gross margin of the farm (R)

O	Overheads excluding owner's remuneration for management, interest on capital and rentals (R)
RM	Remuneration for management (R)
I	Interest paid on borrowed money (R)
TA	Total assets managed (R)
L	Total liabilities (R)

Financial sustainability requires ROE to be greater than ROA to achieve a positive financial leverage, which indicates profitable employment of foreign capital. Thus, it will not be necessary for the farm to use own capital to meet interest payments. Equation (3) shows that the gross margins will be affected by the amount of water that is available for irrigation in each state of nature. Consequently, the level of ROE will be the result of the state contingent gross margins that are optimised and therefore will take on a distribution. The probability of achieving a positive leverage could be calculated, if the level of ROE at which ROE break even with ROA could be established.

The breakeven level of ROE was calculated by firstly calculating the level of TGM at which ROE will be equal to ROA. The breakeven level of TGM is then substituted into Equation (9) to calculate the level of ROE. The breakeven level of TGM, BTGM, is calculated by equating ROE to ROA and then solving for TGM as follows:

$$BTGM = RM + O + \frac{TA}{L} I \tag{10}$$

3.2.3.3.2 Livelihood

Some farmers may not be driven by profitability; rather they strive to achieve a non-operational objective (Backeberg, 1984b) such as to make a decent living from sugarcane farming. Strictly speaking a non-operational goal is not achievable in financial terms. However, it is possible to quantify such a non-operational objective indirectly if one assumes that the non-operational objective could be achieved if enough cash is produced to satisfy consumption expenditure (Backeberg, 1984b). Given the assumption that the farm manager's remuneration is used to pay for consumption expenditure, the net cash flow surplus/deficit is calculated as follows:

$$CS = TGM - O - I - C - RM \tag{11}$$

Where

C	Capital payment on borrowed money (R)

A positive cash surplus implies that enough cash is generated to achieve the non-operational goal of making a decent living from sugarcane farming. On the contrary a deficit implies that the goal is not met.

3.3 HYDROLOGICAL CATCHMENT AND FARM-SCALE MODEL CONFIGURATION

In this Section, the model setup that is configured for the Crocodile Catchment on catchment scale and the Mhlati farm on the farm scale are discussed. In the catchment scale, the Crocodile Catchment is configured in the MIKE BASIN model, where the operating rules for the catchment are derived. In the Farm Scale, Mhlati farm is configured in the MIKE BASIN Irrigation model.

3.3.1 CATCHMENT SCALE: MIKE BASIN SETUP AND OPERATING RULES FOR CROCODILE CATCHMENT

The operations of the Crocodile Catchment are divided into specific areas. The main Crocodile River is managed with a daily release from the only major dam, Kwena Dam, in the river, which is used to supply water to the irrigation, domestic and industrial users in the area at consistent assurance of supply. White River and Crocodile Sand River are operated by the White River irrigation board and the main objective is to supply water to the white water irrigation board users (Domestic and Irrigation users), using the sub-catchment supply Dams (Witklip, Klipkopjie, Longmere, Primkop), hence there are no restrictions of water users from the dams. The other two sub-catchments, namely Kaap and Elands, have no major resources on them and users extract water from a run of river, where water is abstracted at numerous locations.

3.3.1.1 Kwena Dam operating objectives

Kwena Dam operating objectives, which are used in this study, are the operating objectives drafted by the Crocodile Irrigation Board and were used in the Kwena Dam during the period when this study was conducted. Since then, the Department of Water and Environment have revised the operating rules used in the Kwena Dam and there is a new set of operating rules for the dam. However, there is no final agreement as to which set of operating rules will be enforced or used. In this study, operating rules that are derived from the operating objectives that are drafted by the Crocodile irrigation board have been used.

The Crocodile Irrigation Board, has two approaches to the operating objectives for Kwena Dam in main Crocodile river; a normal year and a drought year approach, based on the medium term forecast including the El Nino and La Nina forecast. The forecast determines what approach will be followed for the next water year. The dam level at May will also be taken into account. The two approaches are summarized below; the first approach is identified as normal or for normal forecasted weather conditions and second approach as for a drought year forecast.

a) Normal

- The Kwena Dam level should be back above 90% the next May. An increase in dam level of more than 40% can be expected from November to May.
- The Kwena Dam level should preferably not go down below 60%, but be kept above 50% as far as possible.
- Restrictions should normally be implemented from May to October/November.
- It is assumed the turning point of the dam (when it normally starts to increase again) to be in November/December. Therefore, the level of the dam is draw down to 60% at 15 December.

b) Drought

- The Kwena Dam level should at least be back at 70% if the previous year was a drought year. Increase in dam level of 30% to 35% could be expected if it is a dry year again.
- The Kwena Dam level should not go down below 35%, but preferably be kept above 40% under these conditions.
- Restrictions will be dependent on the situation. During the first year of a drought, the restrictions will be fairly in line with the rules detailed above therefore maximizing crop production under these conditions and therefore severe restrictions from half-May to half-August and making more water available from September to January. Rainfall could change the situation overnight.
- If it is the third or fourth year of a drought and still a dry year ahead, then normally the dam would not be able to come back to the 70% level. At this stage, water is allocates just enough for the crops to survive. Normally, at this stage, most of the irrigators have cut back their area under irrigation by ploughing out their poorest fields and orchards to lie fallow until after the drought. Under these conditions, it is possible to go down to below 20%, but not lower than 15%, depending on the time of the year and the forecast.
- In a drought, the turning point is assumed to be the end of January.

Kwena operating rule curves that are developed based on the above operating objectives are shown in Figure 3.14. In the operating rule curves development, the historical hydrology is classified statistical into three categories. All the streamflow data that falls below 25 percent is classified as dry, while above the 75 percent is classified wet and the data that falls above 25 percent and below 75 percent, as normal.

The Crocodile setup in MIKE BASIN is configured to run for each of the streamflow data sequences (dry, wet and normal) with different Kwena Dam storage levels. The objective functions for dry and wet optimization exercise is to achieve 70 % and 90 % dam storage levels at the end of water year respectively.

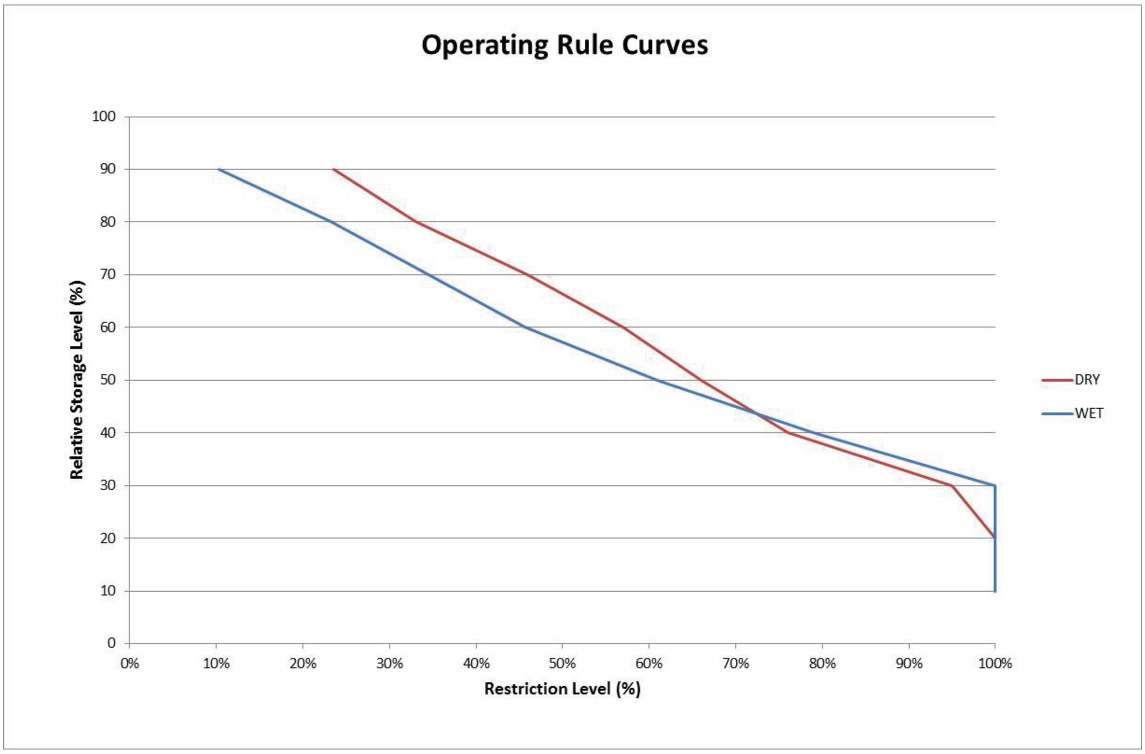


Figure 3. 14: Kwena Operating Rule curves

3.3.1.2 *International Flow Obligations*

The Crocodile Catchment is located in IncoMaputo trans-boundary catchment, which is shared between South Africa, Mozambique and Swaziland. In August 2002, the riparian countries signed an agreement (Interim IncoMaputo Agreement) on optimal and sustainable use of the Catchment. The utilisation of the water course is based on a principle of equitable use as explained in the Interim IncoMaputo agreement (IIMA) on Article 7(1), "the three countries (parties) shall be entitled, in their respective territories, to optimal and sustainable utilisation of and benefits from the water resources of the Incomati and Maputo, taking into account the interest of the other parties concerned, consistent with the adequate protection of the water courses for the benefit of the present and future generations."

The IIMA outlines the agreed flow regimes for the catchments and maximum utilisation of the water for each of the catchment management units in Incomati and Maputo water courses in AnnexI. Maximum water utilisations from the Crocodile Catchment by South Africa – outlined in Table 1, as indicated in the IIMA agreement, Article 4 of Annex I are based on the evaluation of the availability of water in the two water courses at the time the IIMA was signed (August 2002).

Table 1: IMA Maximum Utilisation of Crocodile catchment

	Mozambique	South Africa	Swaziland
First Priority Supplies*	Nil	73 million m^3/a	Nil
Irrigation Supplies	Nil	307 million m^3/a	Nil
Afforestation Area	Nil	199 715 ha	Nil
Afforestation Runoff Reduction	Nil	247 million m^3/a	Nil

As part of the PRIMA (Progressive Realisation of IncoMaputo Agreement), the above allocation might be enforced into the Catchment Management Agencies. It is important that the Crocodile Stakeholders are aware of their international obligations and the process of realisation of the agreement.

3.3.1.3 Ecological Water Requirement (EWR)

The Ecological Water Requirements (EWRs) in the seven EWR sites in Crocodile Catchments are described as flow duration curves. In this study, the flow duration curves that are expected at each site are translated into daily flows, by relating the flow duration curves and the naturalised flows at the EWR sites. Initially, a C-class EWR is assigned at the outlet of Crocodile, EWR site 6. However, a close look at the amount of water required to meet a C-class requirement has led to the adoption of a new set of flow duration curves, which is described as the “present flow regime” class. Figure 3.15, shows the naturalised flow required for a C-class EWR, excluding high flows at different probabilities of exceedence per month. Figure 3.16 shows the naturalised flows required for a “Present flow regime” EWR at different probabilities of exceedence per month.

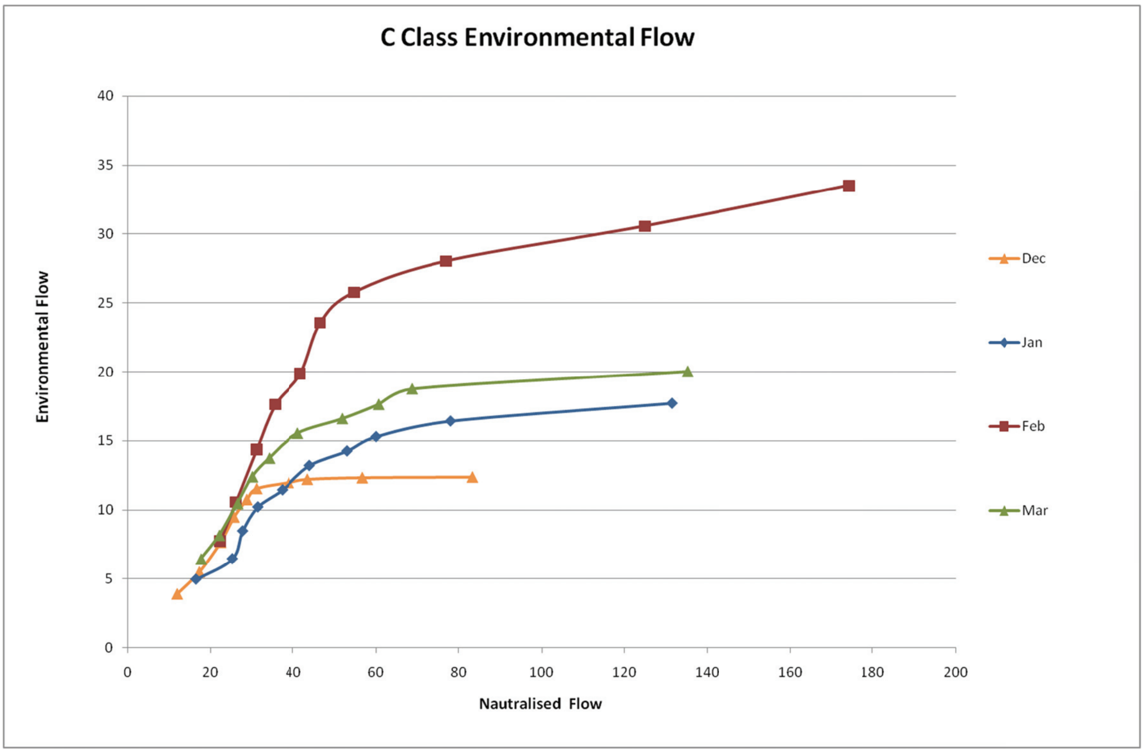


Figure 3. 15: **C-class EWR for specific naturalised flows excluding high flows at different probabilities of exceedence**

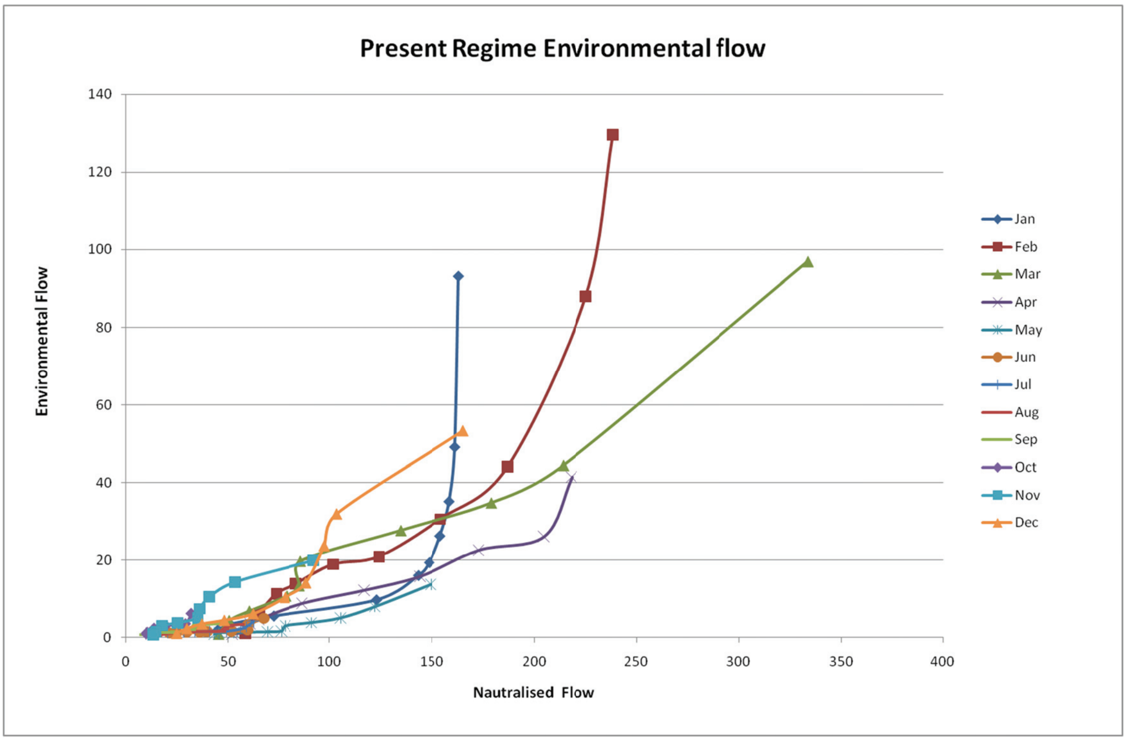


Figure 3. 16: Present regime EWR for specific naturalised flows excluding high flows at different probabilities of exceedence

In Figure 3.17, a comparison is made between a historical simulated flow at the outlet of the catchment with the current water requirement and a trans-boundary flow of 0.9 cubic meters per second against a C-class and Present environmental flow regime. The C-class requirement is greater than the historical simulated flows at the outlet of the Crocodile River for the probability of exceedence from 0.3 to 1. While the present flow regime flows are generally below the historical simulated flows, the present flow regime flows are higher than the historical simulated flows for probability of exceedence from 0.5 to 0.7.

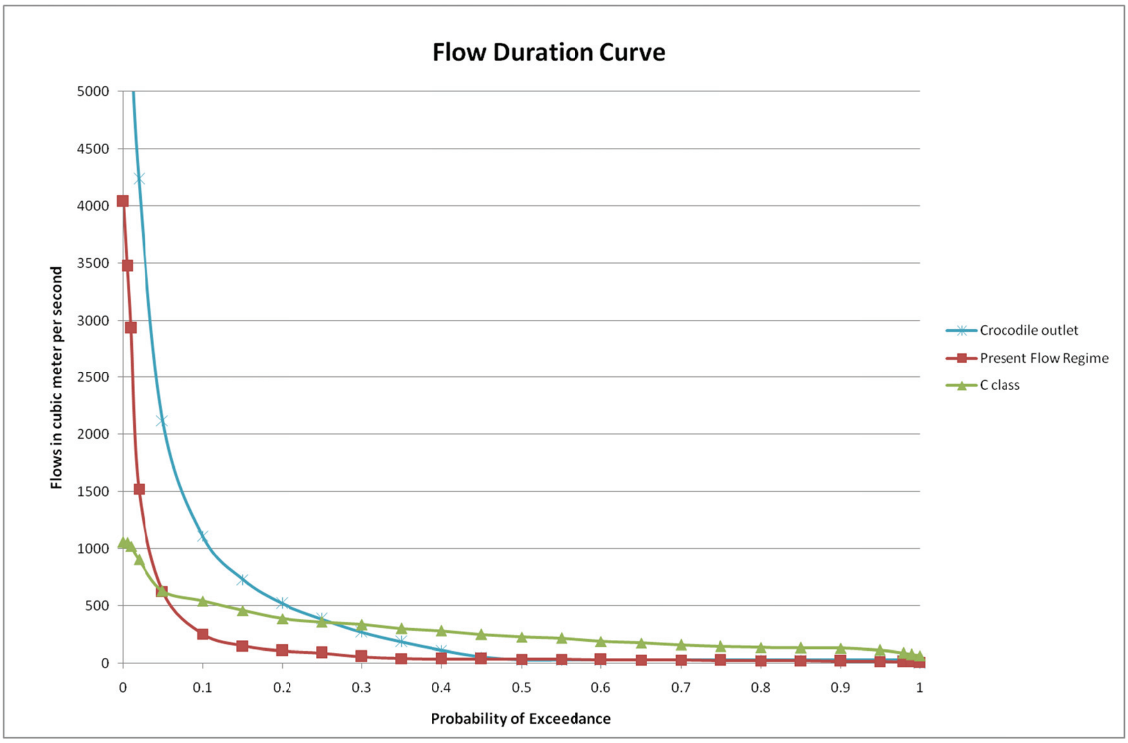


Figure 3. 17: **Comparison between flows at the out let of Crocodile catchment and C-class and Present regiment environmental requirement**

A further comparison between the EWR at the outlet of the Crocodile Catchment (C-class and Present flow regime) and the historical simulated flow for the current water requirement with a trans-boundary flow of 0.9 cubic meters per second is shown in Figure 3.18. The figure clearly shows that the C-class EWR is very high and the rivers will not meet the demand, without a significant release from the Dams (e.g. Kwena Dam) or heavily restricting water users (e.g. Irrigation water users). The present flow regime also exceed the low flow at times and the rivers fail to meet the requirement, hence, to meet the present flow regime requirement, it will require an additional release from the dams or further restriction to water users.

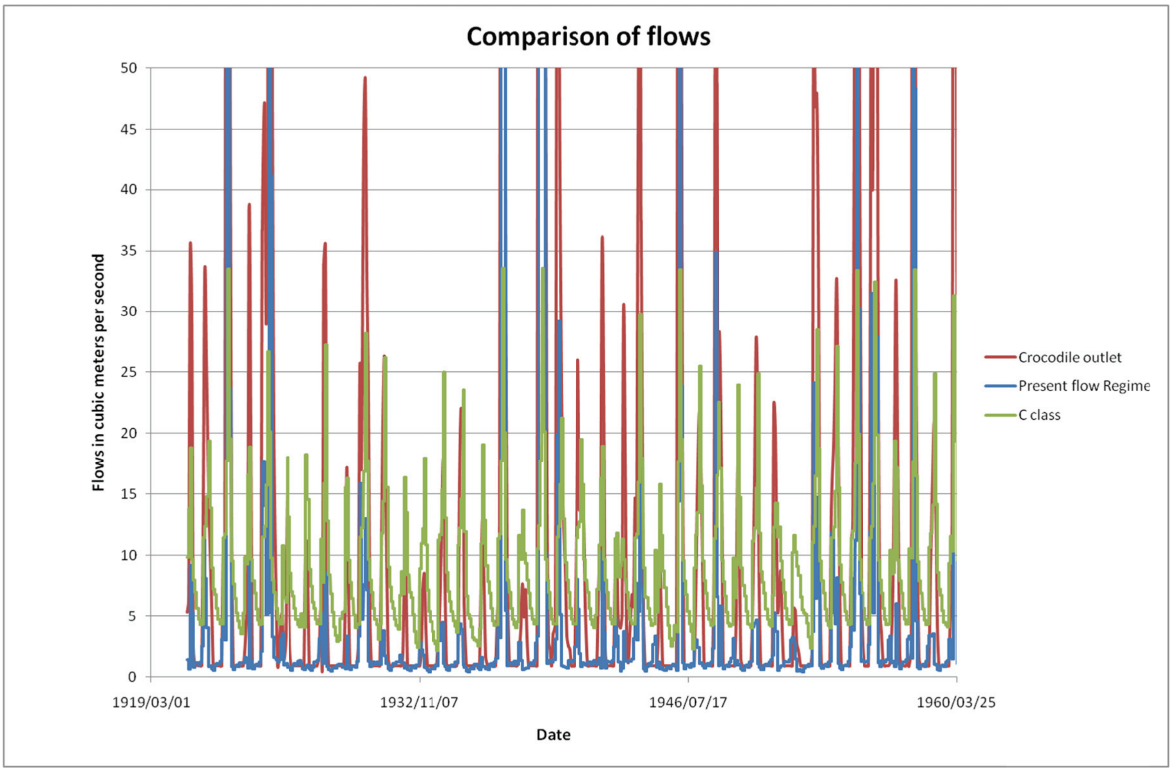


Figure 3. 18 A comparison between the simulated flows at the outlet of the Crocodile catchment for a C-class and Present regime EWRs, including an International Flow requirement of 0.9 m^3/s

3.3.1.4 Catchment scale hydrological management Indicators

Catchment indicators are indicators that explain the status of water availability in the catchment. Catchment indicators can show water managers if a catchment is stressed, over-allocated or if the present infrastructures in the catchment are adequate; or if additional water infrastructure is required to support the current and future water demands. The Catchment indicators used in this project are listed below:

- Reservoir Storage trajectories – storage trajectories are time varying water levels/ water storage of reservoirs
    - Historical reservoir storage trajectory – it a reservoir storage for a time period for which historical streamflow data is available
    - Stochastic reservoir storage trajectories – statistical probable reservoir storage trajectories

- Expected annual water supply reliability to users – it is the expected water supply reliability for coming year to water users.
    - It is assumed the current water demand and distribution is implemented for the coming year
    - Operating rules for the existing dams are developed on the assumption the distribution and the water demand amount is similar to the current water request
- Short term yield curves – short term yield curves are maximum water availability from a catchment/dam at different assurance of supply.
    - Short term yield curves are produced from a stochastic run of the catchment models and no restriction is imposed on the existing dams
    - It indicates whether the resources in the catchment sustainably support the current water request
- Comparison of expected forthcoming water supply reliability against IIMA agreed water allocation
    - South Africa IIMA water allocation for the Crocodile Catchment is deducted from the flow regimes/water availability study done in 2002. It is believed to be an optimal usage from the catchment by South Africa without compromising the interest of downstream- hence it can be used as a measure if the current water supply reliability is sustainable or not.

3.3.2 FARM-SCALE

The farm-scale model configuration consists of the MBIM setup and the configuration of the optimisation model. To setup the optimisation model, data from the irrigation module is used – therefore, the irrigation model setup will be discussed first, followed by the optimisation model setup and data used in the analysis.

3.3.2.1 MIKE BASIN Irrigation model

The Mhlati farm is configured in a detailed physically based MIKE BASIN Irrigation model and the model inputs are discussed in this sub section. Mhlati farm is composed of 32 fields and each field has specific soil properties. The populated soil properties of the fields in the MIKE BASIN irrigation model are described in Table 2.

Table 2: Soil parameters used for Mhlati Farm

Field	Field Capacity [mm/mm]	Wilting Point [mm/mm]	Depth of Evaporable layer[4] [mm]	Porosity [mm/mm]	Saturated Drainage coefficient [m/s]
A01	0.254	0.159	70	0.402	5E-06
A02	0.254	0.159	70	0.402	5E-06
A03	0.254	0.158	70	0.402	1E-06
A04	0.254	0.158	70	0.402	1E-06
A05	0.254	0.159	75	0.402	5E-06
A06	0.254	0.159	75	0.402	5E-06
A07	0.189	0.093	70	0.448	6.5E-06
A08	0.189	0.093	70	0.448	6.5E-06
A09	0.254	0.159	55	0.402	5E-06
A12	0.254	0.159	40	0.402	5E-06
A13	0.254	0.159	40	0.402	5E-06
A14	0.254	0.158	75	0.402	1E-06
A15	0.254	0.158	75	0.402	1E-06
A16	0.254	0.159	70	0.402	5E-06
A17	0.254	0.159	60	0.402	5E-06
A18	0.254	0.159	70	0.402	5E-06
A19	0.254	0.159	75	0.402	5E-06
A20	0.254	0.159	75	0.402	5E-06
A21	0.416	0.298	60	0.482	1.5E-06
A22	0.416	0.298	60	0.482	1.5E-06
A23	0.254	0.159	75	0.402	5E-06
A24	0.254	0.158	40	0.402	1E-06
A25	0.254	0.159	40	0.402	5E-06
A33	0.254	0.159	70	0.402	5E-06
A34	0.254	0.159	55	0.402	5E-06
A35	0.254	0.159	40	0.402	5E-06
A36	0.254	0.159	40	0.402	5E-06
A37	0.254	0.159	40	0.402	5E-06
A38	0.254	0.159	40	0.402	5E-06
A39	0.254	0.159	40	0.402	5E-06
A40	0.254	0.159	40	0.402	5E-06

Table 3: Irrigation technology and schedule

	Wetted Fraction (%)	Spray Loss (%)	Application Depth [mm]	Cycle Time[5] [days]
Centre pivot	100	10	42	6 to 7
Drag line	100	10	42	6 to 7
Drip Surface	40	0	5 to 7	1 to 2
Solid set – floppy	100	10	35	5 to 6
Solid set – Impact	100	10	35	5 to 6

---

[4] Depth evaporable layer is the depth of soil where the soil water evaporation takes place

[5] Cycle time is the actual time lapse between the commencement of two successive application for specific irrigation set

A modified SCS runoff model is used in MBIM, with soil moisture integration depth (Potential maximum retention) of 0.4 m and coefficient of initial abstraction of 0.2. In the Doorenbos and Kassam (1979) crop yield model, four crop stages are considered. However, for sugarcane, based on the validation work of Lecler (2004) and Matsebula (2008), essentially two stages are modelled – with 1, 1, 308 and 55 days for initial, developmental, middle and late stages respectively, with associated yield responses factors (Ky) of 1.2,1.2, 1.2, and 0.1. Crop factors for initial stage is 0.15 and 1.2 for middle growing stage and the late stage of sugarcane. The rate of development of the crop factor is related to thermal time (Lecler, 2004). The cut-off irrigation date is also factored in the crop-yield simulation model. In this project, the crop is irrigated for the first 320 days and irrigation is cut off after that to simulate drying off.

The uniformities information of the irrigation systems were provided by TSB. Crop water requirements were simulated with the irrigation module that was developed as part of this research. The irrigation module is based on the basic methodology proposed in FAO-56 (Allan *et al.*, 1998) to calculate crop water requirements.

3.3.2.2 Water use optimisation model

The water use optimisation model integrates information from MIKE BASIN to determine the impact of changes in catchment scale operating rules and water curtailments on the financial feasibility and livelihoods of irrigation farmers. The main purpose of this section is to give a description of the data that was used to configure the optimisation model for four alternative farm scenarios.

3.3.2.2.1 Farm size and irrigation system combinations

The optimisation model was set up for two different farm sizes comprising different irrigation system combinations. Table 4 is used to define the different irrigation areas and irrigation system combinations.

Table 4: Irrigation system areas of four different farm scenarios

	Farm scenario			
	S100	S150	SD100	SD150
Sprinkler	50	80	20	50
Pivot	30	30	30	30
Drip	20	40	50	70
Total	100	150	100	150

The farm scenarios are differentiated by the total area irrigated (100 ha or 150 ha) and the irrigation systems (Sprinkler, Centre Pivot and Drip) used to irrigate sugarcane. Different irrigation systems have different water application efficiencies and the combinations were chosen such that the farms scenarios identified with S have lower overall application efficiencies when compared to SD farm scenarios with relatively higher overall water application efficiencies. More specifically 30 ha sprinkler irrigation of the S scenarios was converted to drip irrigation to reflect the higher irrigation application efficiencies of the SD scenarios. More efficient irrigation farms should be able to sustain water shortages better since less water is lost and therefore a larger proportion of the water is consumptively used.

The specific irrigation system designs and layouts were taken from Oosthuizen *et al.* (2005). The combination of irrigation systems for the S scenarios were chosen such that the proportional share of each irrigation system type most closely reflects the proportional share of each irrigation system used on the Mhtlati farm.

3.3.2.2.2 Net farm income budgets

The net farm income (NFI) budgets were prepared using data from SA Canegrowers for the Malelane area over the last five years. The NFI budget for each farm scenario is given in Table 5.

Table 5: Alternative farm scenario per hectare net farm income budgets (R/ha) for a crop yield of 100 tons/ha (2010).

	Farm scenario			
	S100	S150	SD100	SD150
GROSS INCOME	28400	28400	28400	28400
Variable cost	9393	9393	9393	9393
Irrigation Costs	3076	2727	3119	2885
Cane Transport	4750	4750	4750	4750
TOTAL VARIABLE COST	17218	16870	17262	17027
GROSS MARGIN	11182	11530	11138	11373
Overheads	5898	6008	5660	5733
NET FARM INCOME	5283	5523	5479	5640

All values are expressed in 2010 values and the numbers reflect the average cost over the period. The average values were used to obtain a better representation of cost structures over the years. However, the irrigation costs were calculated using the irrigation system design developed by Oosthuizen *et al.* (2005) assuming that the farmers use the Landrate electricity tariff. Thus, the irrigation costs are a direct reflection of the irrigation system designs and combinations of each farm. The information contained in the Canegrowers cost survey represents the total cost for the entire farm irrespective of the of the production cycle of sugarcane. Thus, Table 5 represents the average cost over all fields. The cost surveys indicated that on average 85% of the area under cane is harvested which was taken into consideration in the modelling.

The overhead component includes depreciation, which was calculated using the straight line method assuming that 50% of the useful life of the asset has lapsed. The economic life of the drip irrigation systems was selected to reflect the fact that the drip system needs to be replaced when the cane is re-established. According to Radley (2012) replacement takes place every 10 years. The value of the irrigation systems were taken from Oosthuizen *et al.* (2005) while the values of the machinery were taken from the Guide to machinery cost (DAFF, 2010). The specific machinery necessary to operate the farms were provided by Pepworth (2011).

3.3.2.2.3 Return on capital

To calculate the return-on-capital, an estimate of the remuneration of the farm manager, interest and the value of farm assets is necessary.

The assumption was made that the remuneration of the farm manager has to cover living expenses. Remuneration values were estimated based on a percentage of total cost using guidelines proposed by Backeberg (1984b). A value of 14% and 11% were used respectively for the smaller and larger farms which amount to a monthly remuneration of approximately R24000 and R29000 per month respectively for the smaller and larger farm sizes.

The value of the biological farm assets were taken from data provided by TSB. The book value of farm machinery, irrigation systems and other fixed improvements was added to the biological component to establish the total value of land and fixed improvement. The book value of the machinery compliment was estimated by assuming 50% of each machine's economic life has lapsed. The value of the fixed improvements other than the irrigation systems for each farm was obtained from Pepworth (2011). On average, the value amounts to R44000/ha in 2010. Compared to the current market value of land, the value might be more representative of the productive value of the land.

The total amount of interest paid was calculated by making assumptions regarding the amount of liabilities and the distribution of the total liabilities between short, medium and long term liabilities. An asset-to-debt ratio of three was used to calculate the total amount of liabilities, which was distributed 33% short term, 26% medium term and 41% long term (Backeberg, 1984b). The weighted cost of capital was calculated using the Abstract of Agricultural Statistics (DAFF, 2011) and amounts to 9.4%.

3.3.2.2.4 Net cash flows

The information above is sufficient to calculate the net cash flows with Equation 11. The only component that needs to be accounted for is the capital payments on borrowed capital. The capital payments for the long term and medium term liabilities were calculated by assuming that 50% of the payments still need to be paid. The interest rates reported in the Abstract of Agricultural Statistics (DAFF, 2011) were used in the calculations.

3.3.2.2.5 Model configuration

The optimisation model was configured for each farming scenario using the economic data explained above. In order to develop the integrated hydro-economic model it was necessary to assume a steady state situation. The implication is that the optimisation model did not model any structural changes to the farming situation.

Cognisance should be given to the fact that water-use is optimised for each state of nature. Therefore key output variables are represented by a distribution of outcomes. The production functions that are used to optimise water use in each state of nature are based on the soil, crop and irrigation system information provided by TSB for each irrigation field on Mhtlati. The area of each field was scaled such that the total area reflects the area associated for a specific farm scenario. To reflect the more efficient use of irrigation water by drip irrigation systems, the uniformity of the irrigation systems was changed.

CHAPTER 4:

HYDRO-ECONOMIC MODELLING RESULTS

4.1 SCENARIO DEFINITION

According to the New National Water Act, compulsory licensing will be issued to water users; and, in stressed water management areas, curtailments of water use might be implemented. Water is allocated according to a priority-based institutional arrangement, where EWR and BHN needs (together forming the Reserve) have first priority. After discussions with the Inkomati CMA and Crocodile stakeholders, a number of water apportionment scenarios were identified. Scenarios are drafted to imitate the changes which could be implemented by Catchment management agencies. The scenarios are simulated in the framework developed in this project and the scenarios considered are listed in Table 6 and 7 and Schematic description of the scenarios is shown in Figure 4.1. Curtailment scenarios are considered for scenarios where a new dam is not added.

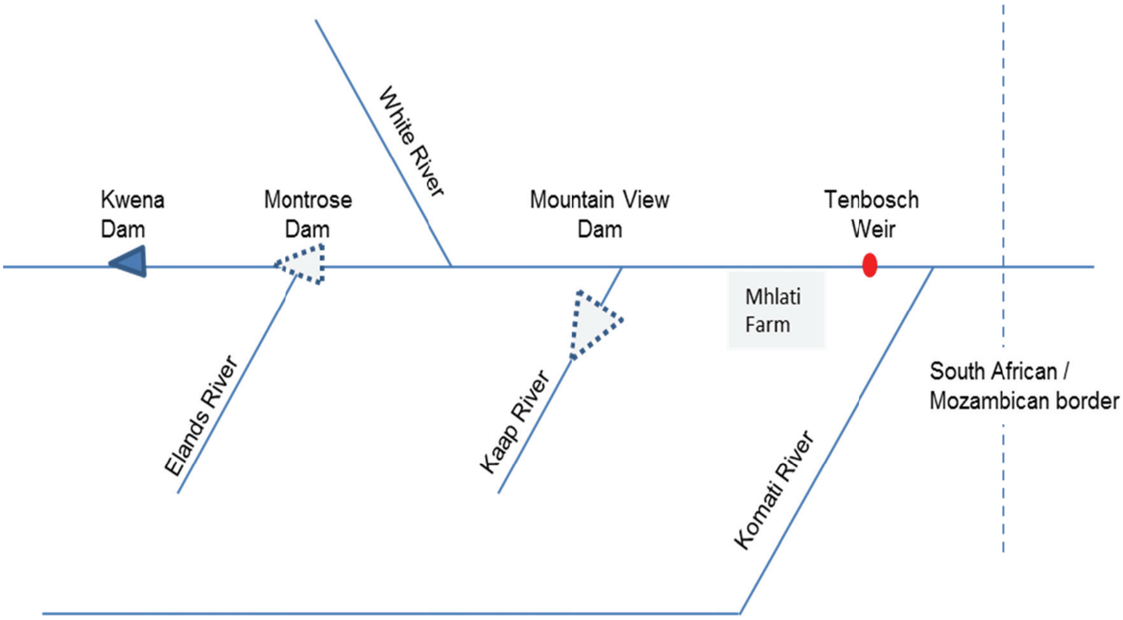


Figure 4. 1: Schematic diagram of Crocodile Catchment that describes the different scenarios considered

Table 6: Description of the Scenarios considered in this study

Scenarios	Existing Kwena Dam (158 M m^3)	Proposed Montrose Dam (253 Mm^3)	Proposed Mountain View Dam (328 Mm^3)	International flow at Tenbosch weir	EWR at Tenbosch Weir
Base Scenario	✓			0.9 m^3/s	None
KD_NO_0.9I	✓			0.9 m^3/s	None
KD_NO_1.2I	✓			1.2 m^3/s	None
KD_Pres_0.9I	✓			0.9 m^3/s	Present
KD_Pres_1.2I	✓			1.2 m^3/s	Present
MD_Pres_1.2I	✓	✓		1.2 m^3/s	Present
MD_CC_1.2I	✓	✓		1.2 m^3/s	C-class
MVD_Pres_1.2I	✓		✓	1.2 m^3/s	Present
MVD_CC_1.2I	✓		✓	1.2 m^3/s	C-class
MDMVD_CC_1.2I	✓	✓	✓	1.2 m^3/s	C-class

The current conditions in the catchment are considered as a base scenario for the Catchment, as described in Table 7.

Table 7: Model Scenarios that are considered

No.	Scenarios
1	Base scenario : current (No EWR, no curtailment to other users, no new dams, Include International flow obligations of 0.9 m^3/s)
2	current (No IFR, no curtailment to other users, no new dams, Include International flow obligations of 0.9 m^3/s)
3	current (No IFR, no curtailment to other users, no new dams, Include International flow obligations of 1.2 m^3/s)
4	(Present Day flow regime at EWR site 6, no curtailment to other users, no new dams, Include International flow obligations of 0.9 m^3/s)
5	(Present Day flow regime at EWR site 6, no curtailment to other users, no new dams, Include International flow obligations of 1.2 m^3/s)
6	Build Montrose (IFR C-class, no curtailment to other users, include new dam, Include International flow obligations of 1.2 m^3/s)
7	Build Montrose (Present flow regime, no curtailment to other users, include new dam, Include International flow obligations of 1.2 m^3/s)
8	Build Mountain View (Present flow regime, no curtailment to other users, include new dam, Include International flow obligations of 1.2 m^3/s)
9	Build Mountain View (C-class, no curtailment to other users, include new dam, Include International flow obligations of 1.2 m^3/s)
10	Build Mountain View and Montrose (C-class, no curtailment to other users, include new dams, Include International flow obligations of 1.2 m^3/s)

4.2 CATCHMENT SCALE SCENARIOS/ ASSESSMENT OF CATCHMENT WATER AVAILABILITY

Catchment's water availabilities are assessed using yield curves, where yield values are determined at different assurance or risk level. As explained in Chapter 3, probabilistic yield curves are produced from short term and long term assessment of the Catchment. In this sub-section, model results for different scenarios and the stochastic outputs form STOMSA are discussed.

Naturalised streamflow data is used from the IWAAS (Inkomati Water Availability Assessment Study). A historical catchment assessment is performed using the naturalised streamflow data to check the assurance of supply of each water user sectors for their legitimate claims. A historical catchment assessment is measure if the historical hydrological sequence could support the existing water requirement from the catchment. The expected historical assurance level of water supply to different water users is described in Table 5. The historical assessment shows that the Crocodile catchment hasn't been able to supply the water required from water users if the water requirement is equivalent to the current water demand.

Table 8: Historical assurance of water supply at different risk level

Water users	1:50 years assurance (million m^3/a)	1: 10 years assurance in (million m^3/a)	1:50 years (% relative to total allocation)	1:10 years (% relative to total allocation)
Irrigation sector	458	476.07	94.05	97.8
Domestic & Industry	70	70	100	100
Total	528	546	94.8	98.03

However, as explained in chapter 3, future water resources planning are based on stochastic catchment water resource assessment. Hence in this study, stochastic streamflow values are generated based on the naturalised flows, adopted from IWAAS study, using STOMSA. The accuracy level of how the statistics of the naturalised flow is mimicked in the stochastic streamflow is critical (important) in the prediction of the assurance level of water supply to water users in the future. There are a number of statistical parameters which could be used to assess the performance of the stochastic streamflow generator on how well the stochastic streamflow values mimic the naturalised/historical flows. Figure 4.3 and Figure 4.4 shows a comparison of the monthly and annual mean of the stochastic streamflow values against the "observed" naturalised flows for two different stochastic streamflow sets. The monthly and annual mean of the stochastic streamflow are summarised using box and whisker plots and the % in the box and whisker plot are shown in Figure 4.2. Figure 4.3 shows that the monthly mean for low naturalised flows are overestimated while the monthly mean for high naturalised flows are underestimated. If the stochastic streamflow sets shown in Figure 4.3 are used to assess the catchment water availability, the assurance of water supply to different water sectors will not reflect the true picture of the catchment water availability. According to the stochastic streamfow values shown in Figure 4.3, there will be less failures during low flows, because there will be consistent flows in the river more than what the naturalised flows.

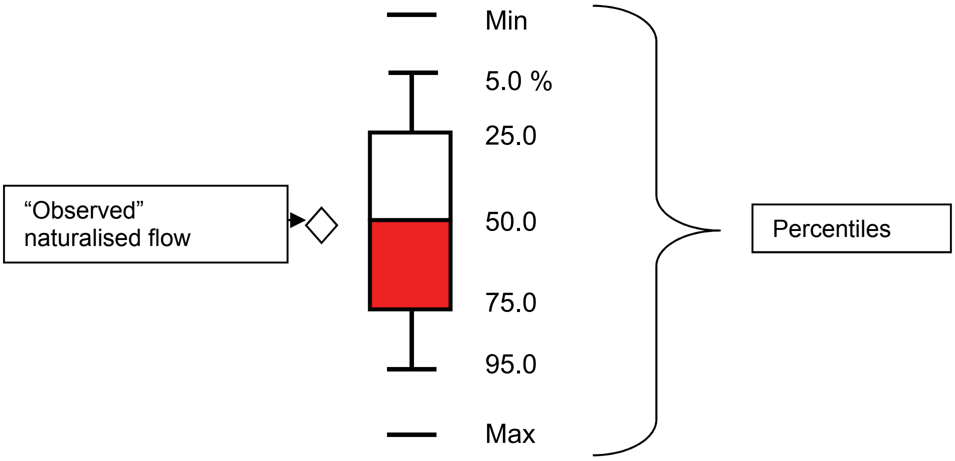


Figure 4. 2: **Definition of a box and whisker plot**

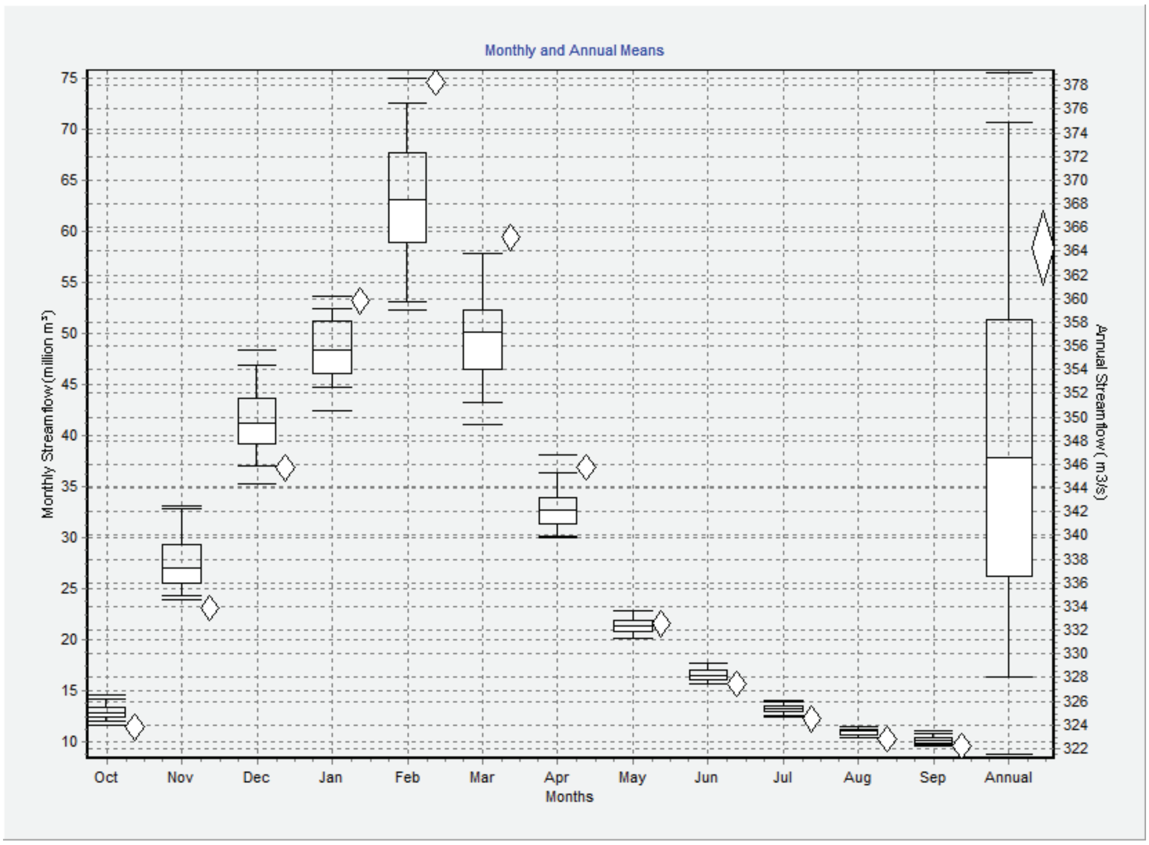


Figure 4. 3: **Comparison of the monthly and annual means of the stochastic streamflow against the naturalised flows for stochastic sequence 1**

The mean of the stochastic streamflow values which are shown in Figure 4.4 are consistent with monthly and annual mean of the naturalised flows. Generally the stochastic flows are assumed to be acceptable if the “observed” naturalised flow is between the 25 and 75% of the box and whisker plot of the monthly or annual mean of the stochastic flows. For the stochastic streamflow values shown in Figure 4.4, the “observed” naturalised streamflows are mostly between the 25 and 75% of the box and whisker plot.

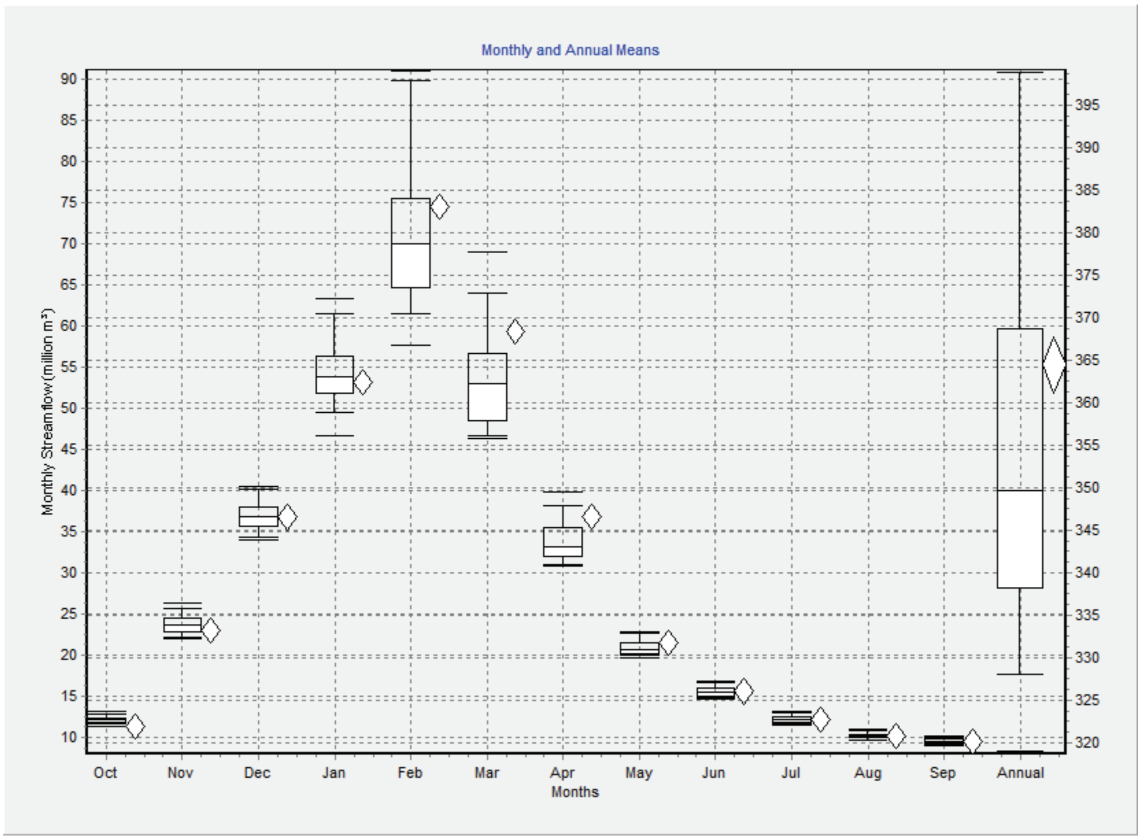


Figure 4. 4: Comparison of the monthly and annual means of the stochastic streamflow against the naturalised flows for stochastic sequence 2

The standard deviation is another statistical parameter which could be used to measure the performance of the stochastic generator software. Figure 4.5 and Figure 4.6 show a comparison of the monthly and annual standard deviation of the stochastic streamflow values against the standard deviation of “observed” naturalised streamflows for two different sets of stochastic streamflow values. The stochastic streamflow values in Figure 4.5 don’t particularly capture the standard deviation of the “observed” naturalised streamflows. In the low flows there is higher deviation from the mean as compared to the deviation of “observed” naturalised from the mean, while for high flows it is the opposite. Figure 4.6 shows that the standard deviation is mostly between 25 and 75% of the standard deviation of stochastic streamflow box and whisker plots or near to the 25 and 75%. This set of stochastic streamflow has captured the standard deviation of the “observed” flow reasonable well.

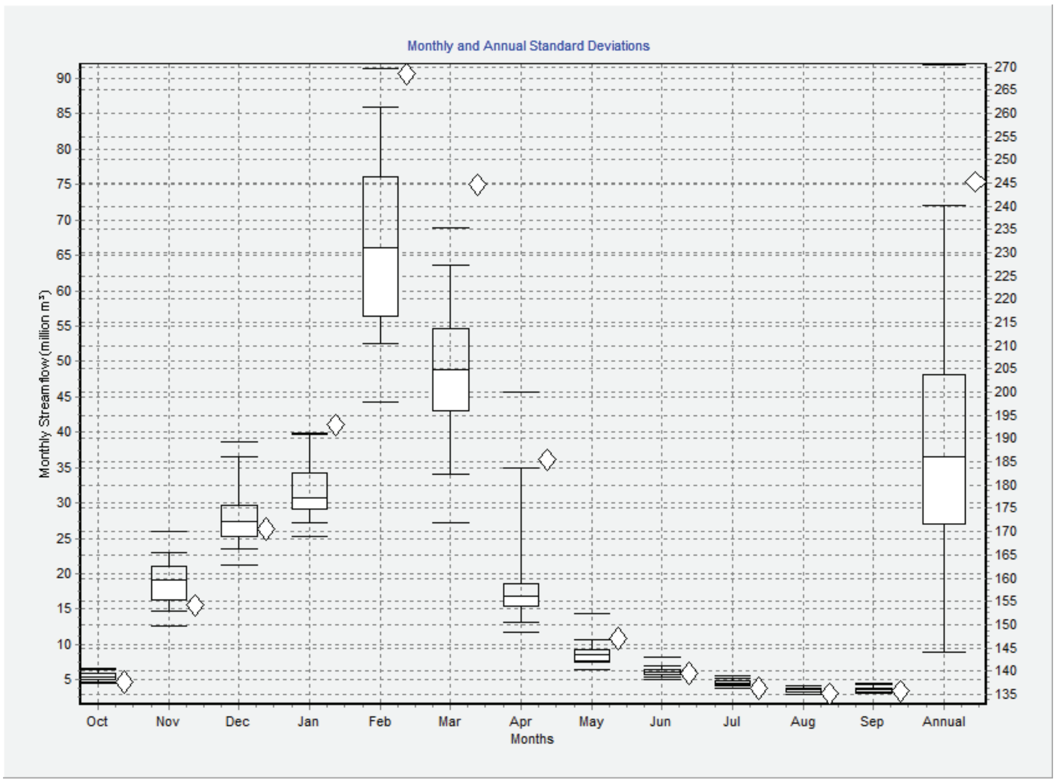


Figure 4. 5: **Comparison of the monthly and annual standard deviation of the stochastic streamflow against standard deviation of the naturalised flows for stochastic sequence 1**

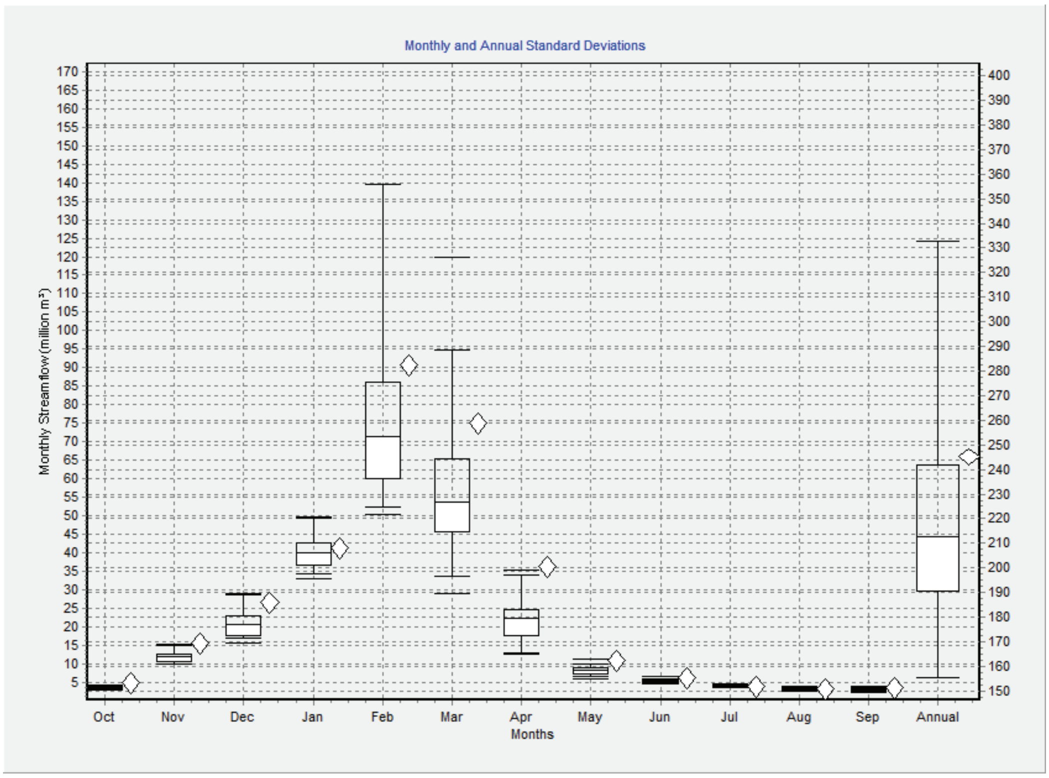


Figure 4. 6: **Comparison of the monthly and annual standard deviation of the stochastic streamflow against means of the naturalised flows for stochastic sequence 2**

Figure 4.7 and 4.8 show the capacity yield curve of the two set of stochastic streamflow values against the capacity yield curve of the naturalised streamflow. The blue curve shows the naturalised streamflow capacity to yield relationship, while the green curve is the median of the stochastic streamflow capacity yield relationship. If the median of the stochastic streamflow capacity yield curve is close to replicate the naturalised capacity yield curve, then we can deduct that the stochastic streamflow set is mimicking the naturalised streamflow well. The second stochastic streamflow set (Figure 4.8) to replicate better the naturalised capacity yield curve than the first stochastic streamflow set (Figure 4.7). In this Study the second set of stochastic streamflow is used to assess the stochastic yields of Crocodile catchment.

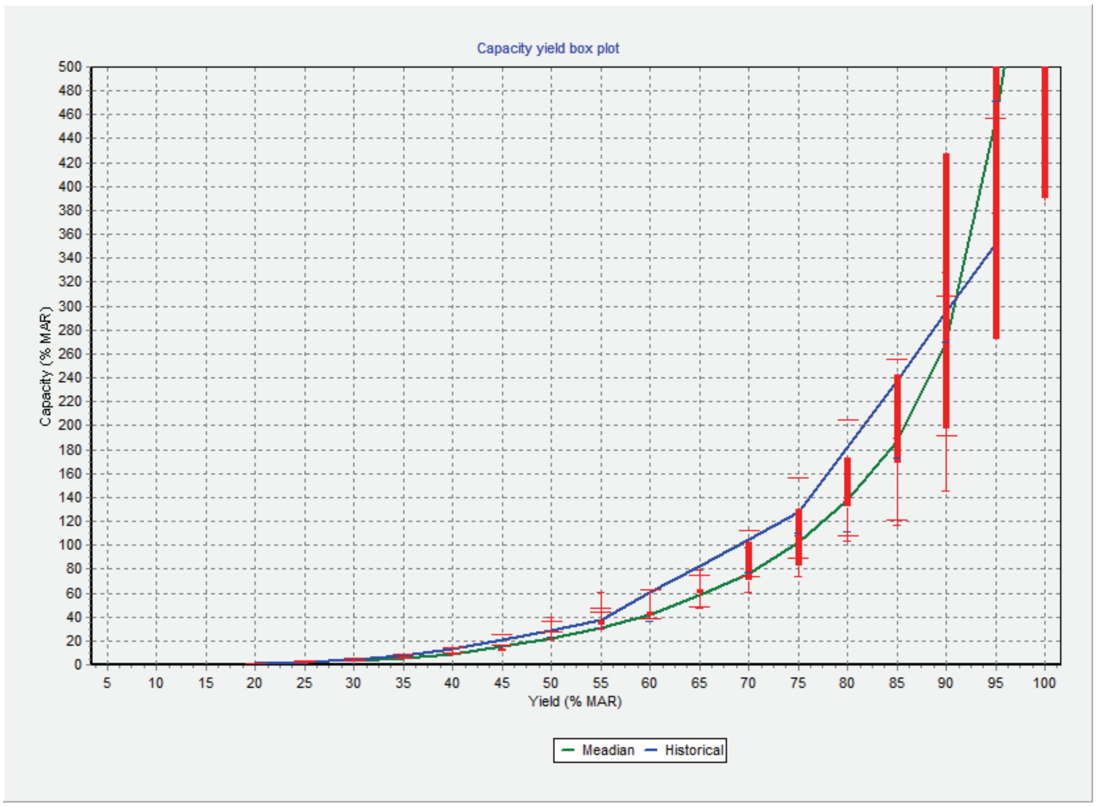


Figure 4. 7: Capacity Yield Curve for stochastic sequence 1

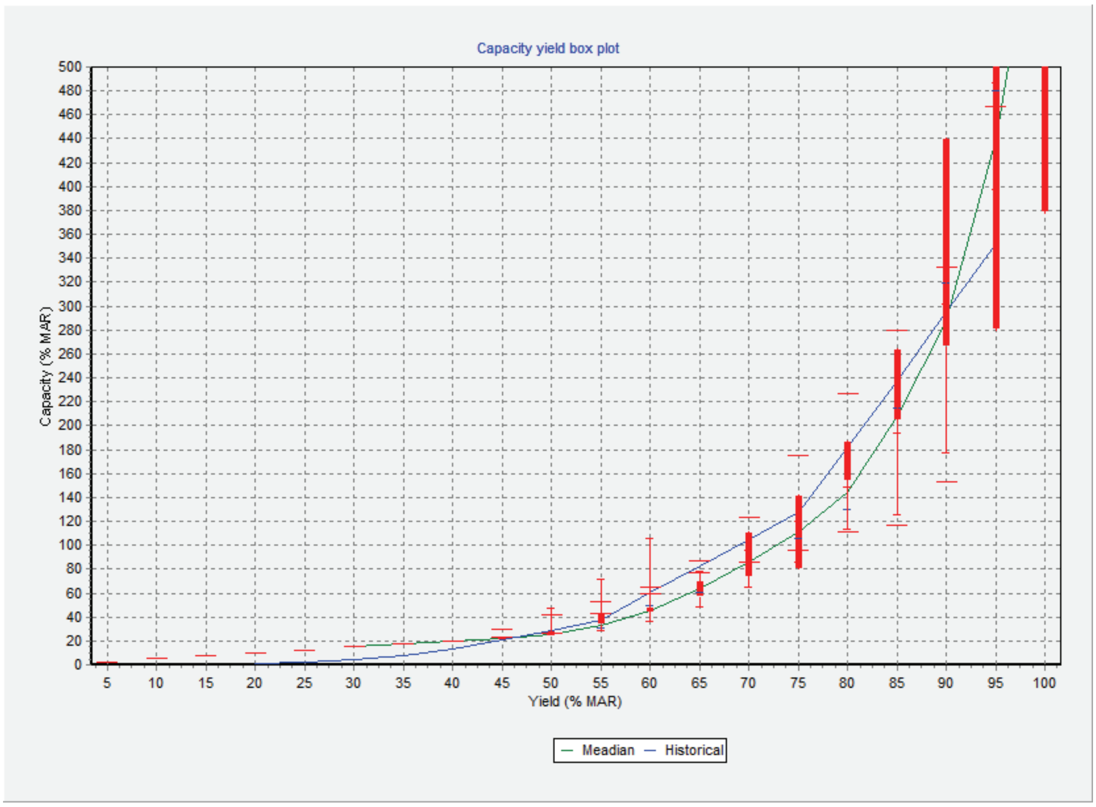


Figure 4. 8: **Capacity yield Curve for stochastic sequence 2**

The long term allocable yields from a crocodile stochastic water resource assessment shown in Table 9; are total available water from all the dams and the run of rivers. In general, the Crocodile catchment is over allocated given the current infrastructure. However, the figures shown in Table 9 are different from what is reported in previous studies conducted in the catchment. It was reported that Crocodile catchment is over allocated by a fraction more than what is shown in Table 9.

Table 9: **Long term allocable yield of Crocodile catchment**

Water users	1:50 years assurance (million m^3/a)	1: 10 years assurance in (million m^3/a)	1:50 years (% relative to total allocation)	1:10 years (% relative to total allocation)
Irrigation sector	459	481.7	94.2	98.5
Domestic & Industry	70	70	100	100
Total	529	550	95	98.7

The breakdown of the long term allocable yield on subsystem basis is shown in Table 10. The 28.4 million m^3/a that is required for trans-boundary flow from the catchment is factored in the modelling setup and requirement is supplied at 100 % reliability. The breakdown shows that the Kaap and White river systems are highly stressed and they are over allocated by 14 and 9 % respectively.

Table 10: Long term allocable yield

	Water User	Water Allocation [million m^3/a]	Water Supplied at 1: 50 years return period [million m^3/a]	Assurance of Supply [% of demand]
Upstream of Kwena Dam	Domestic	0.475	0.475	100
	Industry	0	0	-
	Irrigation	5.05	5.05	100
	Sub-Total	5.525	5.525	100
Downstream of Kwena Dam	Domestic	0.0	0.0	-
	Industry	0	0	-
	Irrigation	11.80	11.75	99.5
	Sub-Total	11.80	11.75	99.5
Elands	Domestic	1.2	1.2	100
	Industry	13.3	13.3	100
	Irrigation	6.7	6.7	100
	Sub-Total	21.2	21.2	100
White River	Domestic	1.14	1.14	100
	Industry	0	0	-
	Irrigation	53.56	48.54	91.4
	Sub-Total	54.07	49.68	90.8
Middle Crocodile	Domestic	37.11	37.11	100
	Industry	0	0	-
	Irrigation	110.6	106.15	96.0
	Sub-Total	147.71	143.25	97.4
Kaap River	Domestic	0	0	0
	Industry	0	0	-
	Irrigation	90.6	77.73	85.8
	Sub-Total	90.6	77.73	85.8
Lower Crocodile Allocation	Domestic	7.75	7.75	100
	Industry	8.95	8.95	100
	Irrigation	218.11	214.354	98.28
	Sub-Total	234.81	231.1	98.4
Total		556.9	529	95.0

Table 11: Current water demand and supply for Crocodile catchment

	Water User	Water Allocation [million m^3/a]	Water Supplied at 1: 50 years return period [million m^3/a]	Assurance of Supply [% of demand]
Upstream of Kwena Dam	Domestic	0.6	0.592	98
	Industry	0	0	-
	Irrigation	5.147	4.271	90.40
	Sub-Total	5.747	4.863	84.62
Downstream of Kwena Dam	Domestic	0.6	0.592	84
	Industry	0	0	-
	Irrigation	11.94	11.01	80.23
	Sub-Total	12.54	11.605	92.54
Elands	Domestic	0.55	0.526	97
	Industry	14.5	14.5	98
	Irrigation	6.8	6.313	90.87
	Sub-Total	21.75	21.339	98.11
White River	Domestic	2.42	2.37	82
	Industry	0	0	-
	Irrigation	23.27	18.472	77.81
	Sub-Total	25.69	20.842	81.13
Middle Crocodile	Domestic	41.61	40.919	98
	Industry	0	0	-
	Irrigation	107.55	99.029	86.76
	Sub-Total	149.16	139.948	93.82
Kaap River	Domestic	3.88	3.8	98
	Industry	0	0	-
	Irrigation	75.7	63.56	73.21
	Sub-Total	79.58	67.362	84.65
Lower Crocodile Allocation	Domestic	5.39	5.32	98
	Industry	7.39	7.368	98
	Irrigation	215.27	187.114	78.44
	Sub-Total	228.05	199.802	87.61
Total		522.517	465.761	89.14

4.2.1 CURRENT WATER REQUIREMENT, INTERNATIONAL FLOW AT TENBOSCH 0.9 M^3 PER SECOND (KD_NO_09I)

Presently the Crocodile catchment is expected to meet a 0.9 m^3/s trans-boundary flow at Tenbosch, which is equivalent to the Piggs Peak agreement. The Crocodile catchment is simulated with the current water requirement, trans-boundary 0.9 m^3/s at Tenbosch, and similar operating rules for all the dams to what is applied currently in the Crocodile catchment on short to medium term basis. The output for the Crocodile and its sub-catchment (allocation subsystems) from the MIKE BASIN catchment scale are summarised in Table 12 and 13.

Table 12: Long term Crocodile water users supply reliability at 1 in 50 years and 1 in 10 years risk level

Water users	1:50 years assurance (million m^3/a)	1: 10 years assurance in (million m^3/a)	1:50 years (% relative to total allocation)	1:10 years (% relative to total allocation)
Irrigation sector	459	481.7	94.2	98.5
Domestic & Industry	70	70	100	100
Total	529	550	95	98.7

Table 13: Long term water users supply reliability at 1 in 50 years risk level for Crocodile subsystems

	Water User	Water Allocation [million m^3/a]	Water Supplied [million m^3/a]	Assurance of Supply [% of demand]
Upstream of Kwena Dam	Domestic	0.475	0.475	100
	Industry	0	0	-
	Irrigation	5.05	5.05	100
	Sub-Total	5.525	5.525	100
Downstream of Kwena Dam	Domestic	0.0	0.0	-
	Industry	0	0	-
	Irrigation	11.80	11.75	99.5
	Sub-Total	11.80	11.75	99.5
Elands	Domestic	1.2	1.2	100
	Industry	13.3	13.3	100
	Irrigation	6.7	6.7	100
	Sub-Total	21.2	21.2	100
White River	Domestic	1.14	1.14	100
	Industry	0	0	-
	Irrigation	53.56	48.54	91.4
	Sub-Total	54.07	49.68	90.8
Middle Crocodile	Domestic	37.11	37.11	100
	Industry	0	0	-
	Irrigation	110.6	106.15	96.0
	Sub-Total	147.71	143.25	97.4
Kaap River	Domestic	0	0	0
	Industry	0	0	-
	Irrigation	90.6	77.73	85.8
	Sub-Total	90.6	77.73	85.8
Lower Crocodile Allocation	Domestic	7.75	7.75	100
	Industry	8.95	8.95	100
	Irrigation	218.11	214.354	98.28
	Sub-Total	234.81	231.1	98.4
Total		556.9	529	95.0

The breakdown of the water availability per sub systems in Table 13 shows that the White River and the Kaap River are the two sub systems who will face severe restrictions for their respective water users. In the Kaap River there is no storage infrastructure that could store the unregulated Kaap River flow, and as a result all the water uses are run-of-river. Whereas in the White River sub system, there are four sub-catchment seasonal dams that support or supply water users. That is probably why the sub systems are over-allocated because they don’t have an adequate storage infrastructure.

In the stochastic catchment assessment of the Crocodile catchment, the operational operating rules for Kwena and the four sub-catchment seasonal dams in the White River sub system are factored in the setup, as explained in Section 3.3.1.1. As a consequence, the operating rules placed for Kwena Dam in the MIKE BASIN setup kept the relative storage volume to minimum 20 % as shown in Figure 4.9. A relative storage volume of Kwena Dam for different probability of non-exceedence is processed from the 201 long term stochastic run for the Crocodile catchment. In Figure 4.9 the relative storage for Maximum (100 %), 50 % and Minimum (0 %) probability of non-exceedence is plotted against months.

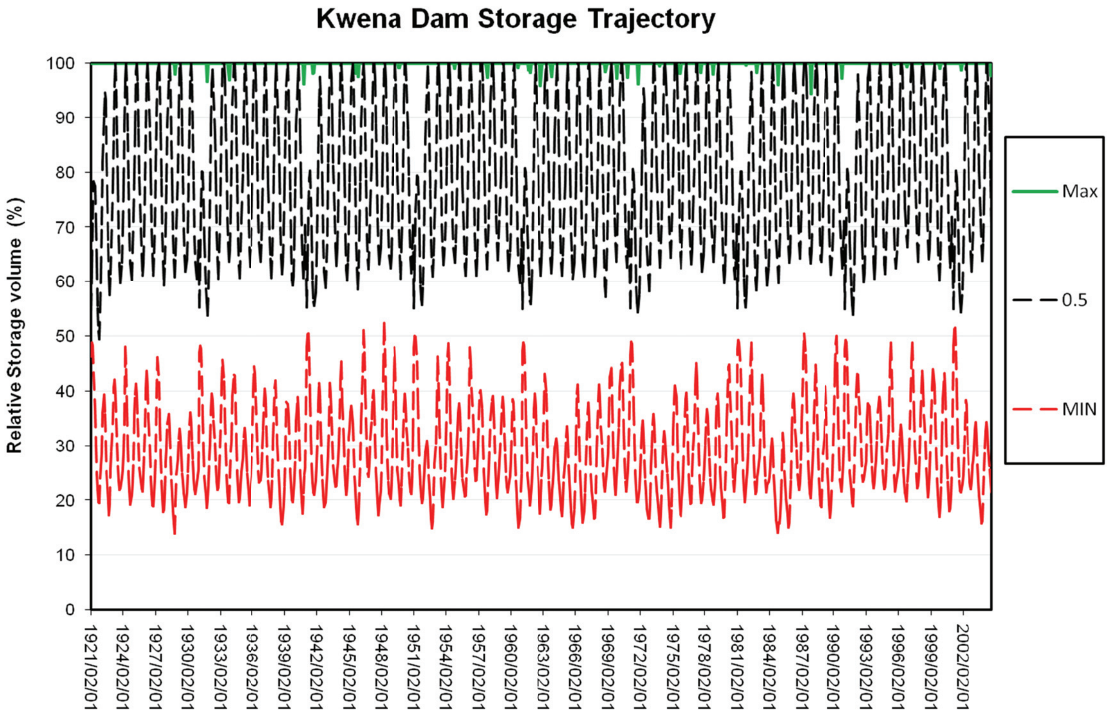


Figure 4.9: **Kwena Dam relative storage volume**

4.2.2 CURRENT WATER REQUIREMENT, IIMA INTERNATIONAL FLOW OF 1.2 M^3 PER SECOND (KD_NO_12I)

The Interim Inco-Maputo Agreement (IIMA) between the three riparian countries signed stipulates the trans-boundary flow at Tenbosch to be 1.2 m^3/s. The implementation of the agreement is expected to be with the finalisation of the PRIMA (Progressive realisation of the Inco- Maputo Agreement) programme. If the IIMA agree trans-boundary flow at Tenbosch is implemented as expected, the trans-boundary flow required will increase from 28.4 million m^3/a to 37.87 million m^3/a. With the implementation of the IIMA agreed flow, the yield reliability at 1: 50 years return period for irrigation water users decreases from current reliability 94.2 % to 92.8 %, which is a decrease 1.4 %, as described in Table 14 and the storage level in Kwena Dam also be affected negatively as shown in Figure 4.10 as compared to Figure 4.9 . The implementation will affect the irrigation water users negatively (Table 15), and the lack of water availability will affect crop yields and as a consequence farmers' net return to their investments will also be affected negatively. This may also have a bigger impact in terms of food security and impact on the country economy. Hence it is important to quantify the financial impact of implementing trans-boundary flows or environmental flow requirement.

Table 14: Long term Crocodile water users supply reliability at 1 in 50 years and 1 in 10 years risk level

Water users	1:50 years assurance (million m^3/a)	1: 10 years assurance in (million m^3/a)	1:50 years (% relative to total allocation)	1:10 years (% relative to total allocation)
Irrigation sector	451.9	479.5	92.8	98.5
Domestic & Industry	70	70	100	100
Total	521.8	549.5	93.7	98.7

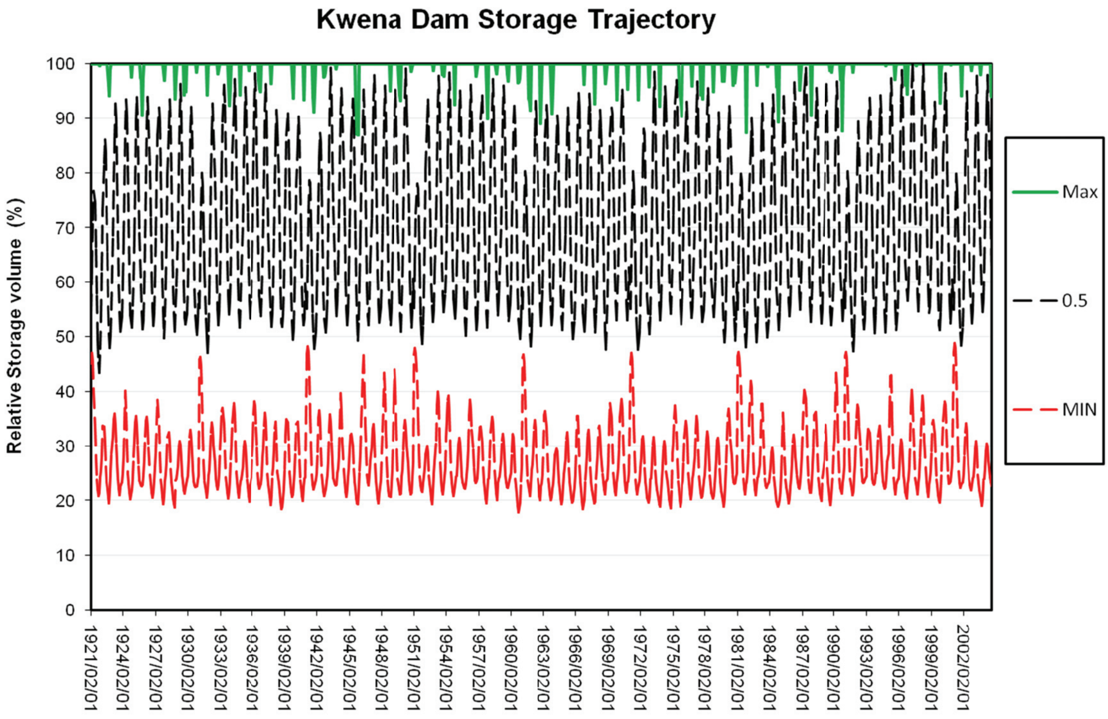


Figure 4. 10: Kwena Dam relative storage volume

Table 15: Long term water users supply reliability at 1 in 50 years risk level for Crocodile subsystems

	Water User	Water Allocation [million m^3/a]	Water Supplied [million m^3/a]	Assurance of Supply [% of demand]
Upstream of Kwena Dam	Domestic	0.475	0.475	100
	Industry	0	0	-
	Irrigation	5.05	5.05	100
	Sub-Total	5.525	5.525	100
Downstream of Kwena Dam	Domestic	0.0	0.0	-
	Industry	0	0	-
	Irrigation	11.80	11.70	99.16
	Sub-Total	11.80	11.70	99.16
Elands	Domestic	1.2	1.2	100
	Industry	13.3	13.3	100
	Irrigation	6.7	6.7	100
	Sub-Total	21.2	21.2	100
White River	Domestic	1.14	1.14	100
	Industry	0	0	-
	Irrigation	53.56	45.8	85.5
	Sub-Total	54.07	45.8	85.5
Middle Crocodile	Domestic	37.11	37.11	100
	Industry	0	0	-
	Irrigation	110.6	104.5	94.5
	Sub-Total	147.71	141.6	95.87
Kaap River	Domestic	0	0	0
	Industry	0	0	-
	Irrigation	90.6	77.78	85.70
	Sub-Total	90.6	77.78	85.70
Lower Crocodile Allocation	Domestic	7.75	7.75	100
	Industry	8.95	8.95	100
	Irrigation	218.11	211.14	96.80
	Sub-Total	234.81	227.85	97.03
Total		556.9	535	96.0

4.2.3 PRESENT FLOW REGIME EWR FOR EWR SITE 6 (KD_PRES_12I)

In the new National Water Act (1998), water is “Reserved” for environment as a first priority. A desktop study has been done to estimate the EWR at different Instream flow requirement sites in Crocodile catchment. IFR Site 6 is located at lower section of the Crocodile River, and the EWR at the site from the desktop study is estimated to be C-class. However, the C-class Environmental Water Requirement, which is 288 million m^3/a in average, is believed to be high by the Irrigation boards and Inkomati Management Agency. As a result a study has been commissioned to investigate into the environment water requirement at the site. Consequently, a present environmental flow regime, which is 156 million m^3/a in average including high flows, is believed to be adequate to sustain the ecology of the Lower section of the Crocodile River. In this scenario where the present environmental flow regime water requirement is implemented, the yield for the irrigation users at 1:50 years return period is 92.5 %of the total demand, as described in Table 16,. This is 1.7 % less than the current yield reliability to the irrigation water users. This scenario clearly shows any type of EWR implementation will affect negatively to the yield reliability of irrigation water users (see Table 17).

The same operating rules are used for the implementation of the present environmental flow regime scenario as the scenarios for the current water requirement with international trans-boundary flows. The EWR has a first priority to water from the river and the dam. As a consequence if there is no water from run-of-river flows, the EWR is provided with water from Kwena Dam without any restrictions. In those instances there is a risk of Kwena Dam failure as shown in Figure 4.11 as compare to Figures 4.9 and 4.10.

Table 16: Long term Crocodile water users supply reliability at 1 in 50 year and 1 in 10 year risk level

Water users	1:50 years assurance (million m^3/a)	1: 10 years assurance in (million m^3/a)	1:50 years (% relative to total allocation)	1:10 years (% relative to total allocation)
Irrigation sector	450	481.7	92.5	98.8
Domestic & Industry	70	70	100	100
Total	520	551.7	93.5	99

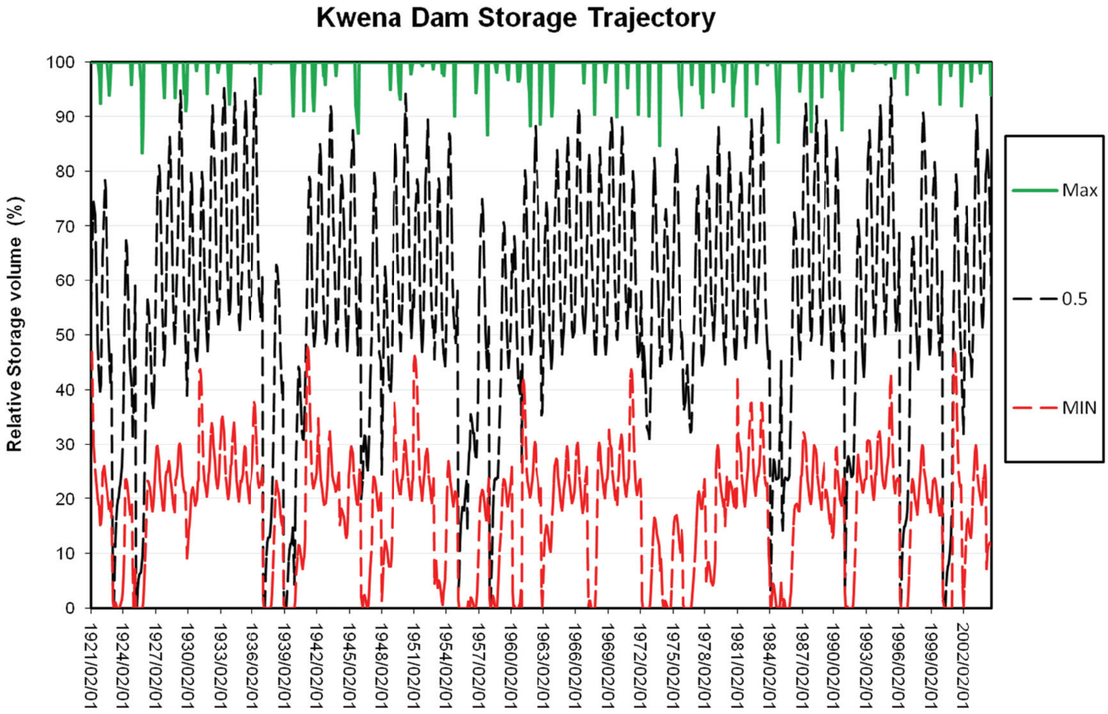


Figure 4. 11: Kwena Dam relative storage volume

Table 17: Long term water users supply reliability at 1 in 50 year risk level for Crocodile subsystems

	Water User	Water Allocation [million m^3/a]	Water Supplied [million m^3/a]	Assurance of Supply [% of demand]
Upstream of Kwena Dam	Domestic	0.475	0.475	100
	Industry	0	0	-
	Irrigation	5.05	5.05	100
	Sub-Total	5.525	5.525	100
Downstream of Kwena Dam	Domestic	0.0	0.0	-
	Industry	0	0	-
	Irrigation	11.80	11.77	99.74
	Sub-Total	11.80	11.77	99.74
Elands	Domestic	1.2	1.2	100
	Industry	13.3	13.3	100
	Irrigation	6.7	6.7	100
	Sub-Total	21.2	21.2	100
White River	Domestic	1.14	1.14	100
	Industry	0	0	-
	Irrigation	53.56	48.94	91.4
	Sub-Total	54.07	50.08	91.55
Middle Crocodile	Domestic	37.11	37.11	100
	Industry	0	0	-
	Irrigation	110.6	106.15	96.0
	Sub-Total	147.71	143.25	97.4
Kaap River	Domestic	0	0	0
	Industry	0	0	-
	Irrigation	90.6	78.15	86.26
	Sub-Total	90.6	78.15	86.26
Lower Crocodile Allocation	Domestic	7.75	7.75	100
	Industry	8.95	8.95	100
	Irrigation	218.11	216.65	99.32
	Sub-Total	234.81	233.35	99.38
Total		556.9	535	96.0

4.2.4 ADD MONTROSE DAM

Water Authorities and irrigation boards acknowledge that if the IIMA transboundary flow and Present flow regime or C-class EWR at the outlet of the Crocodile catchment are implemented, it will be difficult to supply the current and future water requirement from the catchment at an acceptable assurance level. One of the proposed solutions is to build a new dam (Montrose Dam) at the confluence of Elands and Crocodile rivers.

With addition of a new dam, it is expected that the Crocodile catchment will able to meet the C-class EWR at the outlet of the catchment. In this category two scenarios are simulated, in the first scenario present flow regime EWR is implemented and in the second scenario C-class EWR at the outlet of the catchment is implemented.

4.2.4.1 *With present flow regime EWR at EWR site 6, IIMA international flow of 1.2 m^3 per second (MD_Pres_12I)*

An addition of Montrose Dam at the confluence of Elands and Crocodile River stabilises the unregulated crocodile river below the confluence and increase the overall water supply reliability to crocodile irrigation water users' from 92.5 % to 95.1 % as summarised in Table 18. The 92.5 % water supply reliability is for the scenario where the present flow regime in combination of the IIMA water agreed trans-boundary flows are implemented. In this scenario, a trans-boundary flow of 1.2 m^3/s or 37.87 million m^3/a, and a present flow regime environmental flow at the outlet of Crocodile catchment are met with less than 100 % reliability. Though the water reliability to water users increased the water reserve in Kwena Dam is highly depleted as compared to the Kwena Dam relative water storage in the current water requirement scenario with a trans-boundary flow of 0.9 m^3/s (see Figure 4.12 and Figure 4.13) . This scenario demonstrates the impact of environmental flow implementation to the Crocodile catchment water availability, even with the addition of Montrose to capture the water flows from the Elands River.

Table 18: Long term Crocodile water users supply reliability at 1 in 50 years and 1 in 10 years risk level

Water users	1:50 years assurance (million m^3/a)	1: 10 years assurance in (million m^3/a)	1:50 years (% relative to total allocation)	1:10 years (% relative to total allocation)
Irrigation sector	463	479.7	95.1	98.5
Domestic & Industry	70	70	100	100
Total	533	549	95.7	98.7

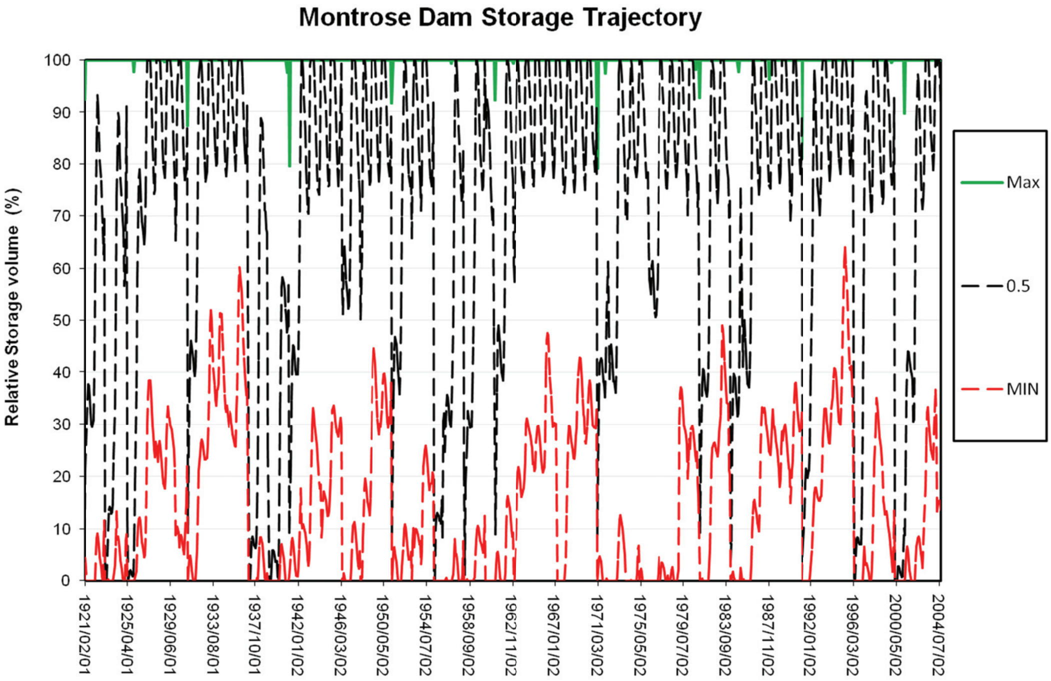


Figure 4. 12: Montrose Dam relative storage volume

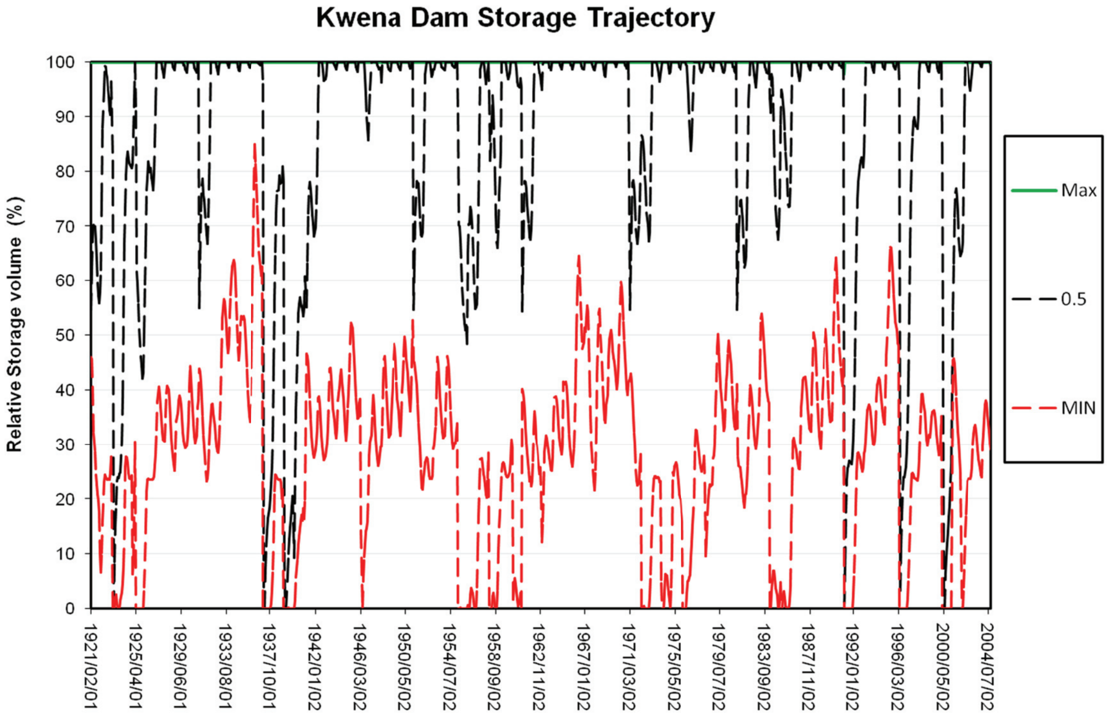


Figure 4. 13: Kwena Dam relative storage volume

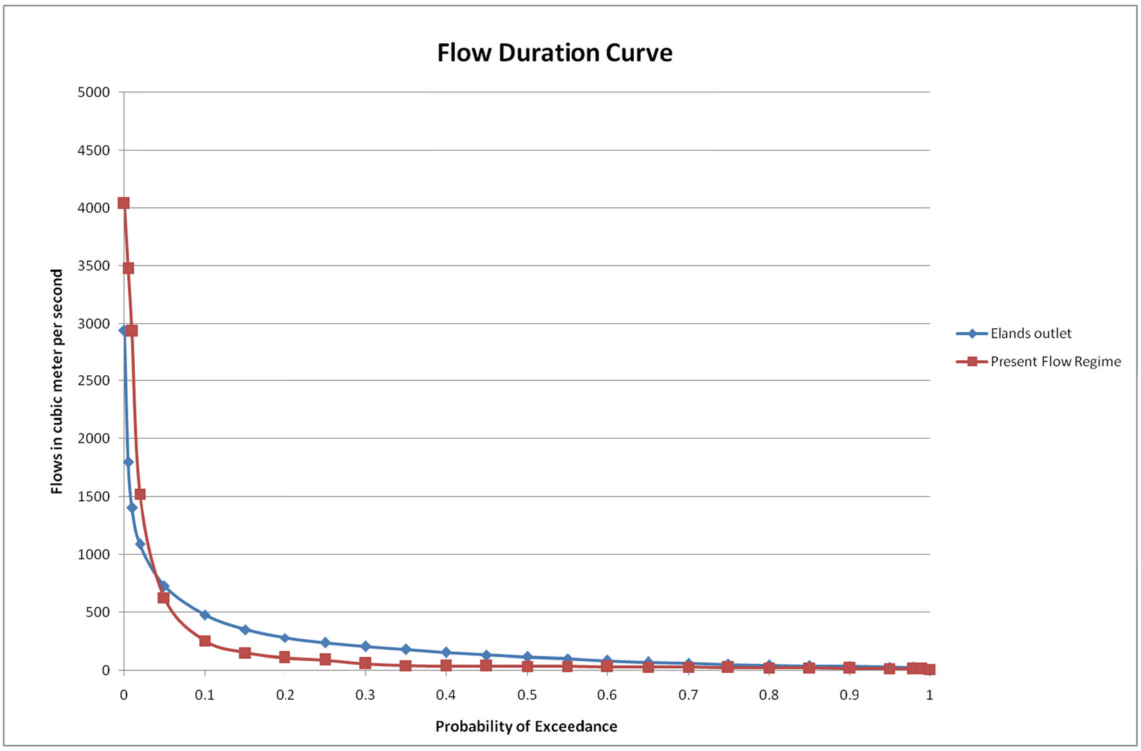


Figure 4. 14: Comparison of flows at the outlet of Elands Catchment and the Present flow regime environmental water requirement

Figure 4.14 compares the current flows at the outlet of the Elands catchment against the present environmental flow regime requirement at the outlet of the Crocdile River. The Elands catchment yiled could satisfy the low flow of the present environmental flow regime, whereas the high flows of the present flow regime are much higher than the yield at the outlet of the Elands catchment.

Table 19: Long term water users supply reliability at 1 in 50 years risk level for Crocodile subsystems

	Water User	Water Allocation [million m^3/a]	Water Supplied [million m^3/a]	Assurance of Supply [% of demand]
Upstream of Kwena Dam	Domestic	0.475	0.475	100
	Industry	0	0	-
	Irrigation	5.05	5.05	100
	Sub-Total	5.525	5.525	100
Downstream of Kwena Dam	Domestic	0.0	0.0	-
	Industry	0	0	-
	Irrigation	11.80	11.71	99.24
	Sub-Total	11.80	11.71	99.24
Elands	Domestic	1.2	1.2	100
	Industry	13.3	13.3	100
	Irrigation	6.7	6.7	100
	Sub-Total	21.2	21.2	100
White River	Domestic	1.14	1.14	100
	Industry	0	0	-
	Irrigation	53.56	48.54	90.62
	Sub-Total	54.07	59.68	90.82
Middle Crocodile subsystem	Domestic	37.11	37.11	100
	Industry	0	0	-
	Irrigation	110.6	105.93	95.8
	Sub-Total	147.71	143.05	96.84
Kaap River	Domestic	0	0	0
	Industry	0	0	-
	Irrigation	90.6	77.73	85.8
	Sub-Total	90.6	77.73	85.8
Lower Crocodile Allocation	Domestic	7.75	7.75	100
	Industry	8.95	8.95	100
	Irrigation	218.11	218.11	100
	Sub-Total	234.81	234.81	100
Total		556.9	533	95.7

4.2.4.2 *With comprehensive C-class EWR at EWR site 6, IIMA international flow of 1.2 m^3 per second (MD_CC_12I)*

The water users' water supply reliability in this scenario is similar to the scenario where Montrose Dam is added and the present environmental flow regime EWR is implemented. However, the water available in Montrose and Kwena Dam is much lower. This scenario clearly shows that even with the addition of Montrose Dam, meeting a C-class EWR at the bottom of the Crocodile catchment will severely affect the water storage in the Kwena Dam. In these two scenarios where Montrose Dam is added, the same operating rules that are used for the

Current water requirement with an international flow of 0.9 m^3/s or 1.2 m^3/s is implemented. As a consequence, the EWR is much more dependent on the storage in the Kwena and Montrose Dam. The severity of the C-class environmental impact in the water use is not highlighted because the same operating rules are used as the current water requirement scenarios (Table 20 and Table 21).

If the C-class EWR is going to be implemented in the Crocodile catchment, with the addition of Montrose or Mountain View Dam, the current operating rules will need to be adjusted and it will result in severe restriction of the water users, specifically the irrigators. In this scenario, the severity of the C-class EWR is highlighted in the depletion of Kwena and Montrose Dam reserve, as shown in Figures 4.15 and 4.16 as compared to the Figures 4.13 and 4.14.

Table 20: Long term Crocodile water users supply reliability at 1 in 50 year and 1 in 10 year risk level

Water users	1:50 years assurance (million m^3/a)	1: 10 years assurance (million m^3/a)	1:50 years (% relative to total allocation)	1:10 years (% relative to total allocation)
Irrigation sector	463.2	479.5	95.1	98.5
Domestic & Industry	70	70	100	100
Total	533.2	549.5	95.7	98.7

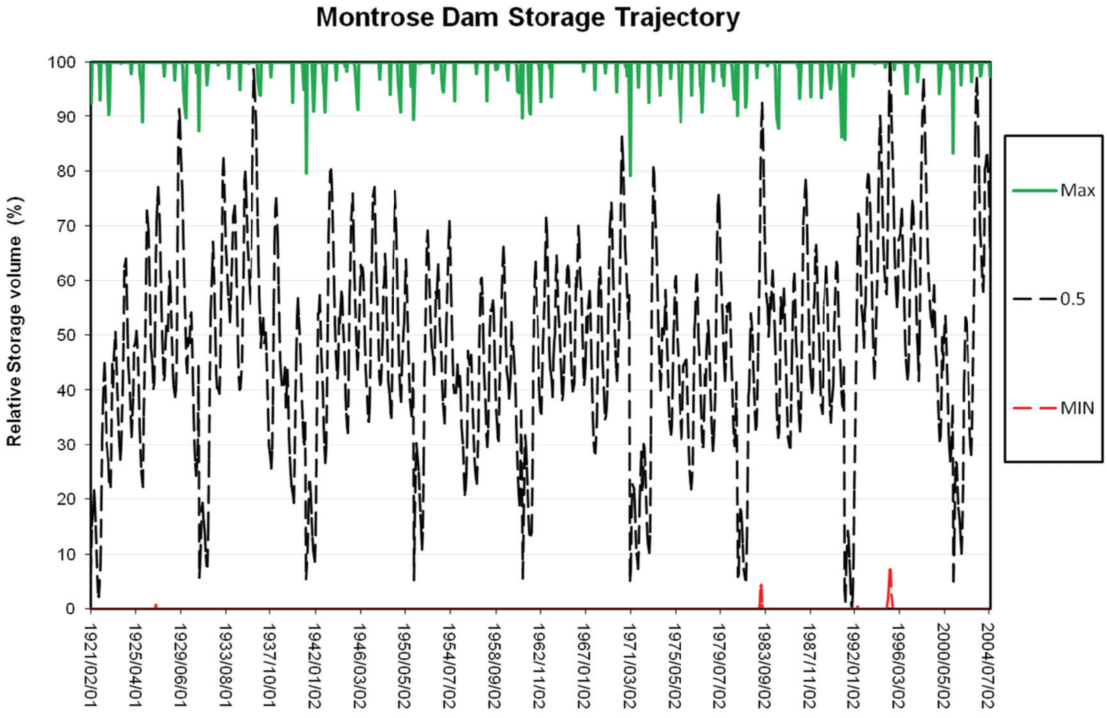


Figure 4. 15: Montrose Dam relative storage volume

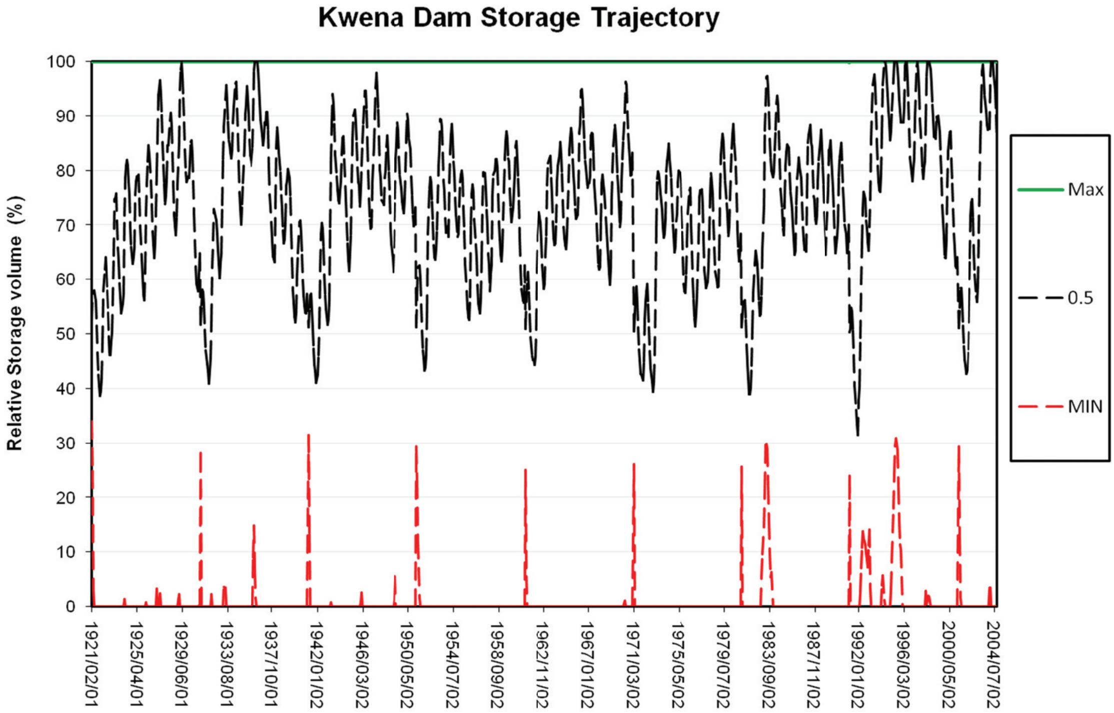


Figure 4. 16: Kwena Dam relative storage volume

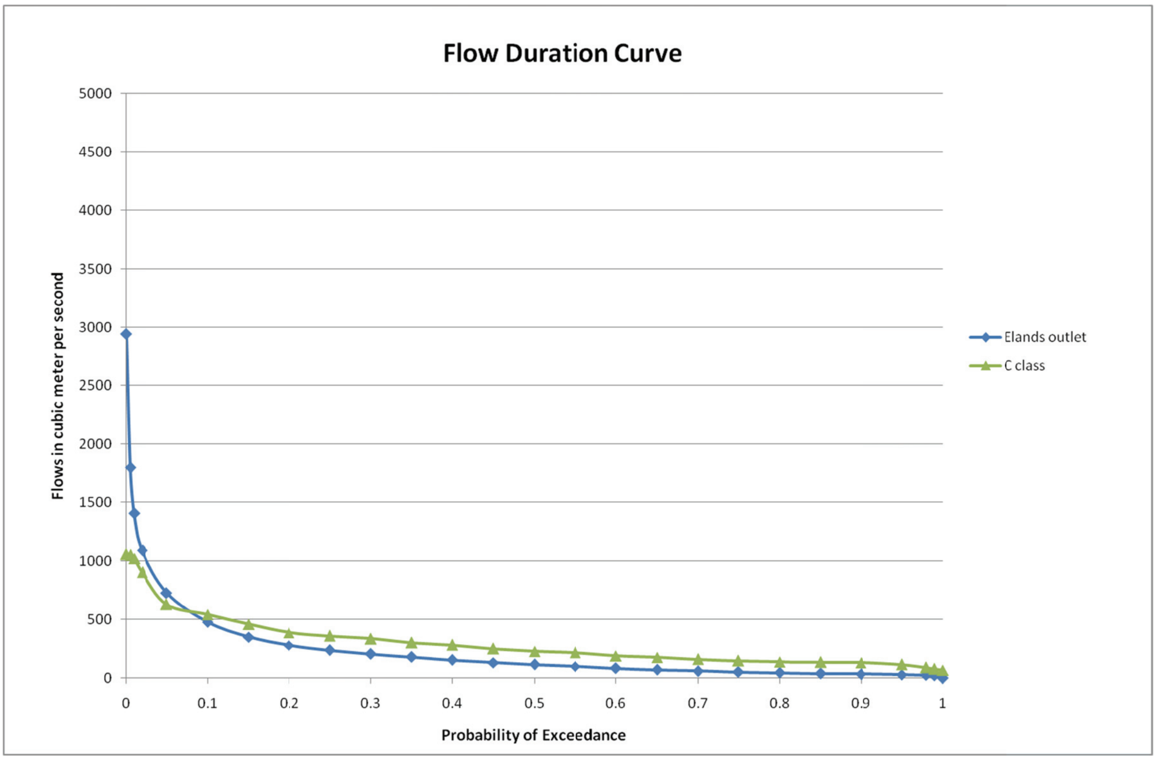


Figure 4. 17: Comparison of flows at the outlet of the Elands catchment and the C-class EWR

Figure 4.17 compares the current flows at the outlet of the Elands catchment against the C-class EWR at the outlet of the Crocdile River. The low flows Elands catchment yiled are much lower than the low flow of the C-class environmental flows, whereas the high flows of the Elands catchment yield are much higher than C-class EWR at the outlet of the Crocodile catchment. The conclusion that could be drawn from Figre 4.17 and 4.14 is that the Present environmetal flow regime have a very high of high flows of environmetal water requirment while the C-class are high low flow enviromental requirement.

Table 21: Long term water users supply reliability at 1 in 50 years risk level for Crocodile subsystems

	Water User	Water Allocation [million m^3/a]	Water Supplied [million m^3/a]	Assurance of Supply [% of demand]
Upstream of Kwena Dam	Domestic	0.475	0.475	100
	Industry	0	0	-
	Irrigation	5.05	5.05	100
	Sub-Total	5.525	5.525	100
Downstream of Kwena Dam	Domestic	0.0	0.0	-
	Industry	0	0	-
	Irrigation	11.80	11.77	99.74
	Sub-Total	11.80	11.77	99.74
Elands	Domestic	1.2	1.2	100
	Industry	13.3	13.3	100
	Irrigation	6.7	6.7	100
	Sub-Total	21.2	21.2	100
White River	Domestic	1.14	1.14	100
	Industry	0	0	-
	Irrigation	53.56	48.54	90.62
	Sub-Total	54.07	59.68	90.82
Middle Crocodile	Domestic	37.11	37.11	100
	Industry	0	0	-
	Irrigation	110.6	106.15	96.0
	Sub-Total	147.71	143.25	97.4
Kaap River	Domestic	0	0	0
	Industry	0	0	-
	Irrigation	90.6	78.15	86.26
	Sub-Total	90.6	78.15	86.26
Lower Crocodile Allocation	Domestic	7.75	7.75	100
	Industry	8.95	8.95	100
	Irrigation	218.11	216.65	99.32
	Sub-Total	234.81	233.35	99.38
Total		556.9	535	96.0

4.2.5 MOUNTAIN VIEW DAM

Building Mountain View Dam in the unregulated Kaap River is another proposed solution to the over-allocation of the catchment. With the addition of Mountain View Dam, the dam can support the supply of water to the lower section of the Crocodile catchment, where half of the total water demand of the catchment comes from.

Similar to the Montrose Dam, if Mountain View is built in the Kaap River, the Crocodile catchment is expected to supply the EWR at the outlet of the catchment. Hence, two scenarios are considered one is with present environmental flow regime and the second one is with C-class EWR at the outlet of the catchment.

4.2.5.1 With present flow regime at EWR site 6, international flow of 1.2 m^3 per second (MVD_Pres_12I)

In this scenario, a Mountain View Dam is added at the outlet of the Kaap Catchment, a present flow regime environmental flow and IIMA agreed trans-boundary flow is implemented at the out let of the Crocodile catchment, site 6. The reliability of irrigation water users increased from 92.5 % to 93.9 % (Table 22). The reliability increase is lesser as compared to the addition of Montrose Dam; the increase in this scenario is 1.4 % while in the case of Montrose Dam the addition is 2.6 %. Mountain View Dam is located at the Lower section of the Crocodile catchment and it can only supply the lower section of the Crocodile catchment while the Montrose Dam can supply to the middle and lower section of the Crocodile catchment (Table 23).

The depletion of Kwena Dam reserve is more severe on this scenario, than the scenario with the addition of Montrose and present flow regime environmental flows. This could be due to more flows in the Elands River in comparison to the Kaap catchment (Figure 4.18 and 4.19).

Table 22: Long term Crocodile water users supply reliability at 1 in 50 years and 1 in 10 years risk level

Water users	1:50 years assurance (million m^3/a)	1: 10 years assurance (million m^3/a)	1:50 years (% relative to total allocation)	1:10 years (% relative to total allocation)
Irrigation sector	461.99	479.9	94.85	98.55
Domestic & Industry	70	70	100	100
Total	531.96	549.95	95.51	98.74

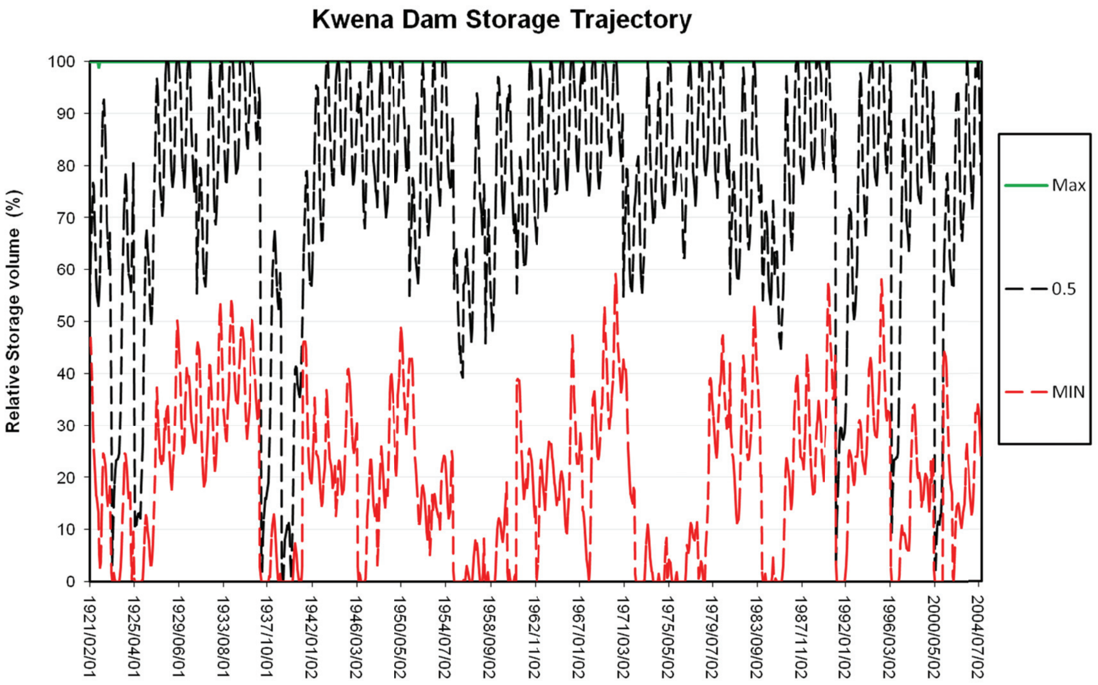


Figure 4. 18: Kwena Dam relative storage volume

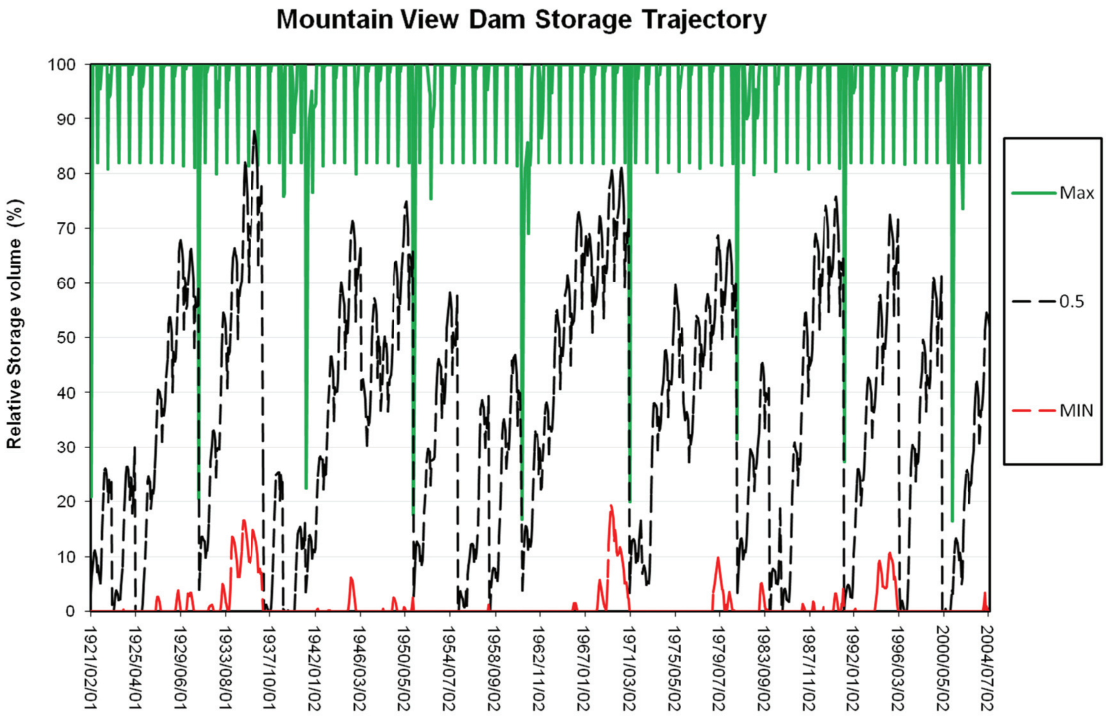


Figure 4. 19: Mountain View Dam relative storage volume

Figure 4.20 compares the current flows at the outlet of the Kaap catchment against the C-class EWR at the outlet of the Crocodile River. The low flows Kaap catchmentt yiled are equivalent to the the low flow of the Present environmental flow regime, whereas the high flows of the Kaap catchment yield are much lower than Present environmental flow regime water requirement at the outlet of the Crocodile catchment.

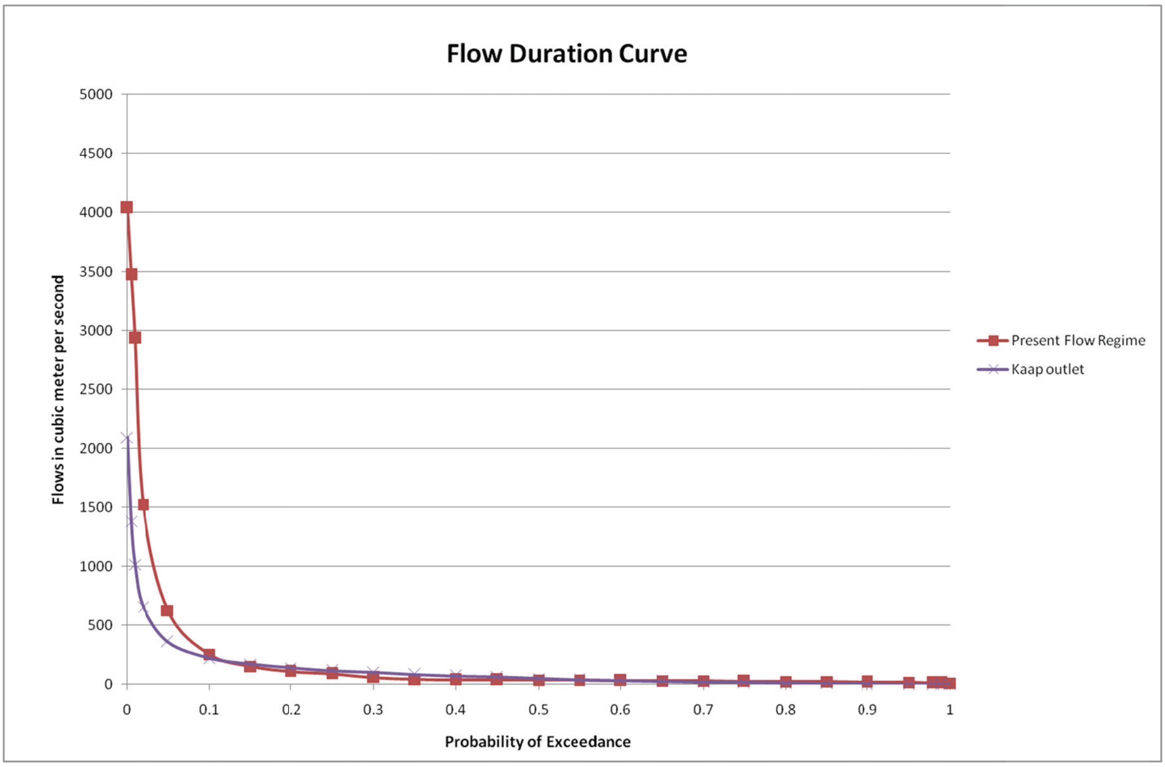


Figure 4. 20: **Comparison of flows at the outlet of Kaap Catchment and the Present flow regime environmental requirement at the outlet of Crocodile**

Table 23: Long term water users supply reliability at 1 in 50 years risk level for the Crocodile sub-systems

	Water user	Water Allocation [million m^3/a]	Water Supplied [million m^3/a]	Assurance of Supply [% of demand]
Upstream of Kwena Dam	Domestic	0.475	0.475	100
	Industry	0	0	-
	Irrigation	5.05	5.05	100
	Sub-Total	5.525	5.525	100
Downstream of Kwena Dam	Domestic	0.0	0.0	-
	Industry	0	0	-
	Irrigation	11.80	11.67	98.8
	Sub-Total	11.80	11.67	98.8
Elands	Domestic	1.2	1.2	100
	Industry	13.3	13.3	100
	Irrigation	6.7	6.7	100
	Sub-Total	21.2	21.2	100
White River	Domestic	1.14	1.14	100
	Industry	0	0	-
	Irrigation	53.56	48.54	90.62
	Sub-Total	54.07	59.68	90.82
Middle Crocodile	Domestic	37.11	37.11	100
	Industry	0	0	-
	Irrigation	110.6	105.72	95.5
	Sub-Total	147.71	143.25	97.4
Kaap River	Domestic	0	0	0
	Industry	0	0	-
	Irrigation	90.6	75.4	83.2
	Sub-Total	90.6	75.4	83.2
Lower Crocodile Allocation	Domestic	7.75	7.75	100
	Industry	8.95	8.95	100
	Irrigation	218.11	215.75	98.92
	Sub-Total	234.81	232.46	99.0
Total		556.9	527.6	94.7

4.2.5.2 *With comprehensive C-class EWR at EWR site 6, international flow of 1.2 m^3 per second (MVD_CC_12I)*

If the comprehensive C-class environmental requirement at the outlet of the Crocodile catchment is implemented instead of the Present environmental flow regime that used in section 4.2.5.1. The yield to the irrigation water users decreases from 93.9 % to 92.4 %, as shown in Table 24. The decrease occurs as the C-class EWR is greater than the present environmental flow regime requirement. The reserve of the Kwena and Mountain View Dam is also highly depleted in this scenario as compared to the scenario with addition of the Mountain View Dam and present environmental flow regime. This also demonstrates the impact that the C-class environmental flow will have on the supply reliability of the water users and the water reserve in Kwena Dam (see Table 25). The addition of Montrose or Mountain View, could help in stabilising the river, however they will not fully supply the C-class or present environmental flow regime water requirement without severely affecting the water supply reliability of the water users or the water reserve in the dams (see Figure 4.21 and 4.22).

Table 24: Long term Crocodile water users supply reliability at 1 in 50 year and 1 in 10 year risk level

Water users	1:50 years assurance (million m^3/a)	1: 10 years assurance (million m^3/a)	1:50 years (% relative to total allocation)	1:10 years (% relative to total allocation)
Irrigation sector	449.9	479.7	92.4	98.5
Domestic & Industry	70	70	100	100
Total	519.9	549.7	93.3	98.7

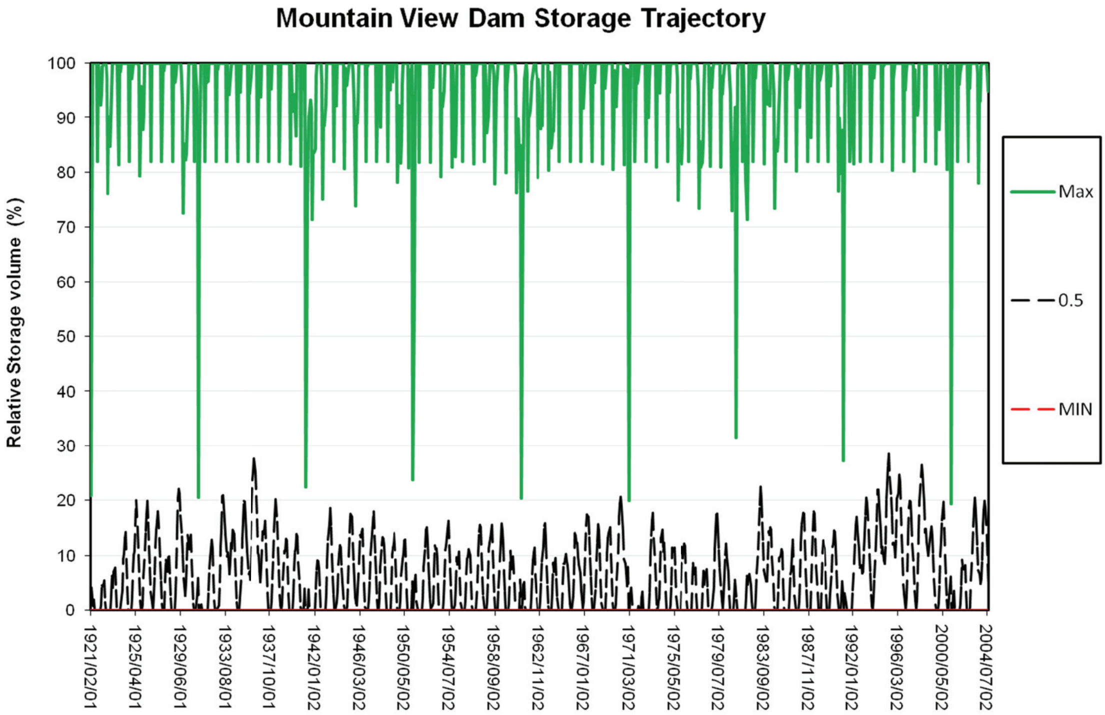


Figure 4. 21:Mountain View Dam relative storage volume

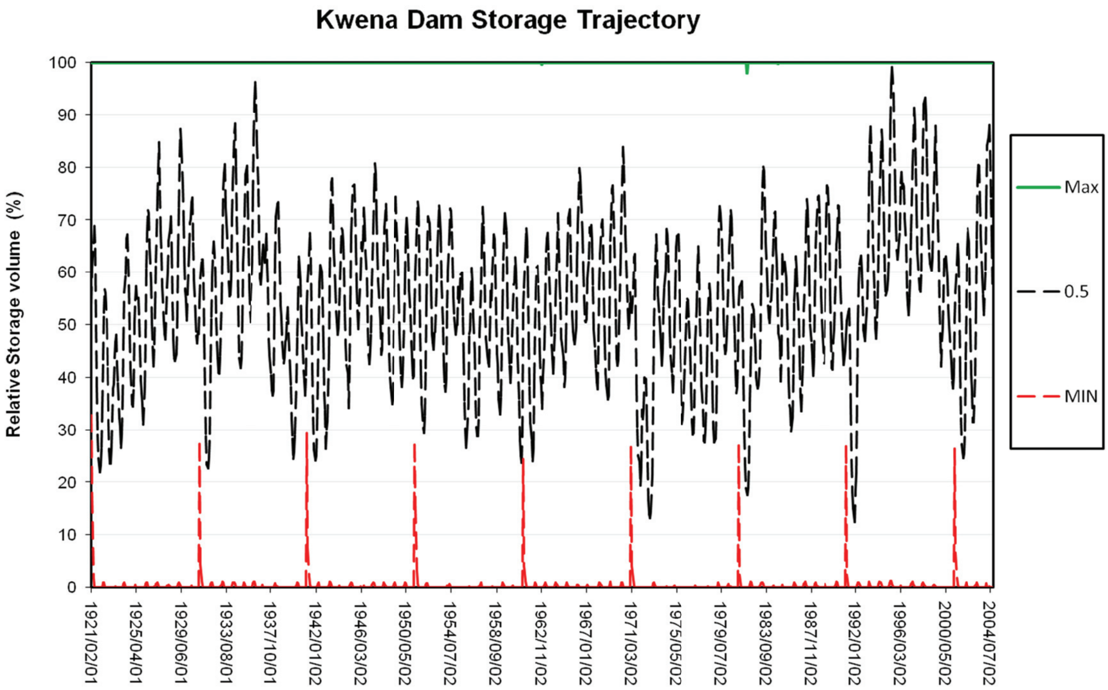


Figure 4. 22: Kwena Dam relative storage volume

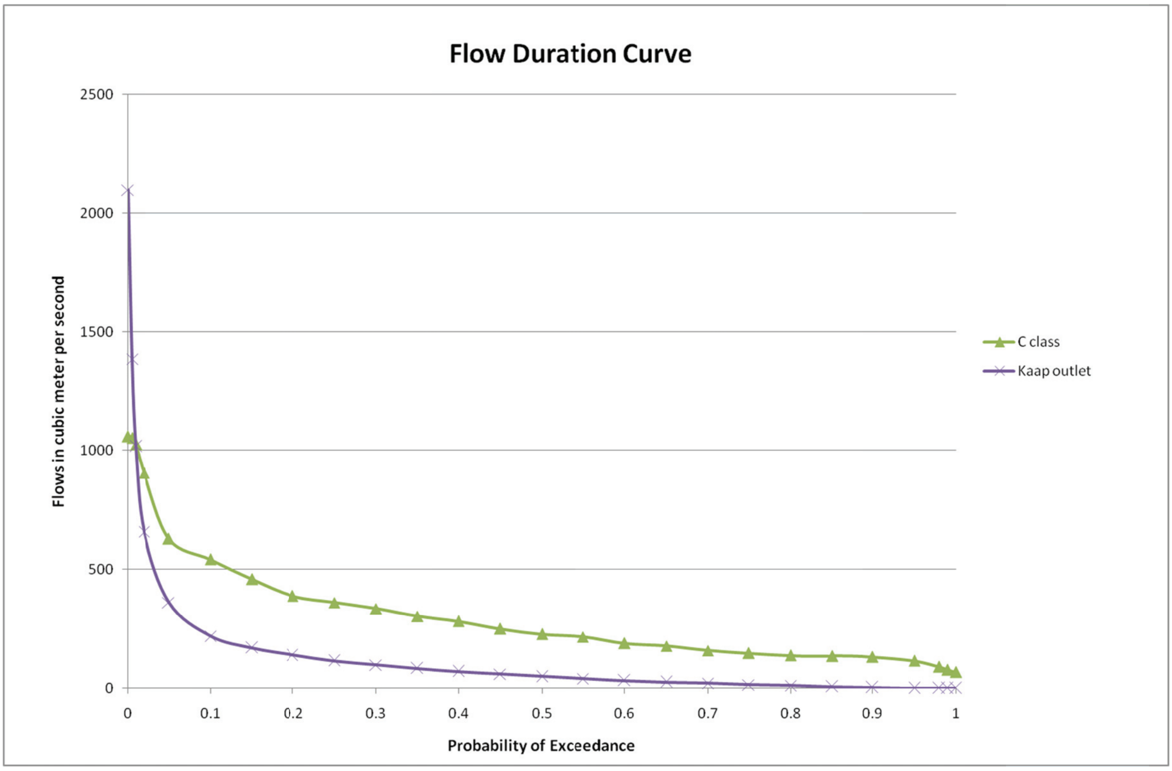


Figure 4. 23: Comparison of flows at the outlet of the Kaap Catchment and C-class Environmental Water Requirement

Figure 4.23 compares the current flows at the outlet of the Kaap catchment against the C-class environmental flow regime requirement at the outlet of the Crocodile River. The low flows and high flows Kaap catchment yiled are much lower than to the the low flow and highe flows of the C-class environmental flow regime at the outlet of the Crocodile catchment, except for the flows of 99.9 % of probablity of non-exceedence.

Table 25: Long term water users supply reliability at 1 in 50 years risk level for Crocodile subsystems

	Water user	Water Allocation [million m^3/a]	Water Supplied at 1: 50 years [million m^3/a]	Assurance of Supply [% of demand]
Upstream of Kwena Dam	Domestic	0.475	0.475	100
	Industry	0	0	-
	Irrigation	5.05	5.05	100
	Sub-Total	5.525	5.525	100
Downstream of Kwena Dam	Domestic	0.0	0.0	-
	Industry	0	0	-
	Irrigation	11.80	10.84	91.8
	Sub-Total	11.80	10.84	91.8
Elands	Domestic	1.2	1.2	100
	Industry	13.3	13.3	100
	Irrigation	6.7	6.7	100
	Sub-Total	21.2	21.2	100
White River	Domestic	1.14	1.14	100
	Industry	0	0	-
	Irrigation	53.56	48.70	90.93
	Sub-Total	54.07	49.85	91.12
Middle Crocodile	Domestic	37.11	37.11	100
	Industry	0	0	-
	Irrigation	110.6	102.52	92.70
	Sub-Total	147.71	146.85	94.53
Kaap River	Domestic	0	0	0
	Industry	0	0	-
	Irrigation	90.6	74.19	81.88
	Sub-Total	90.6	74.19	81.88
Lower Crocodile Allocation	Domestic	7.75	7.75	100
	Industry	8.95	8.95	100
	Irrigation	218.11	212.43	97.4
	Sub-Total	234.81	229.14	97.58
Total		556.9	535	96.0

4.2.6 BUILD MONTROSE AND MOUNTAIN VIEW DAM (MDMVD_CC_12I)

There is higher water assurance to water users by 0.7 percentages at 1:50 year risk level (see Table 26), while lower reliability than the scenario where Montrose Dam is built and present environmental flow regime water requirement is implemented. The Reserve in the three dams is not stable, as it is always trying to satisfy the high EWR implemented in this scenario, which is C-class, as shown in Figure 24, 25 and 26.

Table 26: Long term Crocodile water users supply reliability at 1 in 50 years and 1 in 10 years risk level

Water users	1:50 years assurance (million m^3/a)	1: 10 years assurance (million m^3/a)	1:50 years (% relative to total allocation)	1:10 years (% relative to total allocation)
Irrigation sector	462.2	497.7	94.9	100
Domestic & Industry	70	70	100	100
Total	532.2	567.7	93.3	98.7

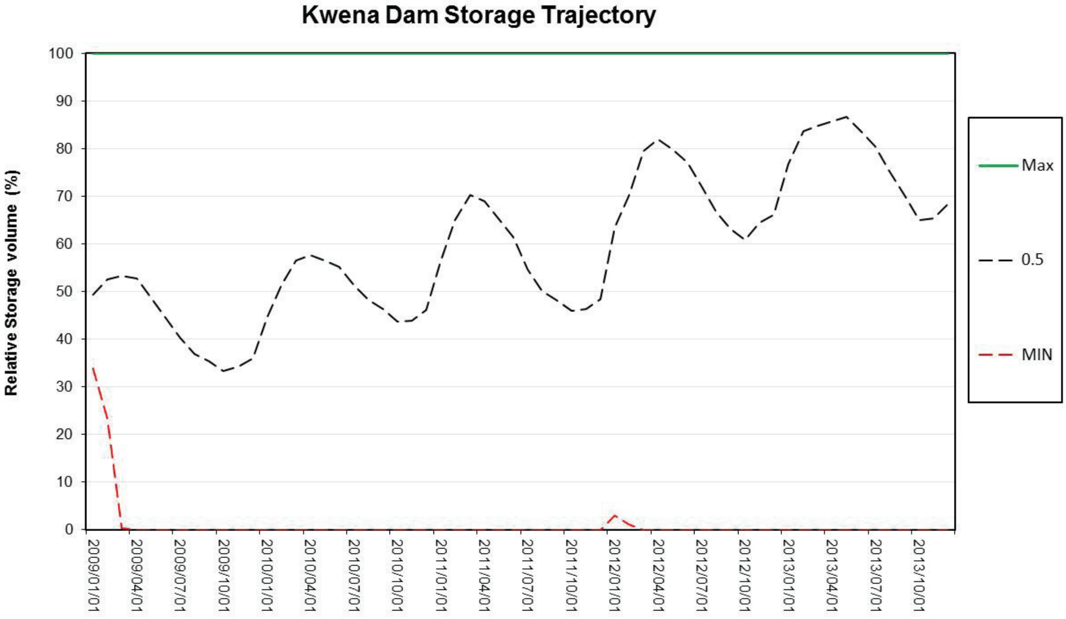


Figure 4. 24: Kwena Dam relative storage volume

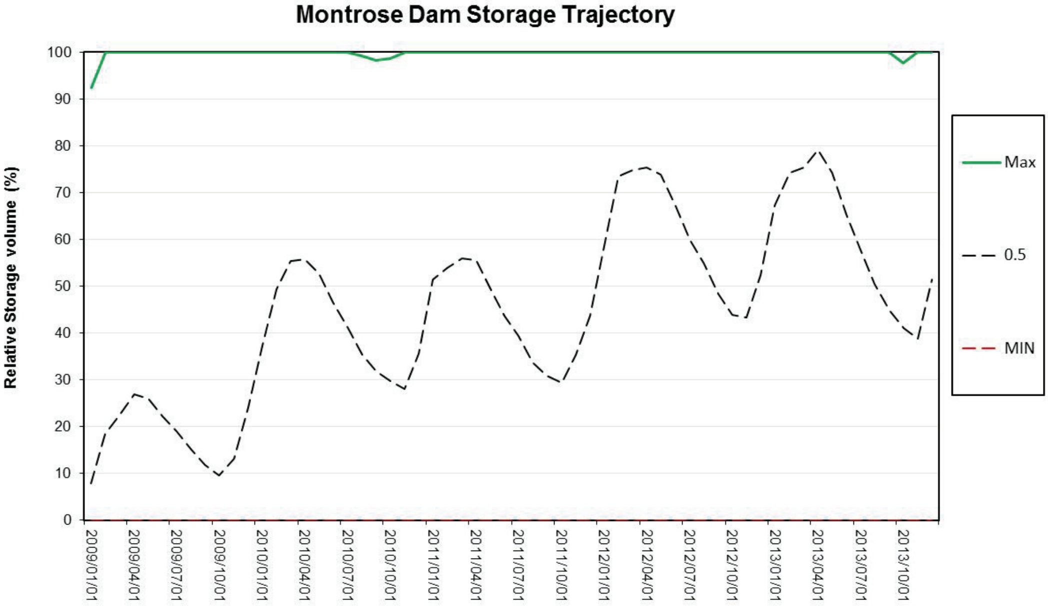


Figure 4. 25: Montrose Dam relative storage volume

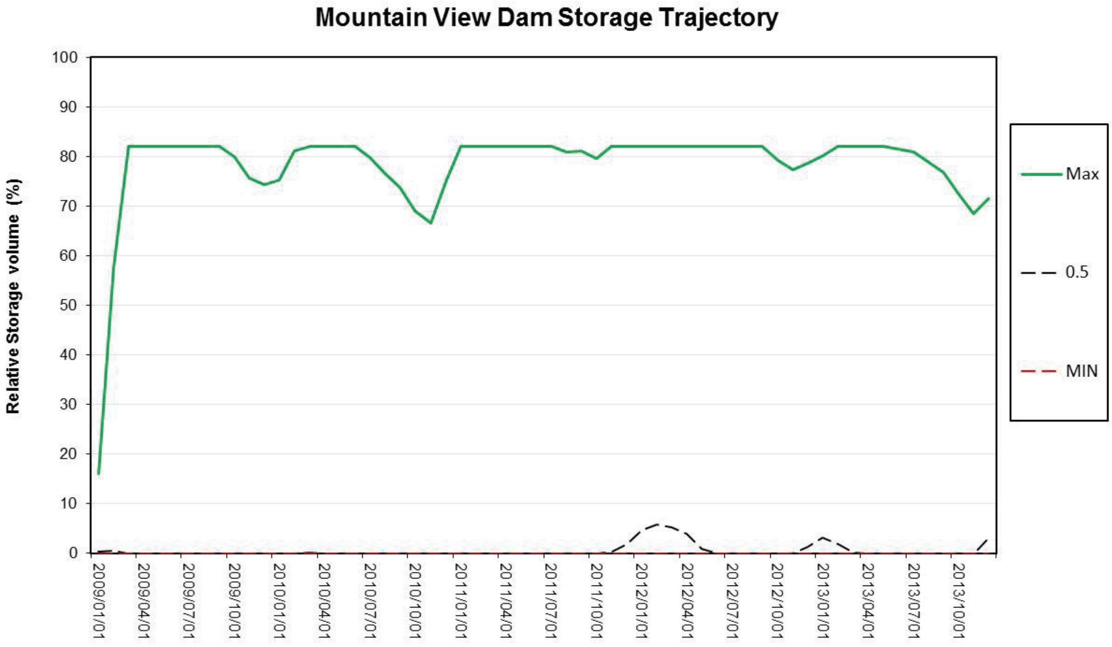


Figure 4. 26: **Montrose Dam relative storage volume**

4.3 FARM SCALE WATER AVAILABILITY

A number of outputs are simulated in the MBIM for each field of the Mhlati farm. Some of the outputs are Crop yield, Water application or availability to the farm, evaporation, deep percolation, return flow or runoff. In the subsequent subsections, analyses of Mhlati water availability for different scenarios are presented.

4.3.1 CURRENT WATER REQUIREMENT, INTERNATIONAL FLOW AT TENBOSCH OF 0.9 M^3 PER SECOND (KD_NO_09I)

For the current international water requirement Scenario, which is 0.9 m^3/s at Tenbosch, the Mhlati Farm irrigation water demand is calculated dynamically using the MBIM. There was almost no supply for the requested water during the two drought spells that occurred in the considered period. The length of simulation is from 1970 to 1999, and the catchment experienced drought in 1983/84 and 1990 to 1994. The drought spell from 1990 to 1994 wasn’t as severe as the 1983/84 however it was for an extended period.

Mhlati farm has rights to access water from the run of river, the Crocodile River, and it can request water from Kwena Dam if there is no sufficient water in the river. From the Figure 4.27 and 4.28 it shows that in most cases during the simulation period water is available to the farm; however in those drought spells the farm doesn’t get enough to sustain crop production.

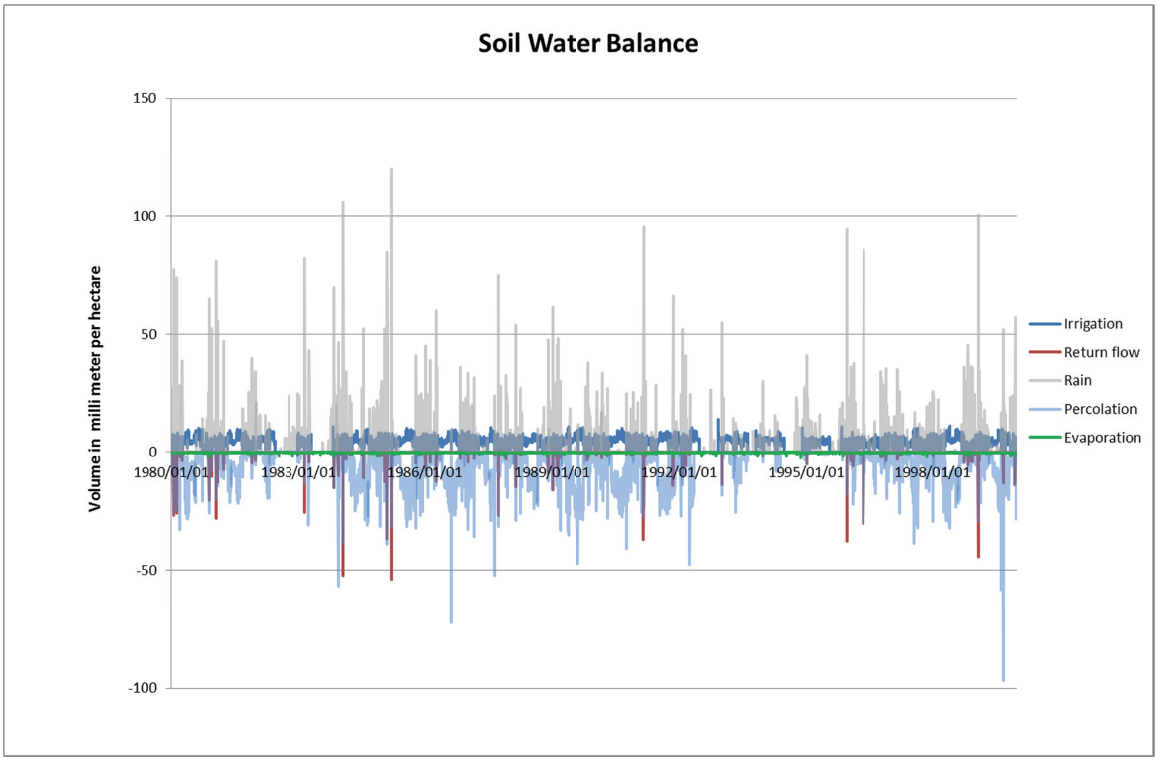


Figure 4. 27: Graphical description of the Mhlati Farm soil balance

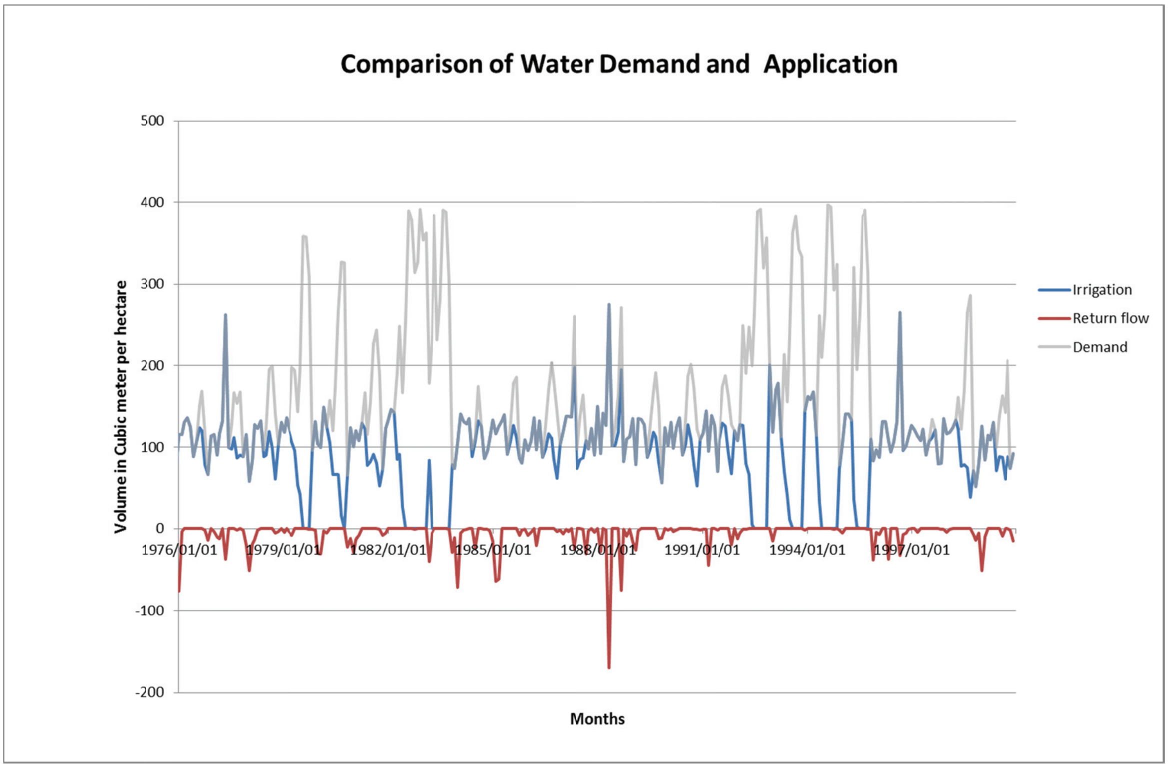


Figure 4. 28: Comparison of Monthly water demand volumes and application of the Mhlati farm

4.3.2 CURRENT WATER REQUIREMENT, IIMA INTERNATIONAL FLOW OF 1.2 M^3 PER SECOND (KD_NO_12I)

In this scenario, IIMA agreed international boundary flows are implemented to assess the implication of water availability to the Mhlati Farm. The water demand of the farm is calculated using MBIM, and the demand is not capped to 1300 mm per hectare. As shown in Figure 4.30 and 4.31, the difference in restrictions if the IIMA international flow is implemented as compared to the Piggs Peak agreed flow which is 0.9 m^3/s is not clearly visible. However, there is more restriction to the farm when the IIMA international flow is implemented.

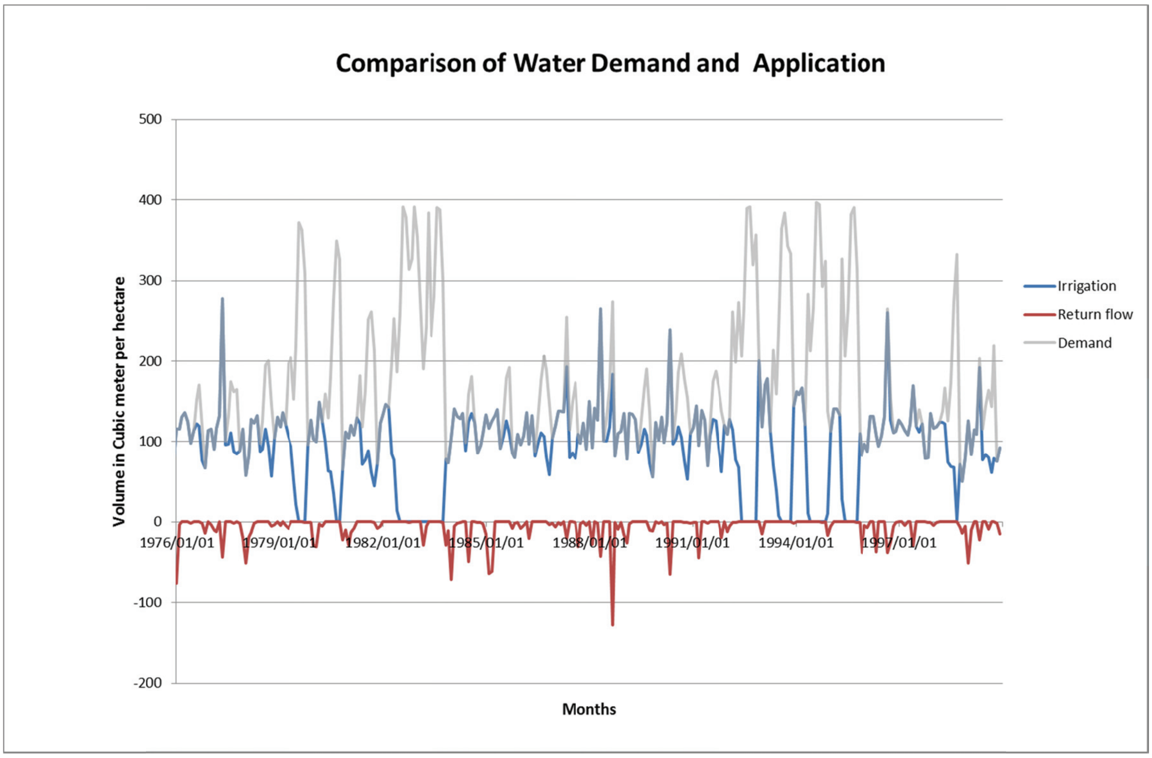


Figure 4. 29: Comparison of Monthly water demand volume and application of the Mhlati farm

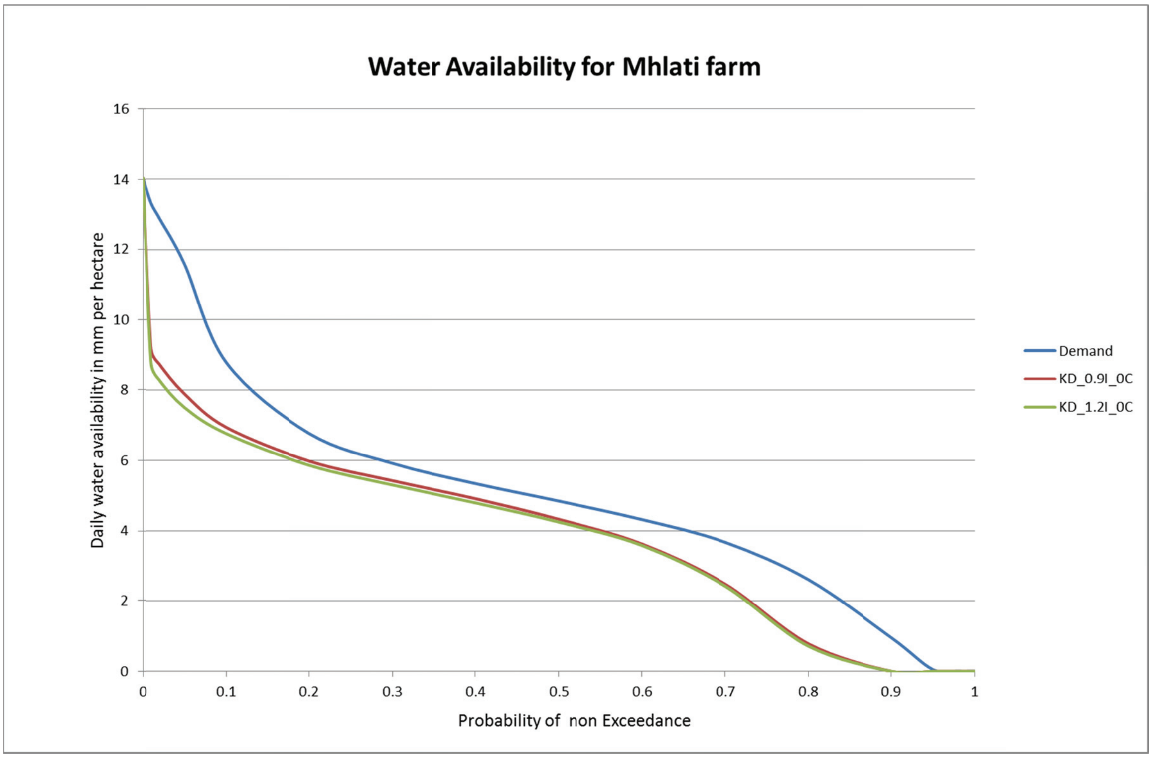


Figure 4. 30: Daily water availability to the Mhlati farm at different probabilities of exceedence

4.3.3 PRESENT FLOW REGIME EWR FOR EWR SITE 6 (KD_PRES_12I)

As explained in the Catchment scale scenarios, an EWR at different sites will be implemented in the future in addition to the international flow requirement. In this scenario, a present flow regime is implemented at outlet of the Crocodile River in addition to the IIMA agreed international water requirement and the implication to Mhlati farm water availability is assessed. Figure 4.32 shows that the severity of restriction to the water availability is comparable to scenario 2, where IIMA international flow is implemented.

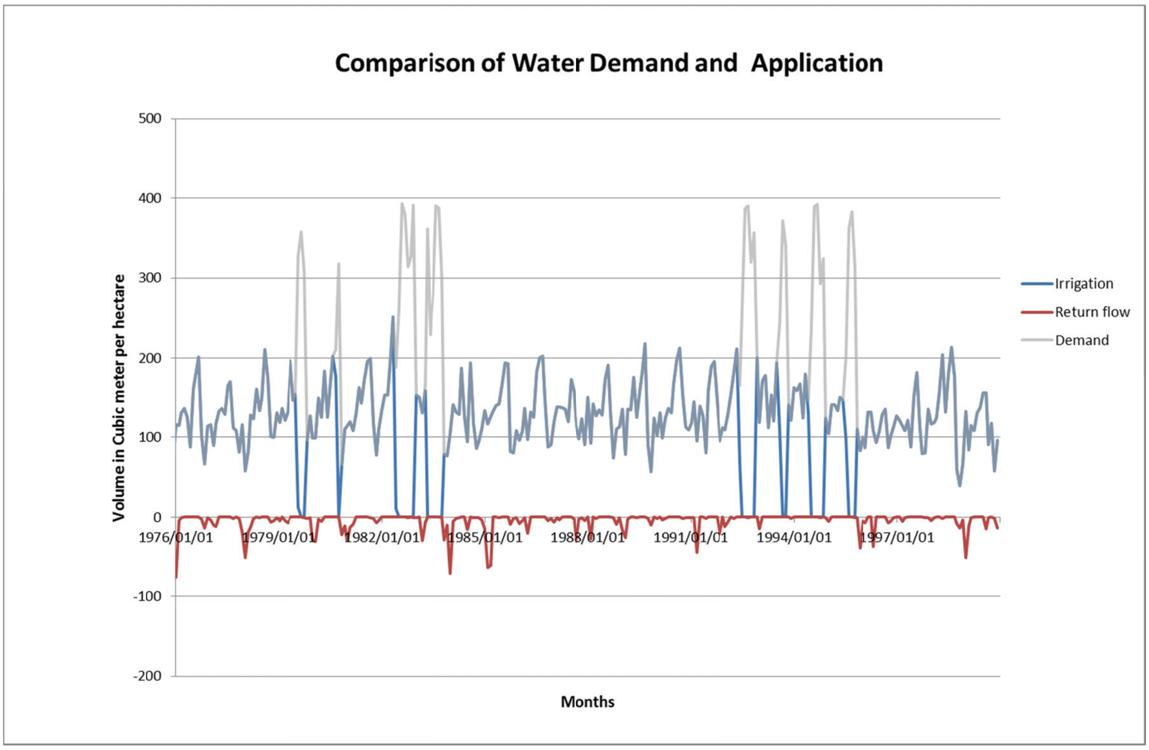


Figure 4. 31: Comparison of monthly water demand volumes and application of the Mhlati Farm

4.3.4 ADD MONTROSE DAM

In the catchment scale scenarios, it was stated that addition of Montrose Dam was assessed as a planning scenario to solve the possible water shortage in the catchment due to the implementation of the international IIMA agreed flows and environmental requirement at the outlet of the Crocodile River. In this case, a farm scale scenario with Montrose Dam in the setup is simulated to assess the positive effects that could have on the Mhlati farm water availability.

4.3.4.1 With present flow regime at EWR site 6 (MD_Pres_12l)

With the addition of the Montrose Dam, two types of environment flow regime are implemented. In this scenario Present environmental flow regime water requirement is considered, and the impact on Mhlati water availability is assessed. Mhlati farm will have more water available if Montrose Dam is built, where the Present environmental flow regime is implemented in the exercise. The availability of water to the farm in this scenario is compared to the current water requirement scenario, where 0.9 m^3/s trans-boundary water is considered, as shown in Figure 4.33.

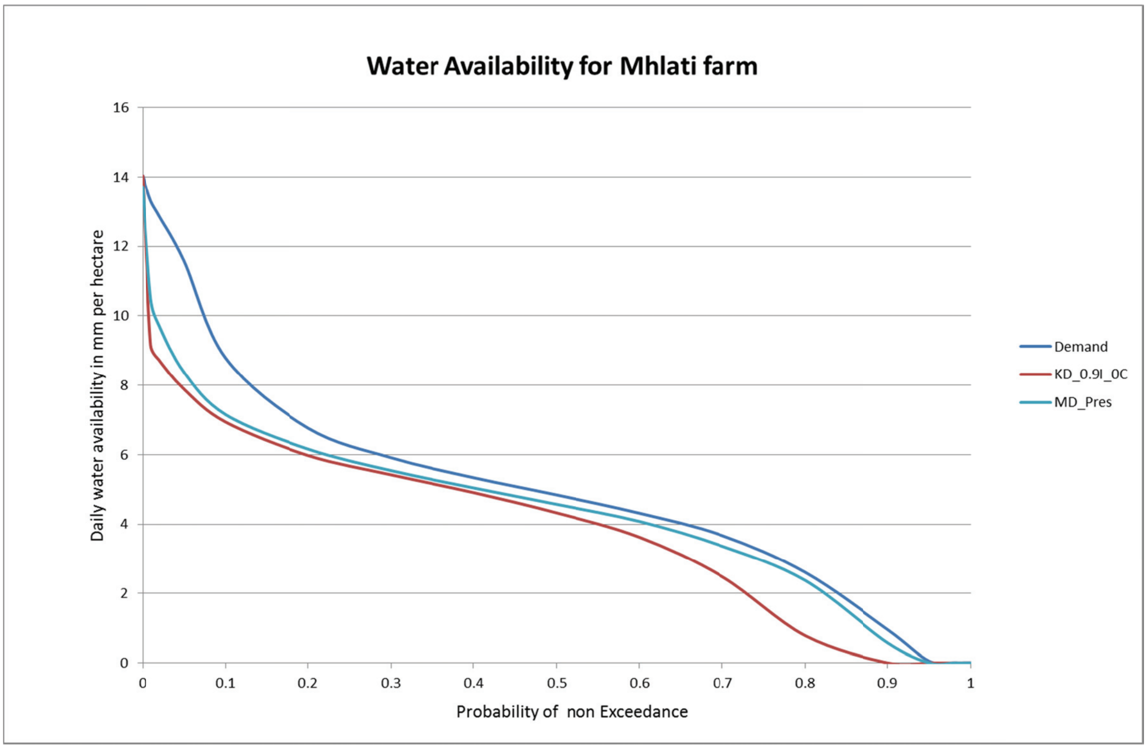


Figure 4. 32: **Daily water availability to the Mhlati Farm at different probabilities of exceedence**

4.3.4.2 With comprehensive C-class EWR at EWR site 6 (MD_CC_12I)

Figure 35, shows that if the C-class EWR instead of the Present EWR is implemented, then the water availability to Mhlati farm decreases sharply. This is due to high amount of water required to meet the C-class EWR as compared to the Present environmental flow regime. If the water availability to Mhlati Farm in this scenario is to be compared to the current water requirement scenario, there are high volumes water available when the water requirement is low and less water available when the water requirement is high. This is could be due to the fact that Montrose Dam stabilises the river and supplies Mhlati farm according to operating rules when the river water availability is not adequate.

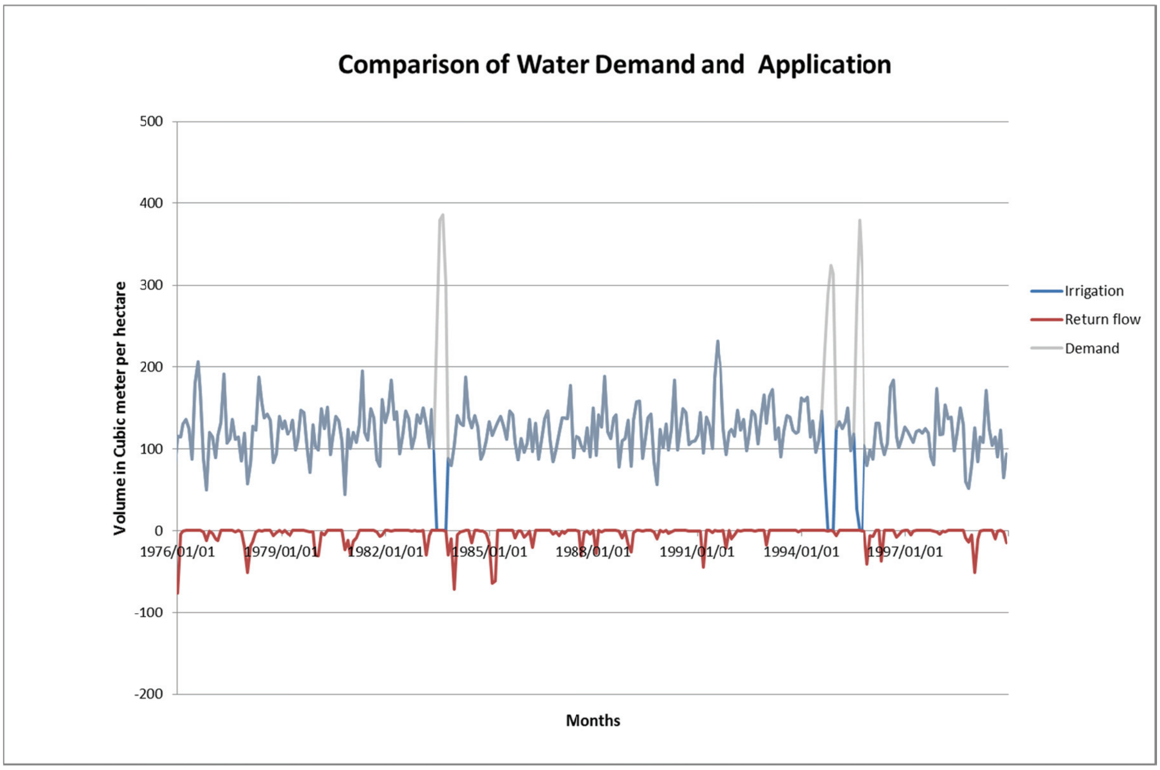


Figure 4. 33: Comparison of Monthly water demand volumes and application of the Mhlati Farm

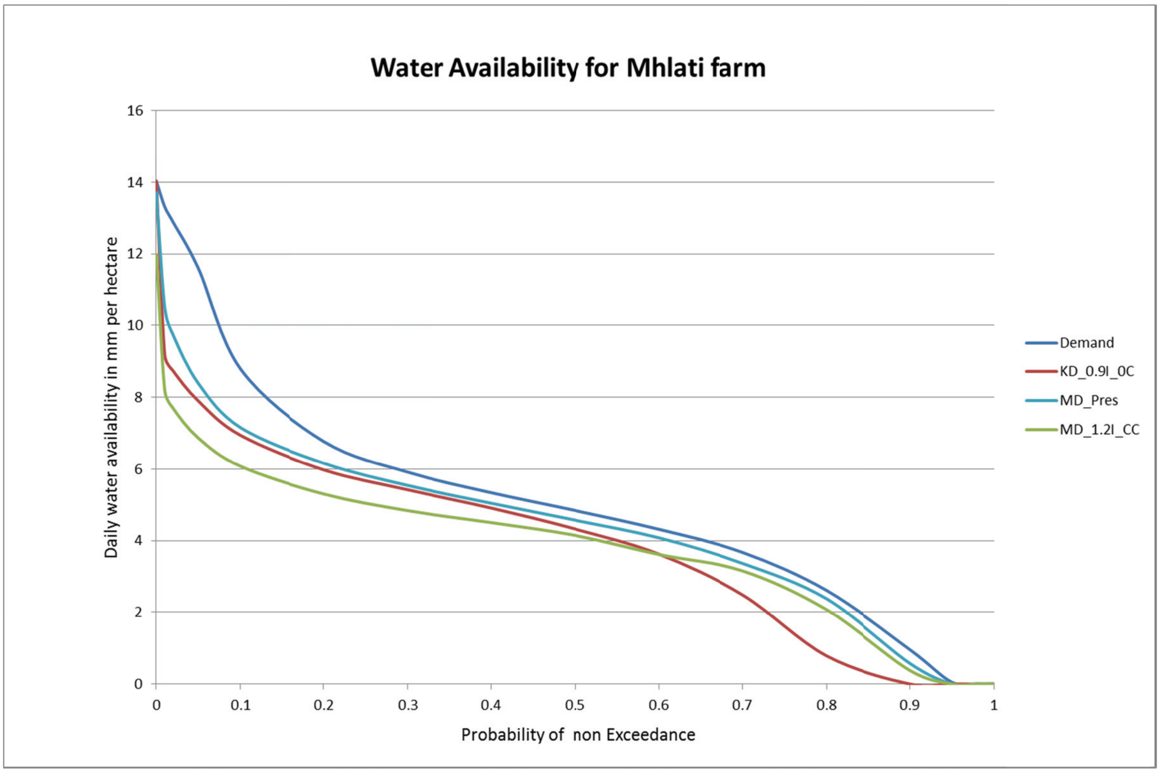


Figure 4. 34: Daily water availability to the Mhlati Farm at different probabilities of exceedence

4.3.5 MOUNTAIN VIEW DAM

4.3.5.1 With present flow regime EWR at EWR site 6 (MVD_Pres_12l)

In this scenario, where Present environmental flow EWR is considered and Mountain View is added, the water availability to the Mhlati farm is higher than all the scenarios considered. Mountain View captures water at the outlet of the Kaap River, and Mhlati farm is located below the Crocodile and Kaap river confluence. In this scenario, as shown in the Figure 36, it captured adequate water to supply the present regime EWR at the outlet of the Crocodile River and improve the water availability to water users located below the confluence of the Kaap and Crocodile River.

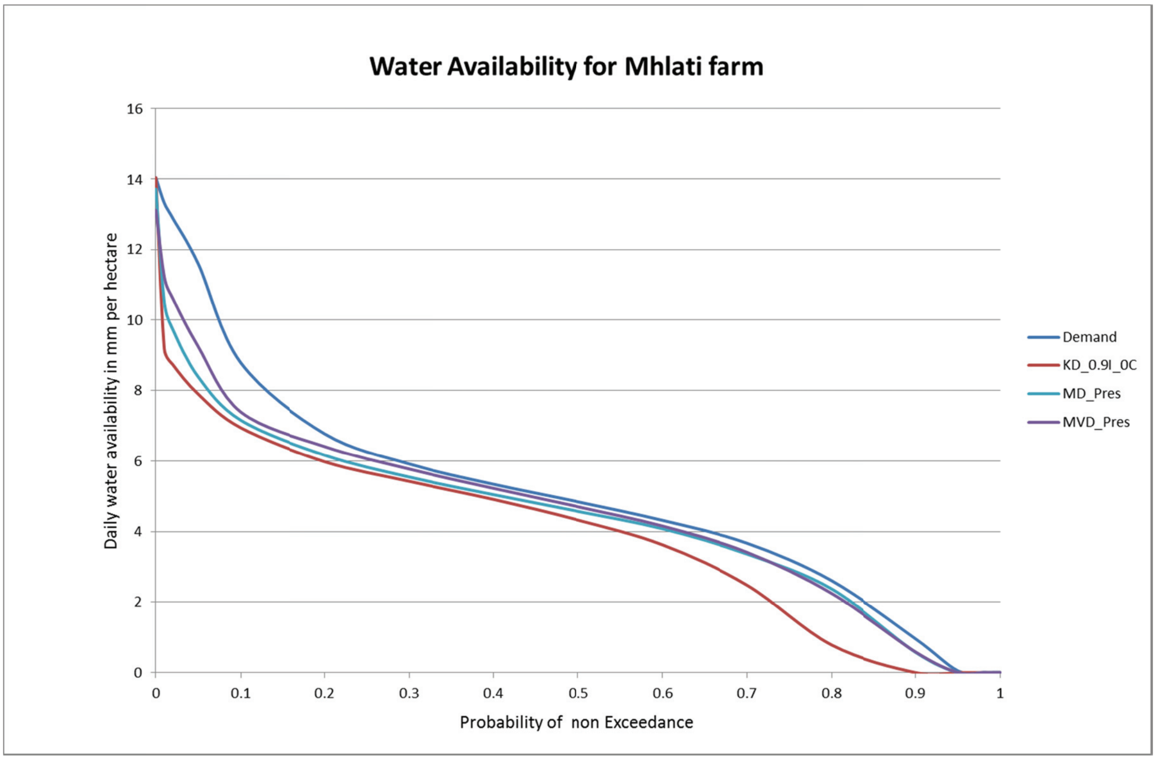


Figure 4. 35: Daily water availability to the Mhlati Farm at different probability of exceedence

4.3.5.2 With comprehensive C-class EWR at EWR site 6 (MVD_CC_12l)

Mhlati water availability decreased significantly when the C-class EWR is implemented in place of the present flow regime. This shows that the Captured Kaap river flow is not adequate enough to supply the C-class and improve the water reliability of water users below the confluence of the Kaap and Crocodile River.

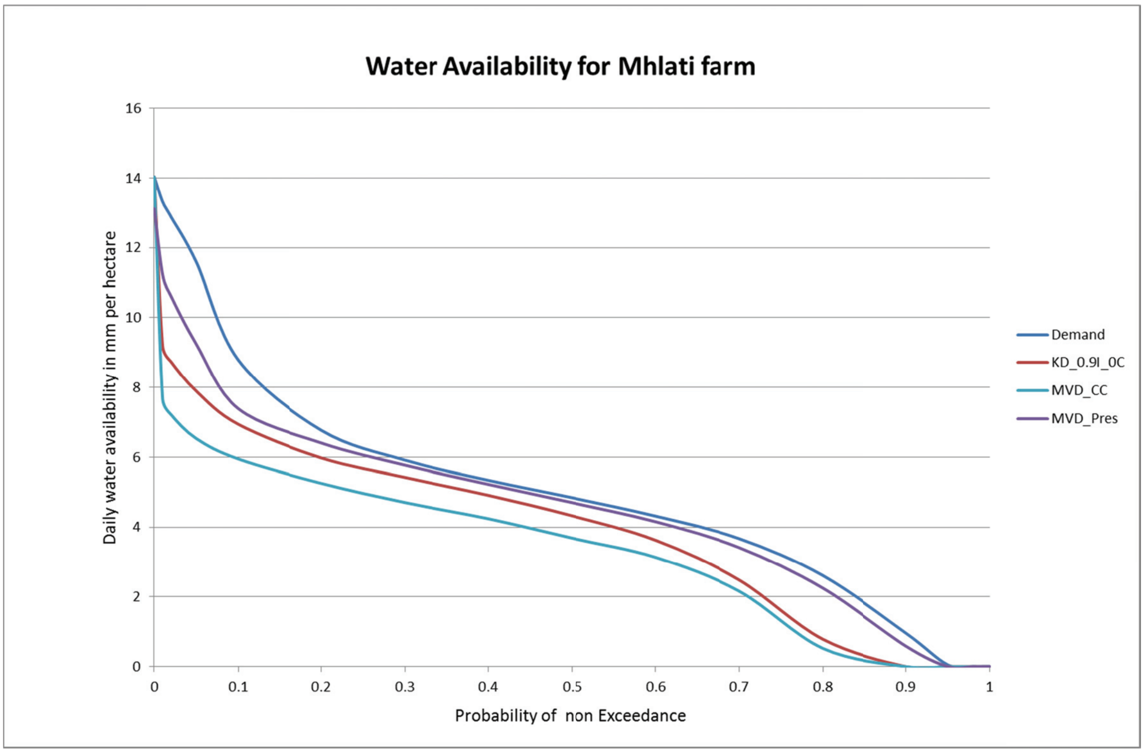


Figure 4. 36: **Daily water availability to the Mhlati Farm at different probabilities of exceedence**

4.3.6 *BUILD MONTROSE & MOUNTAIN VIEW DAMS WITH COMPREHENSIVE C-CLASS EWR AT EWR SITE 6 (MDMVD_CC_12I)*

If both the Montrose and Mountain View Dams are built, operating rules will be implemented for the two dams in a vision to manage the Crocodile catchment water sustainably and efficiently. Hence, there will be less runoff river water to the Mhlati farm, as water from the Elands and Kaap catchments are conserved in Montrose and Mountain View Dams respectively. However, the supply of water to the farm will be stable and there is higher reliability for the minimum required amount water to sustain the farm.

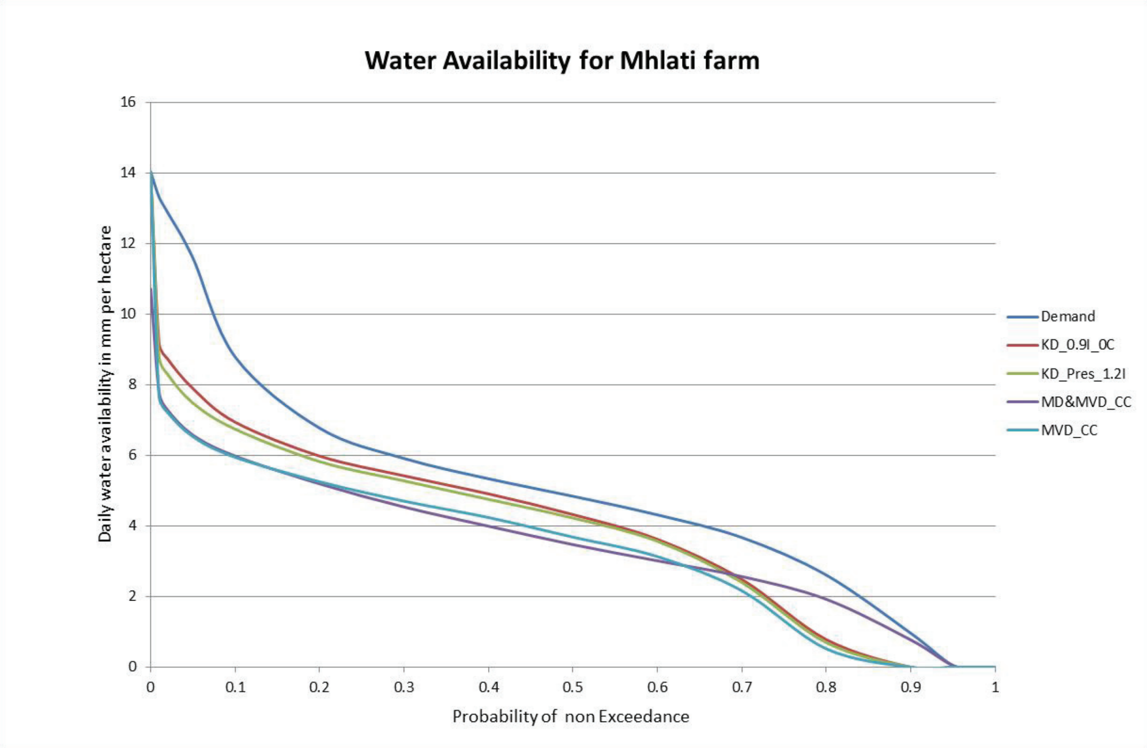


Figure 4. 37: Daily water availability to the Mhlati Farm at different probabilities of exceedence

In all of the above scenarios discussed above, the return flow from the Mhlati irrigation farm averaged between 6-10 % of the water application. At the start of this study it was envisaged that the impact of the return flow from the irrigation fields on the total catchment water availability will be investigated. However, to estimate the return flow from each of the irrigation fields in the Crocodile catchment, it requires a detailed farm scale modelling of each of those irrigation fields. And it is beyond this study, to put a detailed farm scale MBIM model for each of the irrigation farms of Crocodile catchment.

4.4 *FARMS-SCALE ECONOMIC ANALYSES*

The farm-scale economic results show the impact of the alternative catchment scale management options on the profitability and the livelihood of different irrigation farms. The results should be interpreted taking cognisance of the steady state assumption. Thus, the different farm situations should not be interpreted as a transition from one to another, but rather as an entity on its own. The same scale is used to portray the cumulative probability distributions of return on equity and the net cash flows. Thus, the graphs are visually directly comparable. Figure 4.38 is used as an example to aid interpretation of the results that follow.

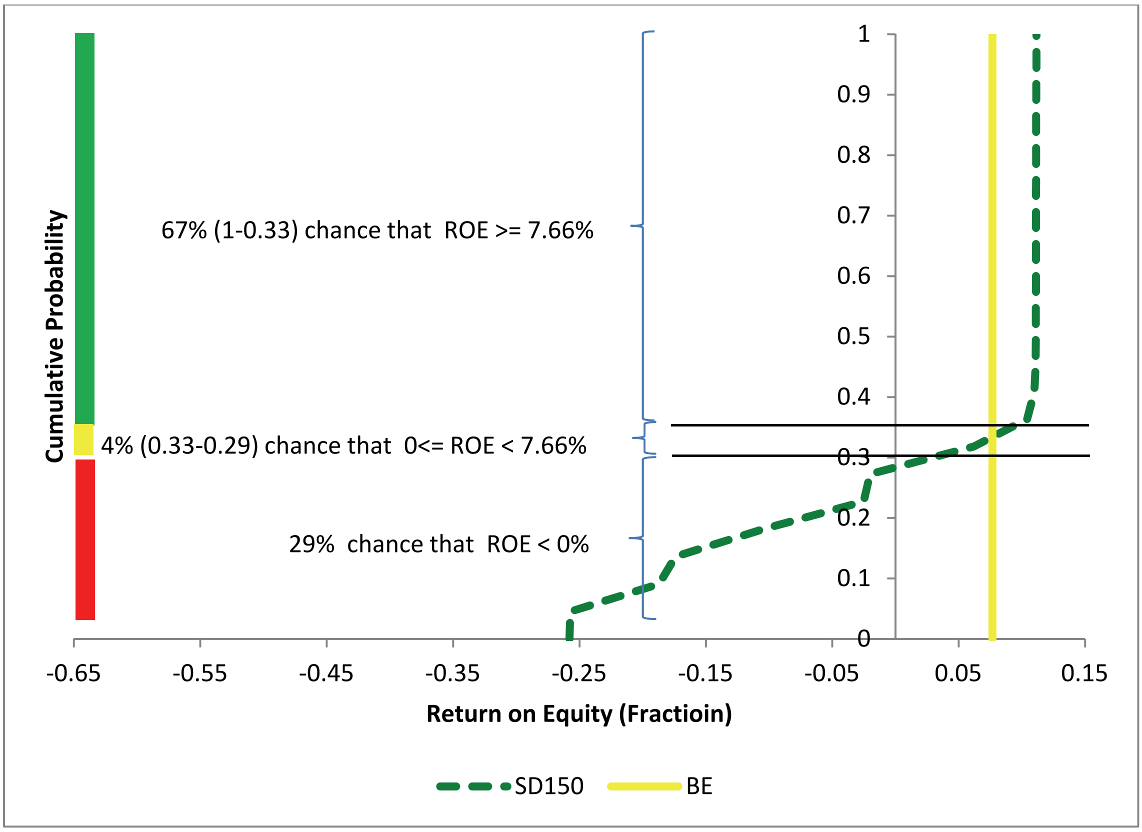


Figure 4. 38: Example cumulative probability distribution of ROE

Figure 4.38 shows the cumulative probability distribution of ROE for one farming scenario as well as the breakeven ROE of 7.66%. The cumulative probability distribution indicates the chance to obtain a specified ROE or less. The probability to obtain a ROE less than zero is 29% (red) whereas the probability to obtain a ROE greater or equal to 7.66% is 67% (1-0.33) (green). The results for each scenario is summarised using a stoplight chart where red is used to indicate ROE levels below zero, yellow for ROE levels greater than zero but less than the breakeven of 7.66% and green if ROE is greater than the breakeven level. The same logic is applied to the livelihood analyses.

4.4.1 CURRENT WATER REQUIREMENT, INTERNATIONAL FLOW AT TENBOSCH OF 0.9 M^3 PER SECOND (KD_NO_09I)

4.4.1.1 Profitability

Profitability is measured by the return on equity (ROE) of the farming business. The farming business is financially feasible if ROE is greater than the return on total assets (ROA). A positive leverage is obtained when ROE > ROA which indicates that foreign capital is employed profitable in the farming business. Capital is profitably employed if the returns exceed the cost of capital. The amount with which the ROA is greater than the cost of capital accrues to the owner.

Consequently the ROE of the farming business should be greater than ROA. In cases where ROA < ROE, a negative financial leverage prevails which means that own capital needs to be used to pay for interest and rental obligations. Figure 4.39 shows the cumulative probability distributions of the ROE for four farming businesses.

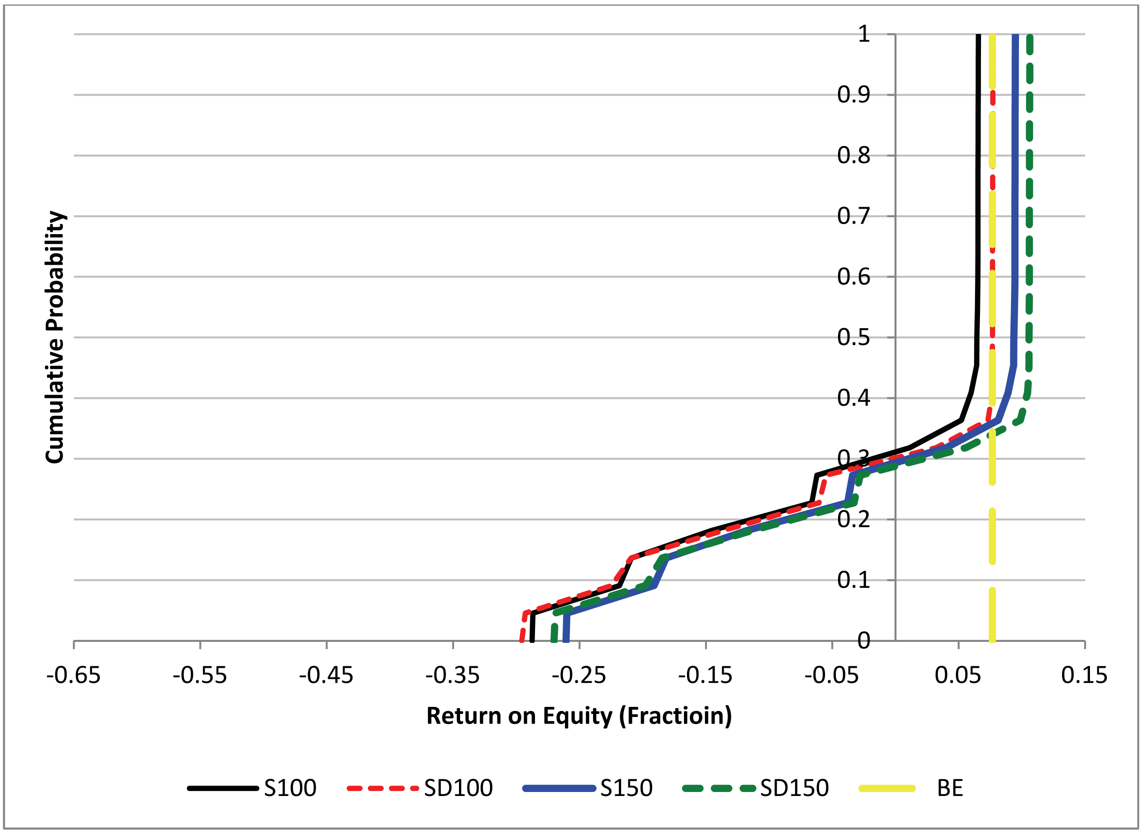


Figure 4. 39: Cumulative probability distributions of ROE for four farming businesses for catchment water management scenario KD_NO_09I.

All four the cumulative probability distributions show similar forms with the larger farm sizes dominating the smaller farm sizes. The drip irrigation farms (SD100 and SD150) are also more profitable than their counterparts. Results also show that water availability is not secure. The vertical portions of the cumulative probability distributions for the alternatives indicate that water availability has only marginal effects on the profitability of the irrigation farms. The sprinkler dominated farms will be affected for about 45% of the time by water restrictions while the farms with relatively larger areas of drip will be affected for about 35% of the time. The impact of using water more efficiently is therefore evident from the results. The probability of achieving a negative return on equity is around 30% for all the farm scenarios considered. Although the probability of achieving negative returns hover around 30% only farm scenario SD100 of the smaller farm sizes are financially feasible (ROE=ROA).

Next the results from the cash flow analysis are discussed to determine whether the farms are generating enough cash flows to sustain a livelihood.

4.4.1.2 Livelihood

Figure 4.40 indicates the cumulative probability distributions of net cash flows for the four different farming businesses.

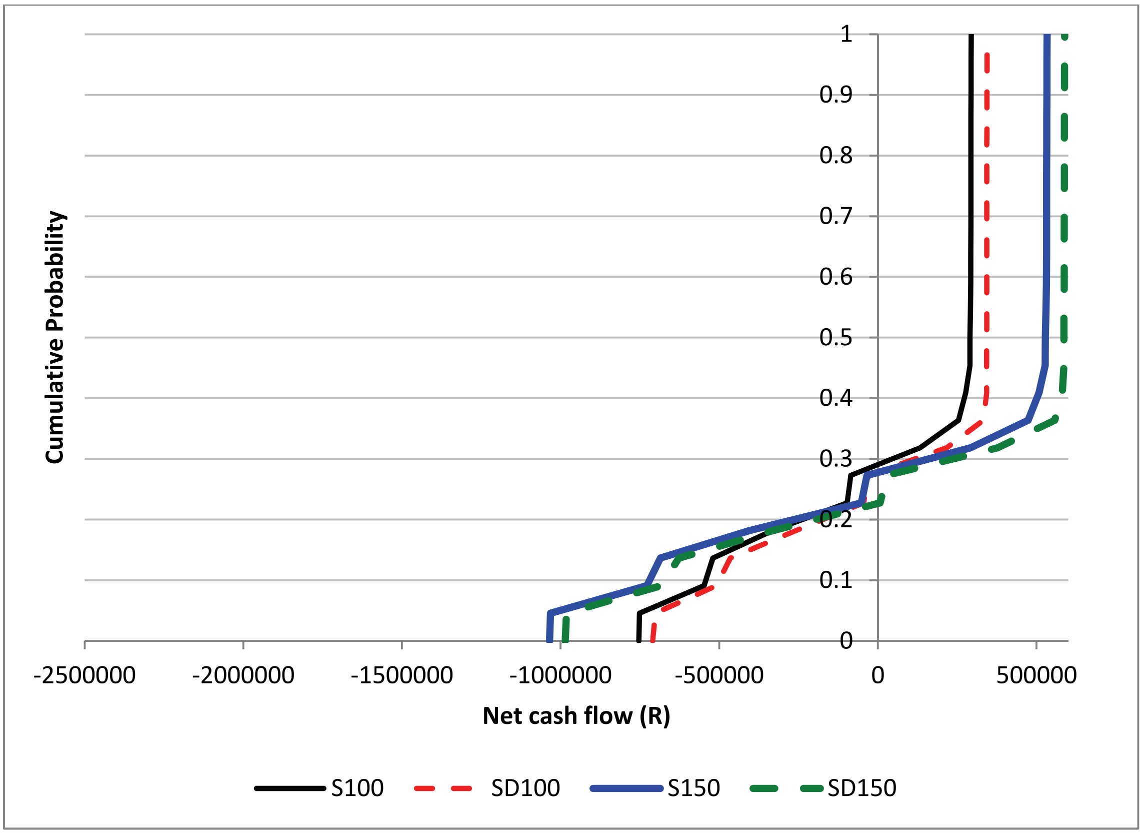


Figure 4. 40: Cumulative probability distributions of net cash flow for four farming businesses for catchment water management scenario KD_NO_09I.

The results clearly shows the ability of the larger farms to generate larger cash flow surpluses (values > 0) when compared to the smaller farms. Within each farm size category the drip irrigation farms dominate the sprinkler irrigation farms. Contrary to the larger farms ability to generate larger cash surpluses, these farms also have the greatest possibility of generating larger cash flow deficits when compared to the smaller farms. The last mentioned is mainly due to the effect of larger overheads and debt repayment requirements. The probabilities of generating positive cash flows vary between 71% and 78% for all the farm scenarios. The analysis shows that although the farm scenario S100 is not financially feasible it does generate enough cash flows to provide a livelihood more than 70% of the time.

4.4.2 CURRENT WATER REQUIREMENT, IIMA INTERNATIONAL FLOW OF 1.2 M^3 PER SECOND (KD_NO_12I)

4.4.2.1 Profitability

Scenario KD_NO_12I represent the situation where the international flow requirement is increased to 1.2 m^3/s. The results from the profitability analyses are given in Figure 4.41.

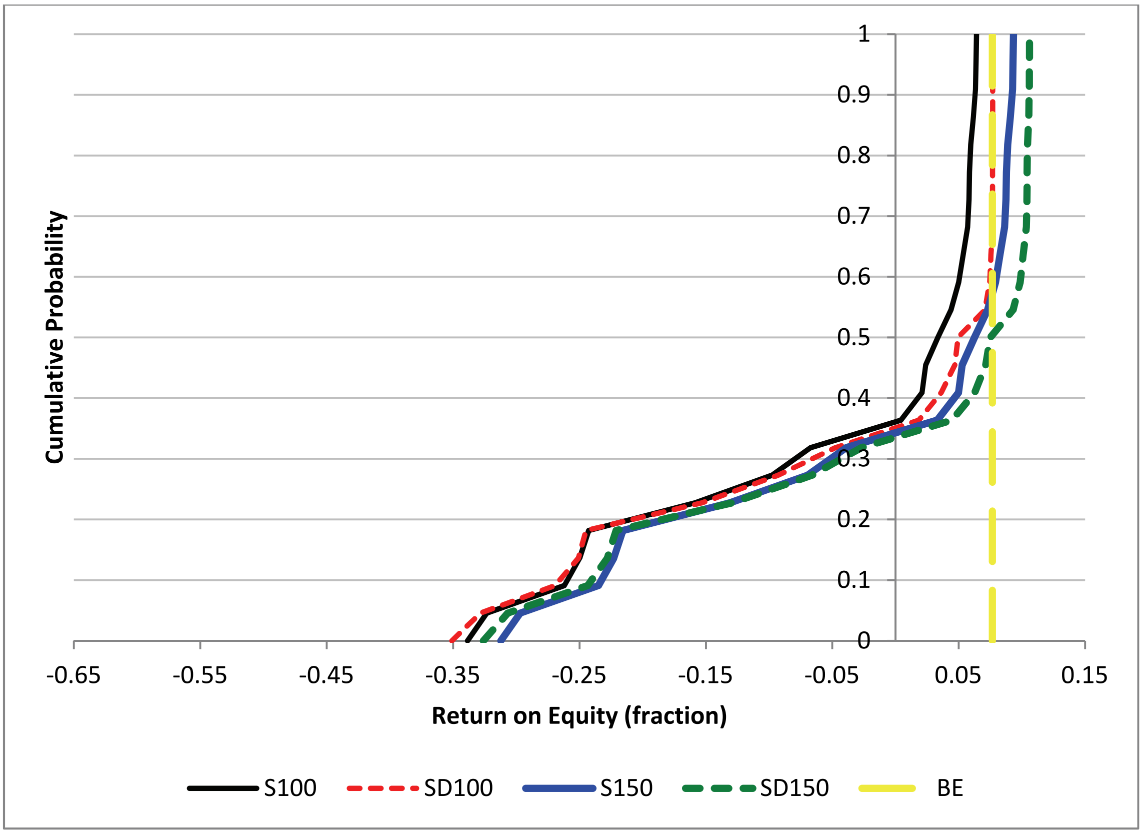


Figure 4. 41: Cumulative probability distributions of ROE for four farming businesses for catchment water management scenario KD_NO_12I.

The results show that the same general trends as with Scenario KD_NO_09 are observed with Scenario KD_NO_12I. There are, however, some noticeable differences between the scenarios. Water restrictions will impact the profitability of farms with relatively lower water application efficiencies more quickly when compared to the farms with relatively higher efficiencies. As a result ROE of the sprinkle farms diverges more quickly from the maximum obtainable values to lower levels before converging to more or less the same levels as the SD farms. The point of convergence corresponds to a probability level of 35%. From there on the farm scenarios within a specific farm size category follows the same path till it reaches the minimum level of profitability. The minimum levels are, however, lower than Scenario KD_NO_09. Cognisance should also be taken of the fact that water restrictions will occur more frequent and therefore the probability of achieving a positive leverage is reduced to 40% for SD100 and S150 and 50% for SD150.

4.4.2.2 Livelihood

The cash flow results shown in Figure 4.42 suggest that the more frequent restrictions imposed by the increase of the international flow requirement will decrease the probability of all the scenarios to generate positive cash flows by about four percentage points. In addition the magnitude of net cash flow deficits have increased by about R250 000.

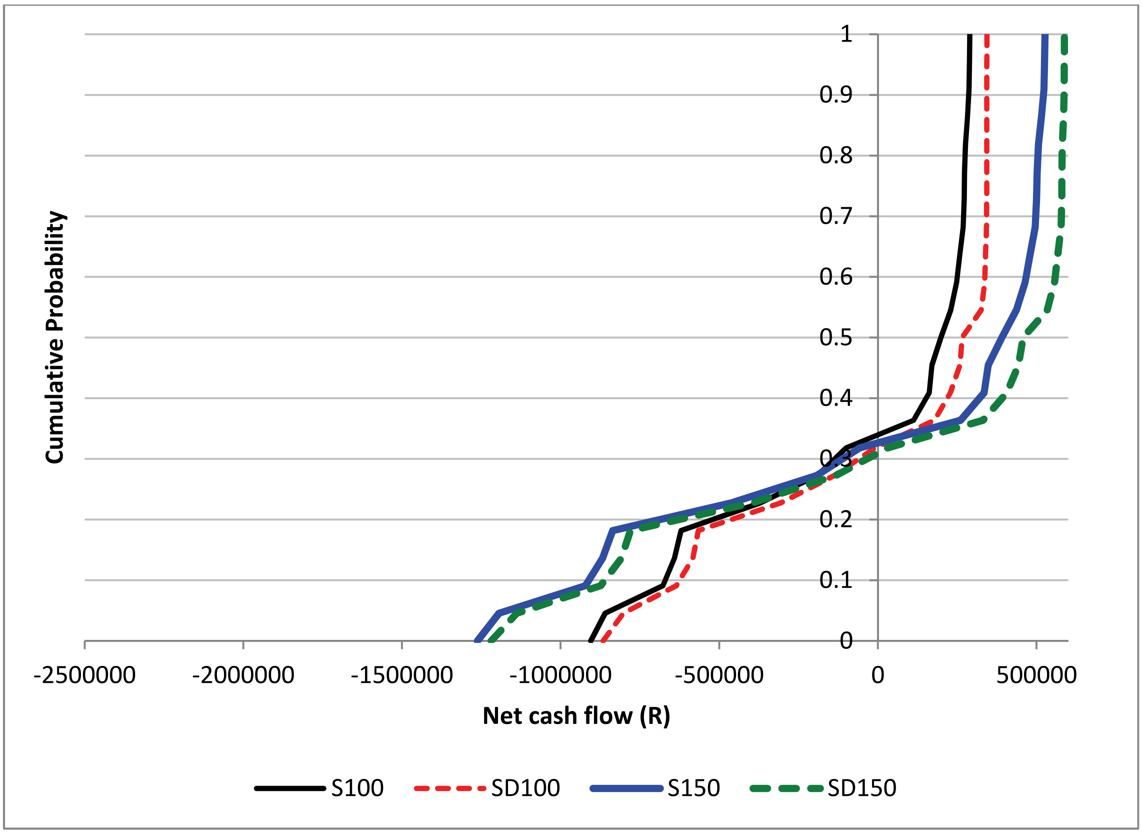


Figure 4. 42: Cumulative probability distributions of net cash flow for four farming businesses for catchment water management scenario KD_NO_12I.

4.4.3 PRESENT FLOW REGIME FOR EWR SITE 6 (KD_PRES_12I)

4.4.3.1 Profitability

Figure 4.43 shows the profitability results from imposing an EWR based on the present flow regime in addition to an international flow requirement of 1.2 m^3/s.

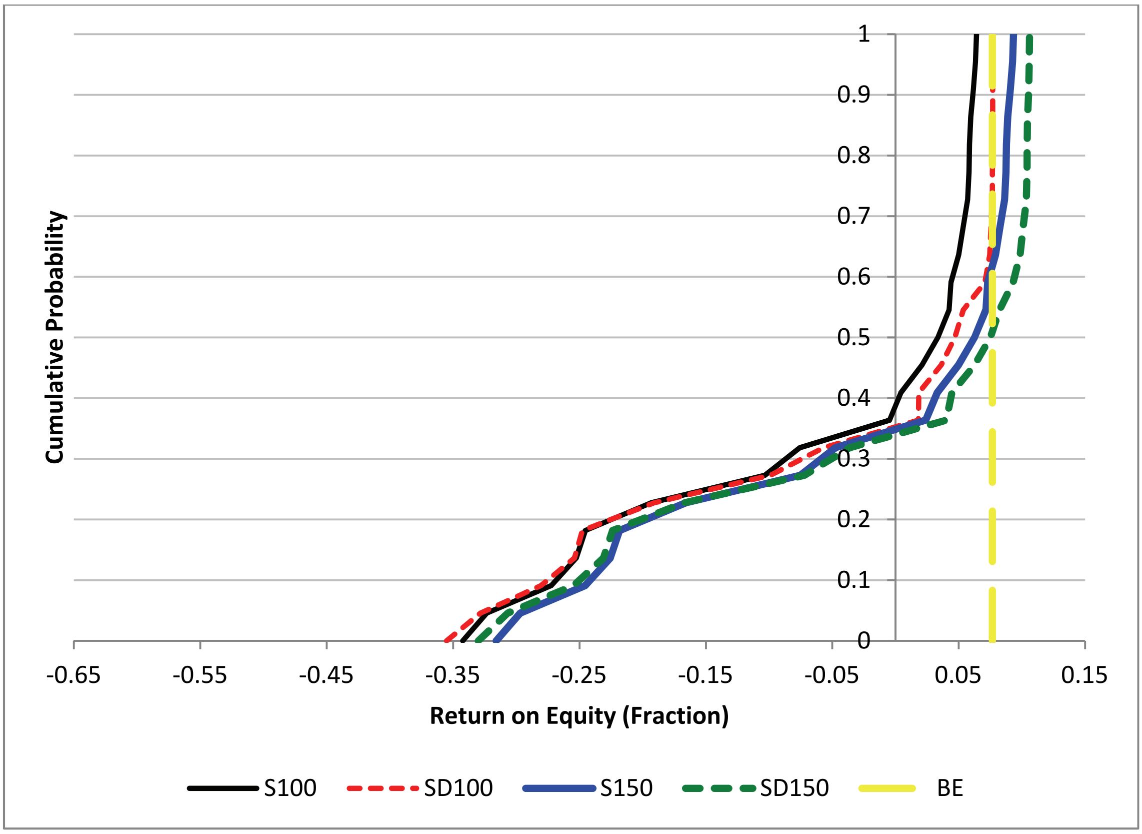


Figure 4. 43: Cumulative probability distributions of ROE for four farming businesses for catchment water management scenario KD_Pres_12I.

Figure 4.43 shows that the general form of the distributions of ROE are almost identical to the distributions portrayed in Figure 4.41 for Scenario KD_NO_12I. The only difference is that the distributions are slightly stretched to the left resulting in a small increase in the probability of not achieving financial leverage.

4.4.3.2 Livelihood

The fact that the EWR based on the present flow regime in addition to an international flow requirement of 1.2 m^3/s has minimal impact is also echoed in the results of the cash flow analysis shown in Figure 4.44.

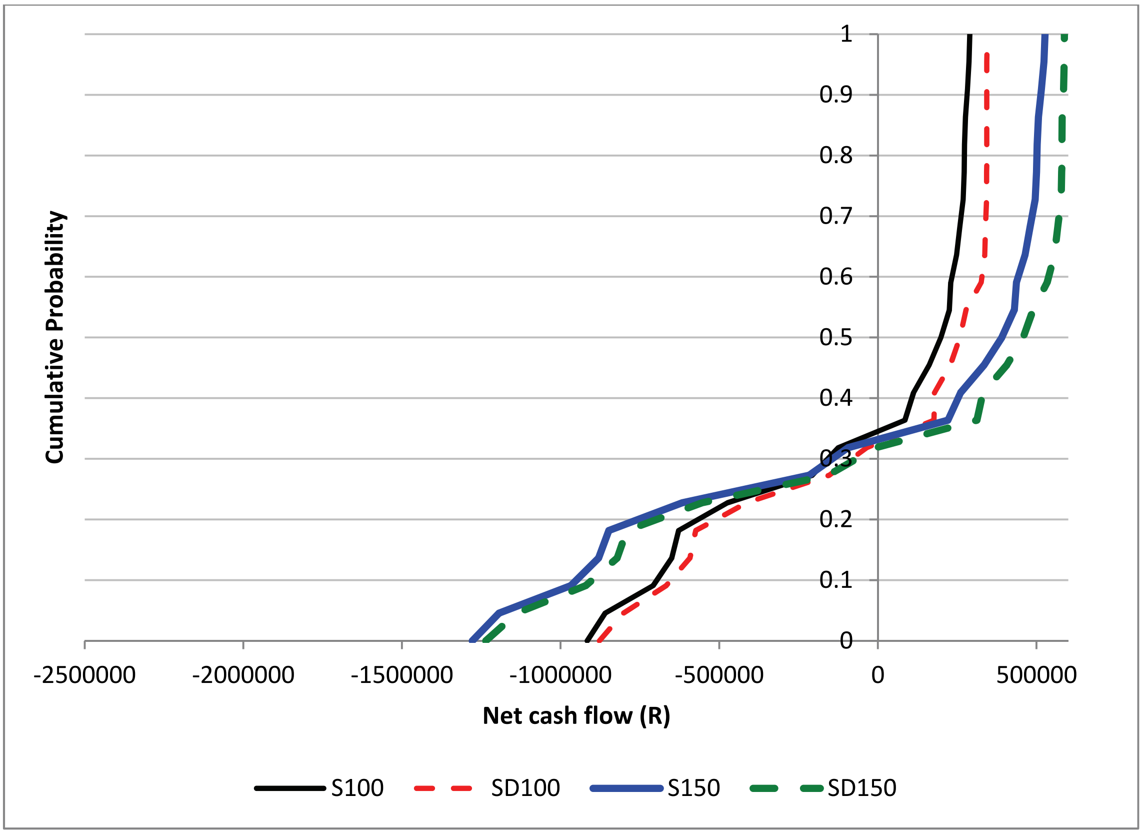


Figure 4. 44: Cumulative probability distributions of net cash flow for four farming businesses for catchment water management scenario KD_Pres_12I.

Visual inspection of Figure 4.44 and Figure 4.42 shows that the results are almost identical. Thus, the conclusion is that the addition of the EWR based on the present flow regime will have little effect on the farmers.

4.4.4 ADD MONTROSE DAM

4.4.4.1 With present flow regime EWR at EWR site 6 (MD_Pres_12I)

4.4.4.1.1 Profitability

The purpose of building the Montrose Dam is to stabilise flows in the river and to increase the availability of water in the system. The profitability results from building the Montrose Dam with an international flow of 1.2 m^3/s and an environmental flow requirement based on the present flow regime are shown in Figure 4.45.

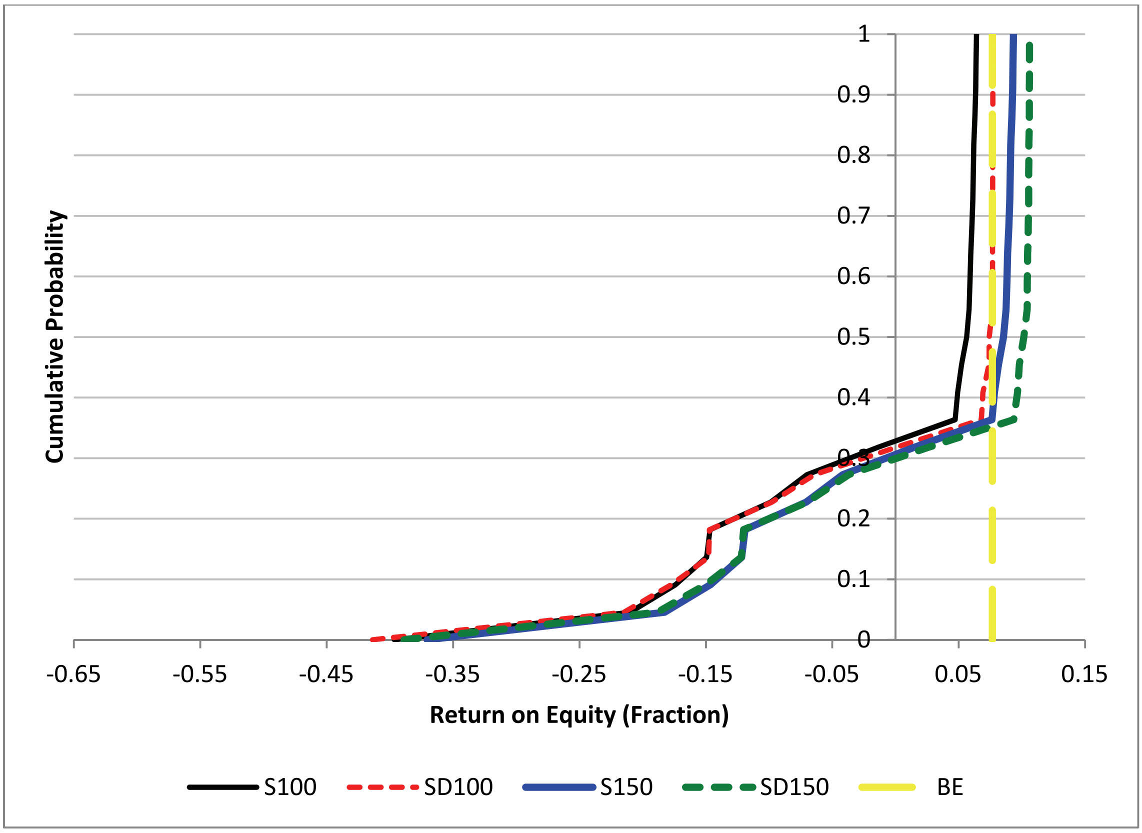


Figure 4. 45: Cumulative probability distributions of ROE for four farming businesses for catchment water management scenario MD_Pres_12l.

The impact of water availability on profitability is evident from the fact that for 64% of the time ROE will not deviate much from the achievable levels of ROE under conditions of no water restrictions (vertical part of the distribution). When compared to Scenario KD_Pres_12I the results indicate that the probability of achieving a positive financial leverage has increased when the Montrose Dam is built

to about 65% for the larger farming scenarios and 48% for scenario SD100 while S100 which is still infeasible. The probability of achieving a negative return has also decreased slightly. More significant is the reduction in the level of shortfalls that were reduced significantly as indicated by the reduction of the area under the graphs to the left of a ROE of zero.

4.4.4.1.2 Livelihood

The positive impact of Montrose Dam on the profitability of the farm has also translated into a positive impact on the net cash flows of the farms as shown in Figure 4.46. Although the reduction in the probability of realising a negative cash flow is not significant, the reductions in average shortfalls are substantial.

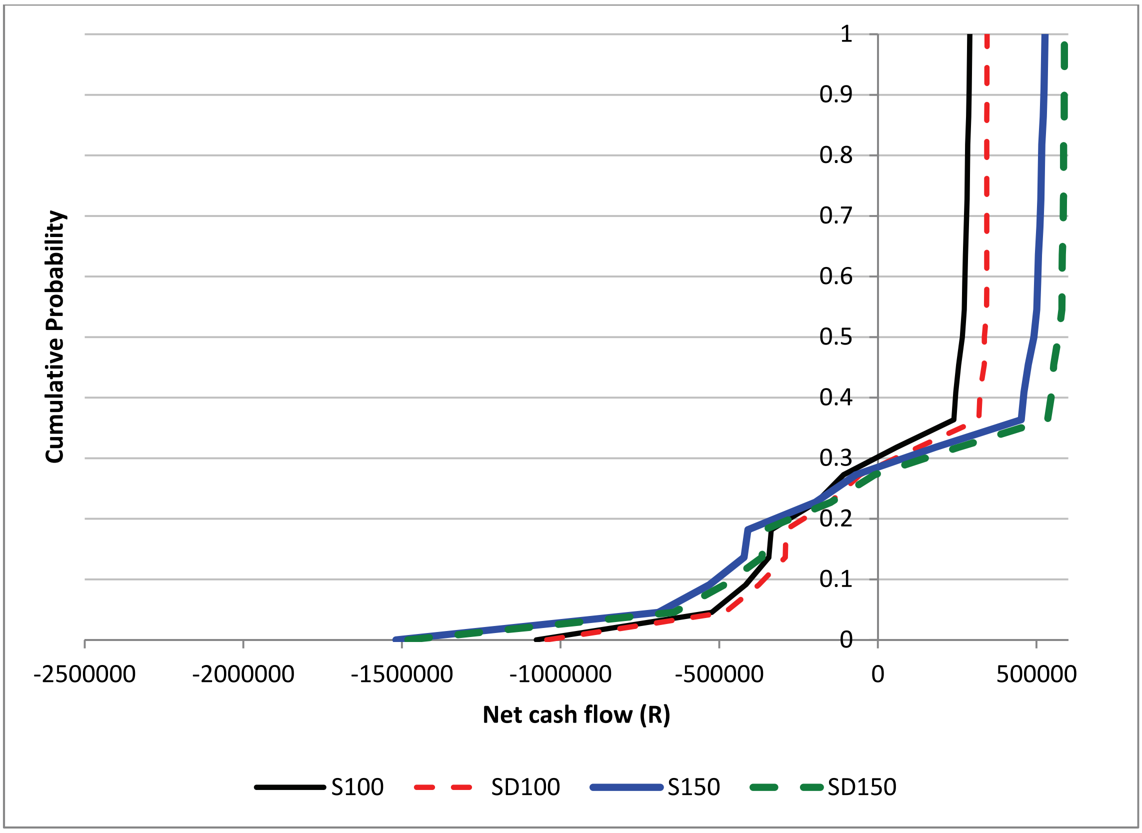


Figure 4. 46: **Cumulative probability distributions of net cash flow for four farming businesses for catchment water management scenario MD_Pres_12I.**

4.4.4.2 With comprehensive C-class EWR at EWR site 6 (MD_CC_12I)

4.4.4.2.1 Profitability

The hydrological simulations for Scenario MD_CC_12I indicated higher water availability when demand for water is low and the converse if water demand is high. The impact of the water availability scenario on profitability is shown in Figure 4.47.

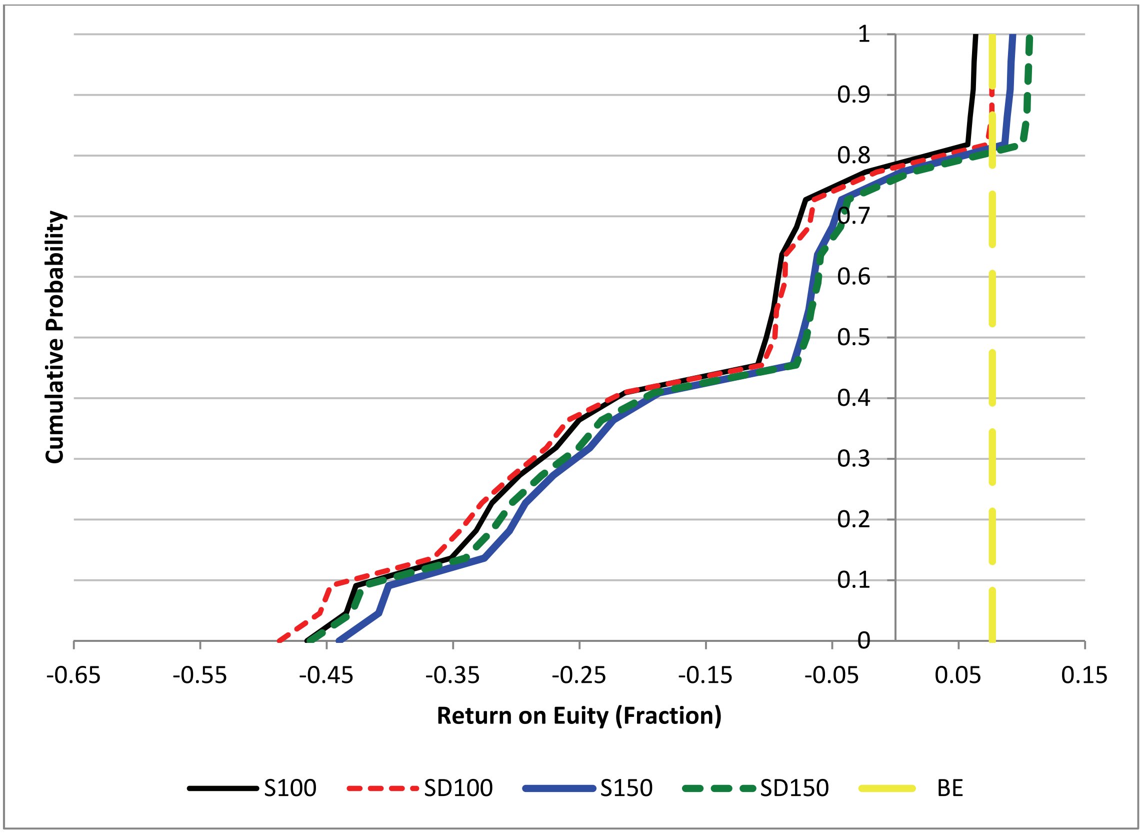


Figure 4. 47: Cumulative probability distributions of ROE for four farming businesses for catchment water management scenario MD_CC_12I.

Figure 4.47 indicates that the profitability of the irrigation farms will be severely reduced when the environmental flow requirement is enforced using the Class C flow regime. Farm Scenario S100 remains infeasible and the probability of achieving a positive leverage for the other farm scenarios is less than 20% while the probability of achieving negative returns are all above 75%. When compared to Scenario MD_Pres_12I the minimum return has decreased with only about seven percentage points. Cognisance should be taken of the fact that the average size of the shortfalls is significantly higher.

Overall the results clearly show that enforcing the environmental flow based on a Class C flow regime will cause these farms to cease farming.

4.4.4.2.2 Livelihood

Implementing the Class C environmental flow regime is also detrimental to the livelihoods of the farming business as is evident from the net cash flow results shown in Figure 4.48

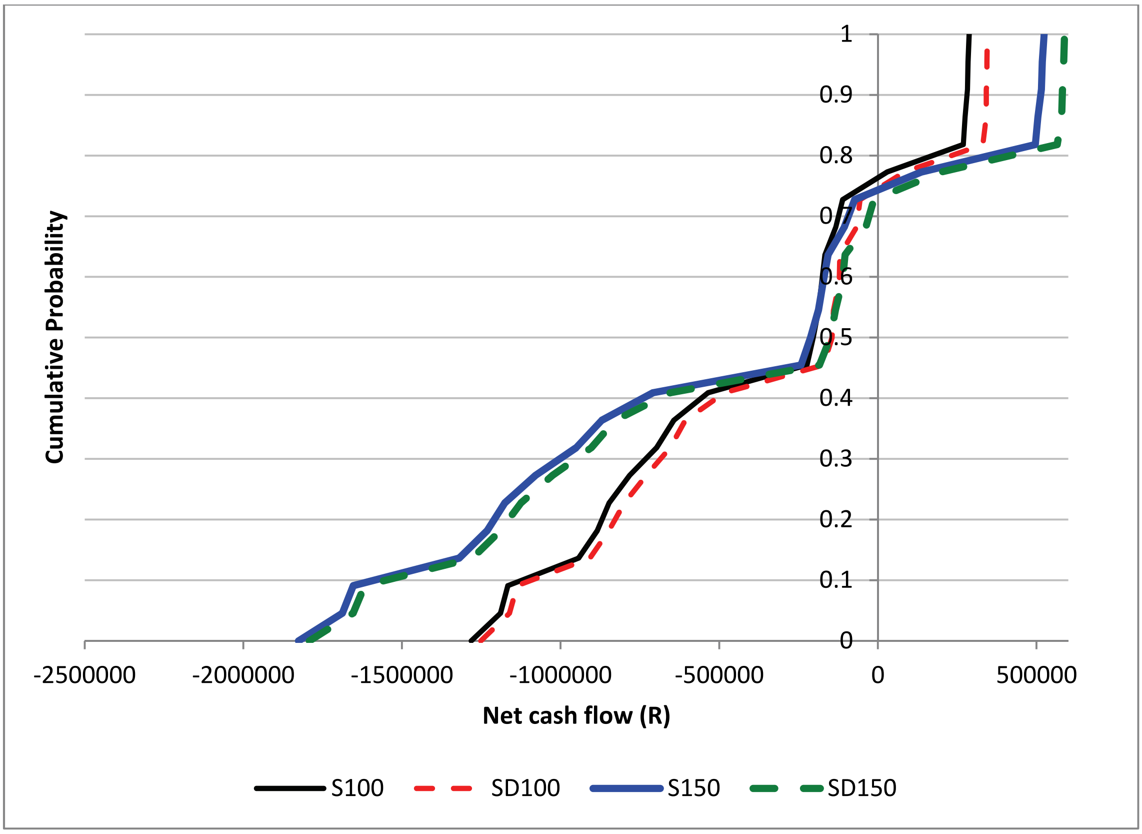


Figure 4. 48: Cumulative probability distributions of net cash flow for four farming businesses for catchment water management scenario MD_CC_12I.

The results are in accordance with the profitability analysis where the probability of achieving cash surpluses is low and average shortfalls are high. Thus, none of the farm scenarios will be able to sustain their livelihoods.

4.4.5 MOUNTAIN VIEW DAM

4.4.5.1 With present flow regime EWR at EWR site 6 (MVD_Pres_12I)

4.4.5.1.1 Profitability

The hydrological simulations indicated that the introduction of Mountain View Dam will increase the water availability in the catchment the most. Significant improvements in the profitability of all the farming scenarios are observed. The results from the profitability analysis are shown in Figure 4.49.

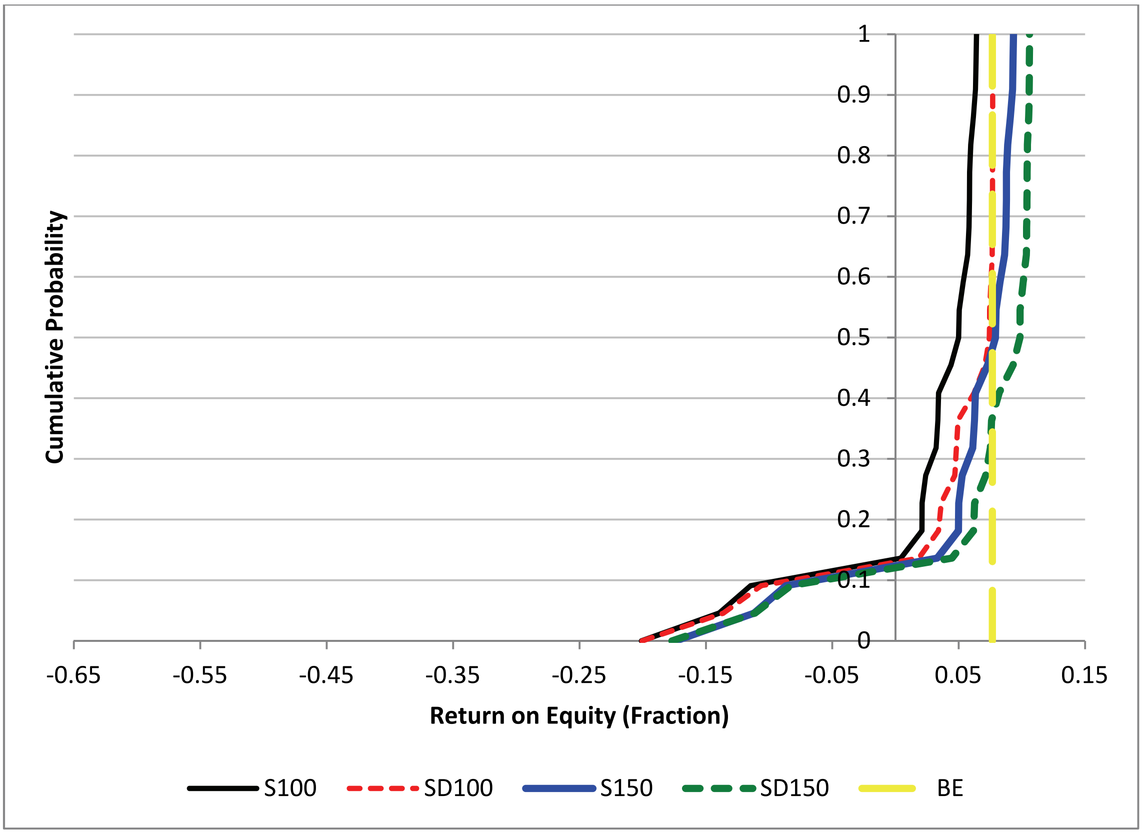


Figure 4. 49: **Cumulative probability distributions of ROE for four farming businesses for catchment water management scenario MVD_Pres_12I.**

The positive impact of increased water availability is observed by the fact that the cumulative probability distributions for which a positive leverage is obtained has become much more vertical. More verticality indicates a lesser chance of deviating from the maximum profitability that could be obtained when water is not limiting. However, increased water availability did not necessarily increase the chance of obtaining a positive leverage for all farms (again excluding S100 since it has negative leverage all of the time) when compared to scenario MD_Pres_12. SD150 has the same probability of achieving a positive leverage while the probabilities for S150 and SD100 have decreased. Important to observe is that the magnitude of returns below ROA were significantly reduced. Furthermore the chance of achieving a negative return is only 12% for all the farm scenarios considered. The overall result may be directly linked to the operating rules associated with operating the new dam.

4.4.5.1.2 Livelihood

Figure 4.50 shows the results of the net cash flow analysis for scenario MVD_Pres_12I.

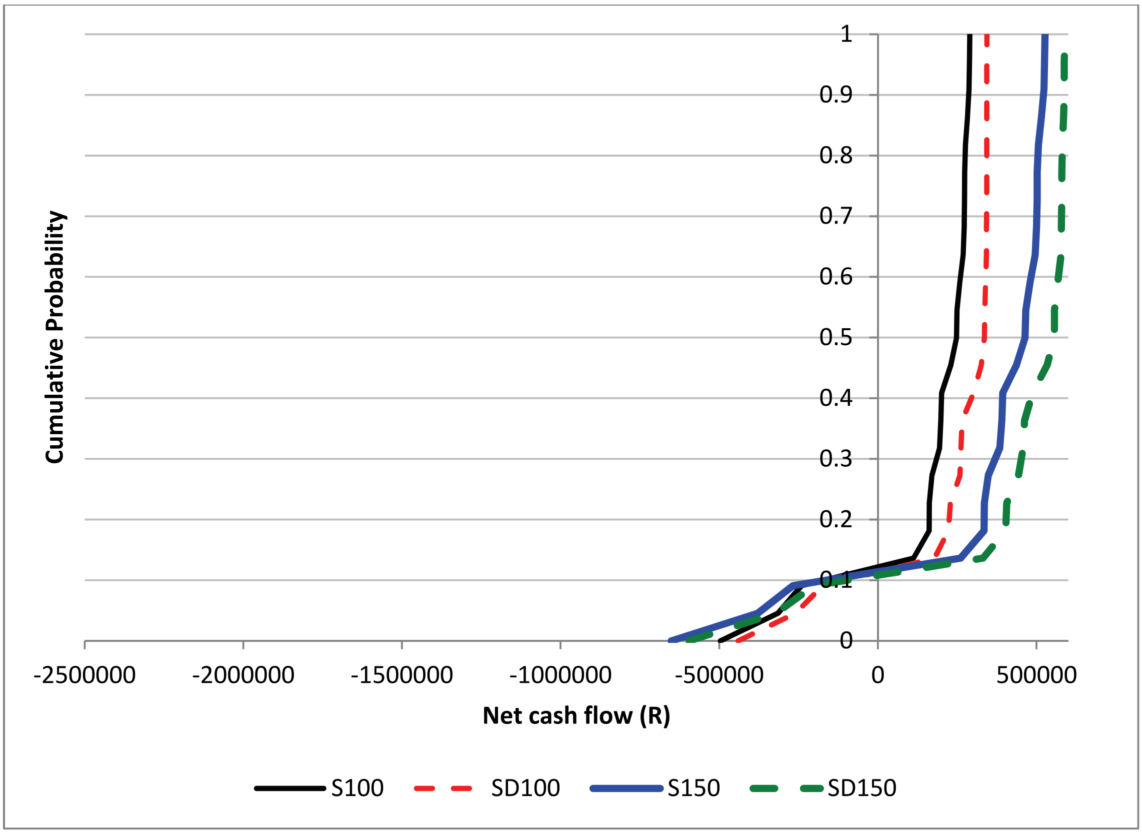


Figure 4. 50: **Cumulative probability distributions of net cash flow for four farming businesses for catchment water management scenario MVD_Pres_12I.**

The net cash flow distributions follow the profitability distributions. Results show a very favourable situation where there is only a 11% chance of not achieving a positive net cash flow. The maximum net cash flow deficits are also much less when compared to the other scenarios.

4.4.5.2 With comprehensive C-class EWR at EWR site 6 (MVD_CC_12I)

4.4.5.2.1 Profitability

Scenario MD_CC_12I is used to demonstrate the impact of implementing the EWR according to a Class C flow regime. Results from the analysis show a profound impact on the ROE as portrayed in Figure 4.51.

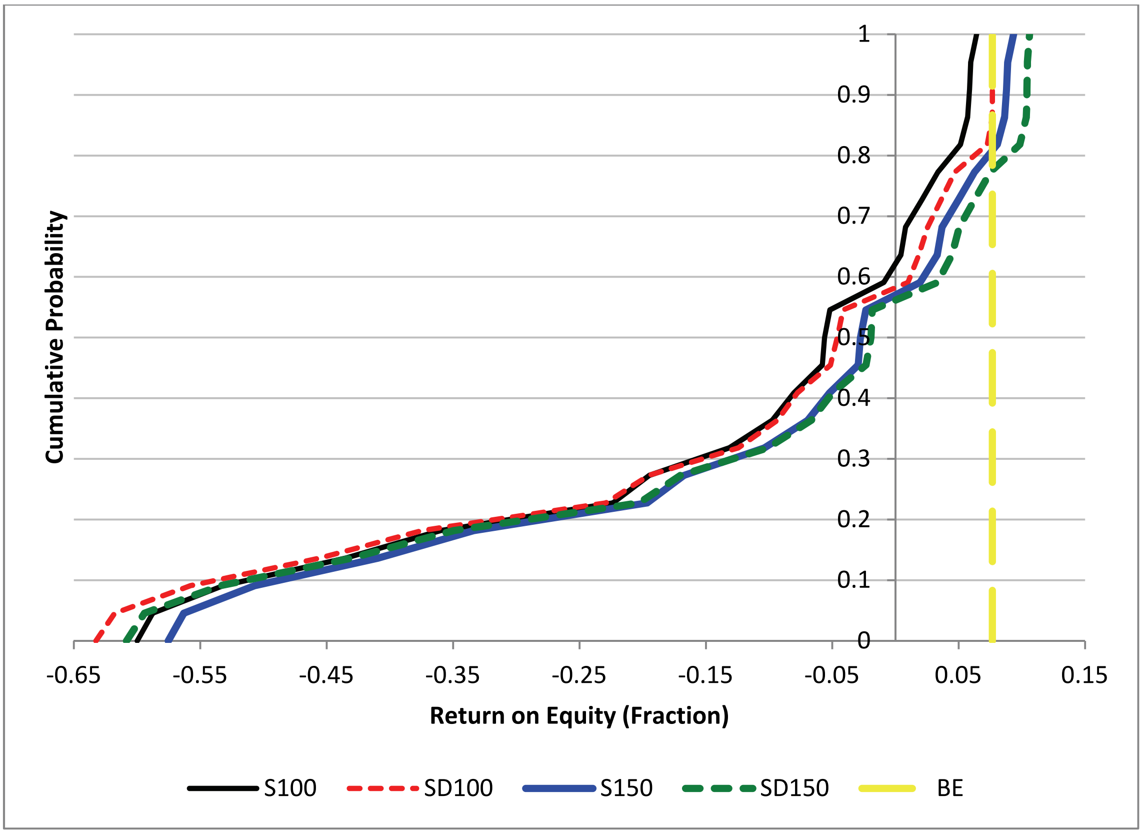


Figure 4. 51: Cumulative probability distributions of ROE for four farming businesses for catchment water management scenario MVD_CC_12I.

Figure 4.51 shows that the probability of achieving a positive leverage varies between 18% and 22% with farm scenario S100 being infeasible. The probability of achieving a negative return has also increased to above 55%. More significant, however, is the magnitude of the negative returns that are realised. The magnitude is of such an extent that it will be impossible to recover.

4.4.5.2.2 Livelihood

The sustainability of the farms contribution towards living expenses also come under severe pressure as is evident from the net cash flows shown in Figure 4.52.

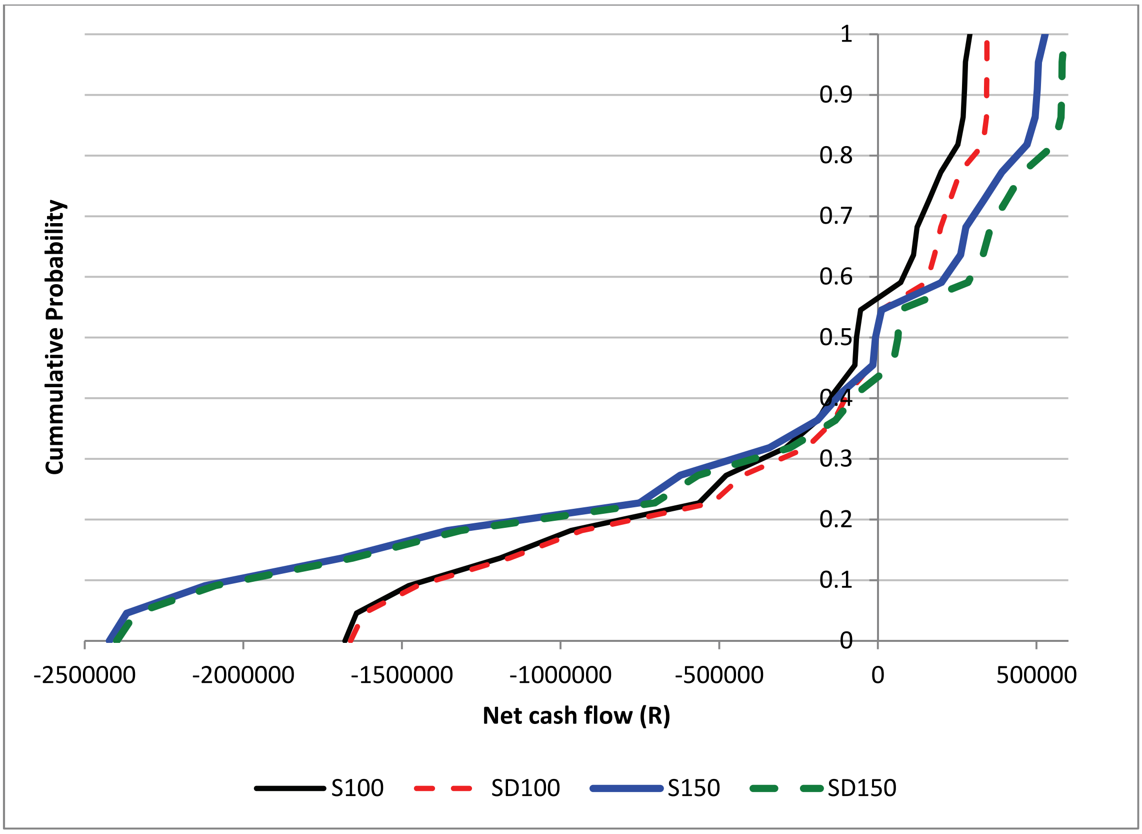


Figure 4. 52: Cumulative probability distributions of net cash flow for four farming businesses for catchment water management scenario MVD_CC_12I.

As with the profitability analysis the concern is not only the high probability of not realising net cash flow deficits but also the extent of the deficits. The probability of not achieving positive net cash flows varies between 42% and 57%. The maximum net cash flow deficit for each of the 100 ha farms 150 ha farms are respectively R1.6 million and R2.3 million.

4.4.6 BUILD MONTROSE AND MOUNTAIN VIEW DAMS WITH COMPREHENSIVE C-CLASS EWR AT EWR SITE 6 (MDMVD_CC_12I)

4.4.6.1 Profitability

Scenario MDMVD_CC_12I was included to determine whether building both the Montrose and Mountain View dams will stabilise water supply to such an extent that it is financially justifiable to implement a Class C environmental flow requirement. The simulated water availability (Figure 4.37) indicated that building two dams will increase water supply reliability when water availability is low. However, there exist a 45% chance that the water availability might be slightly less when compared to a situation where only the Mountain View dam is built. Figure 4.53 shows the impact of the two dams on the profitability of the case study farms.

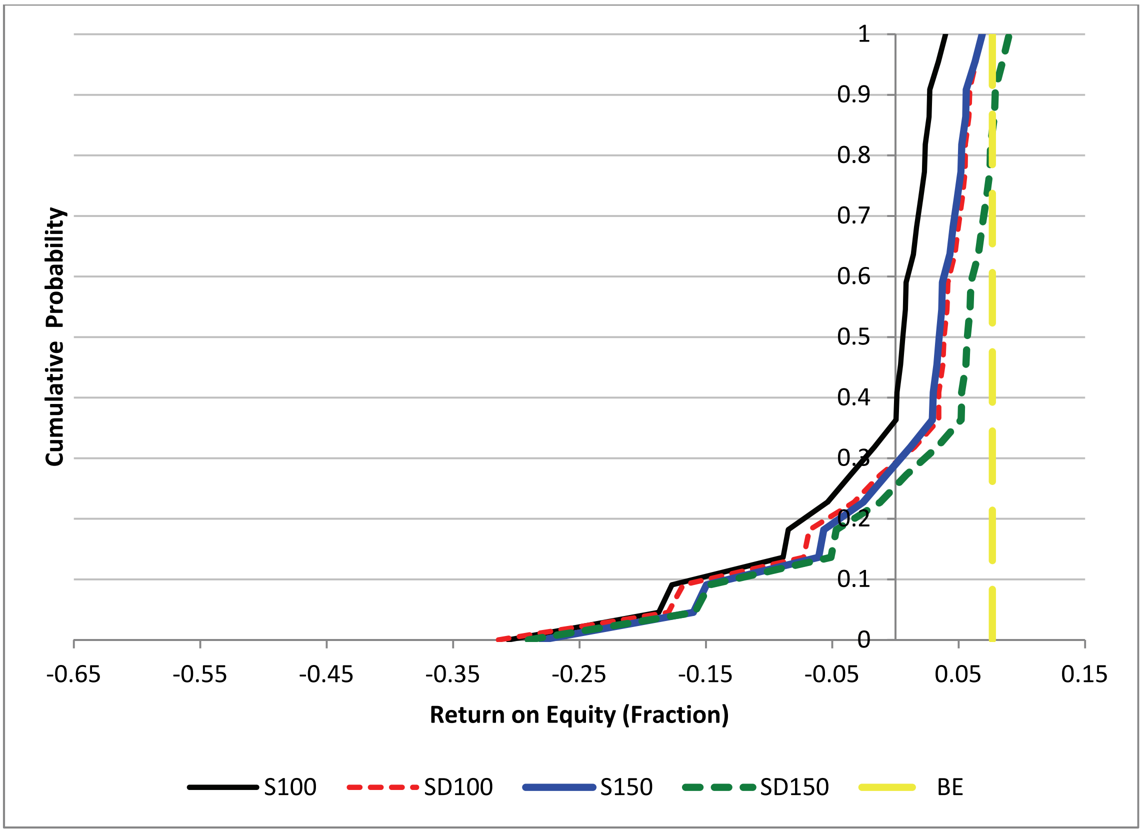


Figure 4. 53: Cumulative probability distributions of ROE for four farming businesses for catchment water management scenario MDMVD_CC_12I.

The impact of stabilising the flows with increased reliability to satisfy water requirements is evident from the rightward shifts in the lower tails of the distributions for all the farming scenarios. Although the magnitude of the losses was reduced, there still exists a chance of between 25% and 36% to realise a negative ROE irrespective of the farm scenario. SD150 has a 20% chance of a positive financial leverage whereas all the other scenarios are infeasible. The results further show that the financial situation of farms with higher irrigation efficiencies will improve most. The conclusion is that building both dams will definitely improve the financial situation of the farmers but the magnitude of the improvements is too little to render the implementation of a C-Class EWR profitable.

4.4.6.2 Livelihood

Figure 4.54 shows the results of the net cash flow analysis for scenario MDMVD_CC_12I.

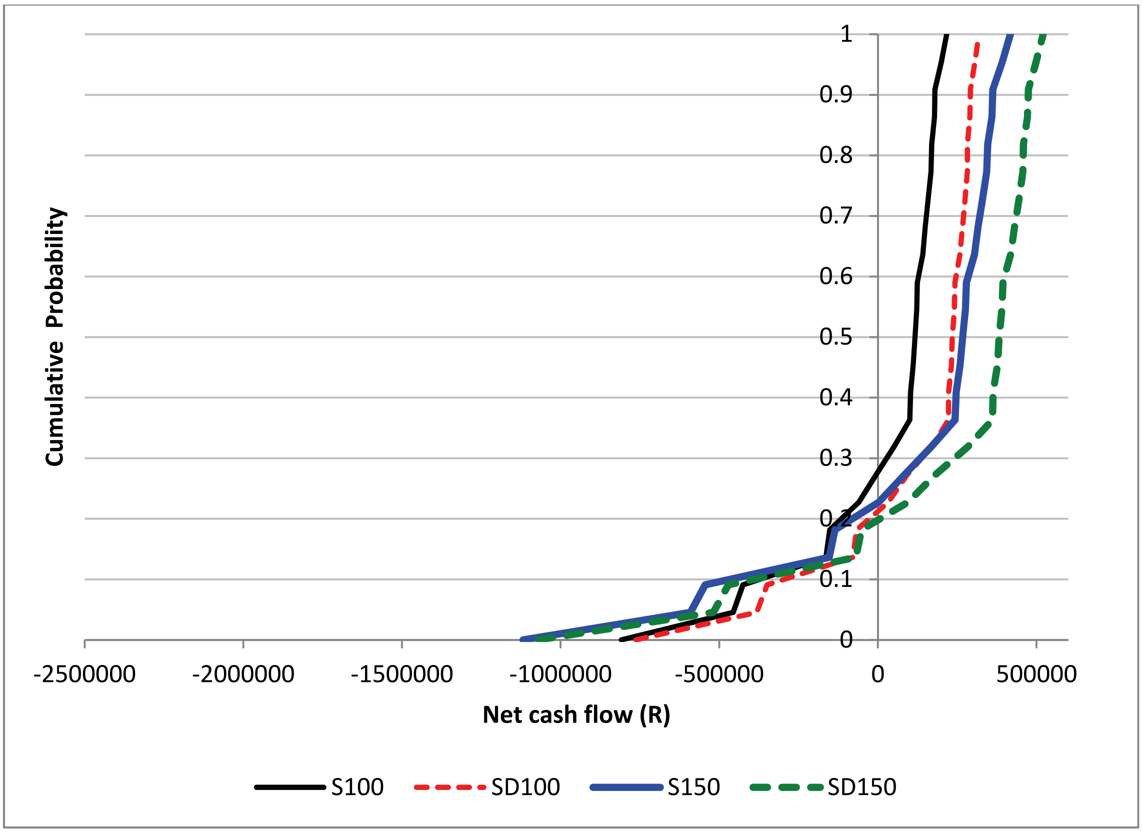


Figure 4. 54: Cumulative probability distributions of net cash flow for four farming businesses for catchment water management scenario MDMVD_CC_12I.

Again the net cash flow distributions tend to follow the general shape of the ROE distributions. Differences in the net cash flow situation of the farms are less profound for negative cash flows when compared to positive cash flows. Results also corroborate the results from the other scenario which indicate the tendency that larger farms are able to generate larger cash surpluses, but also that the shortfalls are greater. From a livelihood perspective building both dams may stabilise the situation to such an extent to provide a livelihood.

4.4.7 SUMMARY OF KEY PERFORMANCE INDICATORS

In this section a summary of the catchment water management scenarios with respect to profitability and net cash flows is given. Stoplight charts are used to summarise the results. A Stoplight chart provides an indication of the probability that a key output variable will be within a specified range.

4.4.7.1 Profitability

The stoplight chart that summarises the profitability of the alternative catchment scale water management scenarios is shown in Figure 4.55. Three ranges were used in the graph. The bottom part of a bar indicates the probability to realise a negative return on your investment while the top part of the bar indicates the probability to achieve a positive leverage. The middle section shows the probability that ROE will be greater than zero but smaller than ROA.

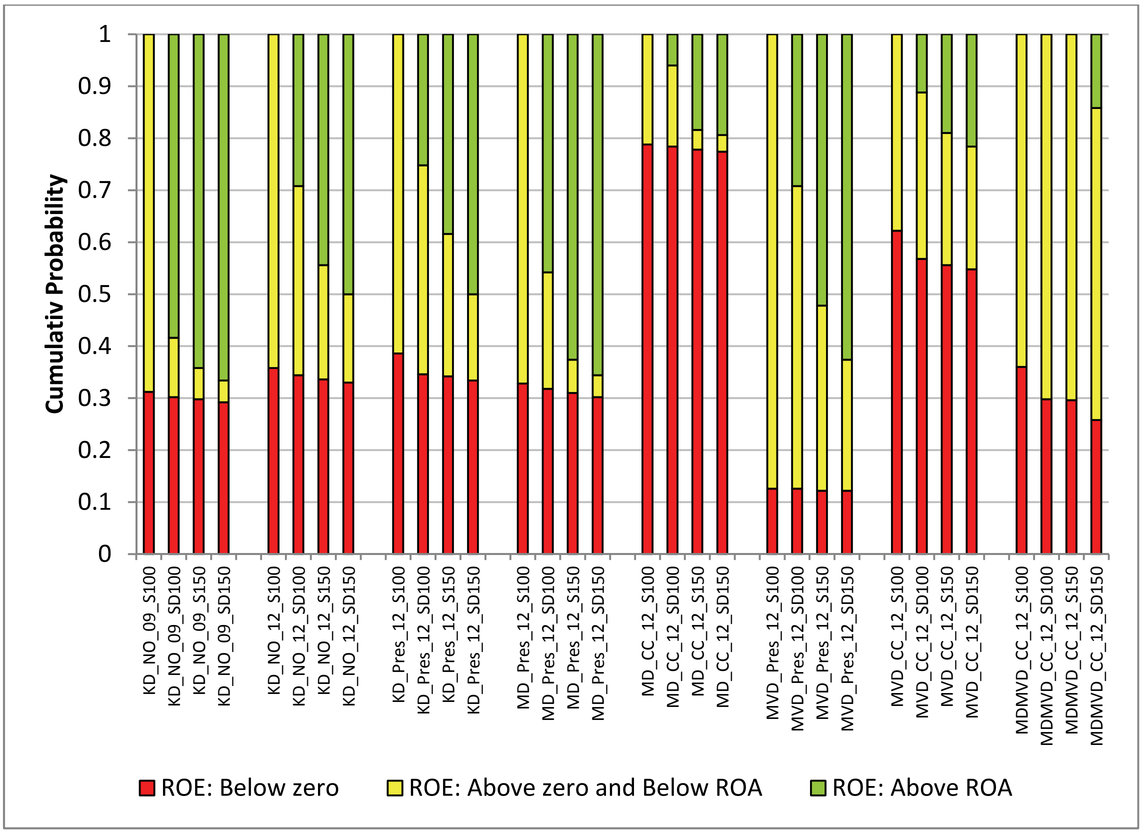


Figure 4. 55: Stoplight chart of the profitability of four farming businesses under different catchment water management scenarios.

Figure 4.55 shows that farm scenario S100 has no chance of obtaining a positive financial leverage and is therefore financially infeasible. Next only the other farm scenarios are considered. Increasing the international flow requirement to 1.2 m^3/s from 0.9 m^3/s will negatively affect farming profitability of all the farm scenarios. Introducing the EWR based on the present flow regime will affect SD100 and S150 negatively while the impact on SD150 is negligible when compared to a 1.2 m^3/s international flow requirement.

The logic behind building dams in the system is that it will stabilise the flow in some rivers thereby increasing water availability in the system. Building the Montrose Dam will increase the chance of being financially feasible for the larger farms to more than 62% of the time while maintaining an EWR that is implemented using the present flow regime. Of the two dams considered, the Mountain View Dam has the greatest potential to increase overall profitability of the farms. However, the scenario tends to decrease the probability of achieving a positive financial leverage. Implementing the Class C EWR will be detrimental to the farming profitability of the irrigation farms. With a Class C environmental flow the probability to be profitable is reduced to 20% and 24% respectively for a water management scenario that includes the Montrose and Mountain View Dams. Contrary to expectation building both dams did not enhance the ability of the farmers to improve their financial leverage. However, the chance of achieving a negative ROE was decreased significantly. The fact that SD100 and S150 became infeasible highlights the importance of further refinements to the operating rules of the two dams.

4.4.7.1 Livelihood

The stoplight chart that summarises the net cash flow position of the farms for alternative catchment scale water management scenarios is shown in Figure 4.56. Only two ranges were used in the graph. The bottom part of a bar indicates the probability to realise a negative net cash flow while the top part of the bar indicates the probability to achieve a positive net cash flow.

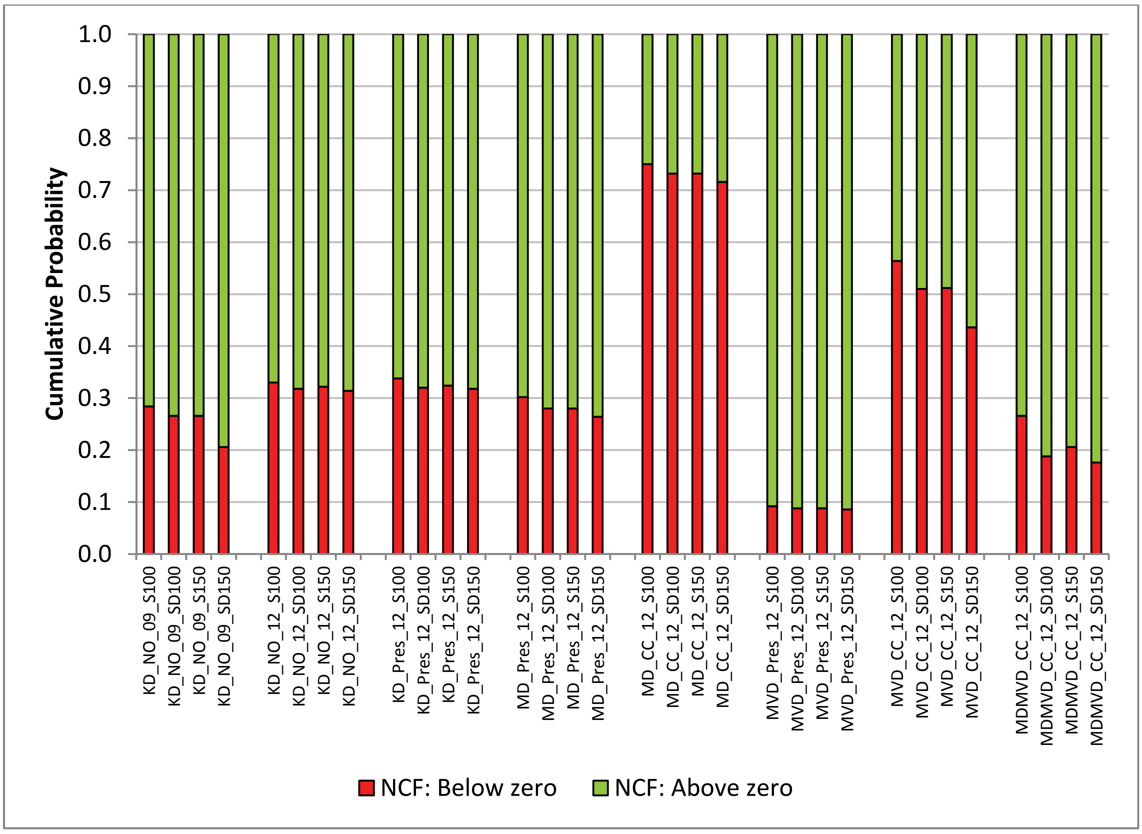


Figure 4. 56: Stoplight chart of the net cash flow (NCF) position of four farming businesses under different catchment water management scenarios.

In general the cash flow results confirm the results obtained from the profitability analyses. From a cash flow perspective implementing a Class C EWR will be detrimental to the livelihoods of the farms. Construction of the Mountain View Dam has the largest positive impact on the cash flows of the farmers since it increases water availability most. Building the Montrose Dam will only marginally increase cash surpluses. From a livelihood perspective, building both dams will improve the probability of a decent livelihood most when a Class C EWR is maintained.

4.4.8 WATER CURTAILMENT SCENARIOS

All the catchment water management scenarios considered this far cause the water availability of the farms to change. The curtailment scenarios test whether the irrigation farms will sustain a curtailment in their water allocation.

4.4.8.1 10% Curtailment

4.4.8.1.1 Profitability

The cumulative probability distribution of ROE for a 10% water curtailment is given in Figure 4.57.

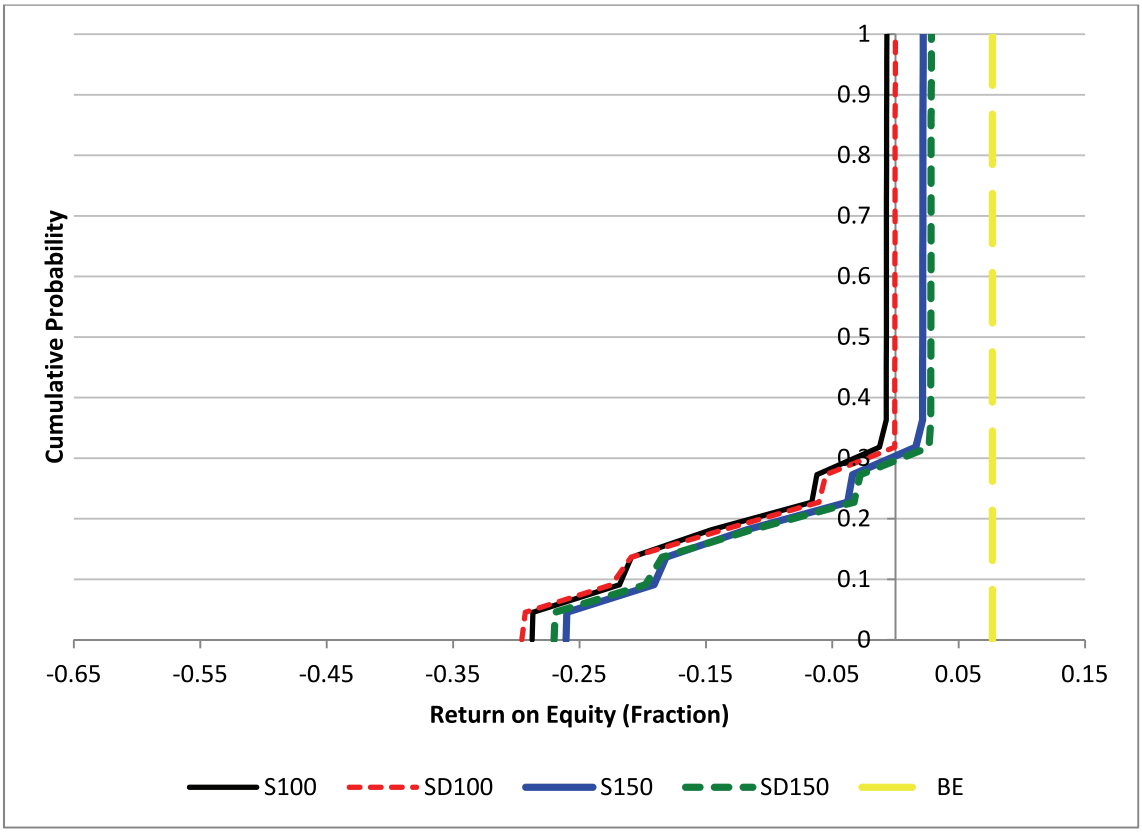


Figure 4. 57: Cumulative probability distributions of the profitability of four farming businesses for a water curtailment of 10%.

The results show that a 10% curtailment will reduce the profitability of the farm under the status quo management and irrigation technology because the water applications per unit area will be reduced. Thus, the reduction in profitability is directly related to changes in crop yields. The reduction in crop yields will cause a reduction in returns to such an extent that none of the farms will achieve a positive leverage.

4.4.8.1.2 Livelihood

The impacts of a 10% water curtailment on the net cash flow of the different farms are shown in Figure 4.58.

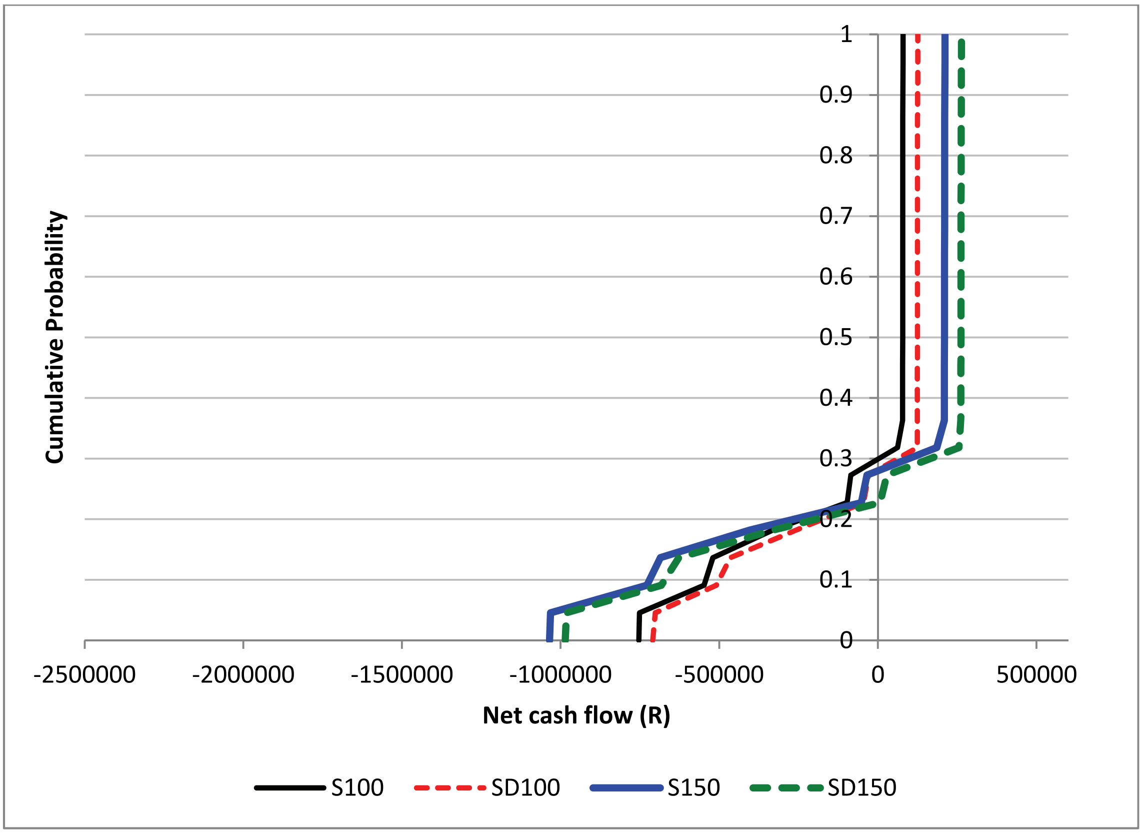


Figure 4. 58: Cumulative probability distributions of the net cash flow position of four farming businesses for a water curtailment of 10%.

The results from the cash flow analysis show that the ability of the farm to provide a livelihood will not be jeopardised. However, the magnitude of the cash surpluses is reduced.

4.4.8.1 20% Curtailment

4.4.8.1.1 Profitability

The profitability analysis of a 20% curtailment in the water allocation is shown in Figure 4.59.

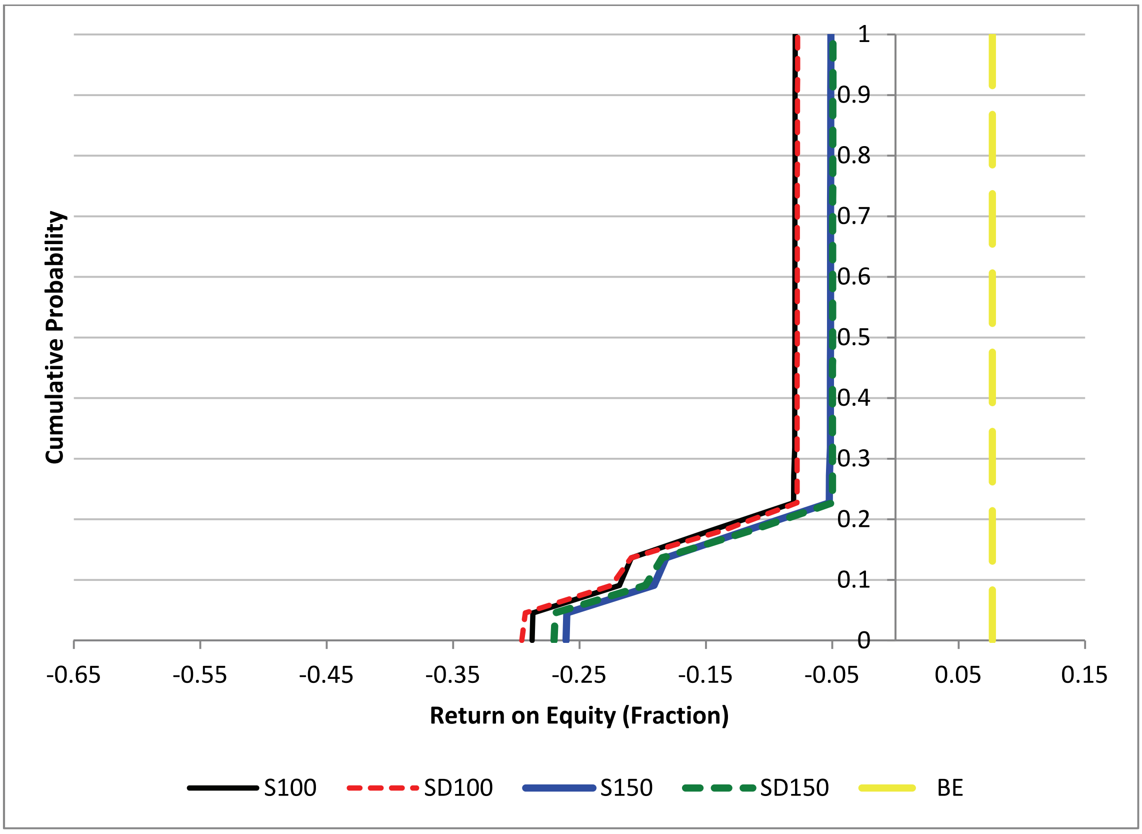


Figure 4. 59: Cumulative probability distributions of the profitability of four farming businesses for a water curtailment of 20%.

Figure 4.59 shows that the impact of a 20% curtailment in the water allocation will be detrimental to the irrigation farms. None of the farms will generate a positive return on their investment.

4.4.8.2.2 Livelihood

The net cash flow analysis of for the 20% curtailment scenario is shown in Figure 4.60.

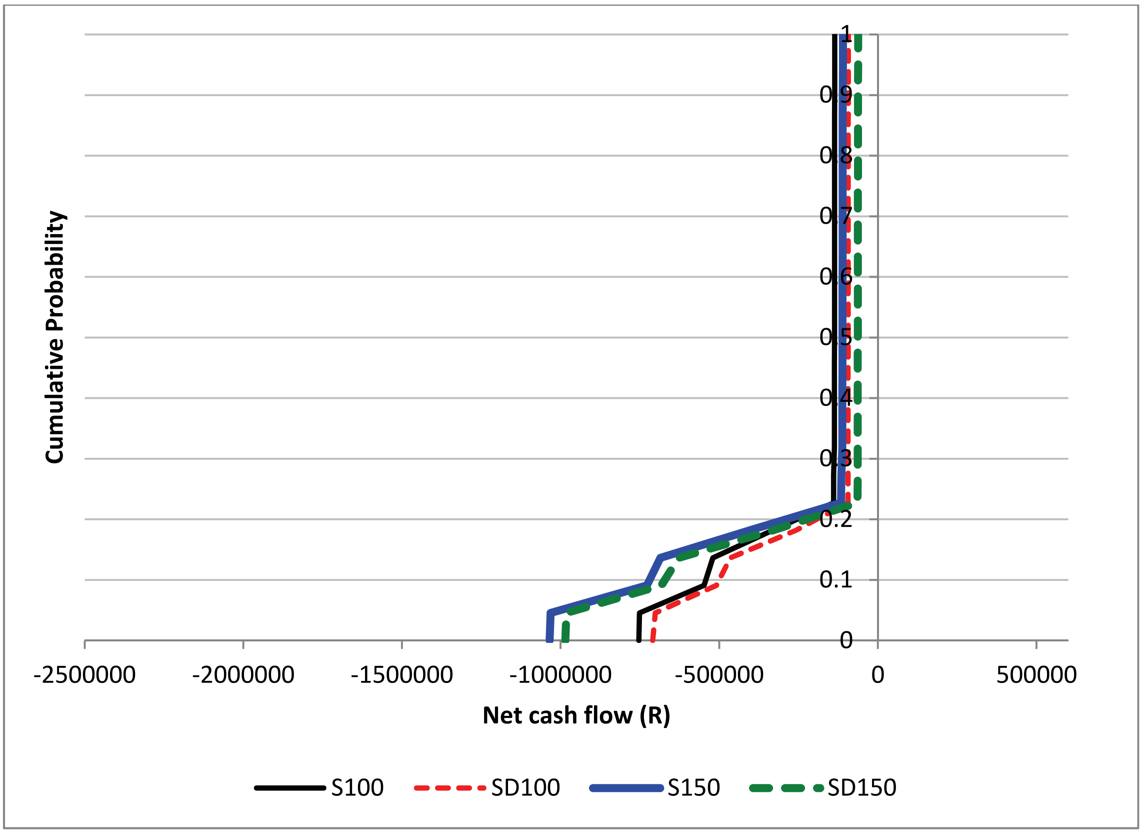


Figure 4. 60: Cumulative probability distributions of the net cash flow position of four farming businesses for a water curtailment of 20%.

The results echoed those of the profitability analysis in a sense that the farms will be unable to generate enough cash flows to cover living expenses. The conclusion is that the irrigation farm will not be able to sustain a 20% curtailment in the water allocation.

CHAPTER 5:

CONCLUSIONS AND RECOMMENDATIONS

5.1 BACKGROUND

The National Water Act (Act No. 36 of 1998) requires that water must be allocated to the environment. The Crocodile East catchment presents an interesting situation in that the Crocodile River forms the southern border of the Kruger National Park, which makes allocating water for the environment a sensitive endeavour. Furthermore, South Africa is obliged to increase the international flow requirement to Mozambique from 0.92 m^3/s to 1.2 m^3/s. The challenge is that the catchment is now over-allocated, which requires a reconciliation of the water balances in the catchment. Irrigated agriculture is the dominant water user in the catchment and is likely to face water curtailments required to reconcile the water supply imbalances. Water curtailments imply that water availability will be permanently reduced. As a result, the financial feasibility of the farming enterprises and the farmers' livelihoods are threatened. Questions that stakeholders and water managers are currently grappling with are:

- How will different levels of water use curtailments influence the financial viability of irrigation farms? This can help identify the break-even point, after which curtailments will be detrimental to the sustainability of the irrigation farms.
- Can other water management options be considered to address the over-allocated nature? How will these options impact the financial viability of the irrigation farms? Examples of other (non-curtailment) related options include:
    - The building of one or more new dams
    - Improving the dam operating rules associated with existing dams
    - Changing the quantity of water allocated to the EWRs
    - Changing the quantities of water associated with the International Flow
    - A combination of the items listed above

The overall objective of this research was to develop an integrated hydro-economic modelling framework that can be used to explore the potential impacts of the afore-mentioned alternative catchment scale water management strategies and water curtailments on the financial feasibility and livelihoods of irrigation farming. The water use optimisation model was set up for two different farm sizes comprising different irrigation system combinations to reflect relatively more and less efficient water use.

The literature review indicated that the compartment modelling approach will be the best suited for the research. With compartment modelling, it is possible to represent the institutional setting that provides the rules for using and developing water resources with a hydrological systems model like MIKE BASIN. The resulting water availability time-series generated from MIKE BASIN, and associated with the water intervention scenarios identified by the stakeholders, could then be linked to an economic optimisation model to determine the likely economic impact associated with each intervention scenario. Linking the different models proved to be difficult, due to fact that the economic and hydrological models operate on different spatial and temporal scales. In order to meaningfully link the SKELETON optimisation model to MIKE BASIN, a steady state needs to be assumed, therefore no long-run adjustments to the farm structure were modelled. Irrigation system specific state contingent production functions were developed to quantify the impact of changes in irrigation water use on sugarcane yields – to reflect differences in irrigation water application efficiencies.

Via a process of consultation, stakeholders in the Crocodile Catchment identified 12 catchment scale water management intervention scenarios, as well as two water curtailment scenarios, which could be possible solutions to help address the over-allocated nature of the catchment. . The integrated hydro-economic framework was used to generate results for all the scenarios where after the modelling results were validated with the stakeholders.

5.2 SUMMARY OF RESULTS AND CONCLUSIONS

The research made a significant contribution towards a better understanding of the potential hydro-economic impact of alternative water management intervention scenarios (to address the over-allocation) through the development and application of the integrated hydro-economic modelling framework. Application of the adopted modelling framework demonstrated the ability of the framework to realistically capture changes in catchment water management scenarios on the financial feasibility of irrigation farming. The following represents a summary of the results – and the conclusions made:

- Results for the baseline (the baseline simulation includes the existing Kwena Dam and the international flow requirement of 0.9 m^3/s, but with no EWR) showed that the irrigated farms do not have secure water supply reliability. On average, the farms will not be able to achieve their potential production levels 40% of the time. Achieving a positive financial leverage (Return on equity >Return on assets) for the larger farms (150 ha) was closely linked to the ability to produce according to potential. The small farm, with relatively higher water application efficiencies, was barely financially feasible – while the other farm with lower efficiencies was not financially feasible. All the farms may provide a livelihood more than 70% of the time. The conclusion is that irrigated farming in the area is risky, which emphasises the importance of conducting risk analyses to determine the potential impact of catchment-scale water management scenarios on irrigation farming profitability and their livelihoods. Furthermore, small farms will be under severe pressure to handle any water curtailments.

- Increasing the international flow requirement to 1.2 m^3/s has a negative impact on both the profitability and livelihoods (potential to generate cash surpluses) of the irrigated farms. Results showed that the potential to achieve a positive financial leverage was affected most, while the probability of a negative return was only slightly increased. The potential to provide a livelihood was affected only marginally. The conclusion is that the irrigation farming may still be viable if the international flow requirement was increased.

- Implementing the Class C EWR was significantly detrimental to the profitability of all farms and none of the farming scenarios were financially feasible or could provide a livelihood to irrigators. As an alternative to the C Class EWR, operating rules were developed to implement the EWR based on the present flow regime. Results showed that the impact on irrigation farming would be minimal when compared to the scenario with an international flow requirement of 1.2 m^3/s. The conclusion is that implementing the Class C EWR should be seriously reconsidered since it would have a devastating impact on irrigation farming in the area. Alternatives, such as implementing the EWR based on the present flow regime, should be further investigated.

- Several scenarios, which included the development of new dams in the catchment, were investigated to determine whether it will be possible to allocate water to the environment while stabilising the flow in the catchment. Results showed that neither of the dam scenarios (Mountain View Dam and/or Montrose Dam) would improve the financial feasibility of irrigation farming to justify implementing the Class C EWR. However, building both dams would improve the ability to provide a livelihood. The conclusion is that implementing the Class C EWR is infeasible – even when building dams is considered. When considering the implementation of the EWR based on the present flow regime, the dam scenarios showed interesting results. Generally, the results showed that building Montrose Dam would increase the ability of the irrigated farms to achieve a positive financial leverage with only slight improvements in the livelihoods of farmers. Contrary to these results, building the Mountain View Dam would not improve the chance of achieving a positive financial leverage as much, but would increase the chance of generating cash flows to provide a livelihood significantly. The conclusion is that building dams will definitely improve the financial situation of farmers in the catchment, given the EWR is implemented using the present flow regime. Cognisance should be taken that the cost of building the dams was not considered in the analysis.

- The impact of water curtailments was evaluated – also considering an international flow requirement of 1.2 m^3/s. Results showed the financial feasibility of irrigation farming would come under severe pressure even with a curtailment of 10%. However, the livelihoods of the farmers would not be jeopardised. A water curtailment of 20% is detrimental to irrigation farming profitability and irrigation farming will be unable to provide a livelihood to farmers. The conclusion is that, of all the water-management scenarios, the impact of water curtailments is the most profound and that the magnitude of water curtailments needs careful consideration before it is implemented.

Overall, the results showed that small farms will come under severe pressure to provide a livelihood to farmers and to be financially feasible. Farms with higher application efficiencies will also be in a better position to handle any changes in their water allocation, or decreased security of supply.

5.2 RECOMMENDATIONS FOR FURTHER RESEARCH

- The research was successful in determining the impact of changes in water management scenarios on different farms within a specific location of the catchment. The implication is that changes in all irrigators' reactions to changes in water management are not incorporated into the modelling framework. More research is necessary to extend the research to catchment level.

  Specific issues that need consideration are the following:

  - Currently, the HE frame allows for the modelling of one irrigation node to represent the case study farms. The modelling framework should be extended to represent all the irrigation areas in the catchment.
  - Modelling the impact of return flows on water availability of users. The current setup of the catchment scale hydrological model is not sensitive to return flows of irrigators, which will change in response to the manner in which these irrigators adapt to the various water management intervention scenarios. The existing hydrological model needs to be improved to better represent how all irrigators may adapt to the water intervention scenarios and the consequent impact on return flows, which may have a significant impact on the flows available to downstream users.
  - Improving economic modelling procedures and hydrological model integration to model dynamic responses by irrigators to changes in water management rules in the long-run.
  - Developing economic decision rules that will enable the MBIM to allocate water economically between different irrigation fields. In this regard, the application of genetic algorithms should be further investigated.

- The economic modelling could be enhanced in various ways. The following points provide directions for further developments and applications:
    - The application of the state contingent framework to modelling irrigators' responses to changes in water availability should be further researched to model long-run responses.
    - Procedures should be developed to reduce the dimensionality of states of nature that is used to represent the security of water supply over the long-term within a state contingent framework.
    - Sources of risk, other than the impact of insecure water availability on crop yield, should be considered.

- The current operational rules should be optimised and other institutional arrangements, such as water markets and capacity sharing, should be investigated. Specifically, a water accounting and auditing framework needs to be developed to give effect to water markets and capacity sharing – and to help enforce compliance.

REFERENCES

AHRENDS H, MAST M, RODGERS CH and KUNSTMANN H. 2008. Coupled hydrological–economic modelling for optimised irrigated cultivation in a semi-arid catchment of West Africa, *Environmental Modelling & Software*, 23(4):385-395.

ALLEN RB and HEROLD C. 1988. *Vaal River Systems Analysis, Water Quality Modelling, Volume A: Water Quality Calibration Model.* Department of Water Affairs and Forestry of South Africa, Chief Directorate: Planning, Report number P C000/00/7086, Pretoria.

ALLEN RG, PEREIRA L, RAES D and SMITH M. 1998. *Crop evapotranspiration: Guidelines for computing crop water requirements*. FAO Irrigation and Drainage Paper No 56. FAO. Rome. Italy.9

BACKEBERG GR. 1984a. *Besproeiingsontwikkeling in die Groot-Visriviervallei*. Ongepubliseerde M.Sc. (Agric)-verhandeling. Universiteit van Pretoria, Pretoria.

BACKEBERG GR. 1984b. Finansiële uitvoerbaarheid van suikerrietboerdery in die Komatiriviergebied. Afdeling Landbouproduksie-ekonomie, Departement van Landbou, Pretoria.

BASSON, MS, ALLEN, RB, PEGRAM, GGS and VAN ROOYEN, J.A. 1994. *Probabilistic management of water resource and hydropower systems*. Water resource publications, Colorado, USA.

BERNARDO DJ, WHITTLESEY NK, SAXTON KE and BASSETT DL. 1987. An irrigation model for managing limited water supplies. *Western Journal of Agricultural Economics,* 12: 164-173.

BHARATI L, RODGERS C, ERDENBERGER T, PLOTNIKOVA M, SHUMILOV S, VLEK P and MARTIN N. 2008. Integration of economic and hydrologic models: Exploring conjunctive irrigation water use strategies in the Volta Basin, *Agricultural Water Management*, 95(8):925-936.

BOTES JHF. 1990. *An economic evaluation of wheat irrigation scheduling strategies using stochastic dominance*. (Afrikaans). M.Sc. Agric. dissertation. Department of Agricultural Economics, University of the Orange Free State, Bloemfontein.

BOTES JHF. 1994. A simulation and optimization approach to estimating the value of irrigation information for decision-makers under risk. Ph.D. thesis. Department of Agricultural Economics, University of the Free State, Bloemfontein.

BOTES JHF, BOSCH DJ and OOSTHUIZEN LK. 1995. The value of irrigation information for decision-makers with neutral and non-neutral risk preferences under conditions of unlimited and limited water supply. *Water SA*, 21(3): 221-230

BOTES JHF, BOSCH DJ and OOSTHUIZEN LK. 1996. A simulation and optimization approach for evaluating irrigation information. *Agricultural Systems*, 51: 165-183.

BROOKE A, KENDRICK D, MEERAUS A and RAMAN R. 1998. *The General Algebraic Modelling System (GAMS). User's Guide*. Boyd and Fraser Publishing Company, Danvers, Massachusetts.

BROTHERTON IA and GROENEWALD JA. 1982. Optimale organisasie op ontwikkelde besproeiingsplase in die Malelane-Komatipoortstreek. *Agrekon*, 21(2): 22-29.

BURCHI, S and D'ANDREA, A. 2003. *Preparing national regulations for water resources management: Principles and Practice*. FAO Legislative Study #80

CAI X. 2008. Implementation of holistic water resources-economic optimization models for river basin management – Reflective experiences, Environmental Modelling & Software, 23(1): 2-18.

DE JAGER JM. 1994. Accuracy of vegetation evaporation formulae for estimating final wheat yield. *Water SA,* 20(4): 307-314.

DE JUAN JA, TARJUELO JM, VALIENTE M and GARCIA P. 1996. Model for optimal cropping patterns within the farm based on crop water production functions and irrigation Uniformity. *Agricultural Water Management*, 31: 115-143.

DEPARTMENT OF AGRICULTURE, FORESTRY AND FISHERIES (DAFF). 2010. *Guide to machinery costs 2010/11.* August 2010, Republic of South Africa

DEPARTMENT OF AGRICULTURE, FORESTRY AND FISHERIES (DAFF). 2011. *Abstract of Agricultural Statistics.* August 2010, Directorate Statistics and Economic Analysis, Republic of South Africa

DEPARTMENT OF WATER AFFAIRS (DWA). 2012. *Draft National Water Resource Strategy 2: Managing Water for an Equitable and Sustainable Future*, Comprehensive July 2012. Republic of South Africa

DEPARTMENT OF WATER AFFAIRS AND FORESTRY (DWAF). 2004a. The National Water Resource Strategy, Pretoria.

DEPARTMENT OF WATER AFFAIRS AND FORESTRY (DWAF). 2004b. Water Conservation and Water Demand Management Strategy for the Agricultural Sector, Pretoria.

DIJKHUIS FJ and BERLINER PR. 1988. *A simple model for the prediction of dryland wheat yield*. Department of Agriculture and Water Supply, Soil and Irrigation Research Institute, Pretoria, RSA

DOORENBOS J and KASSAM AH. 1979. *Yield Response to Water*. Irrigation and Drainage Paper 33. Rome, IT: Food and Agriculture Organisation (FAO).

ENGLISH MJ, SOLOMON KH and HOFFMAN GJ. 2002. A paradigm shift in irrigation management. *Journal of Irrigation and Drainage Engineering*, 128(5): 267-277.

FINDIKAKIS, AN, EL AFTI, T and STEPHENS, JL. 2003. *Evaluation of water resources reliability in morocco*. XI World Water Congress. International water resources association, Madrid, Spain.

REPUBLIC OF SOUTH AFRICA (RSA). 2012. Govern Gazette, 566(35582):1-8.

GROVÉ B. 2006a. Stochastic efficiency optimisation of alternative agricultural water use strategies. *Agrekon*, 45(4): 406-420.

GROVÉ B. 2006b. *Generalised whole-farm stochastic dynamic programming model to optimise agricultural water use.* Report to the Water Research Commission. WRC Report No 1266/1/06. Pretoria: The Water Research Commission.

GROVÉ B and OOSTHUIZEN LK. 2002. An economic analysis of alternative water use strategies at catchment level taking into account an instream flow requirement. *American Water Resource Association*, 38(2): 385-395.

HAILE BO, GROVÉ B and OOSTHUIZEN LK. 2003. *Impact of capital on the growth process of a sugarcane farm in Mpumalanga*. 41st Annual Conference of the Agricultural Economics Association of South Africa, Agribusiness, Profits and Ethics: Pretoria, South Africa, October 2003.

HALLOWES JS and LECLER NL. 2005. Model Linkages for Planning and Operational Systems Analysis at a Daily Timestep. *Proc. 12th S Afr National Hydrology Symposium*, Institute of Water Research, Rhodes University, RSA

HAMILTON JR, GREEN GP and HOLLAND D. 1999. Modeling the reallocation of Snake river water for endangered salmon. *American Journal of Agricultural Economics*, 81(5): 1252-1256.

HANCKE HP and GROENEWALD JA. 1972. Die effek van bronbeskikbaarheid op optimum organisasie in besproeiingsboerdery. *Agrekon*, 11(3): 9-16.

HARDAKER JB, RICHARDSON JW, LIEN G and SCHUMANN KD. 2004. Stochastic efficiency analysis with risk aversion bounds: a simplified approach. The Australian *Journal of Agricultural and Resource Economics*, 48(2): 523-270.

JENSEN, ME, BURMAN, RD and ALLAN, RG (1990) The soil-plant-atmosphere system. In: Jensen, M.E., Burman, R.D. and Allan, R.G., (Eds) *Evapotranspiration and irrigation water requirements*. ASCE, New York, USA

KIRDA, C and KANBER, R. 1999. Water, no longer a plentiful resource, should be used sparingly in irrigated agriculture. p. 1–20. In C. Kirda et al. (ed.) Crop yield response to deficit irrigation. Kluwer Academic Publ., Dordrecht, the Netherlands

LECLER NL. 2004. *Performance of irrigation and water management systems in the Lowveld of Zimbabwe.* PhD thesis. School of Bioresources Engineering and Environmental Hydrology. University of Natal, Pietermaritzburg.

LI J. 1998. Modeling crop yield as affected by uniformity of sprinkler irrigation system. *Agricultural Water Management*, 38: 135-146.

LOUW DB and VAN SCHALKWYK HD. 1997. The true value of irrigation water in the Olifants River Basin: Western Cape. *Agrekon*, 36(4): 551-600.

MANTOVANI EC, VILLA LOBOS FJ, ORGAZ F and FERERES E. 1995. Modeling the effects of sprinkler irrigation uniformity on crop yield. *Agricultural Water Management*, 27: 243-238.

MARÉ HG. 1995. *Marico-Bosveld Staatswaterskema: Stogastiese waterbronontledings gekoppel aan ekonomiese evaluasies*. BKS Ing. Verslag P5425/95/1. Departement van Landbou, Direktoraat Besproeiingsingenieurswese, Pretoria.

MATSEBULA, T. 2008. *Evaluation of the MIKE BASIN 2008 irrigation moduel*. Msc Thesis, University of Zimbabwe, Harare, Zimbabwe.

MCKINNEY D, CAI X, ROSEGRANT MW, RINGLER C and SCOTT CA. 1999. *Modeling Water Resources Management at the Basin Level: Review and Future Directions*. Colombo, International Water management Institute, SWIM Paper 6, 71 pp.

MEIRING JA. 1993. *Die ontwikkeling en toepassing van 'n besluitnemingsondersteuningstelsel vir die ekonomiese evaluering van risikobestuur op plaasvlak*. Ph.D- theses, Department of Agricultural Economics, University of the Free State, Bloemfontein.

MEYER J. 1977. Choice among distributions. *Journal of Economic Theory*, 14: 326–336.

MOTTRAM R, DE JAGER JM, JACKSON BJ and GORDIJN RJ. 1995. *Irrigation water distribution management using linear programming*. Technical Report to the Water Research Commission. WRC Report No TT 71/95. Pretoria.

OOSTHUIZEN HJ. 1995. Berekening van die impak van die Marico-Bosveld Staatswaterskema op die nasionale ekonomie van Suid-Afrika en finale gevolgtrekkings oor die rehabilitasie van die skema. Departement van Landbou, Direktoraat Landbou-ekonomie, Pretoria.

OOSTHUIZEN LK, BOTHA PW, GROVÉ B, MEIRING JA MONKHEI MM and PRETORIUS, IG. 2005. *Cost estimation procedures for micro-, drip- and furrow-irrigation systems as well as economic analysis of the relevant irrigation systems for large- and small-scale farmers in the Onderberg/Nkomaszi region*. Report to the Water Research Commission. WRC Report No 974/1/05. Pretoria.

ORETGA JF, DE JUAN JA and TARJUELO JM. 2005. Improved irrigation management: The irrigation advisory service of Castilla – La Mancha (Spain). *Agricultural Water Management*, 77(1-3): 37-58.

ORTEGA JF, DE JUAN JA, TARJUELO JM and LOPEZ E. 2004. MOPECO: an economic optimization model for irrigation water management. *Irrigation Science*, 23: 61-75.

PEPWORTH D. Personal communication. Farmer, Malelane.

PETERSON JM and DING Y. 2005. Economic adjustments to groundwater depletion in the High Plains: Do water-saving irrigation systems save water? *American Journal of Agricultural Economics*, 87(1): 147-159.

PULIDO-VELAZQUEZ M, ANDREU J, SAHUQUILLO A, and PULIDO-VELAZQUEZ D. 2008. Hydro-economic river basin modelling: The application of a holistic surface–groundwater model to assess opportunity costs of water use in Spain, *Ecological Economics*, 66(1):51-65.

QUIGGIN J and CHAMBERS RG. 2006. The state-contingent approach to production under uncertainty. *The Australian Journal of Agricultural and Resource Economics*, 50:153-169.

RADLEY R. 2012. Personal communication. Farmer, Malelane.

RECA J, ROLDAN J, ALCAIDE M, LOPEZ R and CAMACHO E. 2001. Optimisation model for water allocation in deficit irrigation systems I. Description of the model. *Agricultural Water Management*, 48: 103-116.

REPUBLIC OF SOUTH AFRICA (RSA). 2012. Proposed allocation schedule in terms of Section 45(2) of the National Water Act, 1998 (No 645 of 2012). *Government Gazette*, 566(35582):1-8.

SCHEIERLING SM, YOUNG RA and CARDON GE. 2004. Determining the price-responsiveness of demands for irrigation water deliveries versus consumptive use. *Journal of Agricultural and Resource Economics*, 29(2): 328-345.

SCHULZE RE. 1995. *Hydrology and Agrohydrology : A Text to Accompany the ACRU 3.00 Agrohydrological Modelling System*. Report TT 69/65, Water Research Commission, Pretoria, RSA

SCHÜTZE N, DE PALY M, WÖHLING T and SCHMITZ GH. 2005. *Global optimization of deficit irrigation systems using evolutionary algorithms and neural networks*. ICID 21st European Regional Conference 2005- 15-19 May, 2005. Frankfurt (Oder) and Slubice- Germany and Poland.

SEPASKHAH AR and GHAHRAMAN B. 2004. The effects of irrigation efficiency and uniformity coefficient on relative yield and profit for deficit irrigation. *Biosystems Engineering*, 87(4): 495-507.

SHANGGUAN Z, SHAO M, HORTON R, LEI T, QIN L and MA J. 2002. A model for regional optimal allocation of irrigation water resources under deficit irrigation and its applications. *Agricultural Water Management*, 52: 139-154.

SLABBERS PJ. 1980. Practical prediction of actual evapotranspiration. *Irrigation Science*, 1: 186-196

SMITHERS, JC, SCHULZE, RE and SCHMIDT, EJ (1997) Modelling the impacts of grassland, forestry and sugarcane on runoff at the Umzinto research catchments. Proc S Afr Sug Technol Ass.71, pp15-17

SOUTH AFRICA (Republic). DEPARTMENT OF WATER AFFAIRS AND FORESTRY 1998. National Water Act. Act No 56 of 1998. 20 August 1998.

STEWART, JI, CUENCA, RH, PRUITT, WO, HAGAN, RM and TOSSO, J (1977) Determination and utilization of water production functions for principal California crops. W-67 Calif. Contrib. Proj. Rep., University of California, Davis, USA.

THOMPSON GD. 1976. Water use by sugarcane. *S. Afr. Sugar J*. 60:593-635.

TSUJI GY, UEHARA G and BALAS S (EDS.). 1994. DSSAT v3. University of Hawaii, Honolulu, Hawaii.

VAN ROOYEN CJ. 1979. Waterbeskikbaarheid en Arbeid as Veranderlike Hulpbronne in Beplanning vir Optimale Organisasie in Besproeiingsboerdery. *Agrekon*, 18(1): 9-17.

VAN ZYL WH and DE JAGER JM. 1992. Effect of climate on plant evaporation coefficients for the potato crop. *Agric. For. Meteorol*. 60:167-179.

VAN ZYL J, KIRSTEN JF, COETZEE GK and BLIGNAUT CS. 1999. *Finance and Farmers*. The Standard Bank of South Africa Limited, Johannesburg.

VAUX HJ and PRUITT WO. 1983. *Crop water production functions*, in D.I. Hillel (Editor), Advances in Irrigation. Vol. II Academic Press, New York, pp. 61-97.

VILJOEN MF, DUDLEY NJ, GAKPO EFY and MAHLAHA JM. 2004. *Effective local management of water resources with reference to the middle Orange River*. WRC Research Report No: 1134/1/04. Water Research Commission, Pretoria.

VILJOEN MF, SYMINGTON HM, BOTHA SJ, and DU PLESSIS LA. 1993. Vaalhartsstaatswaterskema: Ondersoek na die finansiële en ekonomiese uitvoerbaarheid van die vergroting van die sekondêre en tersiêre besproeiingskanale. Departement Landbou-ekonomie. Universiteit van die Oranje-Vrystaat, Bloemfontein.

WILLIS DB. 1993. *Modeling economic effects of stochastic water supply and demand on minimum stream flow requirements*. Unpublished Ph.D. thesis. Department of Agricultural Economics, Washington State University, Pullman.