

G Creemers · AJ Pott

WRC Report No. 890/1/02



Water Research Commission



## DEVELOPMENT OF A HYDROLOGICAL ECONOMIC AGRICULTURAL MODEL BASED ON CASE STUDIES IN THE UPPER MVOTI CATCHMENT

by

#### G. CREEMERS AND A.J. POTT

CPH Water Pietermaritzburg

Project Management by Umgeni Water, Pietermaritzburg

Report to the Water Research Commission on the Project "Development of a hydrological economic agricultural model based on case studies in the Upper Mvoti Catchment"

Project leader : Mr M. Summerton
Principal researchers : Mr G. Creemers & Mr A.J. Pott

OCTOBER 2002

WRC Report No: 890/1/02 ISBN No: 1 86845 933 0

#### Disclaimer

This report emanates from a project financed by the Water Research Commission (WRC) and is approved for publication. Approval does not signify that the contents necessarily reflect the views and policies of the WRC or the members of the project steering committee, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

## TABLE OF CONTENTS

L	IST OF FIG	GURES	V
L	ST OF TA	BLES	. VII
L	ST OF AC	RONYMS	X
		EDGEMENTS	
E	XECUTIVI	E SUMMARY	4
1	INTRO	DUCTION	1
2	THE L	INK BETWEEN ECONOMICS, HYDROLOGY AND POLICY INSTRUMENTS	4
	2.1	JNDERSTANDING A FARMER'S DECISION MAKING PROCESS	
	2.1.1	Farm biophysical characteristics	7
	2.1.2	Farm LUMPs, and associated products and by-products	7
	2.1.3	Economic costs and returns associated with LUMPs	8
	2.1.4	The farmer's choice amongst alternatives	8
	2.2	THE NATIONAL WATER ACT (ACT 36 OF 1998)	9
	2.3 F	OLICY INSTRUMENTS: THE POTENTIAL IMPACT ON A FARMER'S LUMP SELECTION	11
	2.3.1	Regulatory policy instruments	12
	2.3.2	Market based policy instruments	]4
	2.3.3	Suasion	17
	2.4	THE HYDROLOGICAL IMPACT OF LUMPS	17
	2.4.1	Streamflow Reduction Activities (SFRAs)	18
	2.4.2	Irrigation	18
	2.5 1	NDICATORS TO EVALUATE THE POTENTIAL IMPACT OF POLICY INSTRUMENTS	19
	2.6 N	MIMICKING THE DECISION MAKING PROCESS OF THE FARMER	21
3	AN OV	VERVIEW OF THE RESEARCH AREA	23
	3.1	THE MVOTI CATCHMENT: AN OVERVIEW	23
	3.2	THE UPPER MYOTI CATCHMENT	25
	3.2.1	Current land-use in U40A and U40B	26
	3.2.2	The Instream Flow Requirements at IFR Site 1: Mvotipoort	27
4	4. LITT	ERATURE REVIEW	
	4.1 1	NTEGRATING ECONOMICS AND HYDROLOGY TO MEET RESEARCH OBJECTIVES	28
	4.1.1	Grové, 1997: Modelling the economic effects of variable water availability to irriga	ition
	farmer	rs in the Winterton area, giving consideration to the maintenance of minimum IFRs	
	4.1.2	Olbrich and Hassan, 1999: A comparison of the economic efficiency of water us	
	planta	tions, irrigated sugarcane and sub-tropical fruits	
		NTEGRATING ECONOMICS AND HYDROLOGY INTO DECISION SUPPORT TOOLS	
		The state of the s	

	4.2.1	The Watershed Management Decision Support System - WAMADSS	31
	4.2.2	The Catchment Resource Assessment Model: CRAM	32
	4.3 C	ONCLUSION	32
5	THE G	ENERAL MODELLING APPROACH	34
	5.1 N	MODELLING FARMER DECISIONS USING AN EXPERT SYSTEM	36
	5.1.1	LUMPs selected for this research	38
	5.1.2	Use of ACRU to simulate crop yields and LUMP hydrological properties	40
	5.1.3	The indicator: Net Social Benefit	40
	5.1.4	Some considerations regarding the initial and revised approach	42
	5.2 N	FOR THE PROPERTY OF THE PROPER	44
	5.2.1	The revised modelling approach	44
6	THREE	FARM CASE STUDIES IN THE UPPER MVOTI	55
	6.1 C	HARACTERISTICS OF THE FARMS IN THE UPPER MVOTI	55
	6.2 T	HE THREE SELECTED FARM CASE STUDIES	56
	6.2.1	Farm A: A privately owned, small mixed farming operation	59
	6.2.2	Farm B: A large company, mixed farming operation	70
	6.2.3	Farm C: A relatively large, independent timber growing operation	72
7	HYDRO	DLOGICAL MODELLING AND CONSIDERATIONS	75
	7.1 T	HE HYDROLOGICAL IMPACT OF LUMPS	75
	7.1.1	Streamflow reduction	75
	7.1.2	Reduction of water availability	76
	7.1.3	Streamflow reduction of SFRAs and irrigated crops	78
	7.1.4	Simulating the streamflow reduction of LUMPs	78
	7.2 A	DESCRIPTION OF THE ACRU HYDROLOGICAL SIMULATION MODEL	79
	7.2.1	The modelling approach adopted for this research	81
	7.2.2	ACRU hydrological input parameters	83
	7.2.3	The hydrological variables ACRU was used to simulate	84
	7.2.4	Water use during "normal" years and "dry" years	84
	7.3 H	YDROLOGICAL RESULTS	87
	7.3.1	Comparing the streamflow reduction of LUMPs during "normal years"	88
	7.3.2	Comparing the streamflow reduction of LUMPs during "dry" years	92
	7.3.3	Conclusion	94
	7.4 V	ALIDATION OF THE HYDROLOGICAL RESULTS	95
8	ECONO	OMIC DATA AND CONSIDERATIONS	97
	8.1 N	METHOD OF ECONOMIC DATA ACQUISITION	97
	8.2 R	EVENUE AND YIELDS	97

	8.3	VARIABLE AND FIXED COSTS	98
	8.4	YIELDS FOR DIFFERENT LEVELS OF IRRIGATION INTENSITY	102
9	THE	HYDROLOGICAL ECONOMIC LP MODEL	105
	9.1	THE MODEL IN A NUTSHELL	106
	9.2	ACTIVITIES	107
	9.3	CONSTRAINTS	108
	9.3.1	l Land constraints	108
	9.3.2	2 Water-related constraints	108
	9.4	HYDROLOGICAL CALCULATIONS WITHIN THE LP MODEL	110
	9.5	THE OBJECTIVE FUNCTION	111
	9.5.1	Calculation of total revenue	111
	9.5.2	Calculation of fixed and variable costs	111
	9.5.3	3 Calculation of water charges	112
	9.5.4	4 Accounting for risk	113
	9.5.5	5 Calculation of farmer income	114
	9.5.6	5 Specific constraints	115
10	REST	ULTS: DISCUSSION AND CONCLUSION	116
	10.1	OVERVIEW OF POLICY OPTIONS	116
	10.1.	.1 Policy objectives and instruments (columns a and b)	117
	10.1.	.2 Policy indicators (column e)	117
	10.1.	.3 Activities targeted – hydrological impact targeted (columns c and d)	118
	10.2	FOCUS OF THE ANALYSIS: ASSISTING THE IMPLEMENTATION OF THE NATI	ONAL WATER
	ACT (1	998)	119
	10.3	STRUCTURE OF THE RESULTS SECTION	120
	10.4	VALIDATION OF THE GAMS MODEL: DEVELOPMENT OF A PARALLEL EXCE	MODEL AND
	Сомра	ARISON WITH ACTUAL SITUATION	121
	10.5	EFFICIENCY ANALYSIS: INCOME-LOW FLOW TRADE-OFF CURVES	125
	10.5	.1 Farm A: small mixed farming operation	126
	10.5	2 Farm B: Large mixed farming operation	128
	10.5	3 Farm C: Large family-owned forestry operation	129
	10.6	LICENSING: SFRAS	129
	10.7	LICENSING: IRRIGATION RIGHTS	132
	10.8	STREAMFLOW REDUCTION CHARGES	134
	10.9	TRADING OPPORTUNITIES	142
	10.10	MEETING THE RESERVE REQUIREMENTS	145
11	CON	ICLUSIONS	148

12	RECOMMI	ENDATIONS AND FURTHER RESEARCH	154
13	REFERENC	ES	157
APPI	ENDIX 1	HYDROLOGICAL MODEL INPUTS	160
APP	ENDIX 2	SIMULATED HYDROLOGICAL OUTPUT	170
APPE	ENDIX 3	VARIABLE COSTS FOR VARIOUS LUMPS	171
APPE	ENDIX 4	STRUCTURE OF THE EXCEL MODEL	177
APPE	ENDIX 5	GAMS CODE OF THE LP MODEL	182

Main report

## LIST OF FIGURES

Figure 1 A flow diagram showing the main factors influencing a farmer's choice of optimal LUMP mix and consequent hydrological and economic impact
Figure 2 An illustration of the expected links between policy instruments and the farmer's LUMP decision-making process
Figure 3 The use of indicators to reflect the cost or benefit of policy instrument to the farmer and to society
Figure 4 A locality map of the Mvoti Catchment (Source DWAF, June 1996)24
Figure 5 An illustration of the original research methodology considered
Figure 6 An illustration of the revised modelling approach
Figure 7 The location of the three farm case studies in the Upper Mvoti
Figure 8 A GIS coverage of Farm A's current land use as well as the slope (gradient) of the farmlands
Figure 9 Land categories (LCs) for Farm A delineated using the coarse and the detailed delineation methods respectively
Figure 10 The ACRU hydrological simulation methodology adopted82
Figure 11 Ranking the simulated Acocks 4 dry month streamflow, from which representative "normal" years and "dry" years can be selected
Figure 12 The average streamflow reduction during "normal" years
Figure 13 The average streamflow reduction during "dry" years92
Figure 14 Marginal productivity of water in irrigation during wet, median and dry years103
Figure 15 Low flow-income trade-off curves for various farm types
Figure 16 The location of the current land use allocation vis-à-vis the the low flow-income trade-off curves
Figure 17 The impact of a reduction of annual abstraction rights (scenario 1)

Figure 18 The impact of a reduction of abstraction rights during low flow months in dry years
(scenario 2)
Figure 19 The impact of a water use charge on mean annual runoff reduction (excluding return
flows)
Figure 20 The impact of a water use charge on mean annual runoff reduction (including return
flows)139
Figure 21 The impact of a water use charge on flow reduction during low flow months in dry years
(excluding return flows)140
Figure 22 The impact of a water use charge on flow reduction during low flow months in dry years
(including return flows)141
Figure 23 An example of a matrix hydrological conversion ratios to promote trading of water use
licences in the agricultural sector145

Main report vi

### LIST OF TABLES

Table 1 The land uses in Quaternary Catchments U40A and U40B
Table 2 Maintenance and drought IFRs for IFR site 1 (After DWAF, 1996)27
Table 3 The original research approach34
Table 4 The revised research approach
Table 5 The 18 LUMPs considered in this research
Table 6 The months in which irrigation occurs40
Table 7 Economic costs and benefits associated to LUMP decisions
Table 8 A classification of the main types of farming operations in the Upper Mvoti
Table 9 The farm area and current land use of the three selected farm case studies
Table 10 Farm A: A breakdown of the current land use on Farm A
Table 11 Farm A: The area of currently farmed LUMPs found in each LC64
Table 12 The LUMPs feasible on the three broad land categories: arable, irrigable and non-arable lands
Table 13 The crop yields associated with the 18 LUMPs69
Table 14 Farm B; A breakdown of the current land use
Table 15 Farm B: Land categories71
Table 16 LUMPs feasible on Farm B – coarse delineation
Table 17 Farm B: The crop yields for irrigated seed maize
Table 18 A breakdown of current land use on Farm C
Table 19 The MAI of forestry species for Farm C74
Table 20 Input data required by ACRU83

Table 21 The average streamflow reduction during "normal" and "dry" years respectively8
Table 22 "Normal" years: The area that can be planted to Gum to have the equivalent average streamflow reduction as the irrigated LUMPs respectively90
Table 23 "Normal" years: The "annual", "4 dry month" and "8 wet month" streamflow reduction expressed as a monthly average
Table 24 "Dry" years: The area that can be planted to Gum to have the equivalent average streamflow reduction as the irrigated LUMPs respectively
Table 25 "Dry" years: The "annual", "4 dry month" and "8 wet month" streamflow reduction expressed as a monthly average
Table 26 A few selected statistical results of the verification of results simulated by ACRU96
Table 27a Yield and revenue for different LUMPs
Table 27b Variable and fixed costs for various LUMPs95
Table 27c Variable and fixed costs for various LUMPs
Table 28 Gross marginal productivity of irrigation water in years during dry and wet years for different irrigation intensities
Table 29 Notations for sets scalars and parameters used in the LP model
Table 30 Notations for variables used in the LP model
Table 31 Average annual revenue per ha and coefficients of variation for each LUMP114
Table 32 An overview of policy instruments and their application
Table 33a Actual and predicted land use and economic variables
Table 33b Actual and predicted hydrological variables
Table 34 Comparison of hydrological impact during dry years of irrigated potatoes and maize127
Table 35 Streamflow from Farm A under virgin conditions compared to under the farm plant generating the Virgin Runoff low flow level
Table 36 The cost of addressing low flow targets through the APS system

Table 37 Illustration of irrigation scenarios for Farm B
Table 38a Four different ways of implementing a streamflow reduction charge
Table 38b Three different ways of implementing a streamflow reduction charge
Table 39 Annual per ha charges from key LUMPs required to generate revenue corresponding to R20/ha for Farm A
Table 40 An example of land based water use licence conversions
Table 41 An overview of the main current streamflow reductions in the upper Mvoti catchment145

Main report ix

#### LIST OF ACRONYMS

ACRU Agrohydrological Catchment Research Unit

APS Afforestation Permit System

CMA Catchment Management Agency

CMS Catchment Management Strategy

DWAF Department of Water Affairs and Forestry

GIS Geographical Information System

HEAM Hydrological Economic Agricultural Model

HHEZ Homogeneous Hydrological Economic Zone

IBT Inter Basin Transfer

LC's Land Categories

LP Linear Program

LUMP LandUse Management Practice

NWA National Water Act

NWRS National Water Resource Strategy

SFRA StreamFlow Reduction Activity

WARMS Water use Authorisation Registration Management System

WMA Water Management Area

WRC Water Resource Commission

WSAM Water Situation Assessment Model

#### ACKNOWLEDGEMENTS

The research in this report emanated from a project funded by the Water Research Commission and entitled 'Development of a Hydrological Economic Agricultural Model based on the Mvoti Catchment'.

The Steering Committee for the project consisted of the following members:

Dr GR Backeberg

WRC

Mr M Summerton

Umgeni Water

Dr SRD Ferrer

University of Natal

Prof RM Hassan

University of Pretoria

Mr EJ Schmidt

South African Sugar Association

Mr M Masson

South African Timber Growers Association

Prof RE Schulze

University of Natal

Mr B Grové

University of the Free State

Mr DR Weston

Department of Water Affairs and Forestry

Dr N Quinn

Institute of Natural Resources

Mr S Lutchman

KZN Wildlife

Mr N Ward

Department of Water Affairs and Forestry

The financing of the project by the Water Research Commission is gratefully acknowledged. This project was only possible with the cooperation and support of many individuals and institutions. The authors would like to record their sincere gratitude to and acknowledge the following contributions to the project.

- Dr G Backeberg, research manager in charge of this project for his support and guidance,
- Mr M Summerton and Mr M Haynes, of Umgeni Water, for their continued support, and the supply of GIS data for this project, and to Mr Summerton for project managing this research,

- · The farmers who participated in the farm studies on which this research is based,
- Prof R Schulze and Dr G Kiker (University of Natal) for their interest, support and guidance,
- To Dr S Ferrer and Mr B Grové, researchers at the Universities of Natal and the Free State respectively, for their advise on the modelling,
- To staff of the DWAF (Mr D Weston, Mr J Perkins, Mr N Ward and Mr J Geringer) for their comments and practical perspectives,
- To staff of KZN Wildlife (Mr T Sandwith and Dr M Brooks) for their initial encouragement to undertake this research,
- To Prof D Ulph (University College London) for his support and sharing of analytical insights,
- To staff of the Cane Growers Association (Mr A Wynne and Mr M Wheeler), for their input regarding data, and suggestions on the modelling approach,
- To the Strategic Environmental Assessment team at DWAF, and Mr D Versfeld, for the opportunity to gain hydro-economic insights at a catchment scale,
- To staff of Cedara Agricultural College (Mr K Camp and Mr R Bennet) for their time and assistance in explaining concept of Bio-Resource Units,
- To staff at the Computer Centre for Water Research for their assistance in getting data for the hydrological modelling,
- To staff at MBB Consulting Engineers for allocating office space and facilities to work on the project,
- . To Mr K Meier for his technical contribution with respect to ACRU modelling
- To Indira and Kirsty, our wives, for all the hours of family time sacrificed for this project.

CDs containing copies of the document as well as data files collecting in the course of the research data are available from:

- School of Bioresources and Environmental Hydrology University of Natal Pietermaritzburg
   3201
- Umgeni Water
   P.O. Box 9
   Pietermaritzburg
   3200.

#### EXECUTIVE SUMMARY

#### The need for hydrological economic thinking

The motivation for this research was the realisation that the increased water scarcity in South Africa, and the implementation of the NWA (1998), which requires the equitable, efficient and sustainable management of water resources, requires the integration of hydrological and economic thinking, especially with regard to the assessment of water use efficiency.

South Africa's water supply is largely dependent on surface water resources, i.e. streamflow, which in turn is driven primarily by runoff from rainfall. Rainfall in South Africa is highly unevenly distributed and variable over time. To deal with this situation, a twofold approach towards water resources development has historically been followed:

- Dams have been built to hold back water in times of plenty, which would otherwise have flowed to the sea, to be released during drier periods, and
- Inter-basin transfers (IBTs) have been constructed to transfer water from dams and rivers in order to distribute the water to areas of high water demand (in areas where such schemes are financially viable).

Water resource scarcity in South Africa is growing for the following reasons:

- Demand is increasing due to the growing economy and population. In many areas one sees an
  intensification of upstream water use over time, bringing pressure to bear on downstream water
  users.
- Meeting the growing demand for water in the past has been met by increasing the 'pie' of water
  that can be made available, especially during dry spells, achieved via the building of dams and
  IBTs. It has become ever more costly to undertake these augmentation schemes (methods to
  increase the size of the "water pie"), as most feasible dam sites have already been utilised.

Hence, the reality is that the increased water demand will increasingly have to be met in ways other than these so-called augmentation schemes. The South African government has recognized this challenge. The National Water Act of 1998 was designed to ensure that:

(i) The water requirements for basic human and environmental needs will be made available by the Government. This amount of water is referred to as the Reserve, and enjoys priority over all other types of water users,

- (ii) Once the Reserve, International Flow Requirements and Strategic Use requirements have been catered for, the balance of the water may be distributed to other water users in accordance with the principles of the National Water Resources Strategy and Catchment Management Strategy.
- (iii) Options other than the increasingly expensive augmentation schemes should be fully explored as a means of meeting the growing demand for water. This is consistent with the principles of IWRM, which is fully supported by the NWA (1998).

#### The latter options range from the:

- Reduction of water used by land-based activities such as SFRAs (streamflow reduction activities), irrigation activities and by invasive trees in riparian zones,
- · Adoption of more water efficient technologies by industry,
- · Reduction of losses by municipal water delivery systems, and the
- Opportunity for water to be traded within and between economic sectors, subject to approval of water management bodies.

The New Water Act (NWA, 1998) tasks water managers to follow an efficient, equitable and sustainable management of water resources. In order to achieve these objectives a new management system is currently being implemented, the cornerstone of which is achieved via the system of water use registrations and licenses. Water users can no longer own water, and can only hold an entitlement to use water (for a limited period) via a water management instrument referred to as a water use license. Water resources can be managed via water use licenses in the following ways:

- (i) Water resource managers can distribute (allocate) water use licenses in a manner which they deem to be most equitable, efficient and sustainable,
- (ii) Water resource managers can impose conditions attached to the water use licenses. One of these conditions is the period for which the water use licenses are valid. The water use licenses are periodically reviewed to assess if the conditions are being adhered to, and that the system is not stressed due to an over-allocation of water use licenses,
- (iii) Water resource managers can impose water use charges, which are to be paid by the holders of the water use licenses, and

(iv) Water resource managers may allow for certain types of water use licenses to be traded, specifying the conditions under which such trades may occur, as well as the conditions of the traded water use licenses.

In essence, it can be seen that via water use licenses, water resource managers have a powerful instrument through which water use in South Africa can be influenced and regulated. The challenge faced by water resource managers is to select options that lead to the most equitable, efficient and sustainable use of water. These terms are currently not comprehensively defined in the NWA.

Within this document a definition of efficiency (which relates in this context specifically to the water use of land-based activities) has been proposed, and indicators for this efficiency have been developed. When it comes to assessing water related policies targeting land-based water uses (i.e. irrigation and SFRAs), the impact of policy options on the landuse decisions of the holders of land-based water use licenses needs to be known, and following this the consequent impact of the new landuse on the hydrological cycle needs to be quantified. If this cause and effect relationship is known, one can evaluate the impact of each policy option on the efficiency of each policy option respectively. Furthermore, if the requirements for the Reserve are known, an indicator can be developed regarding the sustainability of each policy option.

In this framework, the need for hydrological economic thinking is clear: one can only assess costs and benefits of policy options (i.e. the impact on efficiency) if both the economic and hydrological impacts are known.

The objective of this research is to build a Hydrological Economic Agricultural Model (HEAM). The model is to be used to assess the economic and hydrological impact of different water management options targeting land-based water use (irrigation and SFRAs) with the purpose of evaluating the efficiency and equity implications of these options.

#### The context of the research: the Mvoti Catchment

The Mvoti Catchment was selected to undertake this research due to the water scarcity in the catchment (during the dry months of the year) and due to the availability of good hydrological data. The 273,000ha Mvoti Catchment can roughly be divided in three sub-catchments; the Upper, Lower and Middle Mvoti Catchments. Water users in the Lower Mvoti Catchment include irrigators, sugar mills, and the town of Stanger. Rural people live on the relatively steep slopes in the middle catchment, making a living mainly via subsistence or small-scale commercial agriculture, complemented by pensions and wage remittances from urban areas. The Upper Mvoti Catchment is

highly developed with agricultural and forestry crops. There is currently no large impoundment in the Mvoti Catchment.

Although the Reserve determination has not been finalised, it is likely that at least parts of the Mvoti Catchment will be classified as stressed as the natural flow of certain rivers has been altered to such an extent that during dry years, certain of these rivers cease to flow. Downstream water users find their lives and economic activities negatively affected in times of drought due to water shortages.

Under the previous Water Act (DWAF 1996), the government resorted to the implementation of a moratorium on forestry permits in the catchment, in a bid to halt the further reduction of low flows. At the same time, a feasibility assessment for a number of dams in various parts of the Mvoti Catchment was initiated. Studies in 1996 estimated that the most feasible dam site could increase the yield of the system by some 40 million m³ per annum (MCM) at a cost of about R0.50 (1999 Rand) per m³, enough water to make the Mvoti Catchment a potential net exporter of water to areas along the KwaZulu-Natal coast. However, some of the main clients for that water, most notably the irrigators in the Lower Mvoti Catchment, cannot afford the cost of the raw dam water. Furthermore, alternative options, such as raising the wall of a neighbouring dam (Hazelmere Dam) currently seems to be a more cost-effective option in the short term to ensure water to high assurance users (urban and industrial use) along the coast. Hence, all indications are that the building of a dam on the Mvoti River could be delayed by 10 to 15 years before it is economically feasible to build a dam in the Mvoti Catchment.

#### Research objectives

Key questions which the future CMA (Catchment Management Agency) will probably need to address are the following:

- Which of the Quaternary Catchments of the Mvoti are stressed (and the reason for the stress)?
- Depending on these findings, what, if any, conditions will have to be imposed on the licenses (for SFRAs and irrigation activities) in various parts of the catchment to address the stressed situation?
- If the current registered uses exceed the allocatable resource (i.e. the stress is due to an overallocation of water use licenses), how will curtailments (re-allocations) be implemented?
- Can further development be allowed, and under what conditions?
- How best will water use charges be implemented?

 If applications for trade in water use licences are received, how will they be considered and processed?

The aim of the research is to assist policy makers in addressing some of the above-mentioned questions. However, as the work is of a generic nature and focuses on the use of policy tools, there was no scope to focus on the first basic question: which areas in the Mvoti catchment are stressed.

The research contract included the following research objectives.

- 1. The development of a dynamic hydrological economic model for the Mvoti catchment
- 2. The evaluation of water resource management tools such as:
  - a. Land use planning tools
  - b. Clearing of invasive vegetation in riparian zones
  - Encouragement of good management practices among the forestry and agricultural sectors
  - d. Demand management
- 3. Assessment of the cost of meeting the Reserve requirements
- 4. Assessment of the impact of the implementation of water use charges
- 5. Assessment of the opportunities for a system of transferable water rights

During the course of the work this set of objectives was slightly modified. The first objective was scaled down to a static rather than a dynamic model. The focus was further narrowed to the upper catchment instead of the catchment as a whole. Moreover, during the course of the research, the decision was made to take a farm-based approach. This implies that the results are valid for the selected farms, and not necessarily to the catchment as a whole (or other catchments).

The second research objective was also modified. The focus was changed to the use of permits and licences as water resource management tools. The clearing of riparian zones was left out due to a lack of economic and hydryological data. Good management practices was also something that proved difficult to model, and on top of that it appeared that under the pressure of international forestry certification systems such practices are being implemented. The focus on demand management was dropped as this stemmed from the original idea of looking at the catchment as a whole.

#### Research objective 1: The development of a hydrological economic model for the Mvoti catchment

After investigating various modelling options, it was decided to adopt a hydrological economic optimisation modelling approach at the farm level. The HEAM is a linear programming (LP) model that operates on a farm level. Unique features of the approach adopted in setting up the LP model are that the economic component was simplified, and a hydrological component was added. The reason for the simplification was due to the complexity of integrating the hydrological and economic information for this research. As with any normal LP model, the model assumes that the farmer chooses from a set of possible activities. The activities use resources, which are in finite supply (i.e. impose a constraint on the activity mix options available to a farmer). The objective function of the LP model is to select the set of activities (the landuse and management practice mix) that a farmer can select in order to maximise profit while taking into account business risk. (Business risk in this context is taken to be the risk associated to the variability of crop prices and the variability of yields.)

#### The resources that are in finite supply include:

- Different land categories (examples of which are arable, non-arable and irrigable land),
- Water available in the river (at different time periods),
- Water use licenses (i.e. the amount of water that a farmer may legally use).

The water available in the river (streamflow) at different time periods requires further clarification.

For the purpose of this research, four different periods of streamflow were simulated using the ACRU hydrological simulation model. These four periods were selected in order to assess the hydroeconomic impacts of targeting policy instruments on the water use of LUMPs during these periods, which include:

- Streamflow during the 8 wet months (September to April) during normal years (normal years being years with an average level of rainfall and resultant streamflow),
- (ii) Streamflow during the 4 dry months (May to August) during normal years,
- (iii) Streamflow during the 8 wet months (September to April) during dry years,
- (iv) Streamflow during the 4 dry months (May to August) during dry years.

Often the term 'low flow' is used. This classification corresponds to the fourth streamflow listed above. Each of these streamflows can be considered to be a different economic resource. In the context of the Mvoti Catchment, given the problems with low flows, the scarce resource is really the

flow during the dry months in dry years. The use of streamflow during wet months or wet years does not have an economic and equity impact. (Although this situation could be different if a large dam were located in the catchment).

The activities among which the farmer can choose from include:

 The adoption of a specific Land-Use Management Practice (LUMP) p (p is the notation used in the model) on a given type of land, s, during normal years and during dry years. LUMPs include: The 3 main forestry species (pine, gum and wattle), poplar, dry land maize, irrigated sugar cane, irrigated maize and irrigated seed maize, irrigated potatoes and natural veld.

The model allows the farmer to choose among 3 different irrigation intensities, for both sugarcane and maize. Each of these irrigation intensities is considered to be a separate LUMP.

The abstraction of streamflow during a certain period. It is important to note that the amount
of water applied on the field as irrigation is not an activity. If the farmer chooses a given
irrigation LUMP, the model automatically assumes the corresponding irrigation requirement,
which must be met through abstraction from the river or a dam.

The outputs, which the farmer produces, are the following:

- Market outputs: i.e. crop outputs associated with the various LUMPs, which generate revenue.
- Non-market outputs: i.e. contributions to each of the four types of streamflow. At this stage, these outputs do not give rise to any revenue or cost. With the NWA (1998), this can change as water use charges (the economic charges) can be introduced and trading may take place.

The contribution to streamflow during a given period is defined as the runoff during that period, minus the abstraction from the river during that period. Obviously, if farm dams are used, water abstracted during one period can be used for irrigation during another. For example, a dam can be used to hold back "surplus water" during the wet months and this surplus can be applied during dry months.

The water available in the stream during each of the 4 periods available for abstraction, the crop irrigation requirements and yields associated with the different irrigation LUMPS, as well as the runoff for all LUMPs were modelled with ACRU.

The HEAM model is a static model.

- The farmer maximizes his average annual profit taking into account business risk and assuming that as far as water availability is concerned, average conditions apply during the four periods discussed above (dry months in normal and dry years, and wet months in normal and dry years).
- The use of average annual profit meant that income and expenditure figures for forestry operations, for which rotations range from 8 to 20 years, had to be annualised (i.e. average annual figures were used.)
- Given the static nature of the model, the results are interpreted as the farm plan that the farmer will probably adopt in the long run.

The HEAM was set up for 3 different farms, referred to as Farm A, B and C respectively. Farm A is a privately owned, small mixed farming operation. Farm B is a large company, which adopts mixed farming operation and Farm C is a relatively large, independent timber growing operation.

This modelling framework was used to generate the results for the case study farms. The model was tested according to how well it could predict the current land-use configuration, using the parameters characterising the current policy environment as input. Overall, this test was successful. The following remarks need to be made:

- The model performed well in predicting the total area allocated to forestry, but less so in
  predicting the current mix of forestry species planted. This was judged to be acceptable as the
  model results are a reflection of what the farmer would choose in the long run. In the long
  term the farmer would have enough time to deal with short term constraints such as the
  limitations to change the forestry species mix.
- The amount of irrigation, which the model predicted under the current policy environment, was higher than what was observed on Farm A. This was due to the fact that in the light of the New National Water Act, the farmer is holding back his plans to invest in additional irrigation capacity, as he is unsure about future water rights and is weary of water use changes.

Research objective 2: Evaluation of the use of permits and licences as water resource management tools

The results here are categorised in three different sections.

Result a: Marginal costs of producing low flows during dry years differ significantly across farm types.

It was found that the farms have vastly different marginal costs for increasing the flow during low flow months of dry years. Marginal cost is defined as the cost, which the farmer would incur if he were to produce one additional unit of low flow by changing his LUMP mix. The small mixed-farm (Farm A) faced a marginal cost of approximately R1 per m³ of water during low flow months in dry years. In other words the opportunity cost of 1m³ of water during the 4 dry months is R1. Expressed in terms of annual systems yield available for downstream users, this would equate to R0.33 per m³ (R1x 4/12).

The large-scale mixed farm (Farm B) was found to be able to generate additional low flow at a very low cost: about R0.07 per m<sup>3</sup> of low flow, or R0.023 per m<sup>3</sup> of system yield equivalent. This was mainly due to two reasons:

- (i) The farmer uses a farm dam, so whatever irrigation requirements he has during low flow periods, can be met from the farm dam, partly or entirely. In other words, the farmer does not make use of much "scarce water", i.e. the streamflow during the 4 dry months of the year. The dam is a means of holding back "surplus water" from the wet months.
- (ii) The farmer has the opportunity to switch to irrigated seed maize, which generates a higher contribution to streamflow during low flow months in dry years, than the baseline irrigation would have. In other words, due to the timing of the irrigation, irrigated maize augments streamflow during the dry months.

The farm concentrating entirely on forestry (Farm C) was found to face huge marginal costs in producing low flow: up to R45 per m<sup>3</sup> of low flow, or R15 per m<sup>3</sup> if expressed in terms of annual system yield. This is some 600 times higher than for the large scale mixed farm (Farm B).

Result b: The past afforestation permit system (APS) was inefficient.

A further test was undertaken in order to assess the merits of the above-mentioned policy (APS), which was implemented during the previous Water Act, mainly out of a concern for low flows. As can be expected from the previous results, this has been very costly to protect low flows. The calculations showed that the current low flow from all 3 farms (which are currently regulated by the old APS) may be achieved, by adjusting irrigation crops on the large mixed farm, while at the same time giving rise to about R100 000 and R140 000 of additional average farm and labour incomes per annum. This means that it is possible to meet low flow in a more equitable, efficient and sustainable method than was achieved by regulating only forestry through the old APS. For the two upper

Quaternary Catchments as a whole, it was estimated that about 3.7 and 4.9 million Rand of additional labour and farm income could be generated keeping the current low flows in these catchment unaltered, i.e. simply by changing the LUMPs in the Upper Catchment. These results will however need to be verified with future research.

Result c:

In undimmed catchments, managing irrigation licences based on water use during flow flow months, rather than during the full 12 months of a year, can be more efficient in catchments with problems of water availability in low flow periods.

Traditionally, water use licences for irrigation have been specified in terms of the total volume of water, which the farmer can abstract *annually*. This volume is determined by using the scheduled area times an allocation per year per hectare needed for the farmer to achieve optimal crop yields for mean conditions i.e. years with an average amount of rainfall and water availability.

For the large mixed farming operation, Farm B, it was found that reducing annual abstraction rights during normal and dry years would increase both the farm's contribution to annual flows during normal and dry years, as well as low flow, as expected. The increase of annual streamflow would come at a cost of R0.08 per m<sup>3</sup>. The low flow increase would cost about R3 per m<sup>3</sup>.

If rights to abstraction during the *low flow months* in dry years were reduced, both annual flows and low flows would be increased at a cost of R0.08 per m<sup>3</sup>. This shows that trying to improve low flows by using an instrument, which focuses on annual flows, is costly. It also confirms that the value of irrigation water use entitlements to the farmer amount to about R0.08 per m<sup>3</sup>. Please note that these figures apply to an <u>undammed catchment</u>, and will probably change if a large impoundment is built in the catchment.

Instead of reducing water use entitlements for irrigation, one may also consider how new applications should ideally be dealt with. Discussions with water managers suggest that the current thinking is that no new irrigation licences would be allowed in the Upper Mvoti Catchment, although a deal could be negotiated if the farmer is prepared to build a farm dam. Disallowing any additional irrigation makes sense when annual flows are a concern. However, when low flows are a concern, this is not the case. Hydrological simulations indicate that a summer irrigation crop like maize actually adds significantly to low flow compared to Acocks. In other words, the water resource manager should actually encourage such forms of irrigation. The soil is used to store the water, which seeps into the river in the form of returnflow. It must be stated that if a large dam were located downstream of the farms, this statement may not be true, as the water captured by the dam may be more beneficial than the returnflows of crops irrigated in the wet season (i.e. a dam will be more effective at storing water than the soil). There may also be water quality considerations associated with the returnflows.

#### Research objective 3: Assessment of the cost of meeting the Reserve requirements

The exact requirements for the Reserve have not yet been established in the Mvoti catchment. Reserve requirements are generally a complex set of conditions. In the context of this study the Reserve requirements were simplified to minimal flow requirements during low flow months in dry years. In other words, assessing the cost of meeting Reserve requirements was translated into assessing the cost of generating extra flow during low flow months in dry years.

Furthermore, the fact that this study focused on 3 selected farm case studies rather than on a full sample representative farms in the catchment means that only indicative extrapolations can be made regarding the cost of meeting Reserve requirements.

The results generated by the study show that this cost will be influenced by the strategy adopted. Irrigation seems to harbour the most cost-effective options to generate more streamflow during critical dry periods (dry months during dry years). Pushing back forestry on non-arable land is prohibitively expensive. Clearing riparian zones seems to be a relatively cost-effective option but more economic and hydrological data would be required to conclude this with more certainty.

# Research objective 4: Assessment of the impact of water use charges targeting streamflow reduction.

Result:

At the currently proposed levels, the charges do not have an impact on crop decisions. At higher levels land use changes would result, in which case it would be more efficient to base charges on low flow impacts in catchments where low flows are a problem.

At this stage in the implementation of the NWA (DWAF, 1996), water use charges are being introduced with the sole purpose of generating income for the CMAs. DWAF's idea is to have a charge that will be accepted by water users without too much resistance. For forestry, this charge is suggested to be around R5 to R10 per hectare.

For the purpose of this research it was assumed that water use charges are levied on the streamflow reduction of the LUMPs. An impact of this is that charges for the dryland and irrigation LUMPs would have to differ significantly due to the marked difference in streamflow reduction between the two water uses per unit area. If the charges are based on average annual streamflow reduction, intensive irrigation would justify charges that are 8 to 15 times higher than those for forestry. Low intensity irrigation on the other hand, would justify charges that are marginally (30 to 40%) higher than forestry. In other words, the irrigation intensity makes an enormous difference to the streamflow reduction attributed to irrigation. The current thinking around the implementation of water use

charges seems to ignore this, mainly because the monitoring of irrigation intensities would be very costly. Nevertheless, it is important for land-based water users to be aware of this.

If charges are based *on low flows*, the differences between the various LUMPs are exacerbated. Irrigated maize should receive a subsidy, as it *increases* low flow, while irrigated sugar, even at low intensity levels, would have to face charges up to R150 per hectare (as irrigated sugar requires some irrigation during the 4 dry months of the year.

It was further found that for low levels of water use charges, farmers would not change their crop choices. They would obviously use less intensive irrigation practices (however monitoring actual irrigation remains a challenge). For such low charges, it does not matter much whether one focuses on annual or low flow effects. However, should charges increase, it would be worth targeting low flow effect, in that way not just raising revenue, but also giving farmers a clear incentive to be frugal with a scarce resource. This approach seems more consistent with the objectives of the NWA.

#### Research objective 5: Assessment of the opportunity for a system of transferable water rights

Result: Trading opportunities at the Quaternary Catchment level, facilitated by conversion ratios, can create economic gains without impairing the water balance

The three farm case studies were found to face significant differences in marginal costs to produce low flows. This indicates that there are trading opportunities. A closer look suggested that the trading opportunities could rather be seen as licence conversion opportunities. The licence conversion opportunity is a specific form of legal transfer and voluntary trade conceived by authors of this research. Consider the following example. Farmer B might accept a payment from Farmer C to convert from 12 ha of currently irrigated sugar cane to irrigated seed maize (Irrigated sugarcane requires water to be abstracted in one of the 4 dry months, whereas seed maize does not require any irrigation during the dry months). Using simulated runoff and abstraction data, and taking into account the effect of the farm dams, it was estimated that Farmer C could be allowed to plant approximately 144 ha of wattle and still leave the overall water balance of the upper catchment intact. In doing so, the net effect for both farms would be an increase of about R300 000 per annum in terms of labour income, and about R150 000 per annum in terms of farm income. The minimum compensation Farmer C would have to pay Farmer B is approximately R60 per hectare. Currently, non-arable land with an afforestation licence fetches between R700 and R2200 (buying price) per hectare more than land without such a licence. In other words, for Farmer C, the potential cost of acquiring an additional afforestation licence equates to less than 10% of what is currently paid in the market.

The HEAM's estimate of the economic costs and benefits of the above conversion are approximations. Only the farmers themselves have the perfect information to calculate these. However, a critical determinant in evaluating the potential for licence conversions is the conversion ratio. Farmers currently have no information whatsoever on this. The water manager could promote such conversions, which lead to a more efficient use of water, by publicising conversion ratios. This could be a matrix with elements  $a_{ij}^{kl}$  or  $a_{ij}^{kl} - a_{ij}^{kl}$ : for a buyer wishing to convert from land use k to land use l, and for a seller, prepared to convert from land use i to j. The term  $a_{ij}^{kl}$  denotes the number of hectares the buyer can convert for every hectare converted by the seller. As conversion ratios will be dependent on how water is abstracted (directly from river, from off or on channel dam, from large public water scheme), a lower bound  $a_{ij}^{kl}$ : and upper bounds  $a_{ij}^{kl}$  could be stated.

#### Capacity building and technology transfer

Although this project did not directly contribute to the capacity of previously disadvantaged individuals or organisations, the capacity of the research team was expanded. The research is being used to further the qualifications of both Mr Creemers (P.Hd candidate), and Mr Pott (M.Sc candidate). Aspects of the research methodology are being used by the Strategic Environmental Assessement unit in the DWAF for a hydro-economic assessment of the Usutu-Mhlathuze WMA.

#### 1 INTRODUCTION

The current policy situation in South Africa with respect to the management of its water resources is one of transition as water managers and stakeholders seek ways to practically implement the new legislation. In terms of controlling land-based water uses, the key differences between the old and the new legislation include the following:

- The range of activities that could be targeted in the past (pre-1998) was narrow. For example, water managers had little recourse to control water rights associated with the ownership of riparian land.
- ii. The range of instruments and the conditions that could be imposed (pre-1998) was narrow. The promulgation of the NWA (1998) has increased the scope of activities water managers can target, as well as conditions that may be attached to these activities.

The requirement of the NWA (1998) that the Reserve, international flow requirements and strategic water use receive priority of water use above other uses, combined with the water management tools made available to water managers, places water managers in a strong position to meet these objectives. Apart from being able to target more activities with a broader toolkit, water managers now face the challenge to direct their policies more explicitly at water availability. Targeting water availability instead of using averages of annual conditions as a guideline for policy implementation should be a priority to water resource managers. They ought to consider using indicators that reflect what happens during dry years, and particularly during the low flow months of those years.

A Hydrological Economic Agricultural Model was developed to assist water managers in dealing with these three challenges: (i) more activities, (ii) a boarder set of policy instruments, and (iii) the use of more refined hydrological data for policy implementation. The first two of these challenges will be addressed by evaluating the economic and hydrological implications of targeting additional activities and introducing new policy instruments. The third challenge will be addressed by comparing the economic and hydrological implications of policies, which do use more refined hydrological data, with those, which do not. This will give decision-makers the opportunity to compare the hydrological and economic gains, which such more refined implementation may create, with the extra cost associated with its implementation.

The hydrological impacts that were targeted in the past were generally focused on mean annual runoff reduction for afforestation activities, or maximum allowable annual abstraction for irrigation activities.

#### The report is structured as follows:

- Section 2 will deal at a general level with the link between economics, hydrology and policy instruments
- Section 3 provides an overview of the research area in which the model will be applied.
- Section 4 provides an overview of some selected literature, which focuses on issues similar to the ones addressed in this report.
- Section 5 outlines the general modelling approach. The initial approach will be discussed and the reasons for switching to a new approach will be discussed.
- · Section 6 will focus on the farm case studies, which are used in the new modelling approach.
- Section 7 discusses all the hydrological work that served as an input into the model.
- Section 8 discusses the economic data used in the model
- Section 9 discusses the LP model in more detail.
- Section 10 presents the results.
- Section 11 and 12 cover the conclusions and recommendations.
- Three appendices are added. Two provide more detail and background on the hydrological model. One gives the GAMS (General Algebraic Modelling System) code for the LP model.

It is useful to unequivocally restate the aims of the research. For this, the initial proposal will be revisited. At various stages, these aims were modified and simplified but it important to restate them explicitly here, as reference will be made to them later on in this document.

- Integrate hydrological and economic information on the Mvoti River Catchment in a dynamic model to simulate various scenarios of allocations of land-use and water resources in the catchment.
- Use the model to assess the impact of various water resource management approaches in terms of the benefits and costs they create in different parts of the catchment and for different stakeholders.

- Land-use planning (such as changes in amount of permits issued to forestry, and other land-use activities which may be defined in the future as stream flow reduction activities)
- ii. Clearing of invasive vegetation in riparian zones
- Encouragement of good management practices among the forestry and agricultural sectors
- iv. Demand management
- Assess the economic cost of implementing the National Water Act (NWA) with respect to the protection of the Reserve in the Mvoti River Catchment.
- Assess the impact of various pricing strategies to recover costs of water resource development on the economic benefits derived by various stakeholders in the catchment.
- 5. Explore the options of implementing a system of transferable water rights.
- Provide recommendations regarding the implementation of principles of the NWA (1998) in the Mvoti River Catchment, and assess the potential of using a Hydrological Economic Agricultural Model as a tool to guide the implementation of the NWA in other catchments.

Publications resulting from this research include:

Pott, A.J., Creemers, G., Schulze, R.E. and Kiker, G., 1999, Linking Economics and Hydrology: Lessons in Modelling for the New Water Act, Ninth South African National Hydrological Symposium

Technology transfers resulting from this research include:

- The research will contribute to the M.Sc of Mr Andrew Pott: The Development of a Hydrological Economic Agricultural Model.
- The research provided insights that are being used by the DWAF SEA initiative.

#### 2 THE LINK BETWEEN ECONOMICS, HYDROLOGY AND POLICY INSTRUMENTS

Policy instruments may influence the land-use decisions of farmers, either directly (coercively, also known as command and control policies, such as licenses for forestry and irrigation), or indirectly (via market forces, by implementing water use charges or subsidies), and potentially not at all. A low water use charge for example may be levied on SFRAs, yet the charge may be low enough not to "drive" farmers to select a different LandUse and Management Practice (LUMP) mix.

Farmer's have up to now selected the LUMP mix that maximises farm profits (accounting for risk), and will continue to do so after the implementation of NWA (1998). The difference between the NWA (1956), and the NWA (1998) is the fact that with the NWA (1956), the value of water was not made explicit to the farmer, and was consequently not built into the farmer's land-use decision-making process, whereas the NWA (1998) has the potential to value water explicitly via market forces. This value was not previously explicit for two reasons. Firstly, the water use of many LUMPs has not been quantified, and where it has been quantified, either not made available to and/or accepted by farmers and water resource managers.

Secondly, water has up to now been traded with limited success, only within sectors (intra-sectoral trade), especially between farmers. The NWA (1998) makes provision for water licenses to be traded, which opens up the possibility of inter-sectoral trade, which seems to be of mounting importance as a result of continual industrial growth, coupled with fully allocated hydrological resources, is creating an environment in which trade in water us licenses between sectors (e.g. from the agricultural and forestry sector to the industrial sector) is financially feasible, and without which economic growth in South Africa may be hindered.

The first point of departure within this document is not to immediately focus on the water resource related policy instruments, but rather to discuss the land-use decision-making environment of the farmer. The second point of departure is to explore the link between economics and hydrology, needed to better understand how the policy instruments may potentially be most effectively used to incorporate the hydrological impact of LUMPs into a farmers LUMP decision making environment.

### 2.1 Understanding a Farmer's Decision Making Process

The first important point to make is that changes to LUMPs have an impact on hydrological processes and consequently influence the quantity and/or quality of streamflow. Changes to the quantity or quality of the streamflow may influence stakeholders downstream of the farmer, referred to as an externality. The concept of externalities, and how to quantify the costs and benefits associated to them will be further explored in this document. The hydrological simulation tool used for this research, the ACRU hydrological simulation model, allows the impact of LUMPs on streamflow to be simulated, accounting for both overland flows (water flowing over the land surface into the river) as well as baseflows (water seeping through the soil profile into the river). The ACRU model was not used to simulate the impact of LUMPs on groundwater reserves, as there are no significant groundwater reserves in the research area due to the presence of relatively steep slopes and shallow bedrock.

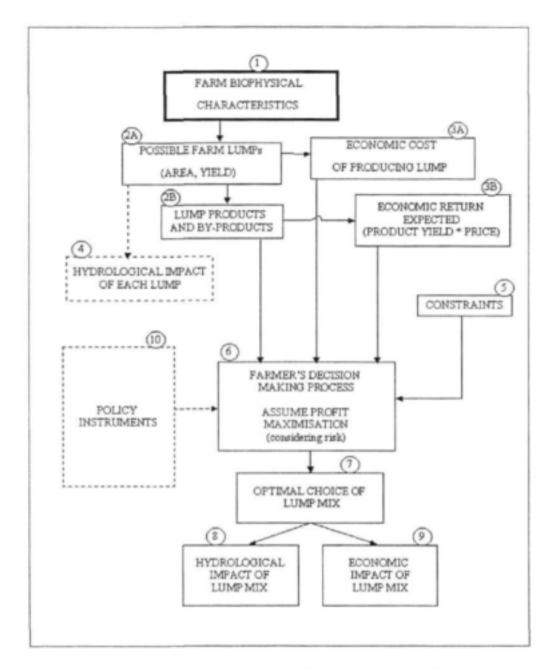
LUMPs reflect not only the land-use (the LU in the acronym), but also the management practice (MP in the acronym) adopted in the production of the given crop. There are a number of management practices that can be undertaken for the various phases of growing a given crop, including land preparation, crop planting, crop tending and crop harvesting techniques. The management practices may themselves have a large impact on crop yields, hydrological impacts, and economic feasibility. For example, different irrigation schedules, as well as irrigation methods, are all examples of management practices that can be used for a given crop. The farmer currently has a relatively good idea as to the cost of the different irrigation methods, however, may be less aware of the resultant impact of the various management practices on yields, as well as the hydrological impact of the various management practices. Due to the high water use of irrigation, an attempt has been made in this research to assess the potential hydrological impact of a few irrigation schedules, as well as the potential impact on crop yields. The results indicate that this may be a prime area for future research.

The second important point to make is that the LUMP mix undertaken by a farmer is usually the LUMP mix that is expected to offer the highest financial return, after adjusting for risk. The adjustment of financial returns to account for risk is explained in Section 9.

The link between economics and hydrology can be summarised by the following two statements:

- LUMPs have an impact on hydrological processes (hydrological impact), which influence the quantity and/or quality to downstream users (an externality), and
- ii. LUMPs influence expected returns (and risk), to the farmer (economic impact).

Figure 1 below is a flow diagram, illustrating the main factors influencing a farmer's LUMP mix decision, excluding the impact of policy, and will be developed and explained throughout this document, as it offers the framework within which the Hydrological Economic Agricultural Model (HEAM) is to operate. Section 2.1.1 to Section 2.1.4 describe the main elements of Figure 1.



Note: The risk alluded to in Box 7 refers to <u>business risk</u> and not financial risk. Business risk is defined in Section 9.4.4.

Figure 1 A flow diagram showing the main factors influencing a farmer's choice of optimal LUMP mix and consequent hydrological and economic impact

#### 2.1.1 Farm biophysical characteristics

With reference to Figure 1, the biophysical characteristics include, amongst others, soil type, slope (gradient), aspect, rainfall and temperature characteristics, wind, altitude and current land-use. Biophysical characteristics may vary from region to region, but may also be highly variable for even small geographical areas. The importance of the biophysical characteristics is that they are one of the dominant determinants of what LUMPs physically are possible for a given area. In Figure 1, box 1 reflects the biophysical characteristics of a farm. The box is highlighted with a bold border in order to stress the importance of biophysical characteristics in the link between hydrological and economic processes. The solid line from 1 to 2 reflects the link between the biophysical characteristics of a location, and suitable LUMPs for that location.

#### 2.1.2 Farm LUMPs, and associated products and by-products

Although there are a number of agricultural practices that can be adopted in the production of a given crop, the LUMPs referred to throughout this document represent the most commonly adopted crop management practices for the study area. Where relatively small changes in management practices have a large impact on either the cost of producing the crop, or the crop yield, the LUMPs should be considered separately. For example, an irrigation schedule of 25 mm of water applied every 7 days may have a significantly different hydrological and economic impact than irrigating 32 mm every 7 days for the same crop. Consequently each LUMP should be considered, as though it were a separate land-use in its own right. There is however a challenge not to select too many LUMPs, as the LP model requires simplification for it to be tractable. A further consideration is the fact that the relationship between management practices and crop yield is currently not well known. Hydrological and crop yield simulation models could potentially be used to assist in demonstrating this relationship.

In addition to possible farm LUMPs, the farmer will need to identify the products (and by-products) the LUMPs can yield. For example, wattle wood can be used for pulp or charcoal, while the bark may be sold as a completely different product. The farmer will need to know where he can market the LUMP products and by-products. The optimal LUMP mix will be based on the potential economic return generated by the LUMP products and by-products giving consideration to the constraints with which the farmer is faced. Figure 1, reflects how farm LUMPs (2A) are a function of the biophysical characteristics, while the products and by-products (2B) are a function of the LUMPs which can possibly be undertaken on the farm. Please note that the term "possible" does not refer to LUMPs which are physically possible, as consideration is given to the economic viability of the crop and

hence only economically feasible LUMPs are considered. If the crop yield is too low to merit consideration, the LUMP is not considered.

Note that the link between LUMPs (2), and the hydrological impact of the LUMPs (4), is represented by a dashed line. This is done in order to reflect the fact that farmers do not currently build the hydrological impact of LUMPs into their decision making process in the determination of the optimal LUMP mix. NWA policy instruments have the potential to formalise this link, and will be discussed below in Section 2.3. An example of a LUMP includes irrigated maize (the landuse) with an irrigation regime of 25mm every 7 days (the irrigation management practice).

#### 2.1.3 Economic costs and returns associated with LUMPs

In Figure 1, box 3A and 3B reflect the economic costs and returns associated with the LUMPs and LUMP products (& by-products) respectively. The expected economic return, 3B, is determined giving consideration to the products that can be yielded by the LUMPs, and the price at which the products (and by-products) are expected to be sold at. As the farmer can not be sure of the prices he will receive for his crop at the time of harvesting the crop, or the actual crop yield (which is usually highly dependent on rainfall), consideration may be given by the farmer to past crop prices and crop yields. These are used to as an indicator of risk associated with the land-uses. In calculating the expected return, the risk element is built into the decision making process of the farmer, which is discussed in Section 9.4.4.

### 2.1.4 The farmer's choice amongst alternatives

Once possible LUMPs, products and by-products, have been identified, the farmer will select the LUMP mix that yields the greatest profit, giving consideration to the *risk* associated with each LUMP and LUMP mix, as well as the *constraints* faced by the farmer. The selection of LUMPs based on profit maximisation (considering risk) is an assumption central to this research. Constraints faced by the farmer include policy-induced constraints and non-policy induced constraints. Water use licenses are examples of policy-induced constraints, which include licenses for streamflow reducing activities (SFRAs) and licenses for irrigation. Forestry is currently the only registered SFRA, and has previously, been regulated for a number of years by afforestation permits (DWAF, 1999c). Non-policy induced constraints include, amongst others, access to finance, labour availability, market quota's and water available for irrigation. Box 10 in Figure 1 represents policy instruments available to manage the water resources. Box 4 is reflected by a dotted line as the policy options, and linkages they have, are more comprehensively illustrated in Figure 2.

The LUMP mix selected by the farmer will have an *impact* (box 4) on hydrological processes. These impacts refer to the changes in the amount of water used on the farm (which results in changes to the quantity of water received by downstream stakeholders), and/or the quality of the water flowing from the farm as a result of changes to the LUMP mix. The point to be made is that the DWAF has previously recognised that LUMPs impact on hydrological processes. However, the legislative actions to regulate water use have up to now only targeted afforestation.

The NWA (1998) has introduced a number of firm policy objectives (discussed in Section 2.2), as well as policy instruments (discussed in Section 2.3) to achieve the policy objectives. The NWA (1998) policy objectives, such as the implementation of the Reserve, may require an assessment of both the currently applied policy instrument/s, as well as the new policy instruments, in terms of the effectiveness of each policy instrument in achieving the policy objectives. In order to assess if a policy instrument is effective, certain indicators need to be identified, and developed as the yardstick with which to judge the effectiveness (efficiency) of both the policy instruments, and how the policy instruments are used (i.e. what characteristic/s of the hydrological impact resulting from a given LUMP is targeted).

The point to be made is that there exists the potential, with the provision of market based policy instruments, to make explicit the hydrological impact of LUMPs.

#### 2.2 The National Water Act (Act 36 of 1998)

This section is not a comprehensive review of the NWA, and only aspects of the NWA relevant to this study will be discussed.

There are two key principles in the NWA (1998), which will have an impact on a farmer's LUMP decisions. These include the following:

- i. The role of the state is to act as custodian of water as a public resource, and
- The water required for basic human needs and the environment must enjoy priority of use by right, while use of water for all other purposes is subject to authorization (Muller, 1999).

Read together, the consequence of the two principles is that the government holds the resource to the benefit of the country. As custodians of the of the Nation's water resources, water resource managers are placed in a position to manage the water resources via the use of water related policy instruments. These instruments broadly include water use licenses (i.e. an instrument which can be used to directly regulate the amount of legal water use in a catchment), and water use charges (which can be used to

indirectly regulate the water use in a catchment dependent on market forces). Both instruments are further discussed in Section 2.3.

In the NWA (1998), a number of water resource management objectives have been identified, including amongst others:

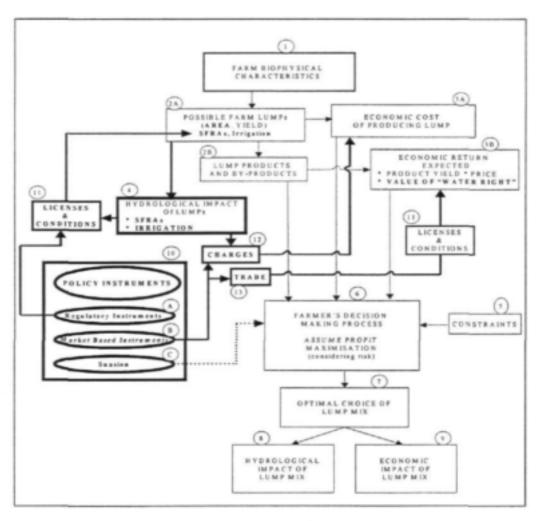
- i. To meet the basic human needs of present and future generations,
- ii. Promoting equitable access to water,
- iii. Redressing the results of past racial and gender discrimination,
- iv. Promoting the efficient, sustainable and beneficial use of water in the public interest,
- v. Facilitating social and economic development,
- vi. Providing for growing demand of water use,
- vii. Protecting aquatic and associated ecosystems and their biological diversity,
- viii. Reducing and preventing pollution and the degradation of water resources,
  - ix. Meeting international obligations,
  - x. Promoting dam safety, and
- xi. Managing floods and droughts.

The purpose of this research document is to explore the costs and benefits of the implementing policy instruments in different ways in order to meet policy objectives (i.e. a review of policy objective iv listed above). The efficiency with which policy instruments can be used is a combination of the type of policy instrument selected to meet a policy objective, as well as the manner in which the policy instrument is introduced. For example, it is possible that a water use charge be based on mean annual streamflow reduction or alternatively the streamflow reduction, in say the 4 driest months of the year. In this example the policy instrument is the same (i.e. a water use charge on streamflow reduction), yet the charge is levied on different hydrological impacts. The focus of this research is to assess both the selection of policy instruments, as well as the manner in which they are used to target the hydrological impact of land-uses, in order to meet the certain policy objectives. The manner in which a given policy instrument targets water use may have an impact on the efficiency of the policy instrument, i.e. the ability to meet the policy objective. This may be the most important consideration

introduced in this document that warrants further research if the objectives of the NWA are to be met efficiently.

# 2.3 Policy Instruments: The Potential Impact on a Farmer's LUMP Selection

The impact of the policy instruments on the farmer's LUMP decision-making process is illustrated in Figure 2.



Note: The policy instruments shown in Box 10 refer to policy provision in the NWA (1998). There are in fact a number of other policy instruments, such as, amongst others, the Conservation of Agricultural Resources Act, that may influence the farmer's decision-making process.

Figure 2 An illustration of the expected links between policy instruments and the farmer's LUMP decision-making process

The different types of policy instruments influence the LUMP decision making process of the farmer in different ways, as reflected by the number of links between box 10 and the other components in the diagram. It is important to understand the *mechanisms* of each policy instrument (i.e. exactly how each policy instrument targets the hydrological impact of the LUMPs), as well as the probable response of the farmer to each policy instrument, in order to accurately mimic the farmer's land-use decision making, which needs to be done to assess the costs and benefits of introducing a given policy instrument.

The water resource policy instruments can be grouped into three broad classes, including, regulatory policy instruments, policy based instruments, and suasion.

### 2.3.1 Regulatory policy instruments

The primary regulatory instrument is a water use license. The license specifies the type of water use permitted, and may have conditions attached to the license. The two types of water use licenses applicable to this research include:

- Water use licenses for dryland crops classified as Streamflow Reducing Activities (SFRAs).
  The license entitles the owner to plant a specified area of the farm to the SFRA for a given
  time period, and subject to the owner of the license adhering to certain conditions with respect
  to the management of the SFRA.
- ii. Licenses for irrigation. The licence entitles the owner to an annual amount of water for irrigation purposes. That amount is calculated by allocating a specific amount per hectare scheduled for irrigation. The per hectare amount allocated is determined by the type of crop and the climatic conditions. That right is not absolute: during periods of water shortage, voluntary or obligatory curtailments may have to be implemented.

Figure 2 illustrates the mechanism with which regulatory instruments, in the form of licenses, influence the LUMP decision making process of the farmer. The link between the possible farm LUMPs (box 2A), and the LUMP hydrological impact (4), is reflected by a solid line, as this cause and effect relationship needs to be quantified and made explicit for the process of issuing licenses. To clarify this statement, water managers will have an allocation plan, in which a quantity of water is set aside for authorised use (i.e. licensed use). Before the entitlements can be issued, the *hydrological impact* of the different water uses needs to be known, or estimated. A high accuracy of the estimates is ideally required in order to ensure that there is a match between the expected water use from a given LUMP, and the actual water use by the water LUMP. If this match is not achieved, two possibilities exist, including:

- The issued water use licenses may result in more water being used than the water resource manager expected to be used, which may place the catchment in a stressed water resource situation (i.e. the amount of water set aside for allocation is breached), or,
- ii. The issued water use license may result in less water being used than the allocatable resource. The impact of this is that economic development may be sacrificed where the demand for water use licenses exceeds the allocatable resource, as water used by the licensed LUMPs is less than the allocatable resources, i.e. there is in fact surplus water which could still be licensed.

In other words, there is a need for the water use estimates of LUMPs to be accurate, or at within acceptable confidence levels. This has been, and will continue to be a challenge for hydrologists to accurately simulate the water use of LUMPs, considering that the use of water by LUMPs is variable in time and space. Figure 2, box 4 illustrates that a distinction needs to be made between SFRAs and irrigation when licensing water use, as the manner in which SFRAs and irrigated LUMPs use water differs. Water resource managers will need to give consideration, to amongst other things:

- i. The manner and timing of water use by the LUMPs, and
- ii. The amount of water that can be allocated in a given period.

Consideration should be given to at least the monthly distribution of allocatable water (i.e. how much water can be allocated in a given month) in order to ensure that licensed water use does not exceed allocatable water for that month (Grové, 1997). The words "at least" are used, as the NWA (1998) makes provision for Instream Flow Requirements (IFRs) to be regulated on monthly temporal scale. However, as the DWAF is in the process of changing from the old to a new system of water resources management, it may take some time before this level of detail is reached. To complicate matters further, consideration should be given to the impact storage facilities (such as large dams) have on the water availability, which can be released to meet IFRs for different months of the year. In other words a combination of both how and when LUMPs use water, as well as how and when the water can be stored and used from a dam, needs to be considered when issuing licenses, as this will influence the ability to meet IFRs.

CMA water resource managers will need to compare the expected water use of licensed water use to the actual water use (i.e. generated with a hydrological simulation model), giving consideration to dams, in order to verify that there is in fact a match between expected and actual water use. In other words there is a need to simulate the expected impact of the licensed water use, and then to compare that to actual water use. If there is a discrepancy, the water use estimates of the LUMPs may need to be revised.

DWAF currently uses the modified Scott-Smith flow reduction curves when considering SFRA licenses. The curves distinguish between the flow reduction of different forestry species, including the flow reduction associated with wet and dry years (DWAF, 1999c). These curves have however only been developed for commercial forest species. Consideration will need to be given to quantify the streamflow reduction of LUMPs (other than forestry species), which may be considered to be SFRAs.

With respect to irrigation, consideration is given to the SAPWAT model, which is used to determine the crop irrigation requirement (i.e. not streamflow reduction) using the Penman-Monteith climatic model for crop water requirements, as well as the effective rainfall for different crops at 350 weather stations countrywide (DWAF, 1999b). It is important to note that no formal consideration is currently being given to the streamflow reduction of irrigated LUMPs. In other words, when reconciling allocatable water to the water use of licensed irrigation, the assumption is being made that the full water use license is being used by the farmer (giving consideration to the curtailments the farmer is expected to experience).

Irrigation, and the licensing of irrigation are not discussed in much detail within this document. However, the authors believe that there is a *strong need* to review the actual water use of irrigated LUMPs (discussed in some detail in this report), and the terms and conditions of irrigation licenses (not discussed in this report).

#### 2.3.2 Market based policy instruments

The NWA (1998) makes provision for a market-based water resource policy instrument, in the form of a water use charge. The authors of this research regard a water use charge as a policy "instrument", as it can be used to influence the LUMP decisions of a farmer, albeit indirectly through market forces. A water use charge may be levied on registered and licensed water use (DWAF, 1999b). The NWA (1998) also makes provision for the trade of water use licenses (i.e. the trade of regulatory instruments).

The authors of this research do not regard the trade of water use licenses as a policy instrument in its own right, as a water resource manager can only regulate, but not direct the trade of water use licenses. The trade of water use licenses has been included in this section as the trade of licenses has a similar impact on the LUMP mix decisions of a farmer as do water use charges. The difference between water use charges and the trade of water use licenses is that licences can be used as a tool

(instrument) by water resource managers to manipulate LUMP decisions by farmers by targeting licensed LUMPs, whereas water use charges influence the LUMP decisions by farmers by market forces outside the control of the water resource managers. Both water use charges and the trade of water use licenses influence the financial viability of LUMP mix combinations available to a farmer. Figure 2, box 12 and 13 represent water use charges and the provision to trade in water use licenses respectively, which are discussed below.

#### 2.3.2.1 Water use charges

In terms of the Act, the Minister may, with the concurrence of the Minister of Finance, from time to time by notice in the *Gazette*, establish a pricing strategy for charges for any water use (S56 (1)). This pricing strategy may make use of charges-

- For funding water resource management (S56 (2)(a)),
- ii. For achieving the equitable and efficient allocation of water (S56 (2)(c)), and
- iii. For funding water resource development and use of waterworks (S56 (2)(b)).

The objective of the water resource charge will to a large extent determine how the water use charge will be implemented, i.e. what target the water use charge will be based on. For example, should the objective of the water use charge be to generate revenue (i.e. to fund water resource management), the water resource manager would probably want to select the easiest and most practical way of implementing the water use charge, which will deliver an adequate revenue. In other words, the water resource manager may charge a water license holder on his full water use entitlement, and not his actual water use. It is important to make this distinction, as it may be necessary to level the water use charge on actual water use, in order for the water use charge to achieve the equitable and efficient allocation of water (objective ii. above).

If a water use charge is applied to the full licensed water use, the efforts of the farmer to use water more efficiently are not considered. For example, in the case of forestry, if a given water use charge targets the licensed afforestation area a catchment (which will be captured in the DWAF Water use Authorisation Management System (WARMS) database), no distinction is made between farmers with licensed forestry in the catchment practicing good forestry management practices, and other who don't. With respect to irrigators, if a water use charge targets the full irrigation water use license, no consideration is given to farmers who have undertaken more efficient irrigation practices (i.e. applying less water to get the same or larger returns).

The problem with targeting water use charges on actual water use, is that detailed monitoring is required to differentiate between when and how water is used, and secondly the hydrological impact of this use (i.e. the timing and magnitude of the use on streamflow reduction) needs to be known with an acceptable confidence level (giving consideration to the impact hydrological structures such as dams may have).

The potential link between a water use charge based on actual wateruse, and the farmer's LUMP decision-making environment is illustrated in Figure 2. The water use charge (box 12), based on the hydrological impact of SFRAs and irrigation LUMPs (box 4), results in an increase in the cost of producing those LUMPs (box 3A), which in turn influences the financial return of a given LUMP mix (box 6) to the farmer.

With respect to the objective to recover the costs of water related infrastructure which a farmer may make use of, the water use charges need to be directed at those farmers using such facilities. The water use charge will be levied on the farmer's full water use license, as the water resource managers need a fixed income to recover the costs of providing the infrastructure.

The National Water Act, 1998 provides for trading in water use entitlements. The Act recognises, however, that while the trading of entitlements between uses may optimise the economic use of water, i.e. increase the efficiency of water use, the trade of water use licences may in turn impose considerable external costs on the rest of the local economy or influence the equitable distribution of water. Thus, trading in water use entitlements will probably be subject to some form of control to protect the public interest.

Water use entitlements, in effect offer the farmer another "product" to sell/lease in addition to the LUMP products and by-products, i.e. the water use license (or part thereof) can be sold. This is illustrated in box 3B in Figure 2. The value of the water use entitlement (license) is dependent on the nature of the license, including the terms and conditions associated to the license. This is reflected by the link between trade (box 13), the license and license conditions (box 11), and the economic return expected by the farmer (box 3B). The term, trade of water use licences, will be used in this document, to represent the sale and/or lease of water use licences. As mentioned above, such trades will need to be regulated, and there will probably be administrative costs associated with this regulation, which the farmer will need to consider. An important point to make is the fact that in the case of irrigation, a portion of the water use entitlement can possibly be traded (i.e. there will need to be a facility to split water use licenses, so that a portion of the original license can be traded). For example if the farmer is allocated 10 000 m<sup>3</sup>/ha/annum, the farmer may be willing to sell of a few thousand cubic meters of his water right. He will do this if the loss in income (due to sacrificed yields associated with lower irrigation application) can more than be compensated for by the return he will receive for his sold

water use entitlement. This however would imply that water use entitlements do not just get traded as parcels.

The authors believe that the ability to split irrigation water use licenses is a topic for further research. Furthermore, it is necessary to research how water use licenses (and/or portions of water use licenses) and license conditions can be converted into water use licences for different uses and different conditions.

#### 2.3.3 Suasion

Suasion is the policy instrument whereby an appeal is made to the farmer to select equitable, efficient and sustainable LUMPs. This may be accompanied by educational drives, making the cause and effect link between LUMPs and the impact on hydrological impacts more explicit. However, due to the fact that we assume the farmer to select LUMPs which maximise profits (after risk), the impact of suasion on the LUMP mix by the farmer cannot be captured. This is reflected by the dotted line linking suasion with the farmer's decision-making environment in Figure 2.

#### 2.4 The Hydrological Impact of LUMPs

Box 4 in Figure 1 and Figure 2 represents the hydrological impact of LUMPs. The point was made that policy instruments can be used to influence the LUMP mix outcome of the farmer, either directly via the use of regulatory policy instruments, or via the use of market based instruments. The point was also made that the trade of water use licenses may influence the LUMP mix of a farmer, however the trade of water use licenses will probably only be regulated, and not initiated, by the water resource manager, i.e. other than regulating the trade, the LUMP mix of the farmer may be influenced by forces outside the control of the water resource manager.

Both regulatory and market based instruments, should target the hydrological impact of LUMPs, ideally the water use during the periods when water is most scarce, in order to manage the water resources efficiently, equitably and sustainably. In order for the management of water resources to be sustainable, the hydrological impact of LUMPs (including the hydrological impact of dams) needs to be quantified with an acceptable level of confidence, especially with respect to the water use of the LUMPs during the dry periods. The hydrological impact of SFRAs, and irrigated LUMPs are further discussed in order to highlight how the mechanism of using water (which influences how and when water is used, and the consequent streamflow reduction that takes place).

### 2.4.1 Streamflow Reduction Activities (SFRAs)

The term SFRAs in this context refers to those dryland landuses classified as SFRAs in the NWA (1998). Although many forms of water use are streamflow reducing activities, the NWA (1998) identifies a category of water users as SFRAs. SFRAs, being dryland crops, are usually dependent on rainfall as the source of water. SFRAs are defined as "activities likely to reduce the availability of water in a watercourse to the Reserve, to meet international water obligations, or to other water users significantly" (Act 36 of 1998). The baseline land condition, against which comparisons are made, is the natural land-use (Acocks landcover) of the region. It is the reduction of streamflow compared to this baseline land-use that is of particular interest to water resource managers, including not only the magnitude of the streamflow reduction, but also the timing of the streamflow reduction (i.e. what is the streamflow reduction during different periods, for example relatively dry versus relatively wet years). Dry years in this research refer to periods of low water availability, i.e. periods of low streamflow. In other words, the streamflow is taken to be equivalent to the water available at a given point in time as there is no significant dam in the Upper Mvoti that can retain streamflow, to be used in different periods.

### 2.4.2 Irrigation

The hydrological impact of irrigation differs from SFRAs (dryland crops), in that the hydrological impact is dependent not only on rainfall, but also on the magnitude, timing and manner in which the water is irrigated. The amount of water actually irrigated, is dependent on the irrigation license (including terms and conditions, such as when and how the license may be curtailed), the physical amount of water available to irrigate, as well as the crop water requirements of the land-use being irrigated (which is dependent on the rainfall).

The streamflow reduction for a given period t (e.g. a specific month or combination of months) associated to the irrigation of a given land-use is calculated as follows:

#### Runoff Acocks, t - Runoff Irrigated LUMP s. t - Irrigation abstraction LUMP s. t

The following points need to be considered with respect to irrigation:

- Irrigation is used as a supplementary source of water to rainfall. Consequently, during periods of good rainfall, all things being equal, less irrigation water may be required.
- A number of irrigation schedules are possible to the farmer for a given land-use, each of which may have significantly different hydrological impact (streamflow reduction), as well as

- crop yield. Five different irrigation schedules were considered for both irrigated maize, and irrigated sugarcane in this research.
- iii. The concept of return flows from irrigation often comes up in discussions on irrigation. The concept refers to the irrigation water that percolates beyond the root zone of the crop, which makes its way to the river over time. In the above equation return flows are included in the runoff from the irrigated lump. Return flows often contribute to runoff weeks or months after the irrigation occurred. This may be quite relevant to the water resource manager. The reason for this is that certain land-uses, which if irrigated during relatively wet months of a year (in which there may be surplus water, which if not used flows into the sea) may result in an increase in streamflow (compared to Acocks) during the driest months, as a result of delayed irrigation return flows. In other words, the soil acts as reservoir for the water, which is slowly released over time. The water is potentially applied (and stored) during periods of surplus water, and slowly released, resulting in some of the return flows entering the river during potentially very dry periods.
- iv. If water for irrigation is abstracted from a dam, the period of abstraction often differs from the time of application. Modelling the impact of irrigation on streamflow requires ideally a dynamic model. During the course of this study, it was only possible to develop a static model (as discussed below).
- v. The authors acknowledge that the following irrigation can possibly have significant impacts on water quality but this fell outside the scope of this study.

# 2.5 Indicators to Evaluate the Potential Impact of Policy Instruments

Figure 3 below shows that a policy instrument may, via the decision making process of the farmer, either lead to a change in LUMP mix, or no change in LUMP mix. There may however be costs or benefits to the farmer or society in response to a policy instrument even though there is no change in the LUMP mix. *Indicators* need to be developed that reflect the costs and benefits to the farmer and society of implementing a given policy instrument (and the way in which it is implemented, i.e. what the policy instrument targets). These indicators are needed to assist water resource managers in assessing both the sustainability, as well as the efficiency of policy instruments (and targets)

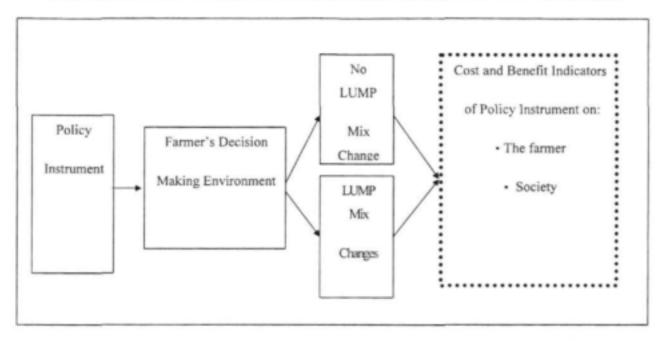


Figure 3 The use of indicators to reflect the cost or benefit of policy instruments to the farmer and to society

It is important to point out that the cost or benefit referred to is due to the change associated with the introduction of the policy instrument. As shown in Figure 3, there need not be a change in the LUMP mix for there to be a change in the financial return to the farmer. For example, a water use charge targeting the forestry industry may effectively only reduce the farm income to the forestry sector (if the water use charge is low enough not to warrant a change from forestry to another LUMP). Society will potentially not be adversely effected, assuming no jobs are lost as a result of the water use charge being implemented (as the forestry area remains constant if the charge is low enough).

However, where an application of a policy instrument does lead to a change in LUMP mix, there is an impact both to society, as well as to the farmer. The farmer will potentially receive less farm income associated with the new LUMP mix. The farmer may lay off labour, as less labour may be needed for the new LUMP mix. Society however may benefit from an increase in streamflow associated with the new LUMP mix.

In other words, indicators are needed to reflect the cost and benefit of different policy instrument, and how they are used to target the streamflow reduction of LUMPs, both for the farmer and for society. The indicators are described in greater detail in Section 5.2.1.9.

#### 2.6 Mimicking the Decision Making Process of the Farmer

The purpose of this research is to assess of the costs and benefits of various policy instruments needed to meet certain NWA policy objective. In order to assess these costs and benefit, there is a need to integrate both hydrological and economic information. The following points reveal why this is necessary:

- LUMPs influence hydrological processes. Certain LUMPs result in a streamflow reduction (which makes less water available to downstream water users).
- A farmer is assumed to select the LUMP mix having the greatest financial return (giving consideration to the risk associated to the LUMP mix).
- iii. The farmer may be constrained by certain policy instruments, such as a water use license, which regulates the SFRA area or irrigation allocation (volume/ha/annum) a farmer may undertake. The licensed area is supposed to reflect the water use by the LUMP. The hydrological impact of LUMPs is often not known by the farmer, e.g. the streamflow reduction of forestry on the farm. There is scope to share this information with farmers, which may result in practices by farmers to increase the water use efficiency of LUMPs.
- Water use licenses can target irrigation activities as well as any declared SFRA. Water use charges can be levied on licensed (or registered) activites, i.e. irrigation or SFRAs.
- v. In order to assess how the farmer will react to the policy instruments a tool will be needed to mimic the optimal LUMP mix selection by the farmer.

This will require the integration of both the economic and hydrological data, and an understanding of how policy instruments will influence the decision-making environment of the farmer.

Once the tool has been developed which adequately mimics the optimal LUMP mix, the cost and benefit indicators can be used to assess the impact of different policy instruments, and the manner in which the policy instruments target the hydrological impact of the LUMPs.

Three distinct components can be identified that are necessary to meet the research objectives. These include:

- A. Determine the hydrological impact of LUMPs
- B. Assess how the respective policy instruments can target the hydrological impact of the LUMPs

- C. Develop a tool that mimics the decision making process of the farmer, i.e. a tool that integrates both economic and hydrological information (via the use of policy instruments).
- D. Develop clear and easily understood indicators with which to express the costs and benefits of the different policy options to the farmer, and to society.

Before reviewing the literature, undertaken in Section 4, the research area and the main issues in the research are introduced. The research document is laid out in this format so that the reader obtains a better understanding of what the issues are, and how the policy instruments reviewed in this research could potentially be used to address the issues. Thereafter a review of literature is undertaken to search for suitable tools and/or methodologies that can be used to meet the research objectives.

#### 3 AN OVERVIEW OF THE RESEARCH AREA

The purpose of this chapter is to introduce the Mvoti Catchment, as well as the Upper Mvoti Quaternary Catchments, highlighting the main hydrological issues in the catchments. The reasons for selecting the Mvoti Catchment as the research area are also discussed.

#### 3.1 The Myoti Catchment: An Overview

Although the research area is restricted to three farms located in the upper two Quaternary Catchments, U40A and U40B, of the Mvoti Catchment, a complete description of the entire Mvoti Catchment is given. This is done to provide the framework within which the research is undertaken, giving consideration to the stakeholders and their concerns.

The Mvoti River Catchment falls entirely within the province of KwaZulu-Natal, and drains into the Indian Ocean, as shown in Figure 4. It comprises a total area of about 273000 ha, stretching from a point some 35km southwest of Greytown in the West, to the estuary at the Indian Ocean some 7km southeast of Stanger/Groutville. The catchment is bordered by the Tugela River Catchment to the north, the Mgeni, Tongati and Mdloti River catchments to the south, and the Mooi River Catchment to the northwest. The Mvoti River Catchment can be subdivided into two main regions: the former Natal areas and the former KwaZulu homeland areas. The former Natal area can further be subdivided into the Upper-Mvoti region, upstream of the former KwaZulu homeland area, and the Lower Mvoti Region, downstream of the former KwaZulu homeland area. The three regions also roughly correspond to a difference in topographic and climatic characteristics. The Upper Mvoti, Middle Mvoti and Lower Mvoti regions each occupy 144000ha (53%), 98000ha (36%) and 31000ha (11%) of the Mvoti respectively (DWAF, 1996).

Towns and villages developed in the Upper Mvoti are Greytown, Dalton and Transco, and in the Lower Mvoti, Stanger and Groutville are found. The inhabitants of the Middle Mvoti region generally live in rural conditions. Stanger/Groutville is the largest single town in the catchment (DWAF, 1996).

Water requirements in the catchment are made up of urban and rural domestic, industrial, irrigation, dryland agriculture (including forestry) and environmental water demand. Four Instream Flow Requirement (IFR) sites have been identified in the Mvoti River Catchment, and are displayed in Figure 4.

The largest commercial water demand centres are situated in the Lower Mvoti region, consisting of large-scale irrigation, heavy industries and urban domestic activities. Both the Middle and Lower Mvoti regions are almost totally reliant on the Mvoti River for water supply. There is currently a moratorium against the further planting of forestry in the Upper Mvoti.

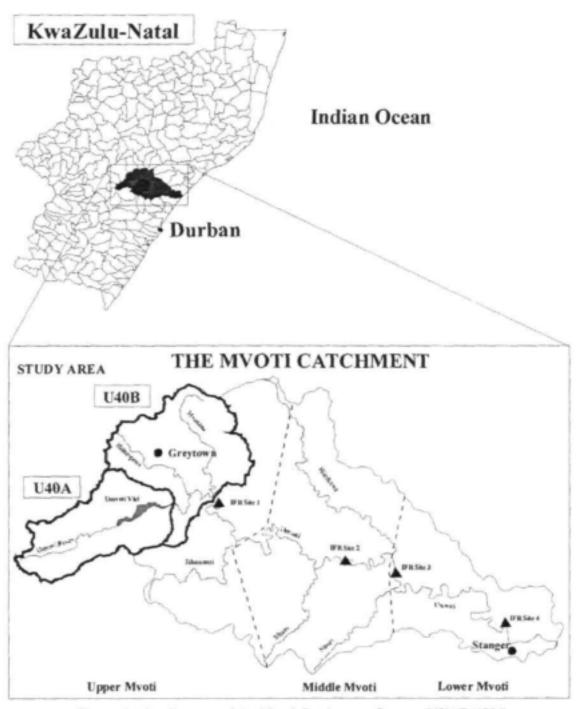


Figure 4 A locality map of the Mvoti Catchment - Source: DWAF (1996)

Interestingly, the Mvoti River is being considered as a future potential export source of water to developed areas north of Beltsville. Studies have been conducted on the possibilities of constructing a dam or system of dams to supply the anticipated growth in water demands. Three proposed dams and their sites are: the Mvoti-Poort Dam in the Upper Mvoti, the Isitundu Dam on the Mvoti River just upstream of the confluence with the Hlimbitwe River and the Mvoti-Hlimbitwe Dam site just downstream of the confluence (DWAF, 1996). The dam sites are located just above IFR site 1,2 and 3 respectively as shown in Figure 4.

Dams however are very expensive to build. Discussions with personnel at Umgeni Water, located in Pietermaritzburg, indicated that the recovery cost of dam water is approximately R0.40/m<sup>3</sup>. Personal discussions with the DWAF water resource planner suggest that irrigation farmers cannot afford to pay R0.40/m<sup>3</sup> (Geringer, 2000, personal communication). Thus, there is a paradox in that firstly there is a need for water supply to be augmented for use by irrigators, industrial and domestic users located in the Lower Mvoti Catchment, secondly there are suitable dam sites, yet the cost of supplying the water (based on cost recovery and maintenance costs) exceeds the ability of some of the potential water users to pay for the water. The implication is that a dam will not be constructed until it is economically feasible to do so.

As the Upper Mvoti has been extensively developed by agriculture and especially forestry, there is scope to assess what the value of water is to the farmers in the Upper Mvoti, and how much water can potentially be liberated if upstream LUMPs are changed. In other words, our research aims to ascertain what water related policies could be imposed on the Upper Mvoti land-users in order to generate a higher assurance of water supply to the lower regions, as well as the economic cost or benefit associated with such a changes in the land-use mosaic. These costs and benefits, among other things can then be compared to the R0.40/m<sup>3</sup> required to supply water augmented by a dam.

# 3.2 The Upper Mvoti Catchment

The Quaternary Catchments, U40A and U40B, were originally selected as the primary research area. U40A and U40B are illustrated in Figure 4, covering an area of approximately 70 500 ha of the total 144 000 ha Upper Mvoti area (49%). The following reasons led to the selection of only U40A and U40B, and the exclusion of the remaining 51% of the Upper Mvoti:

i. The ACRU hydrological simulation model had been configured by the University of Natal, Pietermaritzburg, for the Quaternary Catchments U40A and U40B. Hydrological data for the remaining Mvoti Quaternary Catchments forming part of the Upper Mvoti (U40C to U40I) were not yet available, and would require some time to gather,

- ii. Detailed land-use information is readily available for U40A and U40B, but not for the remaining Quaternary Catchments. The land-use of U40A and U40B had been surveyed by consulting engineers using aerial videography (Umgeni Water, 1997) in order to assess the impact on water resources by riparian infestation of alien invasives and
- iii. Both U40A and U40B lie entirely within the Upper Mvoti, while U40C, U40D and U40F only partially lie within the Upper Mvoti. This is due to the hydrological boundaries not corresponding to the political boundaries of that time. Approximate boundaries separating the Upper, Middle and Lower Mvoti have been included in Figure 4.

#### 3.2.1 Current land-use in U40A and U40B

An aerial videographic survey was used to map the land-use current in 1997 (Umgeni Water, 1997). The survey was taken at a resolution of approximately 2.5m per pixel on the ground, as the focus of the survey was to map the types of land-use present in riparian zones. The land-use map was verified by visits to the field by both MBB after completion of their survey in 1997, as well as independently during the course of the past two years (1998, 1999). Table 1 gives a breakdown of the area planted to different crops, as well as the area expressed as a percentage of the total U40A and U40B area.

Table 1 The land-uses in Quaternary Catchments U40A and B

Land-use	Area (ha)	Percentage	Land-use	Area (ha)	Percentage	
Forestry	38,739	55	Formal (Residential)	498	0.7	
Grassland	13,109	18	Sugarcane	438	0.6	
Maize	10,621	15	Informal (Residential)	318	0.4	
Irrigation	2,393	3	Pastures	126	0.1	
Wetlands	1,593	2	Acacia	107	0.1	
Rocky (No crops)	929	1	Orchards	101	0.1	
Indigenous	631	1	Vegetables	83	0.1	
Dams	538	1	Industrial	19	0.1	

Note: The area was mapped by MBB Consulting Engineers in a project for Umgeni Water (Umgeni Water, 1997).

It is important to note that the survey did not differentiate between forestry species. Wattle, Pine and Gum are all planted within U40A and U40B. This division of forestry into the different forestry types has not been undertaken due to the modelling approach adopted, which is explained in greater detail in Section 3.

The following important points and land-use trends are evident:

i. Forestry is generally limited to mountainous areas, which have relatively steep slopes,

- ii. Irrigation occurs close to rivers or dams, on flat and shallow sloping land,
- iii. Sugarcane is limited to north facing slopes,
- iv. There is no evident correlation between farm size and land-use, and
- v. A gauging weir is situated a few hundred meters below the vlei. The vlei is large, and believed to have a large impact on hydrological processes and it is this that makes verification complicated...

#### 3.2.2 The Instream Flow Requirements at IFR Site 1: Mvotipoort

The maintenance and drought IFRs of IFR Site 1 (shown in Figure 4) derived from the intermediate determination method, i.e. the two month method, are represented in Table 2 below.

Table 2 Maintenance and drought IFRs for IFR site 1 (after DWAF, 1996).

Months	Maintenance Baseflows Volume (MCM)	Maintenance Higher Flows Volume (MCM)	Maintenance Drought His Total Baseflows Flo Volume Volume Vol (MCM) (MCM)		Drought Higher Flows Volume (MCM)	Drought Total Volume (MCM)					
SEP	0.41	-	0.41	0.16	-	0.16					
OCT	0.51	0.17	0.76	0.24	0.15	0.24					
NOV	1.24	0.35	1.59	0.31	0.06	0.46					
DEC	1.61	0.93	2.54	0.37	0.06	0.44					
JAN	1.82	-	1.82	1.82 0.43		0.49					
FEB	1.94	2.62	4.56	0.44	-	0.49					
MAR	2.68	1.94	4.62	0.54	-	0.54					
APR	1.71		-	-	-	-	-	1.71	0.41	-	0.41
MAY	0.86	-	0.86	0.32 -		0.32					
JUN	0.52	-	0.52	0.21	-	0.21					
JUL	0.40	-	0.40	0.16 -		0.16					
AUG	0.37	-	0.37	0.13	-	0.13					
VIRGIN CONDITION		IONS	17.7954	PRES	ENT CONDITI	ONS					
Virgin MAR		95MCM		Present MAR		51 MCM					
Maintenance IFR as % of Virgin MAR		21.23%		Maintenance IFR as % of Present MAR		39.54%					
Drought Virgin M		4.26%		Drought IFR as % of Present MAR		7.94%					

Two important points to be made regarding the IFR results include:

- The IFR was designed to ensure pereniality of flow at this site, although the river currently
  ceases to flow at times, and
- The Mvoti Vlei was identified as having a major effect on the nature of the hydrological regime at the site (DWAF, 1996).

#### 4. LITERATURE REVIEW

The literature review is focused on research undertaken in which hydrology and economics have been integrated with relevance to the focus of this research. This is not a comprehensive literature review of hydrological-economic models. Four separate research undertakings will be discussed, three of which were undertaken in South Africa, and with a review of one international document. Two of the four documents reviewed include the integration of economics and hydrology to meet specified research objectives, whereas the remaining two include the integration of economics and hydrology into desktop tools that can be used to assist decision-making. A brief description of each research is given, including at outline of the research objectives, methodology, and a discussion that compares the research to this research project.

#### 4.1 Integrating Economics and Hydrology to Meet Research Objectives

The two documents that include the integration of economics and hydrology to meet specified research objectives include research by Grové (1997), and Olbrich et al (1999), which are discussed below.

# 4.1.1 Grové, 1997: Modelling the economic effects of variable water availability to irrigation farmers in the Winterton area, giving consideration to the maintenance of minimum IFRs

The main objective of this research was to develop procedures in an LP model which uses hydrological output from ACRU to enable irrigation farmers and water managers in a catchment to assess the economic impact of different irrigation water use strategies, such as such as different levels of deficit irrigation as well increased efficiency subject to different levels of IFRs. Furthermore, a routine was developed in the model to assess the impact of irrigating from a small dam (Grové, 1997).

The objective of Grové's research is very similar to that of this research undertaking, and in many ways guided the development of the research methodology undertaken for this research project. The research allows the economic costs of increasing IFRs to be assessed. Although not expressly stated in the document, the model allows for the assessment of the use of water use licenses as a policy instrument to meet the objective of maintaining the Reserve. As discussed in the preceding chapters, there are two ways in which an IFR could be regulated. The first is for the water resource manager to issue fewer or more water use licenses. The second is to change the conditions of the water use licenses, in effect allowing the holder of the irrigation water license to be curtailed at different levels

of water availability. In other words, the starting point for Grové's research is to assume a given IFR, and then to adjust the IFR up or down.

A representative farm of 200ha in Winterton was used by Grové to meet the research objectives. The temporal focus of the research was directed at the winter months, as stochastic water shortages are a common phenomenon for wheat cultivation. The following approach was undertaken to link the economics and the hydrology into a chance constrained LP model.

ACRU was used to simulate the water availability to the representative farmer, i.e. by simulating the LUMPs upstream of the farmer. The simulated water availability generated by ACRU was converted into deterministic equivalents of water availability using by a "Best Fit", a curve-fitting program. A chance constrained linear programming (CCLP) was used to determine the optimal level of deficit irrigation and water application efficiency together with the yield. The economic cost of different IFR levels was determined by comparing farm income a farmer would have received if he was not constrained by water (the base run), to the farm income he could expect if he was constrained by available water (due to increased IFR levels).

The results of Grové's research shows that measures to reduce the abstraction of water per unit area using deficit irrigation and/or measures to increase water application efficiency (allowing for greater areas to be irrigated with the saved water) may actually put more pressure to bear on streamflow due to reductions in irrigation returnflows. Consequently, water can only be saved if consumptive use is reduced.

The modelling methodology adopted by Grové's is very similar to the revised modelling approach adopted for this research, except that use is not made of chance constrained linear programming. Instead of working with probabilities, it was decided by the researches to identify "normal" and "dry" years, in order that policy instruments could target the streamflow reduction of these years. This is further discussed in Section 7.2.4.

# 4.1.2 Olbrich and Hassan, 1999: A comparison of the economic efficiency of water use of plantations, irrigated sugarcane and sub-tropical fruits

The main objective of this research was to assess the water use efficiency of different land-uses, with a particular focus on forestry and irrigated crops. The economic efficiency is expressed as a ratio of the farm-gate economic returns generated from a given land-use to the water use associated with the land-use. Farm-gate returns include only the costs and benefits accruing to the farm, and do include backward or forward linkages into the economy, as may be the case the case with timber companies who process the timber and generate extra value in this process. The streamflow reduction was used

as the indicator of water use by forestry plantations, whereas net irrigation was used to represent the water use by irrigated crops. The researchers recognized that the ability for downstream users to irrigate crops is influenced by the LUMP activities upstream. Forestry species are usually planted in the upper reaches of a catchment, primarily due to the high rainfall associated with these areas. Olbrich and Hassan identified this conflict in demand for water as a resource in the Crocodile River Catchment located in Mpumalanga, where forestry in the upper reaches of the catchment competes with high value agricultural goods produced under permanent irrigation.

The hydrological and economic information is linked in a spreadsheet, from where the economic efficiencies of water use are calculated. The water use efficiencies of the various crops are then compared, which gave an indication of the *opportunity cost* of the water use. For example, if forestry used the water at the expense of irrigated crops, what was the foregone profit? The finding was that subtropical fruit crops are more efficient in economic terms than forest plantations in using water in the Crocodile Catchment.

It is important to point out that the method with which Olbrich and Hassan use opportunity costs, differs from the use of opportunity costs in the LP model developed for this research. Olbrich and Hassan compare the water use efficiencies of two geographically separate pieces of land. The forestry is shown to have lower economic water use efficiency than irrigated crops. One would thus expect that water use entitlements should move from the forestry sector to the irrigation sector, either via the market through the trade of water use licenses, or directly via the discontinuation of afforestation licenses once the license period has elapsed. The LP model used for this research however calculates the opportunity cost for a given piece of land, and then compares this opportunity cost to opportunity cost of the downstream user. For example, if forestry is removed, the next best crop may offer significantly less returns than the forestry, thus resulting in a large opportunity cost to the farmer should he move from forestry to the alternative land-use. The downstream lands on which irrigation occurs may however have dryland substitutes that were not possible to forestry (due to forestry generally being planted in non-arable lands). Consequently the opportunity cost of the irrigated lands, i.e. the cost of moving from irrigated high value crops to lower value dryland crops, needs to be compared to the opportunity cost of the afforested lands upstream in order to better predict how water use entitlements will move from one sector to another, if at all.

The work of Olbrich and Hassan, 1999, does not include an LP or expert system. In other words the research objectives of this report, to test the impact of policy instruments in order to meet the policy objectives, cannot be met with the research methodology of the aforementioned researcher.

# 4.2 Integrating Economics and Hydrology into Decision Support Tools

The two decision support systems reviewed include the Watershed Management Decision Support System (WAMADSS) developed by Fulcher et al (1996) for the Environmental Protection Agency (EPA) in the United States of America, as well as the Catchment Resource Assessment Model (CRAM) developed by the CSIR locally in South Africa (CSIR, 1994).

### 4.2.1 The Watershed Management Decision Support System - WAMADSS

WAMADSS is a DSS consisting of two environmental models, including AGNPS (Agricultural Non-Point Source Pollution model), as well as SWAT (Soil and Water Assessment Tool), and economic model, CARE (Cost And Return Estimator), as well as a GIS (Geographical Information System). WAMADSS has two main objectives, including:

- A user friendly, interactive water management DSS that identifies the relative contribution of sub-watershed areas to agricultural nonpoint source pollution and evaluates the alternative LUMPs on farm income, soil erosion and surface water quality at the watershed scale, and
- Demonstrate the utility of WAMADSS in identifying and/or evaluating LUMPs for controlling soil erosion and surface ground water pollution.

Using WAMDSS, LUMPs (land-uses/ and or management practices) can be changed by the user, which will automatically write the changes to the hydrological simulation models. The models will run automatically, including the economic model, and the results are stored in a database, and displayed in the GIS (ARC/INFO). In other words the DSS has the ability to test the impact of changes in LUMPs on hydrological and economic indicators.

The shortcoming of the DSS with respect to the research objectives of this research is the inability to explicitly test the impact resulting from the introduction of different policy instruments. The starting point for the DSS is a given change in land-use, whereas the starting point in the LP model developed for this research project is a change in a policy instrument, which then via an optimization process may generate a new LUMP within the model.

Many of the ideas and terminology, such as LUMPs, used in this research project were adopted from the WAMADSS research.

#### 4.2.2 The Catchment Resource Assessment Model: CRAM

The Catchment Resource Assessment Model was developed by the division of Forest Science and Technology, Forestek, of the Council for Scientific and Industrial Research (CSIR), with funding from the Water Research Commission. The objective of the DSS is to enable the user to assess the impact of changing land-uses in a catchment. The results include hydrologic, economic, social and environmental information, which can be displayed graphically.

The model was developed to give water resource managers insights into three main questions, including:

- i. Which type of land-use should be promoted?
- ii. How much of a given land-use should be promoted, and
- iii. Where (i.e. the spatial location), should it be promoted?

These objectives relate to the objectives of this research, in that water resource managers are guided by the Catchment Management Strategy (CMS). The CMS is formulated in collaboration between water resource managers and stakeholders in accordance with the National Water Resource Strategy (Perkins, 2000). However, once a CMS has been defined, water resource manager have the use of policy instruments to ensure that water is managed in accordance with the CMS.

CRAM is used in the same way as WAMADSS. In other words "a decision-maker needs to experiment with a number of alternative scenarios" (CSIR, 1994).

#### 4.3 Conclusion

From the review of literature it becomes apparent that it is necessary to develop a model that can test the impact of changes in the policy instruments, such as the amount of water use licenses that get allocated, as well as different levels of water use charges. Conventional DSS are not suitable to test such changes, as the starting point of the DSS is the change in the land-use pattern. The challenge is to correctly mimic the land-use mix by a farmer in response to constraints imposed on the farmer (direct control via water use licenses or license conditions), changes in the economic return of LUMPs due to the implementation of water use charges and/or the ability to trade in water use licenses.

The research of Grové (1997) had a research objective very similar to the objectives of this research. Grové used a Chance Constrained Linear Programming approach to simulate optimal LUMP mixes and irrigation strategies in order to meet an IFR with a given probability level. It was however decided that this research would make use of an LP (linear programming) model to mimic the LUMP mix by the farmer in response to introducing policy instruments. For this research it was realised that the periods of low flow are probably of most importance to the water resource manager. In other words the policy instruments would probably target the water use in periods of low-flow, as this is the critical period. However, the hydrological impacts (i.e. streamflow reduction) of the LUMPs are not perfectly correlated. It was decided to select a few years, which would be used as years representative of "normal" and "dry" years respectively. The LP model was used to select the LUMP mix that optimises returns for a weighted ratio of "normal" years to "dry" years. This methodology was discussed, and accepted by the farmers participating in this research.

#### 5 THE GENERAL MODELLING APPROACH

In Section 2.6, the following broad requirements were identified as being necessary to meet the research objectives. The requirements include the identification or development of a tool (tools) or methodologies, which are needed to:

- A. Determine the hydrological impact of LUMPs,
- Assess how the respective policy instruments can target the hydrological impact of the LUMPs
- C. Develop a tool that mimics the decision making process of the farmer, i.e. a tool that considers both economic and hydrological information (via the use of policy instruments) into consideration, and
- D. Develop indicators to express the costs and benefits of the different policy options to the farmer, and to society.

In this chapter, two modelling approaches adopted by the researchers are introduced, including the original modelling approach, and the subsequently revised modelling approach. The original modelling methodology (shown in Table 3) made use of ACRU to simulate the hydrological impact of LUMPs, an expert system (in conjunction with use of a GIS) to mimic the farmer's LUMP mix selection, and the concept of net social benefit/cost (NSB), to represent the costs or benefits of intruding policy instruments on the farmer. The original modelling approach operated on a catchment scale, with the catchment being the Upper Mvoti (U40A and U40B). However, due to shortcomings, explained below, the original approach was discontinued, and the modelling approach was revised.

Table 3 The original research approach

Obj	ectives	Tool or method			
Α.	Quantify the hydrological impact of LUMPs	ACRU hydrological simulation model Scale = 67 HHEZ			
B.	Assess what hydrological impacts the policy instruments need to target	Mean annual streamflow reduction, and Mean streamflow reduction in periods of low flow			
C.	Develop a tool to mimic the LUMP decisions of the farmer	Expert system			
D.	Develop cost and benefit indicators	NSB = Bp + Be - Ce, where  NSB = net social benefit  Bp = the personal benefit (or loss) to the farmer,  Be = the benefit to society, and  Ce = the cost to society.			

The revised modelling approach (shown in Table 4) also makes use of ACRU to simulate the hydrological impact of LUMPs, however, instead of an expert system, use is made of a linear programming optimisation model (LP) to mimic the farmer's LUMP decisions. The indicators of the new modelling approach also differ slightly to those of the original modelling approach. Practical limitations required the scale to be revised from catchment scale to a farm scale, primarily relating to the confidence (accuracy) of mimicking LUMP decisions. Three farms were selected as farm case studies, and the costs and benefits of the various policy instruments were assessed for each farm separately. This is further discussed in Section 5.2.

Table 4 The revised research approach

Obj	ective	Tool or method		
Α.	Quantify the hydrological impact of LUMPs	ACRU hydrological simulation model Scale = 67 HHEZ		
В.	Assess what hydrological impacts the policy instruments need to target	Mean annual streamflow reduction, and Mean streamflow reduction in periods of low flow		
C.	Develop a tool to mimic the LUMP decisions of the farmer	Linear Program Optimisation model		
D.	Develop cost and benefit indicators	The change in the farmer's income, The change in farm jobs, and The change in the streamflow		

Reasons for discussing both the original and the revised modelling approaches in this research document include:

- i. Many of the concepts developed in the original modelling approach have been used in the revised modelling approach. The description of the original research methodology places the reader of this research in a better position to understand why certain aspects of the revised modelled approach have been undertaken in the way they have.
- ii. The hydrological impact of LUMPs was simulated using ACRU, delineating the Upper Mvoti Catchment into 67 Homogenous Hydrological Economic Zones (HHEZ). The delineation of the 67 zones was undertaken to improve the predictability (ability to mimic the farmers LUMP decisions) of the expert system. Once the original method was discontinued, the hydrological results from the original method were used in the revised approach.
  - There is academic merit in discussing the shortcomings of the original approach, as often knowing why not to do something is as valuable as knowing what in fact to do.

# 5.1 Modelling Farmer Decisions using an Expert System

The original modelling methodology was to make use of an expert system to mimic the LUMP decision making process of the farmer Figure 5 shows the outline of the original modelling approach, which is described below. Particular attention is drawn to the modelling approached used to simulate the hydrological impact of LUMPs.

The approach adopted in the original research methodology was to delineate the catchment into zones of different growth potential (represented by box 2), and to simulate or estimate the crop yield (box 4) as well as the hydrological impact of each LUMP (box 3) for each of these zones. In order to enhance (or attempt to enhance) the predictability of the expert system, the zones of growth potential were delineated into the smallest spatial units possible area possible (with the data available to the researchers). The Upper Mvoti Catchment was divided into 67 homogenous hydrological and economic zones, based rainfall, soils as well as temperature data. For each of the 18 LUMPs selected to be feasible LUMPs for the Upper Mvoti, the hydrological impact, as well as the crop yield was simulated (using the ACRU model), for each of the 67HHEZs. The land-uses with yields that could not be simulated with ACRU (i.e. not currently possible in ACRU) were estimated from discussion with farmers.

Once the crop yield for each LUMP, on each HHEZ, is determined (18 LUMPs \* 67 HHEZs), the gross margin (box 5) of each LUMP is determined for each HHEZ, which is then captured in all the GIS grids within that HHEZ. The gross margin in this context is defined as the difference between gross income and variable costs (COMBUD, 1997), i.e. the profit before fixed costs and taxes are considered. The gross income is determined by multiplying the crop yield by the crop price. As certain crops grow for longer than one calendar year, it was necessary to express the crop yields as the average annual yield of the crop. In order to do this the total yield that is expected as the harvest of the crop is divided by the number of years from planting to harvesting of the crop.

A GIS was used to capture the biophysical characteristics of the research area in the form of GIS grid cells. In other words, the surface of the research area was divided into grid cells (with a dimension of 200m \* 200m). For each grid cell the following data was captured:

- i. Rainfall (median monthly rainfall, as well as mean annual rainfall)
- ii. The slope of the land represented by each 200m \* 200m grid cell,
- The current land-use in each grid cell,
- iv. The slope of the land represented by each 200m \* 200m grid cell,

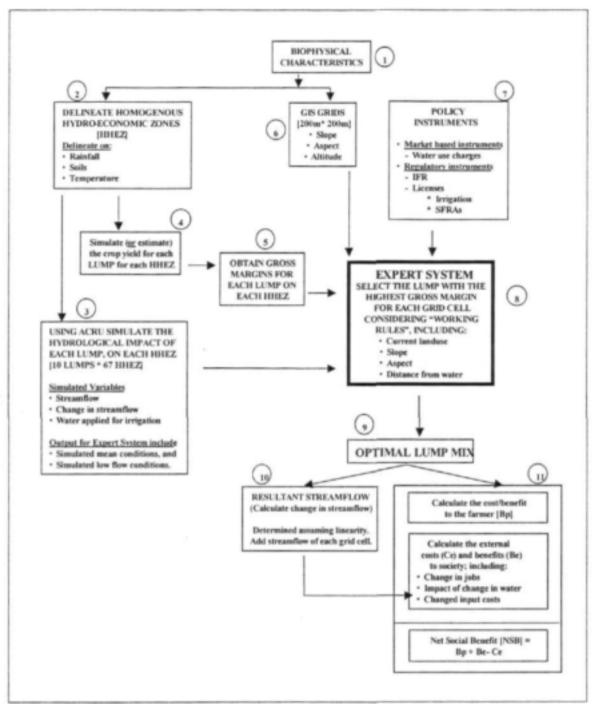


Figure 5 An illustration of the original research methodology considered

- v. The current land-use in each grid cell,
- vi. The altitude of each cell.

vii. The distance of each grid cell from the nearest water source (please note that the researchers never completed this coverage as the methodology was discontinued before it was completed).

The expert system (box 8), was to be used to mimic the selection of the optimal LUMP for each grid cell, giving consideration to the farmer's "working rules", which relate to the biophysical properties of each grid cell, as well as the costs of converting from the current land-use on each grid cell, to a given alternative land-use. For example, discussions with farmers may reveal that it is impractical to plant a land to dryland or irrigated maize if the slope of the land is in excess of say 10% (i.e. a 1m in 10m gradient). Grid cells with slopes in excess of 10% could then be flagged not to allow maize to be a feasible LUMP for that given cell.

Once the optimal LUMP mix had been selected using the expert system, the water that each grid contributes to streamflow could be calculated. In other words, the total streamflow for a given LUMP mix could be determined by summing the contributions of each grid cell (represented by box 10). The economic cost or benefit associated with the given LUMP mix could also be determined (box 11). The idea was to compare the costs and benefits of a given LUMP mix before and after introducing a policy instrument, from which the net costs and benefits, could be derived.

However, the researchers realised that the expert system could be used to assess the impact of water use charges (which would influence the gross margins of the farmers), however, it would be very difficult if not impossible to constrain land-use options (such as afforestation) unless the constraint was levelled at only one grid cell. This was the main reason the use of an LP optimisation model was selected to mimic the LUMP decision mix of the farmer, as it could accommodate both constraints, as well as changes water use charges.

# 5.1.1 LUMPs selected for this research

The LUMPs selected for this research were chosen giving due consideration to the current land-use patterns in the Upper Mvoti (i.e. what LUMPs were currently being practiced in the Upper Mvoti), as well as from discussions with farmers (i.e. what LUMPs could feasibly be practiced in the Upper Mvoti). Table 5 reflects the 18 LUMPs selected for this research.

Table 5 The 18 LUMPS considered in this research

LUMP No.	Land-use	Management Practice				
1	Acocks (Baseline)					
2	Dryland Maize	Planting date = Nov 10, 140 days to grow				
3-7	Irrigated Maize	Irrigation regime: fixed cycle, fixed amount.				
		Irrigation is dependent on rainfall				
		A number of simulations were performed, including:				
		Irrigate 25 mm in 7 days				
		Irrigate 20 mm in 7 days				
		Irrigate 15 mm in 7 days				
		Irrigate 25 mm in 14 days				
		Irrigate 20 mm in 14 days				
8	Dryland Sugarcane	Assume 2-year growth cycle.				
		Model average conditions				
9-13	Irrigated Sugarcane	Irrigation regime: fixed cycle, fixed amount.				
		Irrigation is dependent on rainfall				
		A number of simulations were performed, including:				
		Irrigate 25 mm in 7 days				
		Irrigate 20 mm in 7 days				
		Irrigate 15 mm in 7 days				
		Irrigate 25 mm in 14 days				
		Irrigate 20 mm in 14 days				
14	Irrigated Pasture	Irrigate the entire year				
		Irrigation dependent on rainfall				
15	Irrigated Potato	Planting date = Aug 1, 140 days to grow.				
		Irrigate 25 mm in 7 days.				
		Irrigation dependent on rainfall				
16	Pine	Pitted, 30-year rotation.				
		Model average conditions				
17	Gum	Pitted, 10-year rotation.				
		Model average conditions				
18	Wattle	Pitted, 10-year rotation.				
		Model average conditions				

Table 6 illustrates the months in which the respective irrigable crops are irrigated. The four months in which the streamflow is generally the lowest include May-August. In other words, most of the LUMPs are irrigated in the months in which streamflow is not it lowest. The shaded area represents the months in which irrigation occurs.

Table 6 The months in which irrigation occurs

Irrigated crops	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Sugar	736.3	38	See L	340			_	35%	M. Co	2013	100	10070
Potato								5				
Pasture	<b>司持持</b>	FIFE	BETT I		3000		NEWS T					
Maize												

Note:

The shaded area represents the months in which irrigation occurs for the various crops

# 5.1.2 Use of ACRU to simulate crop yields and LUMP hydrological properties

The ACRU model was used to simulate the hydrological impact of each of the 18 LUMPs. The model was configured to simulate the hydrological impact of 1 ha of land, on which each of the 18 LUMPs was undertaken respectively. A 45 year record of data needed to run ACRU was used, which included daily rainfall, daily maximum and minimum temperature, as well as daily A-pan potential evaporation. The ACRU model was run on a daily time scale, however outputs were aggregated to a monthly output.

These simulation results (i.e. a monthly record for each of the 45 years) were captured in a database, which could be queried to assess the hydrological impact of LUMPs during different periods (more comprehensively discussed in Section 7.2.1). The crop yields for dryland and irrigated maize and sugarcane (including the simulations for the various irrigation schedules were also captured in a database. This information was needed to assess the variability of crop yields in relatively wet vs. dry years respectively.

# 5.1.3 The indicator: Net Social Benefit

The concept of net social benefit (NSB) was originally proposed to be a net indicator of both the costs and benefits of policy instruments. The introduction of policy instruments may result in a change in the NSB. The change in NSB reflects the net increase in welfare of the people affected by changes to a farmer's decision-making environment. These changes are brought about by changes in policy, as well as changes in crop prices, labour and equipment availability etc. The focus however, was to explore the changes brought about by changes in policy.

In theory, NSB can be measured and expressed in a single monetary value, although in practice it is often not feasible to attach a monetary value to certain impacts. An ICM strategy will thus result in an increased efficiency of water use if the value of the positive welfare impacts outweighs the value of

The highlighted box outlining the months of May - August represents the 4 driest months of the year for the Mvoti region.

the negative impacts. NSB is taken to be equal to the private benefits that accrue to a landowner/farmer from a given LUMP, plus the external benefits of associated with the farmers LUMP mix activities, less the external costs associated with the farmers LUMP mix activities. The components of Equation 1 are listed and discussed in below in Table 7.

Table 7 Economic costs and benefits associated to LUMP decisions

Notation	Benefit Category	Description
Вр	Private benefits	These are the benefits (producer surplus) that accrue to the land or business owner. This equates to net financial income.
Ве	External benefits	External benefits refer to those benefits associated to a land-use of business activity that do not accrue to the owner. These include what we term direct effects, indirect effects and induced effects, explained below.  - Direct effects: benefits to external investor (e.g. a forest company), and benefits to employees  - Indirect effects: benefits to owners and employees of businesses supplying intermediate inputs  - Induced effects: benefits to owners and employees of businesses linked to induced effects
Ce	External costs	External costs are costs which accrue via the ecological/hydrological links within the overall catchment ecosystem to water users elsewhere They include:  - Indirect external costs -  Increased costs of water provision though water schemes due to a need to build a dam earlier, or due to increased water treatment cost and/or shorter dam life due to sediment loads  - Direct external costs -  These include costs associated to the increase in the distance to the nearest water supply, possible health implications, increased costs

The concept of NSB was discontinued for the following reasons:

- i. The external costs are both difficult to quantify and may only be present at a scale greater than farm scale. Due to the difficulty in placing a value on the external costs, it was decided that this was not a suitable indicator to select. The concept of external costs, associated with downstream users having to pay for augmentation schemes due to increased water use upstream could be further pursued in further research.
- ii. External benefits are also difficult to quantify.

It was decided to work with three prime indicators to reflect the cost and benefit of introducing policy instruments. These include:

- The impact of policies on the financial income of a farmer (similar to the concept of personal benefit),
- An estimate of the impact of a policy on farm jobs (similar to the concept of external benefit),
   and
- Indicators to reflect the magnitude and timing of water liberated/lost due to the introduction
  of policy instruments, i.e. an assessment of the water availability pre- and post the
  introduction of policy instruments.

#### 5.1.4 Some considerations regarding the initial and revised approach

It became apparent that there was a need to revise the initial research approach for reasons including:

- i. The Upper Mvoti, covering an area of over 70 000ha, is made up of a number of individual farms, and farm types, such as amongst others, farms concentrating solely on timber production, mixed farms and farms concentrating on irrigation. A model operating on a catchment level would need to mimic the aggregate decision making process of the farmers. It was decided that in order to be able to better verify the model with the farmers, it would be more appropriate to select a few farm case studies. By modelling individual farms that could be verified, the ability to mimic the land-use decision making process of a farmer could be improved firstly due the improved data that could be used to drive the model, and secondly because the farmer could verify the ability of the model to predict his/her land-use decisions.
- ii. Although certain farm related economic data are available from the Department of Agriculture in the form of COMBUDs (computerised farm budgets), the economic information is sometimes outdated for certain crops, or may have been obtained from economic farm surveys in geographical areas remote from the research area. Farm case studies would allow for more detailed, and appropriated data being used, than would be the case if the COMBUDs were used on their own.
- Furthermore, the COMBUDs do not include estimates of farm fixed costs, which are needed to quantify the economic costs of policy instruments on a farmer.

However, in spite of the potential advantages of developing the economic module at farm scale, it is more appropriate to run the hydrological simulation models at a scale far greater than farm scale, for the following reasons:

- iv. The ACRU model is a small catchments model (<50Km²), and was not designed to operate at a very fine spatial scale. Although the model has successfully been run at field scales before (Schulze, 1995), in order to simulate accurately at a fine scale great care needs to be given to the input data that drives the model. This reflects one of the hydrological modelling paradoxes, in that it actually becomes more difficult to accurately simulate hydrological process at very fine spatial scales (Schulze, 1995).</p>
- v. There are only 3 rainfall stations with a suitable record length in the Upper Mvoti that are suitable to be used for the hydrological simulations. As rainfall is the dominant hydrological driving force (Schulze, 1995), there seems to be little merit in simulating the hydrological impact of LUMPs at a farm scale, as the variation in rainfall over such a relatively small area (such as a small farm) may be negligible.
- vi. Furthermore, policy instruments probably not be introduced at a scale less than Quaternary Catchment scale, even if there are differences in the hydrological responses of LUMPs within the catchment, due to the complexities involved in quantifying these variation.
- vii. One of the objectives of this research is to develop a methodology that can relatively easily be applied to other areas. It seems most appropriate to develop the Hydrological Economic Agricultural Model to draw on commonly available data, and where necessary to augment this data. However, rainfall-sampling points are a limiting factor in the ability to model at fine scales, and although techniques are being developed to interpolate the rainfall surface between observation points (Dent et al., 1989), this can in many cases not be done with a very high level of confidence, especially in mountainous terrain.

Consequently it was decided to select three farm case studies from which detailed economic records could be obtained, while undertaking the hydrological simulation runs at a coarser scale. It was decided to use the hydrological simulation results generated for one of the 67 HHEZs to be representative of all 3 farm case studies, as the soil and rainfall conditions of the HHEZ were believed to be representative of all three farm case studies.

The use of an expert system to mimic farmer LUMP decisions for each grid cell was also reconsidered. It was realised that it would be difficult to impose constraints on the farmer by using the grid cell and expert system approach. It was decided to make use of a linear programming optimisation model to mimic the decision making process of the farmer.

The "indicators" to assess the costs and benefits were also reconsidered and adjusted. Section 5.1.3 discusses the originally proposed indicators, and the reasons for making adjustment where necessary.

## 5.2 Modelling Farmer Decisions Using a LP Model

This section reviews the revised research methodology.

## 5.2.1 The revised modelling approach

Figure 6 below illustrates the revised modelling approach. The figure is made up of 9 separate boxes, each representative an important component contributing to the development of the HEAM. The first box represents the consideration that needs to be given to biophysical characteristics of the farm. The farm is divided into homogenous parcels of land reflecting different economic potential (box 2). These parcels of land are referred to as land categories (LCs). The delineated LCs are captured in the LP model (box 8), as well as the crops possible on each LC respectively. The crop yields of the LUMPs on each LC are also estimated/simulated using, and captured in the LP model.

LC may reflect not only the types of crops possible on the different lands, but also the expected costs of producing the LUMPs on the various LUMPs. This link is represented by the link to box 4 in the diagram. Policy instruments (box 5) may be used water resource managers to either directly constrain certain land-uses possible to a farmer, or to influence the economic viability of LUMPs using pricing strategies.

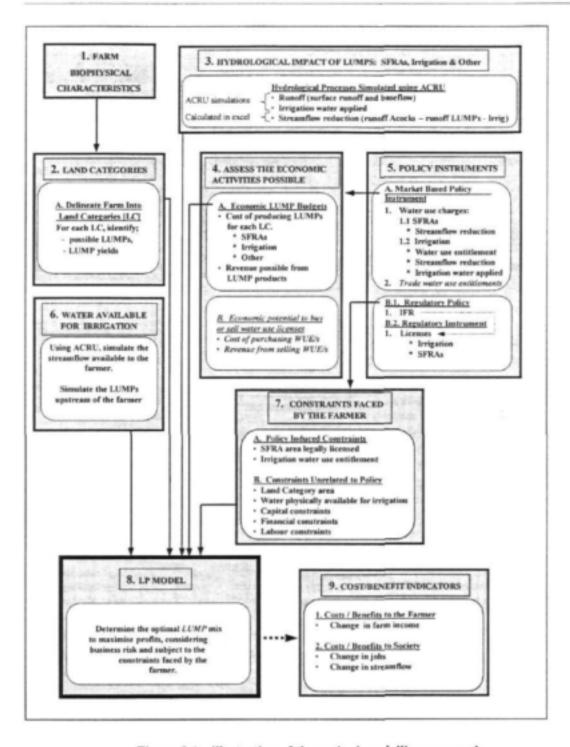


Figure 6 An illustration of the revised modelling approach

In order to ensure that licensed water use is allocated sustainably, it is necessary to quantify the hydrological impact of the LUMPs, so that allocated water use never exceeds the amount of water that may be exceeded, yet at the same time ensuring that overly conservative estimates of water use are not adopted. As the water use of LUMPs is highly variable (temporally and spatially), it is useful to simulate the hydrological impact of the LUMPs (box 3). The information believed to be most important in the LUMP decision making process of the farmer, is fed into the LP model (box 8), from where the expected optimal LUMP mix is simulated using an LP optimization model.

In order to assess the costs and benefits of various policy options, indicators, illustrating the costs and benefits of the implementation of a given policy instrument, need to be developed. The indicators used in the revised research approach are shown in box 9. Each component of the HEAM, i.e. box 1 – 9 of Figure 6 will be discussed in more detail in the Sections 5.2.1.1 to 5.2.1.9 below.

#### 5.2.1.1 Farm biophysical characteristics

The farm is divided into land categories giving consideration to the biophysical characteristics and the related economic potential of the farm's lands. The biophysical characteristics of LUMPs include, amongst others, the farm rainfall, soil characteristics of the lands, slope, and distance from a water source, altitude, aspect, accessibility and the presence of and/or susceptibility of the land to pests.

#### 5.2.1.2 Land categories

Land categories represent lands on which a given set of LUMPs with a given hydrological impact and economic return is possible. If two separate parcels of land can be farmed with the same set of LUMPs (e.g. both can be farmed with say LUMP A, B and C), but the economic and/or hydrological impact differs between the two parcels of land (e.g. the economic return of crop A, B, or C on the one piece of land is not equal to the return from crop A, B or C on the second piece of land), then the lands will be regarded as two separate land categories. With respect to the hydrological impact of LUMPs, the following important points need to be made:

- i. For the three farm case studies, the hydrological impact of LUMPs on all land categories is assumed to be the same as the hydrological results are obtained from the hydrological simulations from the same HHEZ. Although this may in reality not be the case, for the reasons mentioned in Section 5.1.2, this methodology may still be appropriate.
- ii. The impact of alien invasives in riparian zones was not catered for in the revised modelling approach as none of the 3 farms had infested riparian zones. Due to the increased hydrological impact of alien invasives in riparian zones, it may be necessary to develop the HEAM to cater for this if the HEAM is used in other areas in which riparian zones are in fact infested.

The use of land categories is a way of hard coding into the LP model what LUMPs are possible for different parcels of farm lands. Discussions with the farmers revealed that they could delineate with a high level of confidence where certain LUMPs could or could not feasibly be undertaken. A LUMP is considered not to be feasible if the crop yield is so low, that it would realistically never be lucrative to undertake that LUMP on that given piece of land. The farmers were however were more unsure as to the exact crop yields that could be expected from LUMPs on different land categories, as well as the impact of management practices on crop yields. Yields were estimated (based on farmers' experiences, giving consideration to the ACRU generated crop yields) for both LCs, as well as various management practices on a given LC.

The LC's in many ways reflect the "farmer working rules" (which generally reflect the constraints placed on the farmer's ability to farm a given piece of land), and the yields expected for the different LUMPs on the lands. The "working rules" are heuristic rules (i.e. rules of thumb) applied by the farmer, which can potentially be captured in computer code, which together with a GIS package such as Arc-View, could be used to automatically generate LCs. The automation of LC delineation is one of the recommendations for the model to be further developed, as this will potentially allow the model to be quickly set up in new research or model application areas, as coverages of GIS data that relate to the farmer working rules are generally available.

These currently applied "working rules" can to a large extent be observed by the current land-use pattern in the Upper Mvoti (further discussed in Section 6.2). The dominant factors influencing the land-use decisions of the persons farming the three farm case studies include, amongst others, the slope of the land (which influences the ability to work the land with equipment), the altitude (snow belt, frost line), the aspect (e.g. north vs. south facing slopes which receive different amounts of solar radiation) as well as the distance of a land from a water source (important for irrigation).

Two different methods were used to delineate land categories in this research project. For one of the farm case studies, both a detailed delineation approach (involving in depth consultation with the farmer) as well as a coarser delineation approach (which could potentially be easily replicated on other farms). Both methods were undertaken in order to evaluate the potential errors that could be made using the coarser, potentially easily replicable method. The results of this comparison are further discussed in Section 6. The results indicated that the coarser method was appropriate to use in the Upper Mvoti, and consequently the remaining two farm case studies were delineated into LC's using the coarser method (verified by the farmers).

### 5.2.1.3 Hydrological impact of LUMPs

As shown in Figure 6 (box 3), two LUMP hydrological impacts simulated include:

- The runoff generated from 1 hectare of land, for each of the 18 LUMPs (including dryland and irrigated LUMPs), and
- The amount of water abstracted from the river to irrigate 1 hectare of land, for the 12 irrigated LUMPs.

The "runoff" in this context refers to the amount of water reaching the river having flowed either over or through the land (soil profile of the land). In other words "runoff" in this context refers to both the overland runoff, as well as the water reaching the stream via baseflow and interflow. The runoff for each of the 18 LUMPs was aggregated to a monthly scale (as ACRU is run on a daily time scale).

The amount of irrigation water applied to the land refers to amount of water physically abstracted from the river for a given irrigation schedule. It does not necessarily reflect the amount of irrigation water actually reaching the farm land, as there may be losses between the abstraction point and the point of application. These losses include conveyance losses, irrigation water that is lost during the process of conveying it from the source to the application point (Schulze, 1995), and spray evaporation and wind drift losses, i.e. the water lost by spray evaporation and wind drift after leaving the nozzles of an irrigation system (Schulze, 1995). Conveyance losses and wind evaporation losses of .25 and .15 were used in the ACRU model, which are recommended for the type of irrigation practices commonly used in the Mvoti region (Schulze, 1995).

It is important to consider the amount of water actually drawn from the river, as the focus of the hydrological indicators is to assess the streamflow reduction associated with the LUMPs, as it is the streamflow reduction that may impose a negative externality on downstream users, as there is less water available for downstream users.

The streamflow reduction (shown in box 3) for one hectare of land applied to of each of the 18 LUMPs respectively, was calculated in a spreadsheet from the monthly runoff and irrigation abstraction output generated from the ACRU simulations. Streamflow reduction is calculated using the following equations:

Streamflow Reduction Devland LUMPS = Runoff Acoeks - Runoff Devland LUMP, and

Streamflow Reduction Irrigated LUMPs = Runoff Acocks - Runoff Irrigated LUMP - Water abstracted for irrigation

The streamflow reduction was calculated on a monthly scale for each of 45 years for which hydrometeorological data needed to drive the model were available (1950-1995). The monthly, 45 year record of streamflow reduction for each of the 18 LUMPs allows an assessment of the streamflow reduction of the LUMPs in periods of:

- i. High vs. low water availability within a year (i.e. intra-annual streamflow reduction), and
- ii. High vs. low water availability between years (i.e. inter-annual streamflow reduction).

In other words, the pattern of streamflow reduction can be observed for intra- and inter-annual conditions. The 45 year, monthly streamflow reduction records makes it possible to assess the streamflow reduction of LUMPs for given month and year combinations. For example the average streamflow reduction during the 4 driest months in the 10 driest years of the 45 year record can easily be calculated by ranking the years according to annual Acocks runoff, and then finding the mean streamflow reduction of the LUMP for the 10 driest years (with the lowest runoff), and 4 driest months.

In Figure 6 a number of linkages can be observed between the hydrological impact of LUMPs (box 3), and policy instruments (box 5), which will be further explained in the discussion of the policy instruments (Section 5.2.1.5)

#### 5.2.1.4 Assess the Economic Activities Possible to the Farmer

Activities, in this context, refer to all the possible activities the farmer can undertake in order to maximise his profits (considering risk). In box 4, two categories of activities are identified, including:

- The LUMP selection, and
- The trade of water use entitlements.

In other words, the farmer, in order to maximise profits, needs to weigh up the financial costs and benefits of undertaking certain land-use configurations, as well as the potential of trading water use entitlements, which may in turn influence the constraints faced by certain LUMPs. For example, if a farmer buys extra irrigation water use entitlements, the farmer may enjoy the option of either irrigating a larger area of a given crop and/or irrigating the same are with a larger quantity of water.

The LUMP budgets (box 4A) reflect the expected costs and revenue (yield \* price) associated with the different LUMPs. The budgets of the various LUMPs are used to assist in the delineation of LCs (as discussed in Section 5.2.1.2 above). The costs of producing SFRAs and Irrigated LUMPs will increase if water use charges (related to the water use of the LUMPs) are introduced. In other words, even if the farmer does not change his land-use, a water use charge will reduce the farmer's income as discussed in Section 2.5.

With respect to assessing the economic potential to buy or sell water use licenses (box 4B), the HEAM model has currently not been developed to explicitly deal with the potential to trade water use entitlements. As a result the option of buying or selling water use licenses is represented by italic print in box 4B. If the farmer were to buy or sell water use licenses, the amount of water use entitlements accruing to farmer will need to be updated, reflected in box 7A. The HEAM can further be developed by explicitly including the feasibility of buying or selling water use entitlements, however this is an area for future research.

#### 5.2.1.5 Policy instruments

The two main categories of policy instruments are reflected in Box 5, and include:

- i. Market based policy instruments (5A) and
- ii. Regulatory policy instruments (5B2).

As market based policies can only be applied once water use is either registered or licensed, regulatory policies (shown in box 5B) will be discussed before market based policies (box 5A). As shown in box 5B, a distinction has been made reflecting:

- A regulatory policy (5B1), which primarily relates to the setting and maintenance of the Reserve, and
- The regulatory policy instruments designed to ensure that the policy relating to the Reserve is met, by means of water use licenses (5B2)

The link between IFRs (a regulatory policy of the NWA) and water use licenses (the regulatory policy instrument) is represented by a dashed line linking 5B1.1 to 5B2.1 to indicate the fact that the IFR policy is achieved via the use of water use licenses. Of the 18 LUMPs being assessed in this research, currently only SFRAs (presently only commercial forestry), as well as the irrigated LUMPs require water use licenses, as they have been identified as being significant water users. The water use licenses serve as a means to ensure that actual water use in a catchment is regulated to an acceptable level, i.e. by requiring the LUMPs that reduce streamflow significantly be licensed, in order to ensure that the policy of the Reserve is met. Water resource managers must ensure that the amount of water authorised for use (in the form of water use licenses) must be less than the allocatable water resource.

The terms and conditions of the water use licenses differ between SFRAs and irrigated LUMPs, as the water is used differently by the two categories of water users. SFRAs are dryland crops, and once the crop is planted, relatively very little control can be exercised over the crop to influence streamflow reduction (DWAF, 2000a and DWAF, 1999b). The streamflow reduction of irrigated LUMPs on the other hand is dependent on the amount of water actually abstracted from the river, which can be

likened to a tap that may be switched off or on (DWAF, 2000a). In other words, when issuing water use licenses for SFRAs and irrigated LUMPs, water resource managers need to know how and when each category of water use is likely to reduce streamflow in order to issue the correct amount of licenses.

Water resource managers currently use the modified flow reduction curves developed by Scott and Smith (1997) to quantify the water use by forestry species for different regions in South Africa (DWAF, 1999c), and the SAPWAT model for irrigated LUMPs (DWAF, 1999b). The modified Scott-Smith forestry flow reduction curves are used to estimate the average reductions in annual and low flows, for different species of tree, different climates and different forest management regimes. The estimates include both drought years and wet years. However, the Scott-Smith curves do not address the estimates of crops other than plantation forestry, or the impact of SFRAs on the assurance of water supply (DWAF, 2000c). Use of the ACRU model allows the first obstacle to be overcome (i.e. the flow reduction of all 18 LUMPs can be quantified). With respect to the impact of the assurance of the LUMPs on water supply, as there is no dam in the Mvoti system, ACRU can be used to assess the impact of the LUMPs on the impact of the LUMPs on the assurance of the water supplies. The concept of "reduction of the assurance of supply" versus "streamflow reduction" is more comprehensively described in Section 7.1.

#### Box 5A represents:

- iii. Market based policy instruments, consisting of water use charges (box 5A1), and
- A policy that allows for water use entitlements to be traded on the open market (which may require regulation by water resource managers) (box 5A2).

The market based policy instruments can only be applied to registered or licensed water use (DWAF, 1999b). Market based policy instruments, generally in the form of water use charges, will influence the economic feasibility of the various LUMPs. In box 5A, a distinction has been made between water use charges levied on SFRAs (5A1.1), and water use charges levied on irrigated LUMPs (5A1.2) for the following reasons:

v. Water use charges levied on SFRAs will probably be based on the estimated streamflow reduction of the SFRAs (for a given period, e.g. mean annual streamflow reduction, the streamflow reduction in dry seasons, or the average streamflow reduction during dry years). In this research, the water use charges were assessed on a few "representative streamflow reduction periods", including normal and dry years, as well as wet and dry seasons of these years. This methodology is further described in Section 7.

- vi. Water use charges levied on irrigated LUMPs on the other hand can be based on a number of potential "bases", which amongst others may include:
  - a. The full water use entitlement of the farmer. The advantage of selecting this as the irrigation water use charge "base" is that the water resource manager can easily determine the water use charge from the registered water use database. However, the implication of this is that unless farmers can sell their surplus water use licenses (which will reduce their water use charge), there is no incentive for the farmer to use water efficiently. In other words, this promises to be an easily implemented, yet not necessarily efficient option.
  - b. The actual streamflow reduction of the irrigated LUMP. This can be "estimated" by assuming how a farmer will abstract water, using the ACRU simulation model, which gives consideration to the crop irrigation water demand in response to hydrometeorological conditions (such as amongst others, rainfall, temperature and a-pan evaporation) water abstraction. Or, if the farmer submits detailed records of how and when he is both abstracting and irrigating the water, this information can be input into ACRU (which will make the need for assuming the farmer's behaviour redundant). In this way, the streamflow reduction of a given year may be simulated using the ACRU model.
  - c. The third option is to levy the water use charge on the actual irrigation water applied (which can potentially be monitored as is being done for certain farmers in the Mhlathuze Catchment. However, the feasibility of monitoring actual water abstraction nationally will need to be reviewed.

There seem to be advantages and disadvantages with each method, which is an area that should be further investigated. As the streamflow reduction of irrigated LUMPs has been determined using ACRU, option (b) will be used in this research.

Box 5B2 represents a NWA policy which makes provision the trade of water use licenses, both within and between sectors. As was the case in the discussion of IFR, the trade of water use licenses is a legal option provided for in the NWA, and not a policy instrument. The regulation of water use licenses is a policy instrument. There may be a need to regulate the trade of water use licenses as there may be large social implications (such as the loss of jobs) associated to the trade of water use entitlements. The trend observed both in the Mvoti and the Mhlathuze Catchment (the Richards Bay Catchment), is that industrial and residential demand for water is growing steadily, and the ability of these sectors to pay for water is greater than that of the agricultural sector (Dallimore et al, 2000).

The implication of this is that unless the trade of water use licenses is regulated, one can expect a shift in water use licenses from the agricultural sector to the industrial and domestic sector.

### 5.2.1.6 Water available for irrigation

Box 6 reflects the hydrological simulation modelling procedure adopted to simulate the water available to the farmer, i.e. the water flowing either directly into the farm, or close to the farm that the farm can draw from. The importance of the water available during any given month is the impact of water availability on irrigable LUMPs.

As shown in Box 7, there are two main constraints to a farmer's ability to irrigate, including:

- The physical amount of water available to the farmer, which varies annually and seasonally (i.e. inter- and intra-annually) and depends on the LUMP activities upstream of the farmer, and
- ii. The water use entitlement/s (license/s) held by the farmer.

It is possible that the water use entitlement is greater than the physical amount of water, especially during dry years. There are normally "working rules" associated with irrigation water use entitlements, restrict the irrigation water use entitlements during periods of water shortage. The imposition of a curtailment on irrigation water use entitlement (and level of curtailment) may be dependent on, amongst other things, the amount of water flowing in the stream, or on the dam level where water is released from a dam.

#### 5.2.1.7 Constraints faced by the farmer

Box 7 shows the types of constraints that a farmer faces when choosing between the alternative LUMPs. A differentiation is made between:

- i. Policy induced constraints, and
- Constraints unrelated to policy.

The policy induced constraints limit the area that may be planted to a given SFRA, and the volume of water licensed to one hectare of a given irrigated LUMP.

Constraints unrelated to policy instruments include, amongst others:

The physical area that a farmer can farm,

- ii. The physical water available to a farmer for irrigation (discussed above),
- iii. Capital constraints (i.e. equipment that may be needed),
- iv. Financial constraints, and
- v. Labour constraints

The constraints are fed into the LP model.

### 5.2.1.8 The LP Model

Box 8 reflects the LP model. The objective function of the model (i.e. the aim of the model) is select the LUMP mix that maximises profits, giving consideration to risk, and subject to the constraints faced by the farmer. The LP model is more comprehensively discussed in Section 9.

#### 5.2.1.9 Cost/Benefit indicators

In order to ascertain what the costs or benefits of imposing different policy instruments are, both for the farmer, as well as society, indicators need to be developed to reflect aspects that relate to costs or benefits, which may not always be possible to express in financial terms. Box 9 reflects the types of cost/benefit indicators developed for this research, and include:

- The change in farm income (i.e. the cost to the farmer resulting from the implementation of a given policy)
- The change in jobs which may result from changes in the LUMP mix (i.e. potentially one of the costs to society)
- The change in streamflow which may result from the change in LUMP mix (i.e. potentially one of the benefits to society is an increased supply of water)

### 6 THREE FARM CASE STUDIES IN THE UPPER MYOTI

The following sections describe the three farm case studies.

## 6.1 Characteristics of the Farms in the Upper Myoti

It was decided to undertake a review of the types of farming operations present in the Upper Mvoti, before selecting the farm case studies to be used for this research. Discussions were held with a selection of farmers and the regional agricultural extension officer to identify the main categories of farming operations in the Upper Mvoti, which are shown in Table 8, and include three main categories, including:

- i. Farms solely concentrating on timber production,
- ii. Mixed farms, representing farms with some forestry as well as other crops, and
- iii. Farms with no forestry.

The first two categories (i. & ii.) can be further subdivided. With respect to farms fully concentrating on forestry (i.), a distinction was made between

- a. Large timber companies (such as Mondi, Sappi & Masonite), and
- b. Smaller independent growers.

This distinction is important as the cost structures of large companies (such as Mondi and Sappi) and independent growers differ. Large companies carry large overhead costs, such as the costs related to regional and head offices. However, the large companies also benefit from economies of scale, especially with respect to the transportation costs of the timber, which form a substantial proportion of the total forest related costs. The implication of the potentially dissimilar cost structures is the impact of policy instruments on farm income.

With respect to "mixed farming operations" (ii.), a similar distinction can be made between:

- a. Relatively small, family owned farms, and
- b. Larger companies.

The value of classifying farming operations into categories, is that it improves the ability to mimic the decision-making process of the farmer's, as the cost and revenues can be more accurately captured within the LP model. In discussing the costs and revenues of small individual growers versus large

companies, it is important to point out that larger companies may add value to the crops produced on the lands (farm). In other words, the production process need not end at the farm gate. For example, timber companies may amongst other things process the fibers produced by the timber plantations and process logs into timber for furniture and construction, while sugar companies process the cane into sugar and other products.

In other words, the benefits of a given land-use may extend well beyond the "farm gate" of the farmer. This research does not develop the HEAM to consider the forward linkages, and as a result the costs and benefits of policy instruments are what can be termed as "farm gate" costs and benefits, i.e. the costs and benefits generated at the site of agricultural or timber production. The authors of this research acknowledge the importance of the forward linkages to the economy. This is a topic for further research, which can potentially be built into the HEAM.

Table 8 A classification of the main types of farming operations in the Upper Mvoti

Type of farm	Size range (ha)	No of farming operation	
Farms concentrating solely on timber production			
1.1 Big corporate players (Sappi, Mondi, Masonite)	>10,000	3	
1.2 Relatively large, independent timber growers	1000-6000	5	
<ol><li>Mixed farming operations, i.e. includes some timber</li></ol>			
2.1 Relatively small family-owned farms	300-600	30	
2.2 Large companies (e.g. PI-Delta, Argyle Farms)	3000-7000	2	
3. Farms with no forestry	150-300	100	

Source: Personal interviews with a small selection of farmers, and the regional agricultural extension officer.

#### 6.2 The Three Selected Farm Case Studies

In selecting the representative farm case studies the ideal was for a number of different farm categories located on a communal stream with the farmers willing to collaborate in the research. The purpose of selecting farms located on a communal stream was that the trade of water use licenses could be assessed. However, after discussions with farmers in the region, it became evident that finding this combination was virtually impossible. This was mainly due to the fact that the different farm categories were spatially spread out through Upper Mvoti Catchment, and not conveniently located on a communal stretch of river.

Due to time constraints, it was decided to select three farm case studies. The three farms selected include a farm representative of:

- i. A relatively large independent timber grower,
- ii. A small family owned mixed farm, and
- iii. A larger company owned mixed farm.

The location of the farms selected is shown in Figure 7. The location of Greytown, and the Mvoti Vlei are also highlighted.

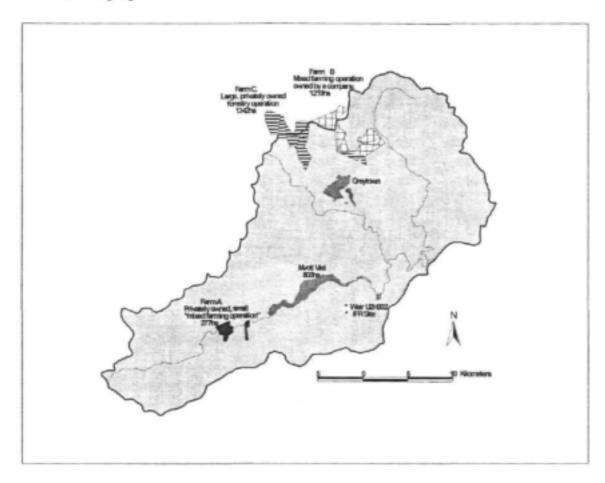


Figure 7 The location of the three farm cases in the Upper Mvoti

Table 9 below shows the farm area of each of the three farms, as well as a break down of current landuse into broad land-use categories. The difference in farm sizes needs to be mentioned, with the privately owned farm with mixed crops including forestry, being almost less than a quarter the size of the other two farms. The reason for this is that the growth cycle of timber species varies from 10 years (wattle and gum species) to 30 years (pine grown for timber). The implication is that a relatively large farm is needed to ensure that each year an economically feasible area of timber can be harvested. Forestry is thus seen as more of an extensive land-use compared to the intensive farming operation of Farm A.

Table 9 The farm area and current land use of the three selected farm case studies

Farm Case Study	Total Farm Area	Forestry	Irrigation	Dryland crops including grassland	Other
Farm A	277 ha	109 ha (39%)	23 ha (8%)	128 ha (46%)	17 ha (6%)
Farm B	1219 ha	885 ha (73%)	218 ha (18%)	75 ha (6%)	41 ha (3%)
Farm C	1342 ha	999 ha (75%)	0	0	343 ha (25%)

Note: "Other" includes riparian areas, conservation areas, servitudes, firebreaks, and household and workshop areas and farm roads.

- Relevant points regarding the three farm case studies include:
- i. As shown in Figure 7, Farm B is some distance from the nearest perennial river, while Farm A and Farm B is either bordered by a river, or has a river flowing through the farm. This is important with respect to the water available to the farmer that can be used for irrigation purposes. Farm C is the only farm of the three farm case studies not having any irrigated crops, due to the lack of available water on the farm.
- ii. Farm A lies entirely within the borders of the Upper Mvoti Catchment, while both Farms B and C fall partially outside the Upper Mvoti Catchment, as can be seen in Figure 7. For the purposes of this research, both Farms A and B are assumed to fall entirely within the Upper Mvoti Catchment.
- iii. Farms B and C are located on the steeper slopes of the Upper Mvoti, close to the catchment boundary. The implication is that there is a relatively small catchment area contributing to the water supply to these farms. In order to address this situation, Farmer C has built two large off-channel storage dams on his farm, as well as two dams on the stream channel, in order to increase the assurance of water supply for irrigation, especially for the dry months of relatively dry years.
- iv. Farm B is one of a number of farms owned by a company. This explains why the farm area (1219ha) is less than the area shown to be representative of large companies with mixed farming operations in Table 9, with an expected area of 3000 – 7000 ha. However, farm B is run as a separate entity, which has made it possible to include the farm in the research.

v. The large percentage of unutilised farm area on Farm C (i.e. 25%) reflects the legal constraint on forestry whereby a maximum of 75% of the farm area may be afforested. Farmer C has indicated that of the 25%, there is land suitable for forestry, which is non-arable, and is currently not being farmed.

Each of the three farm case studies (Farm A, B and C) is discussed.

### 6.2.1 Farm A: A privately owned, small mixed farming operation

A discussion of each Farm case study will follow the same format, including a discussion of:

- i. The general biophysical conditions of the farm,
- ii. The current land-use being practiced,
- A discussion of the land categories, which with respect to Farm A will make a distinction between,
  - a. The LCs delineated on Farm A using the comprehensive delineation method, and
  - b. The LCs delineated for Farm A using the coarse delineation method,
- iv. LUMPs feasible on each LC and
- The LUMP yields (MAIs) applicable to the LCs and

#### 6.2.1.1 The general biophysical conditions of Farm A

Farm A is a relatively small mixed farming operation located in a valley bottom. The Mvoti River flows through the farm. The location of the farm, and Mvoti River is shown in Figure 7. Farm A has a large upstream catchment area of approximately 14200ha, which although being almost entirely afforested, still generates an adequate streamflow for Farmer A to irrigate his lands, both in the wet months, as well as the dry months of both relatively wet and dry years. As there are no dams or irrigation abstraction points upstream of Farm A, Farmer A is the first farmer to irrigate from the river. The farm lands range from rather steep sloped lands (on the south facing lands), to relatively shallow sloping lands located close to the river, becoming gradually more sloping the further one moves away from the river on the north facing slopes. Due to being located in the valley bottom, the lands receive a heavy frost in winter. There has on a few occasions been snow on the upper reaches on the south facing slopes.

#### 6.2.1.2 The current land-use on Farm A

A breakdown of Farm A's current land-use is shown below in Table 10 and graphically displayed in Figure 8 which shows a coverage of both:

- i. The current land-use on Farm A, and
- The slope of the farmlands (represented by 200m by 200m grids cells).

Table 10 Farm A: A break \down of the current land use on Farm A

Land-use	Area (ha)	Percent
Pine	70	25%
Natural Grassland (beef)	63	23%
Dryland White Maize	65	23%
Wattle	30	11%
Other (household, sheds, etc.)	17	6%
Irrigated White Maize	13	5%
Irrigated potatoes	10	4%
Gum	9	3%
	277	100%

The following important points can be made regarding the current land-use of Farm A:

- i. The land-use was mapped using aerial videography by MBB consulting engineers (MBB, 1997). The videography did not accurately identify irrigated lands, which is difficult to detect using remote sensing techniques. Corrections were made to the MBB land-use map subsequent to ground-truthing the research area.
- The aerial videographic survey did not differentiate between forestry species. An accurate breakdown of the forestry species on the farm was obtained from discussion with the farmer, and is reflected in Table 10.
- Farmer A is currently constrained by an Afforestation Permit (APS) of 109 ha. The farmer is currently submitting DWAF forestry and irrigation registration forms, as well as applications for both forestry (SFRA) and irrigation water use licenses.
- iv. The farmer has categorically stated that he would like to plant more forestry on his farm, due to many of his lands being unsuitable for other LUMPs.
- v. A relatively small area of the farm is irrigated for reasons, including:

- Many of the farm lands are waterlogged and are consequently not suitable for irrigation. The farmer suggests that it is not economically feasible to have the lands drained,
- b. There are higher lying lands which are suitable to be irrigated, but are however quite far from the river. Due to a large financial loss in 1997 (as a result of floods), the farmer currently does not have the access to finance to invest in irrigation equipment to irrigate the higher lying irrigable lands, and
- c. The farmer is also very uncertain as to the outcome/implication of the NWA. There seems to be a general consensus among the farmers not to invest in further irrigation until the full implications of the NWA are better understood.
- vi. Figure 8 illustrates how the aspect (slope direction) can influence the feasibility of LUMPs, in that sugarcane is only possible on the north facing slopes. The north facing slopes receive more solar radiation than slopes with other aspects.

The technique of using GIS coverages, mainly drawing from the grid coverage of slope, to delineate farm lands into LCs is discussed in Section 6.2.1.3 below.

#### 6.2.1.3 Delineating Farm A into land categories using the "comprehensive" delineation method

The comprehensive delineation method involves detailed discussions with the farmer. Each farm land is carefully discussed with the farmer, and delineated into LCs. The LCs are delineated giving consideration to:

- i. The combination of LUMPs possible on a given piece of land,
- ii. The yields of the LUMPs possible on the given piece of land, and
- iii. The hydrological impact of the LUMPs on a given piece of land.

In other words, if two geographically separate pieces of land have the same LUMP, yield and hydrological impact combinations, they are regarded as being one LC. It is important to point out that the hydrological impact of the LUMPs is assumed to be homogenous over the area of a farm, and thus is not used in the delineation of LCs.

Of the three, the possible combination of LUMPs on a given piece of land is the most important when delineating LCs. For example, Farm A is characterized by waterlogged lands, on which certain crops cannot be grown, thus requiring an LC to be delineated to reflect this constraint.

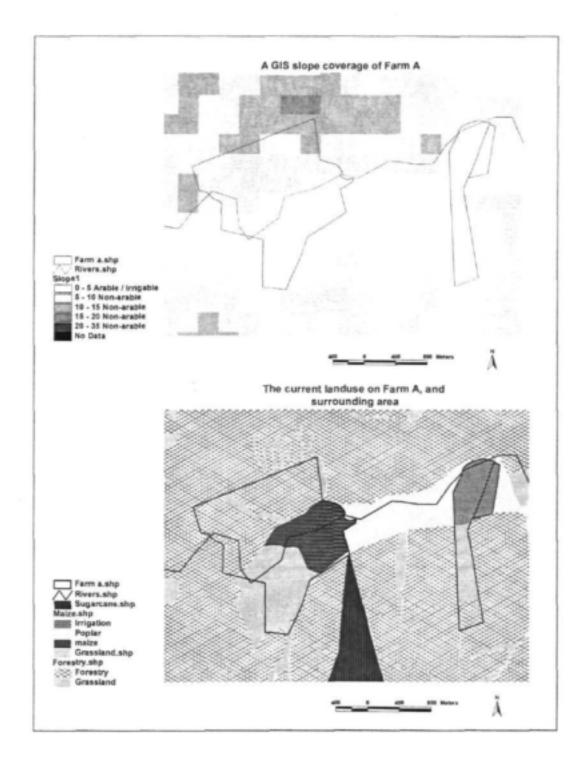


Figure 8 Farm A's current land use, as well as the slope (gradient) of the farm lands

### 6.2.1.4 Current and potential LUMPs on each of the 10 delineated LCs

Table 11A illustrates the current land-use on each of the 10 delineated land categories (the top section of the table), while Figure 9B shows the potential LUMPs for each land category, remembering that there may be a number of management practices associated with each land-use. With respect to the irrigated maize and sugarcane, the crop yield and hydrological impact of several irrigation schedules were simulated using ACRU, including:

- a. 25mm every 7 days (Irrigation schedule currently adopted in the Upper Mvoti),
- b. 20mm every 7 days,
- c. 15mm every 7 days,
- d. 25mm every 14 days (an irrigation schedule possible for drought conditions), and
- e. 20mm every 14 days.

With respect to irrigated potatoes, only one irrigation schedule was simulated (25mm in 7 days), due to the fact that ACRU does not currently have a potato yield routine. With respect to the LCs, note that no two land categories have the same combination of feasible LUMPs (crop yields and hydrological impact are assumed to be constant over the farm), as, if they did, they would have been lumped into one land category.

A few points regarding current and potential LUMPs include:

- The current land-use pattern has a high correlation with the delineated land categories. This is understandable as the farmer's current land-use decisions are influenced by the biophysical characteristics of the farm, which are used to delineate LCs.
- ii. Three of the four forestry species (pine, gum and wattle) are possible all Farm A's LCs (excluding LC 6 which is unproductive land). The only other crop that can match this hardiness is grassland. Grasslands can be used for cattle and/or dairy farming. However, these economic activities were not included in this research as discussions with the farmers suggested the Upper Myoti was not suitable for these activities.
- iii. Although neither dairy nor cattle farming were considered as viable economic activities, the ACRU model was used to simulate the hydrological impact of irrigated pastures (used for cattle and dairy production), as the hydrological results on their own may be of interest to certain readers of this research.

Table 11 Farm A: The area of currently farmed LUMPS found in each LC

Land Category number	1	Area (ha)							F-15		
Land Category number	1	2	3	4	5	6	7	8	9	10	Total
Pine	70										70
Wattle	30										30
Gum							9				9
House, sheds, servitudes, riparian zones, conservation areas, etc						17					17
Dryland White Maize (25 mm in 7 days)		40	25								65
Irrigated potatoes (25 mm in 7 days)								10			10
Irrigated White Maize (25 mm in 7 days)									13		13
Natural Grassland (beef)				35	10					18	63
Total LC area	100	40	25	35	10	17	9	10	13	18	277

B. Potential Land-use area for each LC											
Land Category number	1	2	3	4	5	6	7	8	9	10	
Pine	100	40	25	35	10		9	10	13	18	
Wattle	100	40	25	35	10		9	10	13	18	
Gum	100	40	25	35	10	0	9	10	13	18	
Poplar		40		35		Not Applicable			13		Not Applicable
Dryland White Maize		40	25			ppli	9	10	13		ilon
Irrigated potatoes (25 mm in 7 days)			25			N A	9	10	13		A M
Irrigated White Maize **1			25			Ž	9	10	13		Z
Grassland	100	40	25	35	10	200	9	10	13	18	1
Irrigated Pasture		40	25	35	10		9	10	13		100

### Notes:

- Includes ACRU simulated irrigation schedules (25 mm in 7 days, 20mm in 7 days, 15mm in 7 days, 25mm in 14 days & 20mm in 14 days).
- As 17 ha are non-productive lands, the total area of the productive lands, which can be delineated into LCs, is 260ha.
- iv. Irrigated pasture is possible on a significantly greater area (142ha) than irrigated potatoes (57ha) and irrigated maize (57ha) due to the fact that pastures can be irrigated on waterlogged soils, especially in winter when the soils are drier, whereas irrigation of maize and potatoes is not feasible on waterlogged lands.
- v. Poplar is only feasible on the waterlogged lands.
- vi. Sugarcane is not feasible on any of Farmer A's lands, due primarily to the farm being too cold. As a result, irrigated sugarcane was not included in the HEAM as being possible on any of the LCs (i.e. a way of hard-coding into the model that this LUMP is not possible), as opposed to

adjusting the sugarcane crop yields. It was decided to adopt the "hard-coded" approach in order to keep the model simple.

- vii. The LCs, LUMPs and associated crop yields are all fed into the LP model.
- Conversion costs, i.e. the costs of converting from one land-use into another, are considered in the HEAM.

### 6.2.1.5 Delineating Farm A into land categories using the "coarse" delineation method

The coarser delineation approach is undertaken using GIS coverages, and delineating the farm into LCs giving consideration to broad "farmer working rules". The reason for undertaking both a coarse and comprehensive delineation of LCs, was to assess the potential errors that could be made by using the coarse delineation method. The coarse delineation method can potentially allow the delineation of LCs to be automated by capturing the "farmer working rules" into computer algorithms using GIS coverages of the factors that influence the delineation of LCs.

When delineating land categories with the "coarse methodology", GIS coverages of slope, rivers and dams are used. Using the GIS coverages, farmlands are delineated into three broad categories, including: Arable lands, Irrigable lands and Non-arable lands.

A set of lumps is selected for each of the three broad LCs from discussions with farmers, and giving consideration to the farmer working rules. The implication of this statement is that there are only three land categories (as opposed to the 10 LCs delineated for farm a using the comprehensive delineation method), and the set of lumps possible on each land category is set for all three farm case studies (with the potential to be changed if there is a need to do so).

Figure 9 shows the LCs delineated firstly using the comprehensive delineation method (10 LCs were identified), and secondly using the coarse method (3 LCs).

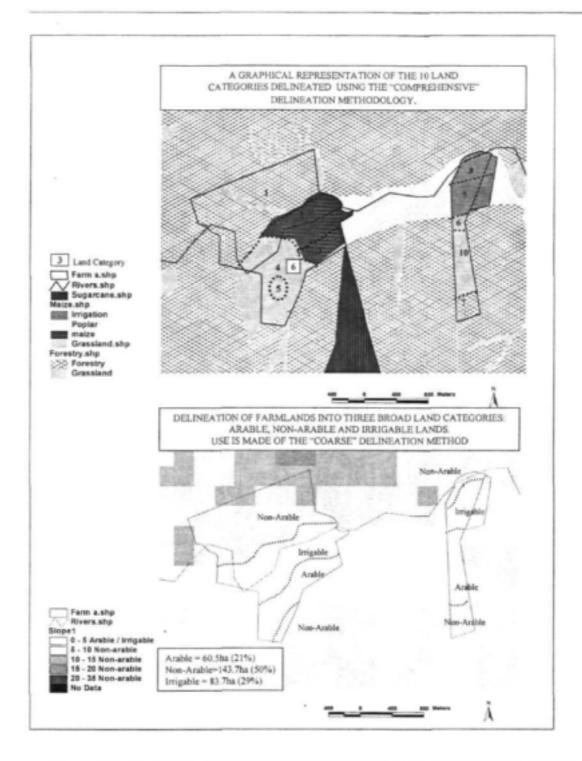


Figure 9 Land categories (LCs) for Farm A delineated using the coarse and the detailed delineation methods respectively

The LUMPs feasible on three LCs are shown in Table 12.

Table 12 The LUMPs feasible on the three broad land categories: arable, irrigable and nonarable lands

- 3	LUMPs feasible on th	e LCs of Farm A (coarse	delineation)	
	Irrigable Lands	Arable Lands	Non-Arable lands	
20 185 (32)	Pine	Pine	Pine	
8 4 6	Gum	Gum	Gum	
Feasible LUMPs	Wattle	Wattle	Wattle	
	Grassland	Grassland	Grassland	
for each —	Dryland maize	Dryland maize		
category	Irrigated maize			
	Irrigated sugarcane			
	Irrigated potatoes			
0.572.0	Irrigated potatoes		-	

#### Notes:

- Poplar cannot be included as a LUMP suitable for any of the LCs as it requires very specific biophysical conditions, which cannot be reflected by the broad LCs.
- In the table, irrigated maize and sugarcane refer to the 5 irrigation schedules simulated for each land-use, i.e. 25mm in 7 days, 20mm in 7 days...

#### The following points can be made regarding Figure 9 and Table 12:

- i. Slope is the dominant factor on which the land categories are delineated. Lands with steep slopes are generally classified as non-arable lands. From observations of current land-use in the Upper Mvoti, it seems that lands with slopes in excess of 5% are non-arable. This seems to be a relatively shallow slope, and it was expected that only lands in excess of 10% gradients would be considered to be non-arable. The relatively coarse scale of the slope grids, being in excess of 200m\* 200m, could be a reason for this anomaly.
- ii. Irrigable lands are lands with low slopes (gradients) proximal to a water source, such as a river or dam (i.e. near a water source). No consideration is given to groundwater sources for this study. None of the three farmers abstract water from groundwater sources presently.
- iii. As discussed above, the some of the lands classified as an irrigable LC using the coarse methodology, are in fact water logged, and are unsuitable for irrigation, and even unsuitable for certain dryland crops as well. This illustrates the importance of discussing the biophysical land characteristics with the farmers of the region.
- iv. Arable lands are lands with shallow slopes (between 0-5%), which are not proximal to a water source. It is important to note though, that it is possible to find one grid cell of flat land surrounded by steep lands. In this case, it may be unfeasible to delineate one grid cell as arable, with the surrounding cells as non-arable. Consequently, consideration needs to be given to the number of adjacent flat grid cells when delineating arable and irrigable lands.

- v. Dryland LUMPs are also possible on irrigable lands.
- vi. The LUMPs assumed to be feasible each of the three broad LCs are shown in below. Note the many possible LUMP substitutes on the arable and irrigable land categories. The point to be made is that a given policy instrument will probably bring to bear different costs and benefits to the farmer and to society dependent on the area a farmer has of each broad land category on his farm. LCs with few LUMP alternatives, such as non-arable LCs (which can be planted to forestry or grassland), will probably have a higher cost to the farmer if policy instruments are target LUMPs on these LCs.

The importance of Figure 9 is that it illustrates a high correlation between the LCs delineated in the relatively time-consuming "comprehensive" delineation method, and LCs delineated using a far quicker, but "coarser" method. Consequently, it was decided to delineate Farm B and Farm C with the coarse delineation methodology, with the proviso that the farmers carefully verify the delineated LCs, and adjusted where necessary.

### 6.2.1.6 LUMP yields applicable to the LC

Table 13 presents the 18 LUMPs considered in this, as well as the crop yields that can be expected from the LUMPs for both normal and dry years. The hydrological and crop yields of both normal and dry years are used in the LP model to mimic the LUMP decision making process of a farmer, as discussions with the farmers suggested that the optimal LUMP mix is selected giving consideration to the average expected farm income from a combination of normal and dry years. In the table, the yield of forestry crops is referred to as the mean annual increment (MAI), which represents the average annual incremental yield of each forestry species respectively.

The following important points need to be raised regarding the crop yields:

- The figures reflect the crop yields for all three farm case studies, as well as the yields for arable and irrigable lands. For example, dryland maize grown on an arable or irrigable land for Farm A, B, and C is identical.
- ii. The reason the crop yields are similar both for irrigable and arable LCs on the same farm, and irrigable and arable LCs between the farms is due to the fact that ACRU was used to simulate the hydrological impacts of the LUMPs at a scale larger than the size of all three farms. Consequently the crop yields for most of the LUMPs on different LCs are the same for all three farms. It is however very easy to make adjustments in the LP model to reflect yield differences both between different types of LCs on a given farm, and yields on the same LC on different farms. However due to the farms being relatively proximal to one

- another, and also due to the fact that the farmers were not very sure of the crop yields, it was decided to keep the yields similar.
- iii. A facility has been built into the LP model to invoke reductions in crop yields (MAIs) on non-arable LCs. This facility was developed to be able to reduce the yields of LUMPs on non-arable lands. Lower yields (MAIs) on non-arable lands are largely due to amongst other factors, steep slopes, shallow soils and shading.

Table 13 The crop yields associated with the 18 LUMPs

	China at the or	Normal Years	Dry Years		
LUMP	Irrigation Schedule	Crop yield or Mean annual increment	Crop yield or Mear annual increment		
	(mm/day every x days)	(Tons/ha/annum)	(Tons/ha/annum)		
Pine (timber = 30 year rotation)		15.2**1	15.2		
Pine (pulp = 18 year rotation)		15.0	15.0		
Wattle (10 year rotation)		13.6	13.6		
Gum (10 year rotation)		16.5	16.5		
Poplar (18 year rotation)		13.6	13.6		
Dryland White Maize		4.68	4.03		
Irrigated White Maize (1)	25mm in 7 days	7.39	7.22		
Irrigated White Maize (2)	20mm in 7 days	7.19	6.80		
Irrigated White Maize (3)	15mm in 7 days	6.76	6.13		
Irrigated White Maize (4)	25mm in 14 days	5.92	5.00		
Irrigated White Maize (5)	20mm in 14 days	5.76	4.79		
Dryland Sugarcane**2	Note: Dryland su	garcane is not feasible in	the Upper Mvoti.		
Irrigated Sugarcane (1)**3	25mm in 7 days	71.4 (8.1)	71.5 (8.1)		
Irrigated Sugarcane (2)	20mm in 7 days	66.5 (7.5)	65.0 (7.3)		
Irrigated Sugarcane (3)	15mm in 7 days	59.0 (6.7)	56.6 (6.4)		
Irrigated Sugarcane (4)	25mm in 14 days	51.2 (5.8)	48.4 (5.5)		
Irrigated Sugarcane (5)	20mm in 14 days	47.9 (5.4)	44.7 (5.0)		
Irrigated potatoes	25mm in 7 days	30	30		
Grassland		NA	NA		
Irrigated Pasture		NA	NA		

#### Notes

- In the HEAM, there is a facility to reduce the mean annual increment (MAI) of the forestry (crop yield)
  on non-arable lands. The yields are reduced by a factor, which can easily be changed in the HEAM.
  From discussions with farmers it was decided to apply a reduction rate of 10% to the forestry on nonarable lands (i.e. the yield of forestry on non-arable lands = 90% of the forestry yield on arable land for
  a given forestry species). The values shown in the table are the MAIs of the forestry on arable lands.
- Due to the presence of frost in the winter season, only irrigated sugarcane is feasible as irrigated sugarcane can be grown within one year, whereas in the Upper Mvoti, dryland sugarcane would take at least two years to grow. The sensitivity of the crop to frost prohibits dryland sugarcane from being practiced.
- The sugarcane yields reflect the harvested sugarcane yields, and not the sucrose yield (which in the Upper Mvoti is approximately 11.3% of the harvested yields). The expected sucrose yields are shown in italic print next to the harvested sugarcane yields.
- 4. Dryland sugarcane was not feasible on the farm case studies due to the impact of frost on the crop.

- iv. From discussions with farmers, it was decided to reduce the forestry MAI (crop yield) by 10% compared to the yields of the same forestry species on arable and irrigable lands.
- There is no variation in the yields of forests, as the yields reflect the mean annual increment (i.e. the average yield for normal and dry years).
- vi. The maize and sugarcane yields during normal and dry years were simulated using ACRU. The potato yields during normal and dry years were obtained from discussions with the farmers in the Upper Mvoti.

## 6.2.2 Farm B: A large company, mixed farming operation

Farm B is one of a number of farms owned by a private company. Each farm is run a separate entity.

### 6.2.2.1 Farm B: Biophysical characteristics

As can be seen from Figure 7, Farm B and C virtually border one another, yet the biophysical characteristics of Farm B differ from Farm C in that some of the lands on Farm B are north facing. Farm B also has water available for irrigation, due to the construction of four dams by Farmer B, two of which are off-channel storage dams, the other two are located on the stream (which does not run through the farm).

#### 6.2.2.2 Farm B: Current land-use

Table 14 below shows the breakdown of current land-use on Farm B, obtained from interviews with the farm manager.

Table 14 Farm B: A breakdown of current land use

Current Land-use	Area	%	
Pine	554	45	
Wattle	275	23	
Seed Maize	146	12	
Other	116	10	
Irrigated Sugarcane	72	6	
Gum	55	5	
	1219	100	

A few points regarding the current land-use include:

- i. The total area of Farm B planted to forestry is 884ha, which translates into 72.5% of the total farm area. If it were not for a moratorium on further afforestation, it would be possible for Farmer B to plant a further 29ha (2.5%) of his farm to forestry (order to make up 75%).
- ii. The quantity of seed maize that may be marketed (i.e. sold) by Farm B is governed by a quota system outside the control of Farm B's management. Farm B's seed maize quota has been declining over the past few years, and Farmer B does not believe the quota will increase in the foreseeable future.
- iii. It is possible to grow irrigated sugarcane on certain farm lands for two reasons, including:
  - a. The farmlands on which the sugarcane is planted are north facing, and
  - b. The sugarcane is irrigated.

The implication of this is that due to the irrigation, the rotation period (i.e. time between planting and harvesting is less than one year), and consequently the sugarcane is not damaged by frost winter.

### 6.2.2.3 Farm B: Land Categories

Using GIS coverages, Farm maps, and discussions with the manager of Farm B, the land categories were delineated for Farm B. The breakdown of the land categories is shown in Table 15

Table 15 Farm B: Land Categories

	Arable	Non-arable	Irrigable	Other
Area (ha)	0	886	221	113
%	0%	73%	18%	9%

It is interesting to note that the productive land is delineated into irrigable and non-arable LCs, with no land being identified as being arable. This is due to the fact that of the land that can be classified as being arable, all of it is currently under irrigation. The farmer has constructed 4 dams, i.e. has invested in the construction and maintenance of the dams, which in turn has transformed arable lands to irrigable lands.

#### 6.2.2.4 Farm B: Feasible LUMPs

Table 16 LUMPs feasible on Farm B - coarse delineation

	LUMPs feasible on	the LCs of Farm B (coars	e delineation)	
	Irrigable Lands	Arable Lands	Non-Arable lands	
10 -6/2	Pine		Pine	
	Gum		Gum	
	Wattle		Wattle	
Feasible	Grassland		Grassland	
LUMPs for each land	Dryland maize			
category	Irrigated seed maize**1			
	Irrigated maize			
	Irrigated sugarcane			
1 10 mg	Irrigated potatoes			

Note

### 6.2.2.5 Farm B: LUMP yields

Table 13 and Table 15 and Table 19 have presented the crop yields for Farm A, and B, which are also applicable to Farm B. However, Farm B has one LUMP not possible to Farm A or B, and that is the production of irrigated seed maize.

Table 17 Farm B: The crop yields for irrigated seed maize

Irrigated Seed Maize	Normal Years	Dry Years
	t/ha/annum	t/ha/annum
25mm in 7 days	5.5	5.2
20mm in 7 days	5.35	4.9
25mm in 14 days	4.4	3.6

## 6.2.3 Farm C: A relatively large, independent timber growing operation

Farm C is privately owned timber-farming operation. The farm lies on the upper reaches of the catchment, as is illustrated in Figure 7

#### 6.2.3.1 Farm C: Biophysical characteristics

The altitude of the farmlands range from 1300m to 1600m above sea level, with the higher reaches of the farm being susceptible to regular snow events. The farm MAP is 975mm. The farmer has on a few occasions tried to plant dryland sugarcane, as well as dryland maize, however, these were a total failure due to the cold temperatures, and poor soil conditions. The farm boundary extends into an

Farmer B has managed to secure a contract (governed by a quota), to supply seed maize (as opposed to table maize). The
other farmers were not able to secure a similar contract to sell seed maize. Consequently, Farmer B has a LUMP, which is
currently not available to the other two farmers.

adjacent catchment, outside the boundary of the Upper Mvoti Quaternary Catchments, U40A and U40B. The implication of this is that the farm has virtually no upstream catchment area, and consequently no perennial river flowing through, or near the farm. This influences the water available to the farmer. As there is virtually no water available, the farmer's irrigation options are limited.

#### 6.2.3.2 Farm C: Current land-use

The current land-use is shown in Table 18. The aerial videography did not distinguish between forestry species. Furthermore, the MBB aerial videographic survey (MBB, 1997) only included the Upper Mvoti Catchment. Consequently it was necessary to obtain a breakdown of the current afforestation by Farmer C.

Table 18 A Breakdown of current land use on Farm C

Land-use	Area (ha)	%	Comments
Pine	282	21	Pine (Pinus Patula) is not damaged by snow Fire is a danger to pine plantations
Wattle	461	34	Wattle is damaged by snow  Wattle is labour intensive, therefore better to plant wattle or shallower slopes  Wattle does not burn easily. Keep on farm perimeter as a firebrea
Gum	256	19	Does not do well on cold sites Fire is a danger
Other	343	26	Household, servitudes, conservation area, etc  A maximum of 75% of the farm area can be planted to forestrunder to old APS.
	1342	100	

Important considerations regarding the current land-use include:

- i. In Table 12 it was inferred that pines, Eucalypts (gum) and wattle are all possible on each of the three broad land categories, i.e. arable, non-arable and irrigable LCs. However, the comments in Table 18 illustrate that there are considerations, such as site species matching, as well as other practical considerations, such as wattle being used as fire-breaks as it does not burn as easily as the other forestry species, which make certain forestry species more attractive on certain lands than others. These considerations require a detailed delineation of the farm, as well as special algorithms in the LP model to capture the forestry related working rules. Due to time constraints, this level of detailed modelling was not undertaken, and the three coarsely defined LCs were used. This may be an area for future model development.
- Farm C is characterized by very few arable sites, and due to virtually no available water, there is no potential for irrigation.

#### 6.2.3.3 Farm C: Land Categories (using the coarse LC delineation methodology)

Of the 1342ha, using the broad GIS methodology of LC delineation, 450ha was identified as being potentially arable. However, after discussions with Farmer C, it was brought to our attention that dryland maize, and dryland sugarcane had been experimented with on a few occasions, and had failed on each occasion. Consequently, these lands were reclassified as being non-arable. The implication is that due to the biophysical characteristics of the farm, associated with the farms location high in the mountains, the *entire* farm is considered to be non-arable.

The total area of non-productive land (including fire-breaks, servitudes for power lines, a conservation area, roads, riparian areas, and the area used for homesteads and the workshop) was estimated to be 343ha. Consequently, the total productive, non-arable land is approximately 1000ha.

### 6.2.3.4 Farm C: Potential Land-use on each of the LCs

As a result of all land being classified as non-arable, only grassland and the forest species (Pine, Gum and Wattle) are considered to be economically feasible on Farm C.

#### 6.2.3.5 LUMP yields

Table 13 presented the forestry MAIs on arable lands. The yield of forestry on non-arable lands is adjusted to reflect poorer growing conditions. The yields of the forestry species on non-arable lands (as used in the LP model) are:

Table 19 The MAI of forestry species for Farm C

Forestry LUMP	Normal years	Dry Years T/ha/annum
Pine (pulp, 30 year rotation)	13.5	13.5
Gum (10 year rotation)	12.2	12.2
Wattle (10 year rotation)	14.9	14.9

### 7 Hydrological Modelling and Considerations

This section introduces the link between hydrology and economics in order for the reader to appreciate the different characteristics of streamflow reduction (as well as other hydrological impacts) by LUMPs that can potentially be targeted by policy instruments. The term "hydrological impact" is explored in more detail, where after the focus of the discussion is on the ACRU model, and how it was used to simulate the streamflow reduction of LUMPs.

## 7.1 The Hydrological Impact of LUMPs

The point has been made throughout this document that certain policy instruments provided for in the NWA, such as water use charges, can target the hydrological impact of LUMPs, illustrated in Figure 2. The assumption can be made that for the policy instrument to be efficient from a hydrological point of view, the policy instrument should target the hydrological impact of LUMPs. In other words, water use charges and licenses, should be based on the water use by the LUMPs. The following quotation supports this point: "equitable and efficient allocation of water to SFRAs depends on accurate calculations of their likely effects on the allocatable water" (DWAF, 1999c,p8). In the body of literature supporting the NWA, including, amongst others, papers on Water Conservation and Demand Management (DWAF, 1999a, DWAF, 2000a and DWAF 2000b), documents related to licenses (DWAF, 1999c, and Perkins, 2000), and the pricing strategy for water use charges (DWAF, 1999b), reference is made to two similar, yet potentially different hydrological impacts. These include streamflow reduction, and, reduction of water availability, respectively. Both terms relate to the hydrological impact of LUMPs, however, are not necessarily coincident.

### 7.1.1 Streamflow reduction

The hydrological impact of a given land-use should be compared against some baseline condition of the catchment (Schulze et al. 1998). The streamflow reduction resulting from a given LUMP mix is the reduction of streamflow compared to the selected baseline land cover. A definition of a given land-use that reduces streamflow is a land-based activity that reduces "virgin" mean annual runoff by a minimum amount is (or will be) declared a SFRA, (Act no 36, 1998). There are a few issues regarding streamflow reduction that need to be discussed in more detail.

- The streamflow reductions of the 18 LUMPs selected for this research were estimated using the ACRU agro-hydrological simulation model.
- ii. The streamflow reduction of the dryland LUMPs is determined using the following equation:

SR dyland LUMP x = Streamflow Baseline Land Cover, - Streamflow dyland LUMPx , with

SR = streamflow reduction

Baseline Land Cover = Acocks

iii. The streamflow reduction of irrigated LUMPs is determined using the equation:

SR impated LUMP x = Streamflow Baseline Land Cover - Streamflow impated LUMPx - Water abstracted for irrigation.

- iv. A problem in determining the streamflow reduction of irrigated LUMPs using the ACRU agrohydrological simulation model relates to the fact that ACRU is not currently coded to consider the manner in which an irrigator is curtailed. The amount of water actually abstracted by the farmer in order to irrigate a given LUMP is a function of the water physically available to abstract (such as the amount of water in the river), the crop water requirements of the irrigated crop, as well as the amount of water legally available to the farmer for irrigation. ACRU has the capability to consider the both the physical amount of water available to irrigate, as well as the crop water requirement of certain irrigated LUMPs, but does not yet consider the manner in which a farmer's irrigation license may be curtailed. At the time of writing this report, a modified version of ACRU, referred to as ACRU 2000 was being developed, in which both irrigation water use licenses, as well as rules to curtail these licenses, was being programmed within the model.
- v. The streamflow reduction represents the reduction caused by a given farm, and not the cumulative effect of the reductions that may have been caused by upstream activities.

## 7.1.2 Reduction of water availability

A highly variable rainfall characterizes South Africa, both intra-annually and inter-annually (Schulze, 1995). Consequently there may be excess streamflow during certain periods, and severe shortages of water during other periods. Dams are built to distribute the water more evenly over time, so that the streamflow highs are not as high, and the lows not as low as would normally be the case. The purpose of dams is usually to capture the water during times of plenty, to be distributed during periods of water scarcity. However, in South Africa relatively large dams may be needed to retain enough water for when it may be needed as South Africa is characterized by a high evaporative demand.

If a large dam is situated in a catchment, the dynamics of the water flowing through the catchment is dramatically changed. Surplus water may be retained by the dam, in a way banking it for periods of water scarcity. The nature of the flows into a dam, the characteristics of the dam, and the manner in which water is either used or released from it, influences the amount of water that may possibly be distributed in times of water scarcity. It is the amount of water that can be allocated (i.e. physically abstracted for use) during periods of water scarcity that is referred to the water available in a system, as it is during this period that water is most critical.

The relationship between streamflow reduction and water availability needs to be introduced at this stage. As stated above, the availability of water in a system usually refers to the amount of water available during dry periods. If no large dam is present in a catchment, the implication is that *only* the streamflow reduced during the dry periods will have an impact on the water availability. In other words, if a given land-use were to reduce streamflow during periods of water abundance (such as during wet periods), but without reducing the streamflow during the dry periods (such as the 4 driest months of the year), then the water availability of the system would probably not be affected, as the water available during the dry periods was not impacted. However, if a large dam were present in a system, the reduction in streamflow during all periods may influence the water available, as the inflows of especially the wet periods is retained for distribution during the dry periods. Consideration needs to be given to the characteristics of the dam, as it may overtop regularly, in which case there is surplus water in the system. Surplus water in this context is defined as water that if not retained or used would flow into the sea. IFRs in this research are considered to be a form of water use.

From the above discussion it becomes evident that it is relatively easier to determine streamflow reduction as compared to the impact on water availability if a large dam is present in a system. However, the water availability reflects the "size of the cake" that can be distributed during periods of water scarcity, and needs to be known with an acceptable level of confidence, before water use licenses can be issued. A water availability model, the Water Resources Yield Model, has been developed, and extensively applied in South Africa to quantify the water availability for different assurance levels at various locations within certain catchments (BKS, 1999).

The streamflow reduction of a given LUMP may be identical directly above and below a large dam, yet the impact of the LUMP above the dam may influence the water availability significantly differently to the LUMP directly downstream of the dam. Consequently, if a large dam (or dams) is/are present in a catchment, the spatial location of LUMPs relative to the dam/s will need to be known in order to calculate the water availability in a catchment.

As there is no large dam present in the Mvoti Catchment, in this research project it is assumed that changes in the streamflow during dry periods reflect the changes in the water availability of the catchment. However, this assumption is tested by assessing the streamflow reduction of changes to a farm LUMP mix on a few different periods, including a review of the streamflow reduction in both "normal" and "dry" periods (further discussed in Section 7.2.1).

## 7.1.3 Streamflow reduction of SFRAs and irrigated crops

Understanding the streamflow reduction processes, such as the timing and magnitude of streamflow reductions over time, of LUMPs is one of the first steps that need to be achieved in order to manage water resources both sustainably and efficiently. With respect to the sustainability, water resource managers must ensure that they do not over-allocate, i.e. issue too many licenses, which will result in IFRs being breached. On the other hand, if water resource managers estimate the water use of LUMPs too conservatively (i.e. over-estimate the use of water by the LUMPs), then too few licenses may be issued, which may constrain economic development when the allocation quota is reached.

The mechanisms, with which SFRAs and irrigated LUMPs use water, resulting in a reduction of streamflow, differ in that:

- i. SFRAs, as with irrigated LUMPs, use water available to the crops via the process of transpiration (Schulze, 1995), however, SFRAs are dependent solely on rainfall as the source of water (assuming the SFRAs are not in a riparian zone, or draw water from a shallow groundwater table), whereas irrigated LUMPs receive water both from rainfall, as well as from supplementary irrigation.
- ii. With respect to irrigation, the farmer has a degree of control over how and when he can abstract the water to be used for irrigation. Constraints to the control the farmer may have to irrigate include:
  - a. The farmer may be constrained by the physical amount of water available to be irrigated, and
  - b. The farmer may be legally constrained as to the amount of water he may abstract. As irrigation is "a tap" that can be turned on or off, water resource managers may limit the amount of water that a farmer can irrigate during periods of water shortage. In other words, the irrigation water use license can be curtailed in periods of water shortage.

It is important to give consideration to the above points when simulating the hydrological impact of the LUMPs. The streamflow reduction of dryland LUMPs, such as SFRAs, is easier to simulate than irrigated LUMPs, are the streamflow reduction is primarily dependent on the observed rainfall pattern. However, when simulating the streamflow reduction of irrigated LUMPs (discussed below), unless actual irrigation records are available, assumptions need to be made regarding when and how the water is abstracted by the farmer.

# 7.1.4 Simulating the streamflow reduction of LUMPs

Use can be made of the hydrological simulation model to determine the impact of the LUMPs on streamflow in different locations. A model is in effect an abstraction of a complex system in order to understand and predict the behaviour of that part of the system. The model can then reproduce, in a sequence of mathematical expressions, the behaviour of some, but not all, of the characteristics of one or more components of the prototype (Schulze, 1995).

One of the advantages of physical process based models is that the water use by different crops can be estimated for different geographical locations. However potential disadvantages include:

- Understanding the dominant water use processes of different LUMPs requires research, which may take a number of years to obtain. In the case of this research, estimates of LUMP parameters have been based on previously undertaken research.
- The physical process based hydrological model may require a large number of inputs (such as soils data, rainfall, temperature) which makes this type of modelling relatively time consuming and expensive, and
- iii. Estimates of LUMP parameters may require a high level of expertise.

## 7.2 A Description of the ACRU Hydrological Simulation Model

The ACRU Agrohydrological modelling system has been developed in the School of Bioresources Engineering and Environmental Hydrology (BEEH) at the University of Natal, South Africa. The ACRU model is a multi-purpose and multi-level integrated physical conceptual model that can simulate streamflow, total evaporation, and land cover/management and abstraction impacts on water resources at a daily time step (Schulze, 1995). The model was used to simulate streamflow for all LUMPs, including the irrigation abstraction requirements for irrigated crops. Input to the menu, which controls input variables, is controlled by a "menubuilder" program where the user enters parameter or catchment related values or uses defaults provided.

The ACRU model consists of multi-layer soil budgeting. Streamflow is generated as stormflow and baseflow, which are dependent upon the magnitude of daily rainfall in relation to the dynamic soil water budgeting. Components of the soil water budget are integrated with modules in the ACRU system to simulate many other catchment components, including irrigation requirement and sediment yield. The irrigation requirement component was used for this research project, however the sediment yield could potentially be used if the HEAM is further developed.

Spatial variation of rainfall, soils and land cover is facilitated by operating the model in "distributed" mode, in which case the catchment to be modeled is subdivided into subcatchments. These subcatchments are usually selected to represent areas of similar hydrological response, based largely on land-use zones, which can then be used to simulate the impact of land-use changes. The method of

delineating the subcatchments for this research project differed to the conventional approach in that due consideration needed to be given to economic returns associated with LUMPs.

Land cover and land-use affect hydrological responses through canopy and litter interception, infiltration of rainfall into the soil, and the rates of evaporation and transpiration of soil water from the soil and canopy. Land cover/use input into ACRU include:

- An interception loss value, which can change from month to month during a plant's annual growth cycle, to account for the estimated interception of rainfall by the plant's canopy on a rainy day,
- ii. A monthly consumptive water use (or "crop") coefficient (converted internally in the model to daily values by Fourier Analysis), which reflects the ratio of water use by vegetation under conditions of freely available soil water to the evaporation from a reference potential evaporation (e.g. A-pan or equivalent), and
- iii. The fraction of plant roots that are active in extracting soil moisture from the topsoil horizon in a given month, this being linked root growth patterns during a year and periods of senescence brought on, for example by a lack of soil moisture or frost (Jewitt et al, 2000).

A further variable, which can change seasonally, is the coefficient of the initial abstraction, which accounts for vegetation, soil surface and climate influences on stormflow generation. In ACRU this coefficient takes cognizance of surface roughness (e.g. after ploughing) and initial infiltration before stormflow commences. The value of using a model that operates at this level of detail, is that if the impact of LUMPs on physical attributes of the soil, and on land-use is know, the hydrological impact of land-uses and management practices can be simulated. However, the problem of using a model which requires this level of detail is that these parameters are seldom known which a high level of confidence for a given study area, and there may in fact be processes which are not included in the model. The point to be made is that over time, these parameter estimates and hydrological processes can only be better understood as the model is continually being developed. Should the value of simulated hydrological responses by the model be large, data of high confidence may be obtained by field research. The model, and the data available for the model, may be imperfect, however both the model and the data can be improved, should there be a need to do so.

The principal applications of the model are the assessment of environmental and land-use related impacts on the generation of both stormflows and baseflows to enable improved management and planning of water resource allocation and utilization (Schulze, 1995). Many verification studies have been performed, both on internal state variables and final model output (Schulze, 1995). In particular,

forest water use and the impacts on streamflows have been verified at several locations in South Africa (Jewitt and Schulze, 1999).

### 7.2.1 The modelling approach adopted for this research

Figure 10 illustrates the ACRU modelling methodology that was adopted for this research, which also illustrates the "conventional" ACRU modelling methodology. The modelling approach is discussed below.

As discussed in Section 4.2.2, the Upper Mvoti was delineated into 67 homogenous Hydrological Economic Zones [HHEZs]. This delineation differs from the conventional delineation of catchments into homogenous hydrological units [HRUs], in that the HHEZs are delineated with no consideration given to the topography, and hence the flow of water. The assumption is made that the runoff (overland flow, baseflow and inter-flow) generated from each HHEZ contributes directly to the Mvoti River. It may be argued that this is a weak assumption as the actual amount of water that reaches the stream may be influenced by adjacent HHEZs. However, as the HHEZs are relatively large units, the assumption may in fact be plausible, in that there are probably small gullies and ephemeral streams linking the HHEZs with the larger perennial rivers.

#### A few points regarding Figure 10 include:

- i. The dotted line joining rainfall to irrigation represents the fact the timing of irrigation by farmers is influenced by the rainfall. Discussions with the farmers revealed that if a rainfall event in excess of 12mm occurs, irrigation is discontinued until the crop requires supplementary irrigation water. There is a facility in ACRU to discontinue irrigation for one cycle if this threshold rainfall is met. The dotted line in Figure 10 represents the link between actual rainfall and the amount of water abstracted for irrigation.
- ii. The dotted line joining land-use and soil reflect the fact that certain land-uses (and management practices) change the properties of the soil. For example, the tillage changes the properties of the soil by increasing the surface roughness as well as the porosity of the soil. Adjustments are made in ACRU to reflect possible changes in soil conditions for the 18 LUMPs where there is a need to do so, which is represented by the dotted line in the diagram.

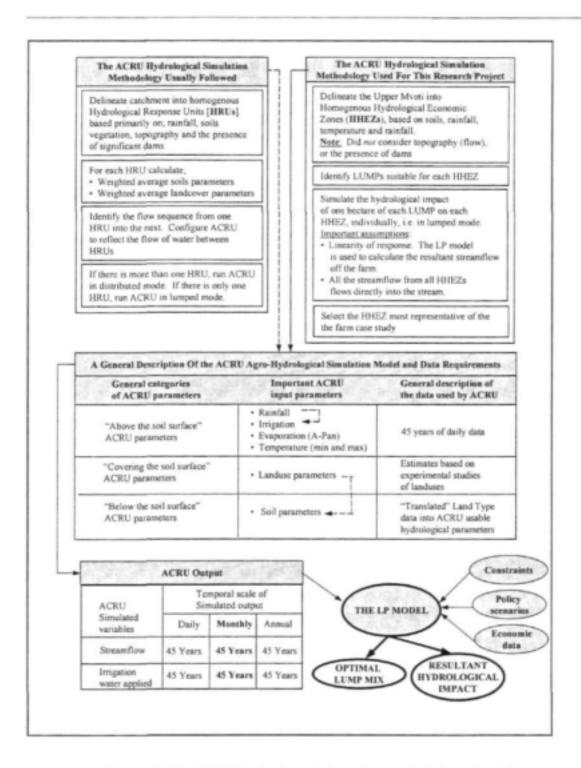


Figure 10 The ACRU hydrological simulation methodology adopted

### iii. ACRU was used to simulate the:

a. Runoff from 1 ha of land planted to each LUMP respectively, and

 Amount of water abstracted from the river needed to irrigate 1 ha of land planted to each of the irrigated LUMPs.

The 45 year record of monthly runoff and irrigation for each of the 18 LUMPs was summarized for two periods, including:

- c. Five years selected to be representative of normal years, and
- d. Ten years selected to be representative of dry years.
- iv. The ACRU simulated hydrological results are fed into the LP model. Figure 10 illustrates that the hydrological results are one of a number of inputs into the LP model.
- v. The LP model is used to select the optimal LUMP mix. However, the LP model also calculates the resultant streamflow from the optimal LUMP mix. In other words, ACRU is not used to calculate the resultant hydrological impact of the optimal LUMP mix, as this is determined within the LP model.

# 7.2.2 ACRU hydrological input parameters

The ACRU model is not a parameter-optimizing model, but rather a physical process based model. What this means is that estimates of physical characteristics of soil, vegetation and atmospheric conditions need to be captured as ACRU model parameters. The ACRU model, driven by the parameters and internal model algorithms, simulates hydrological variables. The main categories for which ACRU requires hydrological parameters is shown in Table 20 below. Each of the categories is discussed in the Appendix of this report, shown in Table 20.

Table 20 Input data required by ACRU

ACRU INPUT PARAMETERS	APPENDIX
Rainfall	Appendix 1 A
Irrigation	Appendix 1 B
Evaporation	Appendix 1 C
Temperature	Appendix 1 D
Landcover (LUMPs)	Appendix 1 E
Soils data	Appendix 1 F

### 7.2.3 The hydrological variables ACRU was used to simulate

The ACRU hydrological simulation model was used to simulate:

- i. The runoff generated from 1 hectare of land planted to each of the 18 LUMPs, and
- ii. The water abstracted for each of the irrigated LUMPs.

"Runoff" in this context refers to the amount of water that flows from the land (1 ha) under a given LUMP, into the stream. The runoff includes surface runoff, as well as interflows and baseflows. The runoff from irrigated LUMPs is higher than that of dryland LUMPs due to the increased application of water on the farmland.

 "Irrigation water applied" refers to the amount of water that is abstracted from the river to irrigate 1 hectare of a given irrigated LUMP.

The purpose was to explore the hydro-economic tradeoffs (i.e. water applied vs. yield) that may exist between the different irrigation schedules. The streamflow reductions resulting from the 18 LUMPs are calculated in the LP model using the following equations:

Streamflow Reduction Devland LUMP = Runoff Acocks - Runoff LUMPs devland

Streamflow Reduction Irrigated LUMPs = Runoff Acocks - [Runoff LUMPs irrigated - Irrigation water applied].

# 7.2.4 Water use during "normal" years and "dry" years.

Throughout this document the statement has been made that it is important for policy makers to understand how and when LUMPs use water, as policy instruments can be used to target the water use of different time periods. A comparison of the timing and magnitude of streamflow reduction by the different LUMPs revealed that although the correlation was high, it was not perfect. In other words, the maximum streamflow reduction of a given LUMP did not always occur in the same year or months as the other LUMPs.

It was decided to use a methodology that allowed the water use of a given year to be compared to the water use of another LUMP in the same year. Consequently, it was decided to select years representative of dry years, and years representative of normal years. The dry years were defined as the 10 years with the lowest simulated Acocks streamflow during the 4 dry months of the year, which include the months of May – August. Figure 11 illustrates the 45 year simulated streamflow record, ranked in descending order on the sum of the streamflow during the 4 dry months of the year. Five

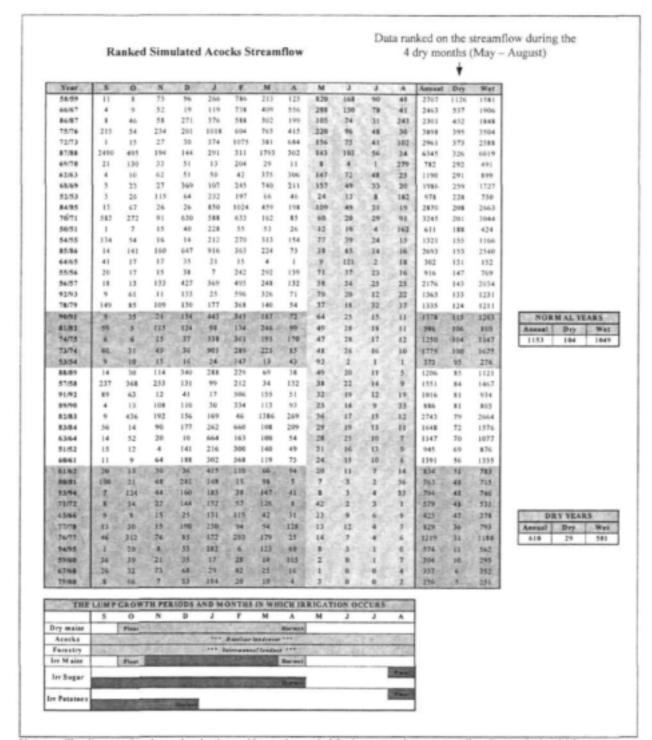
years were selected to be representative of normal years, which included the 5 years with simulated Acocks streamflow most similar to the median streamflow during the 4 dry months of the year.

Furthermore, the streamflow reduction by LUMPs was summarized for three sub-periods, which include:

- i. The annual streamflow reduction (for normal and dry years)
- ii. The streamflow reduction during the 4 dry months (May August), and
- iii. The streamflow reduction during the 8 wet months (September March).

The following points can be made regarding Figure 11:

- The representative "normal" and "dry" years are selected from the ranked simulated Acocks streamflow low-flows (i.e. the sum of the 4 dry months in a year, which include May-August),
- ii. The hydrological year selected for this research includes September to August. In other words, a normal calendar year, i.e. January – December, was not used. The reason for this selection is that September is the first month after the dry months, and there is usually good rainfall in September in the Upper Mvoti. In Figure 11, the years are shown as year combinations, e.g. 91/92, as the hydrological year spans two calendar years.
- Figure 11 also shows the growth cycle of the LUMPs selected for this research. The planting and harvest months have been illustrated in the diagram for crops with an intra-annual growth cycle.
- iv. The ACRU simulations, including runoff and water abstracted for irrigation, are ranked on the simulated Acocks dry months streamflow, and from there the average runoff and water abstracted for irrigation is determined for each of the six period and sub-period combinations (e.g. normal years: annual, wet and dry, and dry years: annual wet and dry). In other words, the streamflow reduction of each LUMP is calculated in the LP model for the six period combinations using the six runoff and water abstracted for irrigation figures.



Note: The diagram also shows the planting and harvesting period for intra-annual crops, as well as the months in which irrigation occurs

Figure 11 Ranking the simulated Acocks 4 dry month streamflow, from which representative "normal" years and "dry" years can be selected

### 7.3 Hydrological Results

Table 21 below illustrates the average streamflow reduction, calculated for three respective periods including the annual, 4 dry months and 8 wet months streamflow reduction, for the years representative of "normal" and "dry" years respectively. The streamflow reduction for each period (normal and dry years) was calculated by subtracting the average streamflow of each LUMP from the average streamflow generated from 1 ha of Acocks for the two periods respectively.

Table 21 The average streamflow reduction during "normal and "dry" years respectively

THE SECTION OF	10 10 20	STREAMFLO	W REDUCTIO	ON (m³/ha)		ik Säx.		
461 User 186 9	N	ORMAL YEAR	RS	DRY YEARS				
LUMP	Annual	4 Dry months	8 Wet Months	Annual	4 Dry months	8 Wet Months		
Acocks	0	0	0	0	0	0		
Gum	567	42	525	397	19	378		
Wattle	436	37	398	312	19	293		
Pine (30 yr)	461	19	442	372	13	359		
Pine (18 yr)	461	19	442	372	13	359		
Poplar	268	14	254	203	8	195		
Dry Maize	-151	-31	-120	-173	-30	-143		
I. Seed Maizel	1647	-134	1781	1977	-147	2125		
I. Seed Maize2	1510	-40	1550	1616	-47	1663		
I. Seed Maize3	751	59	692	468	-10	477		
I. Maize 1	1647	-134	1781	1977	-147	2125		
I. Maize 2	1510	-40	1550	1616	-47	1663		
I. Maize 3	751	59	692	468	-10	477		
I. Sugar 1	6892	1003	5889	7200	969	6231		
I. Sugar 2	5655	861	4794	5677	833	4844		
I. Sugar 3	4319	733	3586	4183	624	3559		
1. Potato	2759	749	2011	2820	677	2143		

Notes:

Seed maize is high quality maize sold as seed.

Three of the 5 ACRU simulated irrigation schedules were fed into the LP model. The irrigation schedules include,

For maize (seed and table): 1 maize 1 = 25mm every 7 days

I maize 2 = 20mm every 7 days, and

I maize 3 = 25mm every 14 days.

For sugarcane 1 sugarcane 1 = 25 mm every 7 days, 1 sugarcane 2 = 20 mm every 7 days, and

I sugarcane 2 = 20 mm every 7 days, and I sugarcane 3 = 15 mm every 7 days.

For potato 1 potato = 25mm every 7 days

Dryland maize increases runoff relative to Acocks primarily due to the fact that the land stands fallow for a number of months of the year. Thus evapotranspiration is lower than that of Acocks, with a resultant increase in runoff.

The streamflow reductions of the LUMPs will be discussed as follows: In Section 7.3.1 the streamflow reductions of the LUMPs during the "normal" years are discussed, i.e. a discussion of the differences in streamflow reduction between LUMPs in a given period. In Section 7.3.1.1 the difference in streamflow reduction between LUMPs during dry years is discussed.

# 7.3.1 Comparing the streamflow reduction of LUMPs during "normal years"

The average streamflow reduction of LUMPs during the years selected as "normal" years is shown in Figure 12 below. A distinction between the average streamflow reduction during the 4 dry months and 8 wet months of the year is made. The annual streamflow reduction is the sum of the streamflow reduction during these periods (as can be seen from Table 21above). From the diagram, the following useful comparisons can be made:

- The average streamflow reduction, including the annual, 8 wet months, and 4 dry months streamflow reduction, of the different LUMPs can be compared to one another (inter-LUMP streamflow comparison), and
- The average streamflow reduction within each LUMP can be compared between the 4 dry months and the 8 wet months.

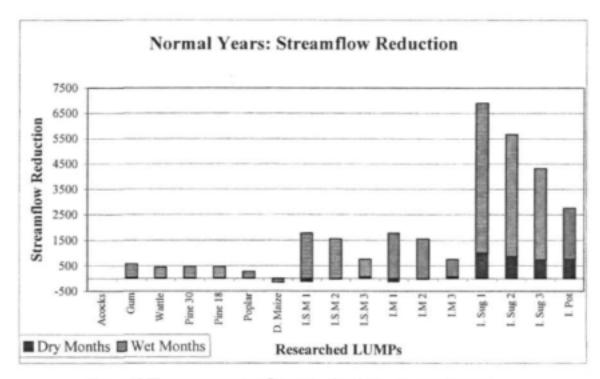


Figure 12 The average streamflow reduction during "normal" years

#### 7.3.1.1 The average streamflow reduction of LUMPs during "normal" years

The importance of assessing the streamflow reduction of a combination of different months (intraannual assessment) is that policy instruments can be fine tuned to target the water use of LUMPs when the water use creates the largest externality to society. It may be pointless to regulate land-uses that only use water during periods when water is in fact in excess. The following section allows policy makers to better understand the temporal use of water. The following points can be made regarding the average streamflow reduction of different LUMPs during "normal" years in the Upper Mvoti, as shown Figure 12:

- The graph represents streamflow reductions, i.e. positive figures in Figure 12 and Table 21
  represent a reduction of streamflow, while negative figures represent an increase in
  streamflow compared to Acocks.
- ii. The average annual streamflow reduction of irrigated LUMPs is clearly higher than that of dryland LUMPs, however with respect to low flow (the 4 dry months), irrigated maize actually leads to an increase in streamflow. The increase in low flows by irrigated maize is a result of the crop being irrigated in the 8 wet months (with no irrigation during the dry months). Due to delayed irrigation returnflows, more streamflow is generated in the dry months than Acocks. A different way of looking at this is to consider the soil as being a form of reservoir. Water applied for irrigation during the wet months is stored within the soil, which slowly makes its way to the stream as it moves through the soil profile. It is important to point out that the soil is not as effective as a dam for storing water (due to the increased evapotranspiration losses from the soil). A second consideration is that irrigation returnflows may reduce the quality of the water, which has not been considered in this research.
- Gum has the highest average simulated streamflow reduction of the forestry species, both with respect to the wet and dry months.
- iv. The total average streamflow reduction of irrigated sugarcane is significantly higher than that of irrigated maize due to the fact that the maize is irrigated for 5 of the 7 months (November – March), as compared to sugarcane that is irrigated for 9 months of the year (as shown in Figure 11.
- v. Both irrigated sugarcane and potatoes have high streamflow reduction during the 4 dry months, as both are irrigated for one of the four dry months of the year, i.e. August.
- vi. Poplar is recognised as an SFRA, yet reduces streamflow by a fraction of the other forestry species, i.e. an average annual reduction of 268m³/ha/annum compared to 567m³/ha/annum. The reason for this is due to the fact that Poplar is deciduous (i.e. loses it's leaves during Winter). Thus the evaporation from the poplar is significantly reduced compared to other forestry species for the winter months.
- vii. Table 22 below gives an indication of the area that can be planted to gum that will result in the same streamflow reduction for annual, low flow and 8 wet month conditions for "normal"

years. These ratios have to potential in themselves to assist water resource managers in the allocation of water use licenses, as well as the trade of water use licenses. For example, should a farmer who is irrigating say 1 hectare of sugarcane, for which he has an irrigation license, wish to convert out of irrigation into forestry, according to the ratios he should receive an forestry SFRA license of 12.2ha and 23.8ha, depending on which period of water use is considered by the water resource manager (i.e. annual, or low flows),

The negative value of -3.2 associated with irrigated maize reflects the fact that irrigated maize actually increases streamflow. This figure does not reflect the fact that 3.2ha of irrigated maize can be planted to have the same streamflow reduction as 1ha of gum. In other words, if the ratio is negative, it is meaningless. The table shows that very large areas of forestry can substitute irrigated sugar and potatoes, and still have the same average streamflow reduction. The economic returns of the different land-uses are discussed in Section 8.

Table 22 "Normal" years: The area that can be planted to Gum to have the equivalent average streamflow reduction as the irrigated LUMPS respectively

	Annual	4 Dry months	8 Wet months
Irrigated Maize 25mm every 7 days	2.9	-3.2	3.4
Irrigated Sugarcane 25mm every 7 days	12.2	23.8	11.2
Irrigated Potato 25mm every 7 days	4.9	17.8	3.8

#### 7.3.1.2 The streamflow reduction in wet versus dry months

Table 21 and Figure 12 illustrate the average streamflow of LUMPs for the 4 dry months, and the 8 wetter months for years representative of "normal" years respectively. The graph and table show that during "normal" years, the greatest streamflow reduction occurs in the 8 wet months, with relatively little streamflow reduction occurring in the 4 dry months. However, although the absolute amount of water is important, it may be useful to express the streamflow reduction of both wet months and dry months to the same base, i.e. an average monthly streamflow reduction for the 4 dry months and 8 wet months respectively.

Table 23 "Normal" years: The "annual", "4 dry month" and "8 wet month" streamflow reduction expressed as a monthly average

LUMP	NORMAL YEARS						
LUMIF	Annual	4 Dry months	8 Wet Months				
Acocks	0	0	0				
Gum	47	10	66				
Wattle	36	9	50				
Pine (30 yr)	38	5	55				
Pine (18 yr)	38	5	55				
Poplar	22	4	32				
Dry Maize	-13	-8	-15				
I. Seed Maizel	137	-34	223				
I. Seed Maize2	126	-10	194				
I. Seed Maize3	63	15	86				
I. Maize 1	137	-34	223				
I. Maize 2	126	-10	194				
I. Maize 3	63	15	86				
I. Sugar 1	574	251	736				
I. Sugar 2	471	215	599				
I. Sugar 3	360	183	448				
I. Potato	230	187	251				

### From the following can be observed:

- The average monthly streamflow reduction of the 4 dry months is significantly lower than the average monthly streamflow reduction for the 12 months (annual) and 8 wet months respectively.
- The average monthly streamflow reduction of the sum of the streamflow reduction for the 12 months (i.e. annual) is not equal to the sum of the monthly averages of the 4 dry months and 8 wet months.
- Dryland maize however has less streamflow generation (opposite to reduction) during the 4 dry months than the 8 wet months.
- iv. The average monthly streamflow reduction of the irrigated LUMPs during the 4 dry months is lower than the average monthly streamflow reduction of the 8 wet months. This is due to the fact that only one of the dry months is irrigated. If a LUMP were to be irrigated for all four

dry months, one would expect the streamflow reduction to be quite a bit higher than that of the 8 months for two main reasons. Firstly, there is a higher probability of rainfall events in excess of 12mm during the wet months (which induces ACRU to skip an irrigation cycle as farmers don't usually irrigate after a decent rain event), and secondly, the soil moisture content during the dry seasons is expected to be lower than that of the wet months (i.e. drier) resulting in less runoff and less returnflows as the water gets trapped by the drier soils.

v. The streamflow reduction results of irrigated maize #3 (25mm every 14 days), for seed and table maize, are anomalous with respect with respect to the streamflow reduction in dry months, as one would expect a generation of streamflow (and not a reduction) in order to be consistent with the other two maize irrigation schedules (i.e. 25mm and 20 mm every 7 days respectively), as well as consistent with dryland maize. The reasons for this anomaly still need to be researched.

# 7.3.2 Comparing the streamflow reduction of LUMPs during "dry" years

Figure 13 illustrates the average streamflow reduction for the 4 dry and 8 wet months for the years representative of "dry" years.

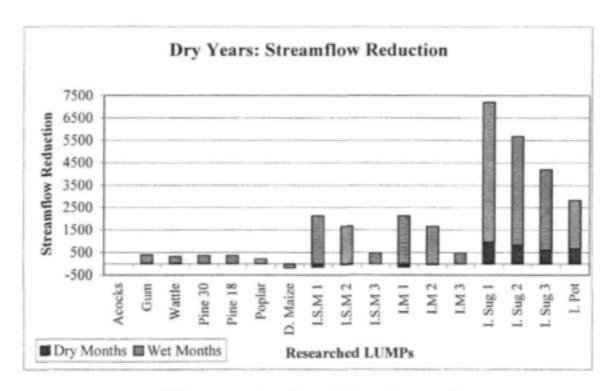


Figure 13 The average streamflow reduction during "dry" years

The streamflow reductions during the "dry" years follow a similar trend to that of "normal" years, except for the following differences:

- The streamflow reduction of dryland LUMPs is lower during the "dry" years for annual, low flow and 8 wet months respectively.
- ii. The irrigated LUMPs on the other hand generally result in an increased streamflow reduction during the "dry" years, due to the fact that more water is needed to supplement rainfall (as rainfall is generally lower in the "dry" years), and also due to the lower soil water level in dry years, which results in less irrigation returnflows.
- iii. The irrigated maize anomaly is again present, and also requires further research.
- iv. Table 24 shows the "equivalent area" ratios, i.e. the area that can be planted to Gum that will result in the same average streamflow reduction as the irrigated LUMPs. The area that can be planted to Gum is significantly higher during the dry years as the assumption was made that the irrigated crop is not curtailed. The curtailment of irrigation has however been included in the LP model. The point to be made here is that if a farmer has the ability to irrigate maize, sugarcane or potatoes with an irrigation schedule of 25mm every 7 days, the farmer, if he discontinued his irrigation, could theoretically convert very large areas of his lands for forestry, and which will have the same impact on streamflow reduction.

Table 24 "Dry" years: The area that can be planted to Gum to have the equivalent average streamflow reduction as the irrigated LUMPs respectively

-	Annual	4 Dry months	8 Wet months
Irrigated Maize 25mm every 7 days	5.0	-7.7	5.6
Irrigated Sugarcane 25mm every 7 days	18.1	51.0	16.5
Irrigated Potato 25mm every 7 days	7.1	35.6	5.7

Table 25 illustrates the monthly average streamflow reduction for the 12 month, 8 wet months, and 4 dry month streamflow reductions respectively. The table clearly shows what has been said above, i.e.:

- v. The dryland LUMPs reduce streamflow by less in the "dry" years, whereas
- vi. Irrigated LUMPs have a larger streamflow reduction in the "dry" years.

Table 25 "Dry" years: The "annual", "4 dry month" and 8 "wet month" streamflow reduction expressed as a monthly average

LUMP	Annual	4 Dry months	8 Wet Months
Acocks	0	0	0
Gum	33	5	47
Wattle	26	5	37
Pine (30 yr)	31	3	45
Pine (18 yr)	31	3	45
Poplar	17	2	24
Dry Maize	-14	-8	-18
I. Seed Maize1	165	-37	266
I. Seed Maize2	135	-12	208
I. Seed Maize3	39	-2	60
I. Maize I	165	-37	266
I. Maize 2	135	-12	208
I. Maize 3	39	-2	60
I. Sugar 1	600	242	779
I. Sugar 2	473	208	605
I. Sugar 3	349	156	445
I. Potato	235	169	268

### 7.3.3 Conclusion

There is a difference in the streamflow reduction of LUMPs during "normal" years and "dry" years. Estimating the streamflow reduction for different years, as well as different periods within a year may be important to water resource managers, especially with respect to the sustainable allocation of water use licenses.

Dryland LUMPs, being dependent on rainfall as the source of water, reduce streamflow less during dry periods than wet periods. However, irrigated LUMPs, use abstractions from an available water sources to supplement the rainfall, in order to provide land-uses with their water requirements. The implication of this is that irrigated LUMPs require more water to be applied both during drier years, as well as during dry months of the year, for a given crop. The streamflow reduction shown in the tables and graphs above depicts the streamflow reduction with the assumption that there is not constraint on water. The water constraint (either in the form of physically abstractable water, or legally abstractable water) is introduced in the LP model.

The concept of "equivalent area" was introduced, which showed what area could be planted to Gum to have the same average streamflow reduction (annual, 4 dry month and 8 wet months), for "dry" and "normal" years respectively. In Section 8, the economic returns of the LUMPs are discussed. These need to be brought into consideration when discussing the "equivalent streamflow reduction areas" in order to ascertain which option a farmer would prefer to adopt, i.e. 1 ha of irrigated LUMP versus a number of hectare planted to forestry. It is this type of calculation that is undertaken in the LP model, giving consideration to constraints, policy instruments and risk.

# 7.4 Validation of the Hydrological Results

Figure 7 shows the location of the gauging weir U2H002, located at the exit of the Mvoti Vlei having a surface area of 800ha. Validation is undertaken by comparing the simulated streamflow at the location of the gauging weir, with the observed streamflow records of the gauging weir. Two points need to be made with respect to the location of the gauging weir. Firstly, the weir has been identified as an IFR site, however the IFRs have not yet been determined for the site. The second point relates to the hydrological impact of the vlei. Due to its size, the vlei may have a significant impact on hydrological processes, which makes validation of simulated hydrological results difficult, due to the influence of the vlei. In order for the simulated streamflow to have a high correlation with the observed streamflow, both the inflow into the vlei, as well as the hydrological impact of the vlei, need to be simulated accurately.

Validation of simulated hydrological results of this project was not possible due to the scale and methodology adopted. The modelling scale was at a farm level, and not for the entire catchment, which is needed for the validation.

However, simulated streamflows using the ACRU model have been validated in two independent studies. The first was a validation undertaken by MBB Consulting Engineers Incorporated, whom had mapped the Upper Mvoti using aerial videography (MBB, 1997). Table 26 below shows some of the statistical results of the MBB ACRU simulated, daily streamflow validation. The hydrology honours class of 1999 undertook the second validation. Detailed statistics of the hydrology honours validation are presently unavailable.

Table 26 A few selected statistical results of the validation of results simulated by ACRU

Difference between total observed and simulated flows	7.1%
Difference between coefficients of variation of observed and simulated flows	6.1%
Difference between the skewness coefficients of observed and simulated flows	4.7%
Correlation coefficient	0.65
Coefficient of agreement, observed vs. simulated flows	0.74
Slope of a scatter plot of observed vs. simulated flows	0.64

Notes. The comparison is between simulated daily streamflow and observed streamflow records at weir U2H002. The validation study was undertaken by MBB Consulting Engineers Incorporated (MBB, 1997).

A few points need to be made regarding the results of the validation study:

- i. Firstly, relatively poor correlation (65%) between simulated and observed streamflow is probably largely due to the hydrological impact of the vlei. MBB consulting engineers did not have time to obtain accurate data regarding the vlei, which would most probably have improved the simulation.
- The ACRU model has been widely validated in catchments other than the Mvoti, with correlations
  of simulated streamflow to observed streamflow far higher than 65% (Schulze, 1995).
- iii. As the hydrological results of HHEZ 24 are used for all three farm case studies, they may in fact not be entirely correct for each farm. However, the results are believed to be in the ballpark as the similar hydrological variables used by MBB consulting engineers were used in this study.

#### 8 ECONOMIC DATA AND CONSIDERATIONS

The hydrological impacts of the LUMPs are discussed in the preceding chapter. In this section the economic costs and returns of each of the LUMPs are discussed, including the method of data acquisition.

### 8.1 Method of Economic Data Acquisition

The managers or owners of the three farms, selected as the 3 farm case studies, were interviewed to obtain the economic costs and benefits of LUMPs presently or previously undertaken on each farm respectively. Of the three farmers, two kept detailed records of the costs and returns of LUMP activities. The third farmer, did not keep accurate records of his farming operation, however did have a strong knowledge of the costs and returns of the LUMPs undertaken on his farm.

In order to present the information in a systematic manner, the COMBUD budgets (COMBUD, 1999) were used as a template for the non-forestry related LUMPs. The forestry related budgets, provided by the Forestry Economic Services (1997) were used as templates for the forestry related LUMPs.

In order for budgets to be consistent for intra-annual and inter-annual crops, the budgets used for this research represent the annualised costs and returns for 1 hectare for each of the LUMPs, discussed below. The financial year 1999 was used as a base year.

#### 8.2 Revenue and Yields

The revenue associated to a given LUMP is equal to the price times the yield. Obviously, a LUMP can result in more than one product (e.g. bark and wood) so one has to take into account the yield of all products. Which price and which yield should be used requires some discussion.

The farm gate price is adequate in the case of a farmer who sell his products under competitive market conditions, and who does not own or have a stake in the businesses that process the raw primary materials from his farm. In the case of a small farmer like farmer A, these conditions where valid to a large degree. Farmers B and C do have a stake in the processing operations of their products, which translates into an 'agterskot', i.e. a premium which is paid on a per tonne basis. The farm models took into account these agterskots. Table 27 shows the various prices that were used. The prices were given by the farmers, and applied to the year 1999.

As far as yield is concerned, it was important to make a distinction between the differences in yield for the various irrigation LUMPs of a given crop. For example: intensive sugar irrigation (irrigated sugar 1) obviously has a higher yield than less intensive sugar irrigation (irrigated suger 2 and 3). Crop yield models within Acru were used to estimate these differences. The absolute levels of the yields predicted by Acru had to be scaled down to bring them in line with the yields reported by the farmers. The simulated maize and sugar cane yields had to be scaled down by 12% and 39% respectively. The high adjustment required for sugar cane is most probably due to the fact that the yield model is not suited fur use in areas with marginal growing conditions.

Acru was also used to estimate the differences in yield during normal and dry years.

The data used in the model are shown in the table below.

Table 27a Yield and revenue for different LUMPs

LUMP	Product	Price/ton (R/ton)	yield/ha median years (t/ha)	yield/ha dry years (Uha)	Expected Rev/ha (R/ha)
Gum	poles	240	5.5	5.5	
	pulp	180	11.0	11.0	3,300
Wattle	bark	690°	1.8	1.8	
	wood	330	11.8	11.8	5,136
Pine - timber	timber	160	12.2	12.2	
	pulp	130	3.0	3.0	2,342
Pine – pulp	pulp	130	15.0	15.0	1,950
Poplar	wood	240	13.6	13.6	3,264
Dryland maiz	maize	780	4.68	4.03	3,523
Irrigated maize seed 1	seed	2,300	5.50	5.20	12,478
Irrigated maize seed 2	seed	2,300	5.35	4.90	12,039
Irrigated maize seed 3	seed	2,300	4.40	3.60	9,666
Irrigated maize 1	maize	780	7.39	7.22	5,735
Irrigated maize 2	maize	780	7.19	6.80	5,532
Irrigated maize 3	maize	780	5.92	5.00	4,439
Irrigated sugar 1	cane	1,197 <sup>b</sup>	8.06	8.08	9,662
Irrigated sugar 2	cane	1,197	7.51	7.35	8,946
Irrigated sugar 3	cane	1,197	6.67	6.39	7,903
Irrigated potato	potatoes	850	30.0	29.0	25,288

Notes

B:

This includes an agterskot of R240 per ton

This includes an agterskot of R157 per ton sucrose

### 8.3 Variable and fixed costs

Variable costs and fixed costs are shown in Table 27b. Details for the variable costs are provided in Appendix 4. As previously, a distinction was made between normal years and dry years for irrigated LUMPs. An attempt was made to take into account that a lower irrigation intensity would cause variable costs to be slightly lower as well. It was assumed that the percentage reduction of variable costs would be half that of the yield: e.g. a reduction of 10% in the yield would lead to a reduction of 5% in variable costs.

Table 27b Variable and fixed costs for various LUMPs

	Labour costs		Non-Lab	our costs	Total vari	iable costs	Fixed costs
	med yrs	dry yrs	med yrs	dry yrs	med yrs	dry yrs	
Gum	8-	44	1,0	000	1,8	844	900
Wattle	14	100	1,2	000	2,6	500	1.430
Pine – timber	6	16	69	92	1,3	308	600
Pine – pulp	5	76	63	36	1,2	212	600
Poplar	3	80	43	30	8	10	600
Dryland maize	4	00	1,9	15	2,3	315	200
Irrigated maize seed 1	2,833	2,833	5,913	5,913	8,746	8,746	600
Irrigated maize seed 2	2,794	2,750	5,831	5,740	8,625	8,490	600
Irrigated maize seed 3	2,550	2,398	5,323	5,004	7,874	7,402	600
Irrigated maize 1	500	500	3,461	3,461	3,961	3,961	600
Irrigated maize 2	493	485	3,413	3,360	3,906	3,845	600
Irrigated maize 3	450	423	3,116	2,929	3,566	3,352	600
Irrigated sugar 1	1,912	1,912	5,568	5,568	7,480	7,480	400
Irrigated sugar 2	1,847	1,825	5,377	5,314	7,224	7,139	400
Irrigated sugar 3	1,746	1,712	5,086	4,987	6,832	6,699	400
Irrigated potato	2,315	2,315	18,342	18,342	20,657	20,657	2,500

Obtaining data on fixed costs per LUMP is very difficult and case specific. In collaboration with the farmers, it was decided to apportion the overhead costs among the various current LUMPs. These fixed or overhead costs include salaries of managerial staff, all costs associated with management vehicles and depreciation of buildings. The results can be seen in Table 27b.

For the purposes of this project the concept of enterprise net margin was defined (also referred to as farm profit before tax) and expressed on a per hectare basis.

Enterprise net margin per ha = Gross income/ha - Variable costs/ha - fixed costs/ha.

The resulting enterprise net margins are shown in Table 27c below.

Table 27c Variable and fixed costs for various LUMPs

	Er	ntreprise net ma	argin
	Normal Dr years Dr		Expected
Gum		556	
Wattle		1,106	
Pine - timber		434	
Pine – pulp		138	
Poplar		1,854	
Dryland maize	1,134	632	1,008
	-		
Irrigated maize seed 1	3,304	2,614	3,132
Irrigated maize seed 2	3,074	2,189	2,853
Irrigated maize seed 3	1,653	282	1,310
Irrigated maize 1	1,207	1,074	1,174
Irrigated maize 2	1,102	861	1,041
Irrigated maize 3	451	(49)	326
Irrigated sugar 1	1,777	1,787	1,779
Irrigated sugar 2	1,372	1,047	1,291
Irrigated sugar 3	752	558	704
Irrigated potato	2,343	1,493	2,131

The following points can be raised regarding tables 27:

- i. Irrigated maize and sugar 1, 2 and 3 reflect the costs and returns associated with different irrigation regimes. With respect to the irrigated maize (table and seed maize), the irrigation regimes include:
  - a. 1 = 25mm every 7 days,
  - b. 2 = 20mm every 7 days, and
  - c. 3 = 25mm every 14 days
- ii. With respect to the irrigated sugarcane, the irrigation regimes include:
  - a. 1 = 25mm every 7 days,
  - b. 2 = 20mm every 7 days, and

### c. 3 = 15mm every 7 days

- iii. Table 27c shows irrigated seed maize to be the most lucrative LUMP, followed by irrigated potato, poplar, irrigated sugarcane, irrigated maize, wattle, dryland maize, gum then pine. It is difficult to secure a market for the seed maize. Farmers who have lands suited to seed maize are regulated by a quota system. In other words, there is a constraint on the amount of seed maize that can be produced by a given farmer.
- iv. Although potatoes have a high enterprise margin, there are risks associated with potatoes, which include diseases, sensitivity to soil water and the high input costs required to plant potatoes. In other words, farmers usually limit the area they plant to potatoes, due to the high risk involved.
- v. Poplar surprisingly has very high returns compared to the other dryland LUMPs. The high return is probably due to the fact that poplar requires very specific biophysical conditions for its growth. In other words, the potential supply of poplar is limited, which could account for the premium return associated with the crop.
- vi. Irrigated sugarcane is not economically feasible in most areas of the Upper Mvoti, partly due to the relatively poor crop yields, and secondly due to the relatively poor sugar price, which has recently been very low.

# 8.4 Yields for Different Levels of Irrigation Intensity

The yields for the different levels of irrigation deserve a special mentioning. Table 27 lists different annual yields for different intensities of irrigation in the case of normal maize, seed maize and sugar cane. These yields reflect annual averages. In other words, these are averages of the yields observed during the full range of years, from wet to dry.

The yield differences between two irrigation regimes therefore are differences between annual averages. During the course of the research it was felt that one should perhaps go one level deeper, and consider yield averages for wet, dry and normal years.

The idea behind this was the following. The opportunity to irrigate more or less depending on crop water requirements and water availability is a key characteristic of water use through irrigation as opposed through dry-land LUMPs. Reducing the irrigation intensity will result in a lower yield. This impact is likely to differ depending on whether this reduction of the amount of in the water applied occurs during wet, median or dry years. One would expect that the dryer the conditions, the higher the marginal productivity of irrigation water.

ACRU was used to simulate the yields for 5 different irrigation regimes during the 45-year reference period. The results for maize and sugar are shown in Figure 14. For each irrigation intensity, yield averages were calculated for 3 groups of years: the 9 wettest years, the 9 years around the median year and the 9 driest years. The upward sloping (yield) curves reflect the yield changes during a given category of years as the irrigation intensity increases. The short downward sloping curves (only shown in the case of maize) connect the averages during different categories of years for a given irrigation intensity.

The slope of the yield curves reflects the marginal productivity of water during those given years. For maize, one observes that during wet years a shift from irrigation intensity level 4 to level 5 (i.e. the highest intensity) results in a rather minimal yield increase. During dry years however, this yield increase is more significant. For lower irrigation intensities, the slopes of the yield curves for dry and wet years do not seem to differ that strongly. A look at the yield curves for sugar shows that slopes of the yield curves hardly differ for dry and wet years.

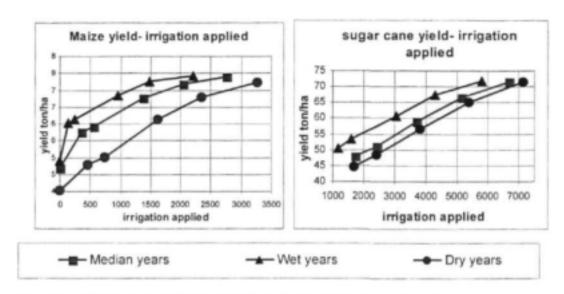


Figure 14 Marginal productivity of water in irrigation during wet, median and dry years.

Table 29 below shows these effects numerically. For each of the points of the above graphs it was calculated how much extra revenue a farmer can expect during a certain category of years if he shifts from one irrigation level to the next. (Obviously, one cannot calculate such a derivative for the highest irrigation level.) The actual irrigation application per hectare is also listed for reference purposes. This shows clearly how the Acru model mimics what would happen in reality, namely that the actual application per hectare differs during dry and wet years for a given irrigation intensity.

For maize, one can observe that that the marginal productivity of water during dry years is almost double that during wet years: 0.36 Rand/m<sup>3</sup> as opposed to 0.19 Rand/m<sup>3</sup>. Everywhere else in the Table, the differences between wet and dry years are less outspoken.

Taken at face value, these results seem to suggest for the two crops considered that the marginal productivity of water does not differ that much during wet and dry years, except for maize at high irrigation intensities. However, more attention for this issue may be required. The data show one anomaly, which suggests that a more refined modelling approach may have to be adopted. That anomaly consists of the fact that the marginal productivity of water does not increase monotonously as the irrigation intensity is increased.

Table 28 Gross marginal productivity of irrigation water in years during dry and wet years for different irrigation intensities

			Low in	tensity		High in	ntensity
			level 1	level 2	level 3	level 4	level 5
Maize							
Wet years	irr applied per ha	M <sup>3</sup>	133	250	967	1489	2222
	extra revenue per extra m3	R/m <sup>3</sup>	0.74	0.77	0.59	0.19	
Dry years	irr applied per ha	$M^3$	460	750	1620	2360	3275
	extra revenue per extra m <sup>3</sup>	R/m <sup>3</sup>	0.59	1.01	0.71	0.36	
Sugar cane							
Wet years	irr applied per ha	M <sup>3</sup>	1178	1611	3050	4311	5806
	extra revenue per extra m3	R/m <sup>3</sup>	0.63	0.49	0.50	0.29	
Dry years	irr applied per ha	$M^3$	1700	2425	3840	5380	7150
	extra revenue per extra m3	R/m3	0.50	0.55	0.52	0.35	

### 9 THE HYDROLOGICAL ECONOMIC LP MODEL

The LP model can best be described by a discussion of its key components: (i) activities, (ii) constraints, (iii) hydrological calculations within the model, and (iv) objective function. Before these key components are discussed, it is necessary to introduce the necessary notations (Table 30).

Table 29 Notations for sets, scalars and parameters used in the LP model

Sets	:					
P	Set of lumps (discussed earlier)					
C	Set of products which result from the lumps (discussed earlier)					
S	Set of land categories (discussed earlier)					
U	Set of variable cost types labour costs, non-labour variable costs					
V	Set of fixed costs: irrigation equipment, non-irrigation assets					
Z	Z Set of inter-annual hydrological periods: dry years, median years					
Tp	Set of intra annual hydrological periods: wet months, low flow months, all months					
Ty	years					
Scalars and Parameter	n					
General scalars and po	arameters					
$\alpha_z$	Percentage of the time that period z applies					
PRICE <sub>c</sub>	Price of product c					
YIELDp,c,z,x	Per ha yield of product c for lump p on land category s during period z					
Cost related scalars an	nd parameters					
VCOSTp.z.u	Variable cost per ha of type u for lump p during period z					
FCOSTp.z.u	Fixed cost per haq for lump p					
CVCs	Annualised cost for conversion from forestry in Rand per ha					
AFFORs	Total area of land category s that is afforested					
REVp, ty	Per ha revenue for lump p during year ty					
REVDEVp, ty	Deviation from the average revenue in year ty					
Φ	Risk coefficient					
Hydrological scalars a	nd parameters					
WAVAILz.tp	Water available in stream at the entrance of the farm during period z, tp					
VWAVAILz,tp	Water available in stream at the entrance of the farm during period z, tp under baseline conditions					
DAMCAP	Capacity of the water storage facilities					
β	Average proportion of the dam which is available for application during dry years					
RUNOFFp, z, tp	Simulated runoff for lump p during period z,tp					
WAPp, z, tp	Simulated irrigation application for lump p during period z, tp					
Land area						
AREAs	Area of land category s					
AREATOT	Total area of the farm					
Policy related scalars	and parameters					
ROREDTAZz,tp	Volumetric charge on runoff reduction during period z, tp					
WABTAXz, tp	Volumetric charge on water abstraction during period z, tp					
γ	Switch to include (1) or exclude (0) the runoff impact of non-licensed dryland land-uses					
δ	Switch to include (1) or exclude (0) the runoff impact of irrigation LUMPs					
SUB	Subsidy offered per Rand tumover					
AFFPERM	Maximum allowable afforestation on the farm					
IFR%z, tp	IFR target, expressed as a percentage of virgin runoff of the catchment above the farm (incl the farm) during period z, tp					
IFRSFz, tp	IFR target expressed as the minimum streamflow required during period z, tp					
WRIGHTz.tp	Abstraction right during period z, tp					

Table 30 Notations for variables used in the LP model

Variables		
Land-use and product	ion variables	
CROPz, p, s	Total area of land category s dedicated to lump p during period z, tp	
TOTCROPz, p	Total area of lump p on the farm during period z, tp	
XPRODz,c	Total ton produced of product c during period z, tp	
Hydrological variables		
RUNOFFTz, tp	Runoff from the farm during period z, tp	
WAPTz, tp	Total irrigation water applied on the farm during period z, tp	
WABTz, tp	Total water abstracted during period z, tp	
ROREDTz, tp	Total runoff reduction during period z, tp	
ROREDNLTz, tp	Total runoff reduction by non-licensed dryland landuses during period z, tp	
ROREDIRTz, tp	Total runoff reduction by irrigated land-uses during period z,. tp	
SFLOWTz, tp	Total streamflow during period z, tp	
SFREDTz, tp	Total streamflow reduction during period z, tp	
Water use charge vari	ables	
TAXRRz, tp	Total tax on runoff reduction during period z, tp	
TAXWABz, tp	Total tax on water abstraction during period z, tp	
TOTSUBz	Total subsidy during period z, tp	
TOTWTAXz	Total water tax due for period z, tp	
Economic variables		
TOTREVz	Total revenue during period z, tp	
PUMPCz	Total pumping costs during period z	
TOTVCOSTZ	Total variable cost during period z	
TOTFCOSTz	Total fixed costs during period z	
TOTCVC	Total conversion cost	
RISKz	Total imputed cost of risk during period z	
YZz	Total farm income before tax during period z	
YEXP	Total expected farm income	

### 9.1 The model in a Nutshell

Before a systematic description of the various key components of the model is undertaken, it is useful to provide a simplified outline of the model.

The model mimics a farmer's decision-making context very much like an ordinary agricultural economics LP model. It assumes that the farmer has perfect knowledge about his revenue and cost factors. What makes the model special is the following:

The farmer knows that on average, out of ten years he will experience a certain number of dry years. (The factor  $\Box_z$  refers to this.) He also knows that he can classify a year as having 8 wet and 4 drier (winter) months. This presents him with four hydrological periods:

- · wet months during dry years
- · dry months during dry years

- · wet months during normal years
- · dry months during normal years

He knows how the rainfall differs during these periods, as well as how the water availability in the river or in his farm dam (if applicable) changes. The farmer is aware that he can only choose one crop mix, which he will have to stick to during all these hydrological periods. The only leeway he has between these periods is that he can vary the intensity with which to irrigate certain crops. In other words, the model is static and assumes that at the outset the farmer must state his farm plan for each these periods, under the constraint that the mixed of crops planted has to remain the same, only irrigation intensities can differ.

#### 9.2 Activities

The activities among which the farmer can choose are represented by the variables CROP<sub>p, z, p</sub>, and the variables WAB<sub>z, pp</sub>. In other words, the farmer has to choose how much of each lump p to allocate to the various land categories s, and how much water to abstract during each period z,tp. Note that it is assumed that the farmer has to make two decisions: one for the farm plan, which he adopts during normal years and another, which he follows during dry years. There is obviously a limit to the extent that these farm plans can differ: for example, forestry crops cannot be changed from one year to another. Within the context of this project, and after consultation with the farmers, it was decided that the only way in which these farm plans are allowed to differ is in the intensity of irrigation. In other words, it was assumed that the farmer would continue to grow the same crops when a dry year occurs, but that he can choose the intensity with which he irrigates those crops. The equations that specify these conditions can be found under Section VII.12 in Appendix 3.

At earlier stages in the research, it was contemplated to include the following activities as well:

- 1. Irrigation investment,
- 2. Buying or hiring of tractors,
- 3. Conversion of afforested land,
- 4. Hiring of temporary labour,
- 5. Beef and diary farming.

The need to include the first two activities as separate activities was circumvented by the linearity assumption that was made for the fixed costs. This assumption implies that the fixed costs increase linearly with the area. It ignores economies of scale. However, this assumption simplifies matters considerable and allows for constant per hectare values of fixed costs to be used for each LUMP.

The third activity, the conversion of afforested land was not included as a separate activity but was nevertheless implicitly integrated in the model. This was done by using the parameter AFFOR<sub>ss</sub>, which reflects the area currently afforested on a given land category s. If the farmer chooses to reduce the afforested area on s, an annualised conversion cost CVC<sub>s</sub> will be added to the fixed cost proportional to that reduction. The conversion cost per ha amounts to R10 000. A straight depreciation over 10 years gives an annualised cost of R1000/ha. The equations under Section VII.5 in Appendix 3 deal with the conversion cost.

Labour is not a constraint for farmers. Labour costs are included as part of the variable costs. Beef farming as a LUMP was excluded in the end. It proved to be overly complex to include it in the model, and it is a LUMP in which the farmers in question expressed very little interest.

#### 9.3 Constraints

#### 9.3.1 Land constraints

The most obvious constraint is that the area of a given land category which is allocated to land-use activities, cannot exceed the area available (equation 1).

$$\sum_{p} CROP_{z,p,s} \le AREA_{z} \quad \forall z, s$$
 (1)

Equation 2 ensures that all available land is allocated. Since Acocks is considered to be a LUMP, leaving land idle is equivalent to choosing Acocks as an activity.

$$\sum_{p,s} CROP_{z,p,s} = AREATOT \quad \forall z$$
(2)

#### 9.3.2 Water-related constraints

#### Water Availability constraints

A first set of constraints characterises the constraints imposed by the water availability in the river. Equation 3 specifies that during a given period, the water abstracted cannot be larger than the water available at the entrance of the farm. (Implicitly it is assumed that the runoff from the farm land occurring during the same time period is not available for abstraction.)

$$WAB_{z,p} \le WAVAIL_{z,p}$$
  $\forall z, tp$  (3)

Equation 4 is simply an equation stating that the average annual abstraction over a given inter annualtime period z needs to be equal to the sum of the averages during the dry (low flow) months and the wet months.

$$WAB_{z,tp=wel} + WAB_{z,tp=dry} = WAB_{z,tp=qrw}$$
  $\forall z$  (4)

Equation 5 specifies the inter-annual transfer of water, which is made possible by the dam. During the dry years, it is assumed that on average a certain proportion  $\square$  of the dam is water captured during normal years, which now becomes available for application. The  $\square$  coefficient was assumed to be equal to 0.25, as according to the farmer, the dam is mostly used for intra-annual transfers. The equation imposes the condition that the annual amount of water applied during dry years, is equal to the amount of water abstracted from the river during those years, plus the amount of water carried over by the dam from previous wetter periods.

$$WAP_{z=drysr, dp=amn} \le WAB_{z=drysr, dp=ann} + \beta * DAMCAP$$
 (5)

Equation 6 is nothing more than a condition assuring a water balance between periods inter-annual periods. It specifies that the amount applied during normal years, plus the amount set aside for the drier years (second terms on the left hand side), is smaller or equal to the amount abstracted during the normal years.

$$WAP_{z=normyrs,p=ann} + \alpha_{z=dsym} / (1 - \alpha_{z=dsym}) * \beta * DAMCAP \le WAB_{z=normyrs,p=ann}$$
 (6)

#### Policy induced water related constraints

The next four equations deal with policy-induced water related constraints. The first one, equation 7, is the constraint associated to the water use entitlement for abstraction. The amount abstracted in a given time period, must be smaller or equal than the amount one is legally entitled to. It is important to note that equation 7 is in fact a set of equations, one for each time period (z,tp). A situation where abstraction rights are only specified in annual terms can easily be accommodated but choosing values in the right hand side, which are non-binding. A point worth noting is that the specification of the right hand side of the equation as a product of the parameters *PERCWR* and *WRIGHT* allows for the flexibility to adjust rights both in absolute and percentage terms.

$$WAB_{z,p} \le PERCWR_{z,p} * WRIGHT_{z,p} \quad \forall z, tp$$
 (7)

Equations 8 and 9 specify different ways in which the IFR conditions can be imposed. If the IFR condition is specified in absolute volumetric terms, equation 8 is to be used.

$$SFLOWT_{z,w} \ge IFRSF_{z,w} \quad \forall z, tp$$
 (8)

If the IFR condition is specified in percentage terms, relative to the streamflow available under natural baseline conditions, equation 9 is to be used.

$$(VWAVAIL_{z,w} + SFLOW_{z,w})/(VWAVAIL_{z,w} + VIRGINRO_{z,w}) = IFR\%_{z,w}$$
  $\forall z, tp$  (9)

Equation 10 specifies that the total area under forestry must be smaller or equal than the area for which a licence has been granted.

$$\sum_{p \in AF(p)} TOTCROP_{z,p} \le AFFPERMIT \qquad \forall z$$
(10)

# 9.4 Hydrological Calculations within the LP model

Equations 11 to 17 calculate the values for the hydrological variables at the farm level. Equation 11 calculates the total runoff from the farm.

$$RUNOFFT_{z,p} = \sum_{p} TOTCROP_{z,p} * RUNOFF_{p,z,p} \quad \forall z, tp$$
 (11)

Equation 12 calculates the runoff reduction for the farm by taking the difference between the runoff under the given farm plan, and that under natural conditions (LUMP='velgro').

$$ROREDT_{z,tp} = VIRGINRO_{z,tp} - RUNOFFT_{p,z,tp} \quad \forall z, tp$$
 (12)

Equations 13 and 14 calculate the runoff reduction for non-licensed dryland land-uses and for irrigation activities respectively.

$$ROREDNLT_{z,p} = \sum_{p \in NL(p)} TOTCROP_{z,p} * (RUNOFF_{p=set_{lgro},z,p} - RUNOFF_{p,z,p})$$
  $\forall z, tp (13)$ 

$$ROREDNLT_{z,tp} = \sum_{p \in IR(p)} TOTCROP_{z,tp} * (RUNOFF_{p=vel_{g,ro},z,tp} - RUNOFF_{p,z,tp})$$
  $\forall z,tp \ (14)$ 

Equation 15 calculates the total water irrigation requirement for each period.

$$WAPT_{z,p} = \sum_{p} WAP_{p,z,p} * TOTCROP_{z,p} \quad \forall z, tp$$
 (15)

Equation 16 calculates the streamflow by taking the difference between the runoff and the abstraction for each time period.

$$SFLOWT_{z,p} = RUNOFFT_{p,z,p} - WAB_{z,p}$$
  $\forall z, tp$  (16)

Equation 17 calculates the streamflow reduction by taking the difference between the runoff under natural baseline conditions, and the streamflow.

$$SFREDT_{z,w} = VIRGINRO_{z,w} - SFLOWT_{z,p}$$
  $\forall z, tp$  (17)

# 9.5 The Objective Function

### 9.5.1 Calculation of total revenue

Equations 18 to 20 deal with the calculation of the total revenue. For accounting purposes, equation 18 is added to calculate the total area for a given LUMP by taking the sum over all land categories.

$$TOTCROP_{z,p} = \sum_{z} CROP_{z,p,s} \quad \forall z, tp$$
 (18)

Then the total amount produced for a given product c is calculated by summing the yields for all LUMP on each land category. The total revenue is calculated subsequently.

$$XPROD_{z,c} = \sum_{\rho,s} YIELD_{\rho,c,z,s} * CROP_{z,\rho,s} \quad \forall z,c$$
 (19)

$$TOTREV_z = \sum_{c} PRICE_c * XPROD_{z,c} \quad \forall z$$
 (20)

# 9.5.2 Calculation of fixed and variable costs

The calculation of variable and fixed costs was kept very simple. The variable cost was calculated as the sum of labour, non-labour and pumping costs. The unit pumping cost was set at 2 cents per m<sup>3</sup>.

$$TOTVCOST_z = \sum_{p,u} VCOST_{p,z,u} * TOTCROP_{z,p} + \sum_{p=abry, wer} UNITPC * WABT_{z,p} \quad \forall z$$
 (21)

The fixed costs were calculated using the simplifying linearity assumption.

$$TOTFCOST_z = \sum_p FCOST_p * TOTCROP_{z,p} \quad \forall z$$
 (22)

# 9.5.3 Calculation of water charges

Equations 23 to 26 deal with the calculation of the total amount of water use charges owed by the farmer. Equation 23 calculates the charges for runoff reduction. If  $\Box$  and  $\Box$  are equal to 1, the actual runoff reduction from the farm is used as the basis for calculating the charge. By setting these coefficients equal to 0, one can exclude the impact on runoff by non-licensed dryland land-uses and irrigation activities respectively.

$$TAXRR_{z,p} = ROREDTAX_{z,p} * \{ROREDT_{z,p} - (1-\gamma) * ROREDNLT_{z,p} - (1-\delta) * ROREDIRT_{z,p} \}$$
  $\forall z, tp$  (23)

Equation 24 calculates that charge due for the water abstraction. Note that the charge is calculated for the abstraction, and not the application, as the application can occur during a different time period.

$$TAXWAB_{z,w} = WABTAX_{z,w} * WABT_{z,w} \quad \forall z, tp$$
 (24)

Both charges for runoff reduction and abstraction are again specified for each possible time period (z,tp): the 2-by-3 matrix of water use charges includes 6 values for water charges. To simulate a certain way of implementing the water use charges, one simply changes the relevant elements in the matrix and keeps the other zero.

Equation 25 calculates the subsidy, which would be allocated to the farmer. The rationale for adding this equation is the following. Assume two LUMPs generate exactly the same hydrological impact and the same farm profit, but significantly different economic impacts as expressed though the revenue per ha. Through the subsidy mechanism based on average revenue per ha, one would be able give an extra incentive to the land-use generating the higher economic impact.

$$TOTS_s = SUB * RAVG_s * TOTCROP_s \forall z$$
 (25)

This equation was added after discussions with representatives from the forestry sector, who felt that the current plans regarding water use charges did not really take into account the broader economic impact created by land-uses. Just like runoff reduction can be considered as a negative externality, this broader economic impact could be considered as a positive externality.

Equation 24 calculates the total net water charge due to the farmer.

$$TOTWTAX_z = \sum_{\varphi} \{TAXRR_{z,\varphi} + TAXWAB_{z,\varphi}\} - TOTS_Z \quad \forall z$$
 (24)

# 9.5.4 Accounting for risk

Farmers face a variety of risks. Generally, a distinction is made between business and financial risk. Business risk is that derived from the uncertainty due to the nature of the enterprise. Price variability, production variability, variable water availability and various internal factors influence business risk. Financial risk is the added variability of net cash flows resulting from the financial obligations associated with debt financing. In the present context, only business risk associated to price and yield variations is considered.

The model accounts for risk by using the Motad approach (Hazell and Norton, 1986). This requires ideally data on revenue per hectare for the past 10 years for each LUMP. As these data could not be obtained from the farmers in question, the authors generated them. Time series for all prices of the products included in the model were collected. For forestry, changes in mean annual increments were introduced, proportional to annual rainfall deviations from the mean rainfall. The yield variations, which, combined with the price variations, resulted in an overall coefficient of variation. These coefficients of variation and the average revenue per ha over that period are shown in Table 32.

For the other crops yields were simulated by ACRU and multiplied with the average price in constant 1999 Rand terms for the corresponding crops in the corresponding years.

Table 31 Average annual revenue per ha and coefficients of variation for each LUMP

LUMP	Coefficient of variation	Average over past 10 years
Gum	6.7%	3268
Wattle	6.4%	5286
Pine – (30 yr)	6.1%	2776
Ping – (18 yr)	4.8%	1926
Poplar	4.1%	3434
Dry maize	24.0%	3570
Irrigated seed maize 1	6.7%	11145
Irrigated seed maize 2	9.1%	10385
Irrigated seed maize 3	18.1%	8491
Irrigated maize I	5.4%	5758
Irrigated maize 2	8.6%	5255
Irrigated maize 3	19.2%	4565
Irrigated sugar cane 1	3.5%	9827
Irrigated sugar cane 2	5.3%	8800
Irrigated sugar cane 3	6.9%	7636
Irrigated potatoes	33.2%	24742

For each year, the total revenue deviation was calculated (equation 27). This way this is done takes into account the impact of possible correlations between the revenue deviations of different LUMPS.

$$DEV_{z,y} = \left| \sum_{p} REVDEV_{p,y} * TOTCROP_{z,p} \right| \forall z, tp$$
 (27)

The risk factor, which enters into the objective function, takes the average revenue deviation, which a farmer can expect in a given year, irrespective of the sign of that deviation, and multiplies it by a risk coefficient  $\Box$ . This factor will be subtracted from the revenue in the objective function. A risk coefficient of 1 means that, according to the model the farmer implicitly considers the average deviations from the expected revenue as an added cost of the same value.

$$RISK_z = \Phi * \sum_{y} DEV_{p,ty}/10 \quad \forall z$$
 (28)

# 9.5.5 Calculation of farmer income

The final two equations calculate the farmer's income. Equation 29 calculates the income for each time period z. Equation 30 calculates the expected value of the farmer's income over the two time periods.

$$YZ_z = TOTREV_z - TOTVCOST_Z - TOTFCOST_Z - TOTWTAX_Z - RISK_z$$
 (29)

$$YEXP = \sum \alpha_z *YZ_z$$
 (30)

# 9.5.6 Specific constraints

Section VII.13 contains another of additional constraints, which were included to ensure the well functioning of the model. These constraints include:

- A condition that not more than 60% of the area under afforestation would be allocated to one crop.
- For farm B it was necessary to impose the condition that no potatoes would be irrigated. The
  correct way of doing so would be to model the extra information and management costs
  explicitly. Given the little added value it was decided not to add this complication.
- The maximum available area for seed maize for Farmer B was set at 147 ha. This was done
  to reflect the quota system to which he is subjected.

# 10 RESULTS: DISCUSSION AND CONCLUSION

# 10.1 Overview of Policy Options

This section presents the results that were derived using the HEAM. The key purpose of the model is to assist managers of water resources by helping them to assess the hydrological and economic impact of policies that target land-based water uses (i.e. the agricultural and forestry sectors).

Policies that target land-based water uses can be applied with different objectives in mind. They can also be implemented through various instruments, target different activities and base the implementation on different hydrological impacts of those activities.

Table 32 An overview of policy instruments and there application

Objective (column a)	Instrument (column b)	Activity targeted (i.e. LUMP) (column c)	Hydrological impact of LUMP targeted (column d)	Indicators at the catchment scale (column e)	
			1.1.1 D-Lisfred		
		1.1 SFRAs	1.1.2 M-Asfred		
			1.1.3 System yield	<ul> <li>Water availability</li> </ul>	
-	20		1.2.1 Max annual abstr	indicators:	
ation	Licenses		1.2.2 Max dry yrs LFabstr	o D-LFflow,	
Allocation	Lie		1.23 M-Aabstr	<ul> <li>System yield,</li> <li>MAflow</li> </ul>	
		1.2 Irrigation	1.2.4 D-Lfabstr	Farm income     Labour income	
			1.2.5 D-Lisfred		
			1.2.6 M-Asfred		
			1.2.7 System yield		
			2.1.1 D-Lisfred		
		2.1 SFRAs	2.1.2 M-Asfred		
			2.1.3 System yield	Revenue generated	
	25		2.2.1 Max annual abstr	<ul> <li>Water availability indicators:</li> </ul>	
nue	Water use charges		2.2.2 Max dry yrs LFabatr	o D-LFflow,	
Revenue	Nat har		2.2.3 M-Aabstr	o System yield,	
	2 2	2.2 Irrigation	2 2 4 D-Lfabstr	o Maflow	
			2.2.5 D-Lfsfred	Farm income	
			2.2.6 M-Asfred	Labour income	
			2.2.7 System yield		

Notation: 1

M-Avariable x D-Avariable x D-LFvariable x Fine – Line

sfred/abstr

Mean (M) annual (A) value of variable x

Average annual (A) value of variable x during 20% driest (D) years

Average of variable x during low flow (LF) months (May-Aug) in 20% driest (D) years

Farmer and Labour income

Streamflow reduction / Abstraction

These various possible policy options will be discussed on the basis of Table 33. The options, for which results have been generated, will be highlighted in the discussion. This will allow the reader to put the results that follow below into perspective.

# 10.1.1 Policy objectives and instruments (columns a and b)

Policies that target land-based water uses generally target two broad objectives. The first, and perhaps most important, objective is to promote allocations that ensure the equitable, efficient and sustainable use of water.<sup>2</sup> This objective will be referred to as the Allocation Objective in the text below. The system of water use licenses is the main instrument, which the National Water Act has made available to water managers to pursue this first objective.

The second objective is the generation of revenue to cover the cost of catchment management activities and water resources infrastructure. This objective will be referred to as the Revenue Generation Objective. The instruments for this objective are the water use charges. The National Water Act acknowledges the fact that water use charges as a tool can also be used to promote the efficiency of water use, but at this stage this is not the first consideration for the implementation of such charges.

# 10.1.2Policy indicators (column e)

To evaluate how effective they are in pursuing a given policy objective, decision makers will require indicators. For the Allocation Objective, the following indicators are important:

- Water availability (i.e., D-LFflow, M-Aflow, system yield),
- Income to the farmers,
- Income to farm employees.

The indicators for the water availability assist managers to assess the impact on the overall sustainability of the water allocation. The income to farmers is mainly used for evaluating the efficiency implications, whereas both income to farmers and employees can be used to assess the equity implications.

The notion of water availability requires different indicators depending on the situation. In catchments (or parts of catchments) where the river flow is not affected by major reservoirs, water availability for the ecology and the economy would be fairly well represented by the D-LFflow indicator. When major storage facilities influence the flow, low flow as an indicator becomes less

<sup>&</sup>lt;sup>2</sup> The notion of sustainability refers to the human and ecological Reserve, which have to be guaranteed before any water is allocated for other purposes.

important. System yield as an indicator is more appropriate in such cases. Mean annual flows, adjusted downwards by a correction factor, could possibly be used as a proxy for the latter.

In the case of the Mvoti Catchment, there are currently no major reservoirs, hence low flow is the appropriate indicator for water availability. If and when the planned Isitundu dam will be built, system yield (and mean annual flows) will become more important, although low flows will still be adequate to characterize the water availability for the ecology and human upstream of the dam. For these reasons, D-LFflow was used as the indicator for water availability throughout this report.

The above indicators are also relevant for the second policy objective, with the difference that in this case, the actual revenue generated through a specific water charge becomes the main indicator.

# 10.1.3 Activities targeted - hydrological impact targeted (columns c and d)

Land-based activities that result in the reduction of streamflow are subdivided in SFRAs and irrigation activities. The reason for this subdivision is due to the different ways in which they impact on streamflow. When applying a policy instrument to these activities, water managers have to decide which hydrological impact of those activities to target.

#### 10.1.3.1 SFRAs

SFRAs impact on streamflow by reducing the runoff from the land relative to the natural baseline vegetation. Decisions regarding the licensing of or the application of water use charges on SFRAs can be based on their impact on indicators of water availability. In catchments without a dam, their impact on annual or low flows (May-Aug) during dry years is the hydrological impact of interest. In catchments with a dam, the impact on system yield should ideally be considered. This impact is generally not well known, and may differ depending on the size of the reservoir downstream relative to the mean annual runoff. This creates a problem for decision makers who want to keep the cost of policy implementation down by using data that are readily available. This is why in practice mean annual runoff reduction, and to a lesser extent the reduction of flows during low flow periods in dry years, have been used as the hydrological impact targeted.

#### 10.1.3.2 Irrigation activities

The case of irrigation LUMPS is more complex. Irrigated LUMPS generally result in a higher runoff compared to the natural baseline vegetation, but against this stands a high volume of water applied on the land. The water applied is either abstracted directly from the river, or drawn from storage facilities, in which case it was abstracted during some previous other time period. The resulting impact on streamflow is a combination of both effects.

From a practical point of view, it is most straightforward approach is to focus on abstraction. One can focus on the maximum abstraction allowed as specified by the licence. This maximum is specified as an annual figure applicable for all years. It reflects the maximum requirement of the crop under the most unfavourable conditions, and is derived through crop yield models such as the Thompson model (Thompson, 1976 in Schulze, 1995). Alternatively, maximum abstraction levels can be specified for a growing season as whole, plus for certain key periods, such as low flows during dry months.

Instead of looking at maximum allowable abstraction, one could also focus on average actual abstraction. As shown in Creemers and Pott (2000), it is possible that actual abstraction and the maximum allowable abstraction differ significantly. These averages can be considered for annual periods or specifically for the low flow periods during dry years.

Irrigation abstraction is a hydrological variable that is relatively easily ascertained. The actual impact on water availability is more complex. As for SFRAs, one can look at the impact on low flows during dry years, or, when major storage facilities play a role, on system yield (and adjusted mean annual flows as a proxy). To determine these impacts, one needs to take into account possible differences in timing between abstraction and application, and critically important and the return flows. This can only be determined by using hydrological models that focus on system yield and runoff processes, such as ACRU, and the WRYM.

# 10.2 Focus of the Analysis: Assisting the Implementation of the National Water Act (1998)

The above discussion gives a brief overview of the variety and complexity of the options which water managers' face when deciding how to best use the toolkit of policy instruments they now have at their disposal. The current policy situation is one of transition as water managers and stakeholders seek ways to practically implement the new legislation. In terms of controlling land-based water uses, the key differences between the old and the new legislation include the following:

 The range of activities that could be targeted by policy makers was narrower. For example, water managers had little recourse to control water use associated to the ownership of riparian land.

<sup>3</sup> Say something about curtailment, natural restrictions because of water availability.

ii. The range of instruments and the conditions that can be imposed while implementing these instruments was narrower. For example, water use charges can now be levied, and the introduction of the Reserve concept gives water managers strong powers in controlling landbased water uses in areas where the Reserve is not met.

Apart from being able to target more activities with a broader toolkit, water managers now face the challenge to direct their policies more explicitly at water availability. The focus on water availability means that averages of annual conditions can no longer be the dominating guideline for policy implementation. Indicators that reflect what happens during dry years, and particularly during the low flow months of those years will have to be considered.<sup>4</sup>

The HEAM is precisely developed to assist water managers in dealing with these three challenges:

- (i) More activities,
- (ii) A boarder set of policy instruments, and
- (iii) The use of more refined hydrological data for policy implementation.

The first two of these challenges will be addressed by evaluating the economic and hydrological implications of targeting additional activities and introducing new policy instruments. The third challenge will be addressed by comparing the economic and hydrological implications of policies, which do use more refined hydrological data, with those that do not. This will give decision-makers the opportunity to compare the hydrological and economic gains, which such more refined implementation may create, with the extra cost associated with its implementation.

Generally speaking, the adopted approach is one in which the HEAM is used to evaluate the economic costs imposed on society, as well as the hydrological implications, which different policy options would create in pursuing a certain policy objective (i.e. a certain target of low flow during dry years, or a certain level of revenue generation).

#### 10.3 Structure of the Results Section

The discussion of the results starts with the validation of the model. The section after that will deal with the so-called efficient or income-low flow trade-off curve. The points on this curve reflect farm plans that a certain contribution to low flow in the most efficient or cost-effective way. This is useful to evaluate the economic and hydrological implications of certain policies. The sections thereafter

<sup>4</sup> The hydrological impacts that were targeted were generally focused on mean annual ranoff reduction for afforestation activities, or maximum allowable annual abstraction for irrigation activities.

deal with the evaluation of a selection of policy options. The following policy options will be considered.

- Licensing of SFRAs. The cost of the implementation of the APS as a strategy to achieve a
  certain low flow objective will be evaluated.
- Licensing of irrigation activities. The costs of achieving a certain low flow objective by
  curtailing water abstraction rights will be evaluated. Particular emphasis will be placed on
  comparing the costs of using an approach which characterizes abstraction rights only in terms
  of their mean annual abstraction versus a more refined approach which would define
  abstraction rights not just annually, but also for the low flow periods during dry years. This
  corresponds to policy options 1.2.3 and 1.2.4 in Table 12.
- Water use charges. The comparison will focus on the inefficiencies induced by basing
  charges on mean annual runoff reduction rather than low flow reduction, in catchments where
  low flow is the prime concern. Furthermore, this section will also look at the implications of
  ignoring the following impacts created by the return flows on irrigated land-uses. Currently,
  water managers focus their attention on abstraction while often ignoring return flows. This
  corresponds to cases 2.1.1 and 2.1.2, and 2.2.3 to 2.2.6 in Table 12.
- Trading of water rights. In the last section, a short discussion will be offered on the potential for trading and requirements for it to occur.

# 10.4 Validation of the GAMS model: Development of a Parallel Excel Model and Comparison with Actual Situation

To guide the development and contribute to the verification of the GAMS model an Excel spreadsheet model was developed. This model is not an optimisation model, but purely an accounting model. Its input variables correspond to the choice variables in the GAMS model: CROP<sub>z,p,s</sub> (although no distinction was made for different land categories) and WAB<sub>z,p</sub>. For a given land-use allocation, the model will then calculate immediately the corresponding economic and hydrological output information. The model was set up in such as way that two land-use scenarios could be compared at the same time.

The main benefits of this Excel model are:

- The flexibility to compare different scenarios, including those that are not optimal,
- The opportunity to verify the GAMS model as it was being developed and expanded,

#### · A better overview of input and output data.

The extent to which the GAMS model is able to predict the farm plan currently adopted by the farmers will be discussed on the basis of Tables 34a and b. The accuracy of the model will be evaluated in terms of the success of predicting the land-use allocation, the value of key economic indicators, and the quantities of water abstracted. The tables will be discussed consecutively, each time farm per farm.

#### Land use and economic variables: farm A

Consider first farm A. As the afforestation permit of 109 hectares is also built in into the model, it is not surprising that the total predicted afforested area equals 109 hectares. The main difference when it comes to species choice, is that wattle and poplar are much more attractive to the farmer according to the model. This is due to the fact that the price of wattle bark has seen a strong increase in recent years whereas the decision to plant pine was taken 10 or more years ago at a time when that species was attractive.

The predicted area under irrigated crops is more than double the current area. This can be explained by the fact that the farmer is currently constrained by access to capital, which does not allow him to invest in irrigation equipment in order to fully exploit his irrigable land. Discussion with the farmer suggested that he would never consider allocating more than about 15 hectares to potatoes given the increased management requirements and risks involved. This was built in as an explicit constraint. Otherwise the model would have allocated a much higher proportion of the irrigable area under potatoes, despite the fact that through a risk factor of 0.25, risk was accounted for.

The farmer currently keeps 63 hectares under veld, most of which he uses for an extensive beef operation which yields marginal benefits, and which has been omitted from the model. About 9 of those 69 hectares are arable. The model predicts that these would be used for dryland maize. The reason why the farmer does not opt currently for the more lucrative maize option lies in the fact that he runs a small-scale tourism operation along the side, and he has plans to increase that operation in the future. The planting of maize on these 9 hectares would create a strongly negative visual impact for his tourism operation.

Table 33a Actual and predicted land use and economic variables

	Farr	m A	Fari	m B	Farm C	
	Actual	Predicted	Actual	Predicted	Actual	Predicted
Land-use (ba)						2 - 15
Forestry	109	109	885	886	999	999
Gum	9	14	55	342	256	400
Pine	70	0	555	0	282	(
Wattle	30	65	275	5/3	461	599
Poplar	0	30	0	0	0	(
Irrigation	23	48	221	220	0	0
Maize	13	33	0	0	0	(
Seed Maize	0	0	147	132	0	(
Sugar cane	0	0	74	88	0	(
Potatoes	10	15	0	0	0	- (
Dryland	65	49	0	0	0	0
Maize	65	49	0	0	0	(
Veld	63	54	0	0	343	343
Economic indicators (199	9 Rand - 000s)	E91.25.05	27 20 20	100000	SYRERSY	
Gross revenue	906	1221	5099	6000	3873	4394
Farm income	162	243	841	978	723	793
Labour income	146	185	1287	1543	1025	1176

Note: The predicted landuse and associated economic variables were generated using the HEAM, whereas the actual landuse is the currently observed landuse for each farm respectively.

As far as the economic indicators are concerned, the observed differences reflect the differences in land-use allocations. Obviously, the 'actual' gross revenue figure for farmer A is significantly higher than his real current annual income, as it includes an annualised component for the forestry component of his farm.

#### Land use and economic variables: farm B

The estimated area under forestry corresponds to the actual area, but the species mix is different. The same explanation as before is valid. The mix of irrigation crops was predicted fairly well. The model predicted that the farmer would adopt an irrigation region of medium intensity for maize and one of low intensity for sugar during the dry years. This corresponds to the actual strategy adopted by the farmer.

The difference between the economic indicators is mainly due to the difference between the actual and predicted species mix for forestry.

Land use and economic variables: farm C

As for the previous farms, the estimated area under forestry corresponds to the actual area, but the species mix is different. This also explains the difference in the economic indicators.

#### Hydrological variables: farms A and B

As far as the verification of the abstraction is concerned (Table 34b), this was more difficult due to the lack of monthly data on actual abstraction and water availability. The water available to both farmers was modelled with Acru. Only forestry plantations and patches of grassland occur within the catchment of these farms. The streamflow at the entry of these farms was therefore fairly straightforward to model. These simulated flows are listed in the columns with the heading 'Streamflow Available'. This streamflow corresponds to the water availability in the case of farmer A but not for farmer B. The latter uses farm dams with a combined effective capacity of 700 000 m<sup>3</sup>. These dams are used to ease out streamflow differences between seasons, as well as a form of insurance during dry years. During normal years he abstracts more than what he needs for his irrigation during these years. It was assumed after consultation with the farmer that this reservoir allows the farmer to apply 200 000m<sup>3</sup> more than the amount abstracted from the river during dry years. It was further assumed that the farmer would not abstract more than 33% of the flow during low flow periods in dry years. These assumptions are embedded in equations 3 to 17 in sections 9.2.2 and 9.3 and they were also integrated into the Excel model.

The actual and predicted abstraction volumes were simulated by the Excel model and the GAMS model respectively. As such the comparison between actual and predicted abstraction does not constitute a true verification of the hydrological results of the HEAM model. It is rather the comparison with the streamflow available that provides an opportunity to test the realism of the hydrological results.

For farmer A, one sees that the actual and predicted abstraction constitutes only a small fraction of the water available. This corresponds to the farmer's statement that he is not constraint at all by water availability. Farmer B is clearly constrained by water. During low flow months, both in normal as in dry years, he requires the use of farm dams. This implies that he uses the 33% of low flow which he reasonably can extract. This also corresponds to that farmer's statement of the constraints he experiences in terms of water availability.

Table 33b Actual and predicted hydrological variables

			Farm A		Farm B			
		Streamflow	reamflow Abstraction		Streamflow	Abstraction		
		Available	Actual	Predicted	Available	Actual	Predicted	
N1	Annual	9777	78	155	1997	950	1009	
Normal	Wet months	8614	67	139	1759	876	933	
Years	Low flow months	1163	11	16	238	74	74	
D	Annual	3447	84	171	704	493	475	
Dry	Wet months	3227	74	156	659	480	462	
years	Low flow months	220	10	15	45	13	13	

Notes to tables 34a/b:

Irrigation intensities were not included in the comparison.

Sources

The current income does not include any income derived from the forestry plantations. \* Actual land-use allocation: Discussion with farmers

Tables 34a/b:

Actual economic indicators: Simulated with Excel model using economic data supplied by farmers.

Verified with farmers.

\* Hydrological indicators: Simulated with Excel model, using hydrological data supplied by ACRU as well as information on abstraction patterns as supplied by farmers.

#### Conclusion

Although the estimated farm plans did not correspond exactly with the actual farm plans, the differences were considered to be acceptable as they were due to factors which were not modelled: capital constraints, the uncertainty created by the National Water Act, and the influence of past prices on the current species mix in forestry.

# 10.5 Efficiency Analysis: Income-Low Flow Trade-Off Curves

To facilitate the discussion on efficiency use will be made of a curve that shows the relationship between the use of low-flow (i.e.streamflow during low flow months during dry years) as a farm input and the corresponding farm income. The streamflow during each of the 4 hydrological periods are different commodities, with a different scarcity value. The streamflow during low flow months in dry years is the scarcest, and is also the most important from an environmental point of view.

The GAMS model was used to calculate the maximum farm income (measured in terms of enterprise net margin) that can be achieved with a given level of maximum allowable streamflow reduction during low flow periods. These points give rise to the curves in Figure 15.

These curves are based on the assumption of current prices for all inputs (i.e. zero charges for water abstraction or streamflow reduction) and the absence any policy-induced constraints on abstraction or streamflow reduction (such as the APS).

The graphs can be read as follows. The x-axis represents the farm's contribution to low flow in the river. The point of zero low flow reflects the contribution the farmer would make if water availability

during whatever period would be his only constraint. This contribution is normalized to zero. In other words, it is the situation that would prevail if no constraints would be imposed by water management policies, or if the farmer would ignore concerns of and pressure from downstream neighbours. This level of low flow contribution will be referred to as the 'No-Policy' (NP) level. The level of low flow at the right-hand extreme of the x-axis represents the flow that would be generated if the entire farm would be covered by the baseline (natural) vegetation. This level is referred to as the Virgin Runoff (VR) level.

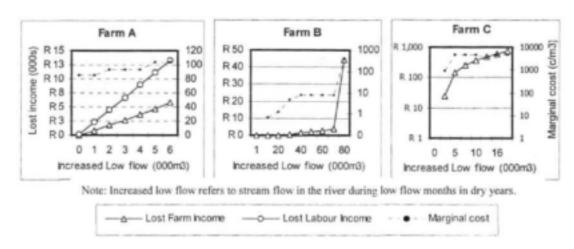


Figure 15 Low flow-income trade-off curves for various farm types

Starting from the No-Policy level, increasing the farm's contribution to low flow necessarily leads to a loss of farm income. Labour income may be affected as well. This change could be either positive or negative, depending on whether the farm plans which contribute more to low flow, are more or less labour intensive. These changes in farm and labour income can be read from the solid lines. The dotted line gives the marginal cost of increasing the farm's contribution to low flow.

# 10.5.1 Farm A: small mixed farming operation

Consider first the small mixed farming operation of Farmer A, who irrigates through direct abstraction from the river. The following key observations can be made:

- The income to the farmer decreases at almost a constant marginal rate of about R1 per m³ of water contributed to low flow.
- Labour income reduces at more than double that rate.

The increased contribution to low flow is achieved by switching some of the area under irrigated potatoes to irrigated maize (high application). This is not surprising: irrigated potatoes do require winter irrigation (i.e. abstraction during low flow months), whereas irrigated maize involves irrigation during summer months. Because of the return flows, irrigated maize actually increases low flows during dry years. Table 35 illustrates this by comparing the water application and streamflow reduction of irrigated potatoes and maize during dry years. The data are generated by ACRU.

Table 34 Comparison of hydrological impact during dry years of irrigated potatoes and maize

Impact during dry years	Water	applied	Streamflow reducti	
	Annual	Dry months	Annual	Dry months
Irrigated potatoes	4175	1000	2820	667
Irrigated maize	3275	0	1977	-147

Note: For both crops the irrigation regime was 25mm every 7 days

#### A number of remarks are worth making.

- i. Within the scope of this project, it was not possible to simulate the hydrological impacts and yields associated to high, medium and low levels of irrigation application for potatoes. Nor was it possible to assess the impact of delaying the planting date so that less or even no abstraction irrigation occurs during low flow periods. With these refinements, the marginal cost of generating more low flow would come down significantly, to levels, which can be observed for farm B (see below).
- The model explicitly takes into account return flows. Current decision-making does not give
  much consideration to return flows given the difficulty in quantifying them. Sections below
  will focus on the implications of not taking into account return flows.
- iii. Due to the positive impact of irrigated maize on low flows during dry years, it is possible for the farmer to generate a contribution to low flows during dry years that is equal to that of the baseline natural vegetation, by simply changing the mix of his irrigated crops. He does not have to change the area under irrigation nor does he have to reduce the afforested area.
- iv. Cognisance must further be taken of the fact the income-low flow trade-off curve as taken depicted here, assumes no constraints other than water availability during the low flow months in dry years (shaded area in Table 36). Due to the irrigation of the maize crop in summer for farm plan VL, it is not surprising that there is a large streamflow reduction (or roughly about 145 000 m³) during the wetter months, both in normal and dry years.

Table 35 Streamflow from Farm A under virgin conditions compared to under the farm plan generating the Virgin Runoff low flow level

	Streamflow contribution (000m <sup>3</sup> )	Annual	Low flow months	Wet
Normal	Streamflow contribution with farm covered by natural vegetation	300	27	273
Years	Streamflow contribution under farm plan VR	149	23	126
Dry	Streamflow contribution with farm covered by natural vegetation	159	7	152
years	Streamflow contribution under farm plan VR	15	7	8

Note: Farm plan VR is the farm plan for which the D-LF streamflow is equal to the Virgin Runoff level. Its land allocation is: 63% forestry, 15% irr maize, 19% dry maize, 3% irr potatoes.

If low flows during dry years are the only concern, farm plan VR demonstrates indeed an efficient use of water. Significant volumes of water are abstracted and applied during wet months when water is not scarce. Through the lagged return flows, this water abstraction generates additional streamflow during low flow periods. In other words, the soil is used partly as a sponge to absorb water during wetter months and release it during the subsequent low flow months.

# 10.5.2 Farm B: Large mixed farming operation

Key observations for farm B include (Figure 15):

- Farmer B can generate a contribution to streamflow during low flow months in dry year, which equates the runoff under virgin conditions at a minimal cost: about R0.07 per m<sup>3</sup>. This is achieved by switching to less intensive irrigation regimes, and by switching from irrigated sugar cane to irrigated seed maize.
- Generating additional streamflow beyond that level sees a rapid rise in the marginal costs.

The following remarks need to be added.

 The impact on labour income was not depicted as it fluctuated significantly. In other words, the monotonous relationship between low flow and labour income, which was observed for the previous farm, does not apply to this farm.

# 10.5.3 Farm C: Large family-owned forestry operation

Key observation for farm C include the following:

- Farmer C has no alternatives to the planting of forestry crops. Most of his land is non-arable
  due to the steep slopes. The suitability for the flatter arable parts for the growing of annual
  crops is limited due to low temperatures.
- As a result, increasing the farm's contribution to low flow can only be achieved by reducing the area under forestry. This is very costly and amounts to a marginal cost R45.00 per m<sup>3</sup> of water during low flow months in dry years.

# 10.6 Licensing: SFRAs

The income-low flow trade-off curves provide a baseline to compare policies against. In this section, the focus will be on the licensing of SFRAs. The policy regarding the licensing of SFRAs has changed significantly over recent years. Policy makers are now firmly convinced of the fact that the focus needs to be shifted or at least broadened from the reduction of mean annual flows to the reduction of flows during low flow periods (DWAF, 1999a). The past system of Afforestation Permits, the precursor of the SFRA policy, often focused on the latter.

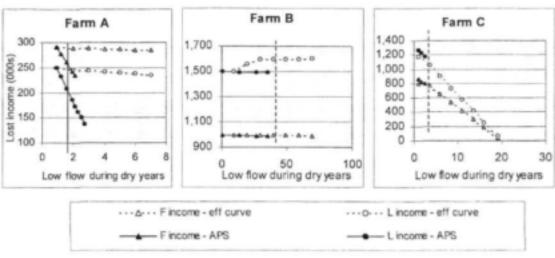
The examples below will illustrate the cost of using the APS to address low flow problems in a catchment. The APS was the only water management policy that was applied in the Upper Mvoti Catchment up to now, this analysis would at the same time provide a perspective on the efficiency of the current situation in the upper Mvoti Catchment.

#### Farm A: small mixed farming operation

Consider first the small mixed farming operation. The farmer's maximum area under forestry has been constrained to 109 hectares. Figure 16 illustrates that through this policy, the runoff from the farm is about 1800 m<sup>3</sup> higher during the low flow months in dry years. The income-low flow trade-off curve (this time shown in terms of the reduction of total farm income, as opposed to the increase in the loss of farm income) shows that the farmer could have achieved this contribution to low flow at a fraction of the cost, simply by adjusting his irrigation practices. His average annual income would be about R45 000 higher. Figure 16 further shows that the income to labourers would have been about R40 000 higher if this low flow target had been met in the most cost-effective way.

#### Farm B: Large mixed farming operation

Farmer B is not constrained by the APS system: his area under forestry is equal to the amount he would plant without any constraints to forestry. Nevertheless, this does not mean he operates at the point, which was defined as the No Policy level. Earlier it was pointed out that he does not exercise his full irrigation right during the low flow periods in dry years out of concern for the environment and for his downstream neighbours. Figure 16 shows that the cost to the farmer of doing so, i.e. Finc<sub>No Policy</sub> – Finc<sub>Current</sub> is relatively low, and corresponds to most cost-efficient path. The contribution to low flow, which he voluntarily makes, is done in the most cost-effective way (i.e. at about R0.07per m<sup>3</sup>).



Note:

- . Increased low flow refers to stream flow in the river during low flow months in dry years.
- The vertical line represents the path followed as a result of policy induced, or in the case of Farmer B, voluntary, LUMP changes

Figure 16 The location of the current land use allocation vis-å-vis the low flow-income trade-off curves

#### Farm C: Large family-owned forestry operation

Farmer C is constrained by the APS in terms of the rule that only 75% of the farm can be planted to forestry. Under the No Policy scenario, it is assumed that the farmer could plant 80% of his farm to forestry. The Figure shows that the extra low flow generated through this measure is limited: only about 1300m<sup>3</sup>. The cost of achieving this is high: about R75 000 and R100 000 in terms of annual farmer and labour income respectively.

Strictly speaking, this 75% rule was introduced primarily for biodiversity purposes, i.e. to maintain corridors for wildlife. However, this rule does have both an economic and hydrological impact, and that is what is focused on here.

#### Summary and Conclusion

The past implementation of licensing for SFRAs through the APS was costly for two reasons:

- · It forced some farmers such as Farmer A to adopt inefficient farm plans.
- It forced certain farmers to release more low flow at a high marginal cost, while ignoring the farms that could make the same contribution at a fraction of the cost.

Table 37 summarises this. Compared to the No Policy situation, the APS imposed costs on all farms, to generate an additional contribution to low flow during dry years of about 33100 m<sup>3</sup>. This amounts to a total cost of about R104 700 and R42 000 in terms of lost farm and labour income respectively.

The three columns on the right hand side indicate that the meagre contribution in low flows from farms A and C could have been made by Farmer C much more efficiently.

Table 36 The cost of addressing low flow targets through the APS system

	APS			Most efficient approach			
	Increase in Lflow	Lost Fine	Lost Linc	Increase in Lflow	Lost Fine	Lost Line	
	(000 m <sup>3</sup> )	R000s	R000s	(000 m <sup>3</sup> )	R000s	R000s	
Farm A	1.8	30	40	0	0	0	
Farm B	30	2.4	-96	33.1	2.6	-98	
Farm C	1.3	74	98	0	0	0	
Total	33.1	104.7	42	33.1	2.6	-98	
	Cost	APS	Lost farm income:	104	9 - 2.6 = 1	02.1	
			Lost Labour incom	ne 42-	(-98) = 140		

Note: The figures in the Table represent a comparison is made with the No Policy situation.

If this opportunity could be exploited, the same contribution to low flow could be guaranteed while increasing farm and labour incomes by about R102 100 and R140 000 respectively (compared to the current level).

These results can be extrapolated to the two upper Quaternary Catchments (U40A and U49B) as a whole. Of the total area of 703 km<sup>2</sup>, about 387 km<sup>2</sup> is under forestry while 131 km<sup>2</sup> remains as grassland. If we assume that from a biodiversity point of view, one could still allow another 35km<sup>2</sup> to be afforested (which would take the afforested area from 55% to 60% of the total catchment area),

<sup>6</sup> This level of 80% is arbitrary in a way, but it was chosen to highlight the impact of choosing different percentages.

farm incomes would increase by R3.7 million while labour incomes in the catchment would see an estimated increase of R4.9 million.

This indicates some of the key deficiencies of the old Water Act. It provided water managers with the legal mechanisms to target afforestation land-uses in a bid to protect low flows within the catchment, but these managers had no legal recourse to deal with the main culprit for low flow reduction, the direct abstraction for irrigation during low flows. These activities were protected by the riparian principle of access to water.

# 10.7 Licensing: Irrigation Rights

The NWA (1998) has done away with the riparian principle and provides the opportunity to regulate irrigation activities where appropriate. The complexities of regulating irrigation activities were alluded to earlier. In this section a comparison will be made between two possible approaches. Under the first approach, irrigation rights are registered in terms of the annual amounts. In other words, farmers will consider how much they maximally need to abstract to satisfy the requirement for his current LUMP mix. The second approach is a more detailed one: irrigation rights will be specified in terms of the abstraction permitted annually, and in terms of abstraction permitted during low flow months periods in dry years. It will be assumed that water managers and farmers agree on a system to declare a year a 'dry year'.

Consider now the situation in which water managers have to approve the licence applications for both irrigation and SFRA activities in a catchment for which the Reserve during low flow periods is not met. This could be the situation in the Mvoti Catchment, although there is no final judgement yet on whether the reserve requirements in the Mvoti Catchment are met or not.

Table 38 below illustrates the two approaches that were modelled for the case of farm B. The data in the top half of Table 38 reflect the No Policy situation for that farm. The farmer would be constrained by water in the dry years, and he is assumed to use *all* the available water in the stream during these years, both during the dry and wet months. During median years plenty of water is available, and he can satisfy his needs by extracting only during the wet period, using the dam for whatever irrigation requirements he has during dry months. Under the first scenario, it is assumed that the farmer would apply for a licence corresponding to the maximum annual amount he needs, i.e. 1 200 000m<sup>3</sup>. Due to a concern regarding low flows, this annual right will then be reduced gradually to about 600 000m<sup>3</sup>.

Under the second scenarios, the farmer has to specify both an annual abstraction amount, as well as an abstraction amount during the low flow periods of dry years, i.e. 1 200 100 m<sup>3</sup> and 45 000 m<sup>3</sup>. The

water manager would then reduce his low flow allocation during dry months from 45 000 to 22 500 m<sup>3</sup>.

Table 37 Illustration of irrigation scenarios for Farm B

		Annual	Dry months	Wet months	
NO POLICY SITUATION		m' (000s)	m3 (000s)	m3 (000s)	
Water availabil	ity vs. abstraction				
Median years	Water Available	1997	238	1795	
	Estimated abstraction	1200	100	1100	
Dry years	Water Available	704	45	659	
	Estimated abstraction	704	45	659	
Scenario 1: red	uction of annual rights				
Median years		1201 → 600	Unspecified	Unspecified	
Dry years		1201 600	Unspecified	Unspecified	
Scenario 2: Rec	luction of rights during lo	w flow periods		-71 EG. 979]	
Median years		1201 (unchanged)	Unspecified	Unspecified	
Dry years		1201 (unchanged)	45- 22.5	Unspecified	

Note: The estimated abstraction under the no-policy situation should not be considered to be equal to the actual current abstraction by the farmer

Figure 17 below shows that restricting annual abstraction rights does increase median annual flows, but it is ineffective when it comes to improving the low flows during dry years. Farm B is used as an example. The increase in average annual flow that is achieved in this way comes at a marginal cost of R0.08 per m<sup>3</sup> for the farmer. The increase of low flow comes at a cost of about R3 per m<sup>3</sup>.

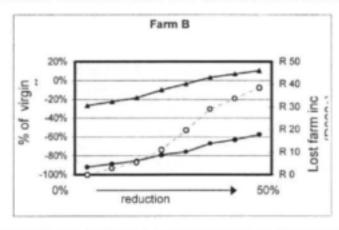




Figure 17 The impact of a reduction of annual abstraction rights (scenario 1)

Figure 18 demonstrates that the second approach is much more effective when it comes to low flows. In this case both low flows and annual flows are increased at a cost of R0.08 per m<sup>3</sup>.

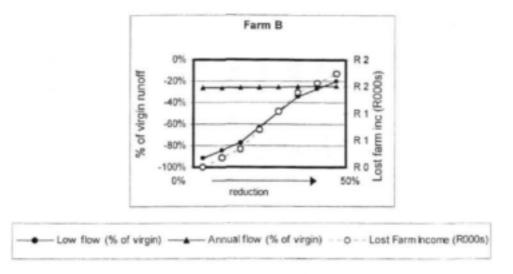


Figure 18 The impact of a reduction of abstraction rights during low flow months in dry years (scenario 2)

#### 10.8 Streamflow Reduction Charges

A further policy option to be considered is the implementation of water use charges to raise funding for catchment management. These charges should ideally be related to the streamflow reduction as this caracterises the impact of a LUMP on the water resources in a catchment, hence the term 'streamflow reduction' charges.

Obviously, water managers are keen to know the side effects of such charges: do they lead to changes in land-use decisions and consequently water availability in a catchment, and do they lead to more efficient use of water.

Four policy options, a, b, c and d, are evaluated. They are explained on the basis of Table 39a/b and Table 40 below. Under options a and b, charges are based on average annual streamflow reduction. Under options c and d, charges are based on the estimated average streamflow reduction during the low flow months in dry years. Options a and c differ from options b and d respectively in that they ignore certain hydrological impacts: (i) runoff changes associated to irrigated land-uses are ignored, i.e. only abstraction is targeted, return flows are ignored, and (ii) runoff changes associated to dry land land-uses which are not declared SFRAs (such as dry land maize) are ignored. In this respect, options a and c correspond more closely to the current views on implementation of water use charges than options b and d. The latter, however, would be the more correct approaches.

Table 38a Four different ways of implementing a streamflow reduction charge

	Return flows (i.e. runoff changes associated to irr land uses) and non-SFRA dryland land-uses				
	ignored	accounted for			
Average annual impact	a	b			
Impact during low flow months in dry years	e	d			

Table 38b shows the hydrological impacts for a selected SFRA LUMP (wattle) and irrigation LUMP (maize, 25 mm every 7 days) and illustrates which impacts would be targeted by which policy option. The hydrological impacts for the irrigated LUMP are broken down as usual between runoff reduction and abstraction, with the sum of the two being equal to the streamflow reduction. It is assumed that abstraction occurs directly from the river. The negative runoff reduction for irrigated maize refers to the fact that irrigated maize generates a higher runoff from the land compared to Acocks. The Table illustrates that the runoff increase resulting from dry land maize is only taken into account by policies b and d. These increases are not insignificant as they amount to close to a third of the annual abstraction.

Table 38b Three different ways of implementing a streamflow reduction charge

m <sup>3</sup> per time period (00	Median years	Dry years		
SFRA	Runoff reduction	Annual	435 <sup>a,b</sup>	312
Wattle		Low flow months	37	19 <sup>c,d</sup>
		Wet months	398	293
Non SFRA	Runoff reduction	Annual	-151 <sup>b</sup>	-173
Dryland maize		Low flow months	-31	$-30^{d}$
		Wet months	-120	-143
Irrigation activities	Runoff reduction	Annual	-1103 <sup>b</sup>	-1298
		Low flow months	-134	-147 <sup>d</sup>
Maize		Wet months	-969	-1150
(25 mm every 7 days)				
	Abstraction	Annual	2750 <sup>a,b</sup>	3275
		Low flow months	0	0 <sup>c,d</sup>
		Wet months	2750	3275

Notes: Policy options a,b,c, and d target the values where they appear as superscript

Abstraction is assumed to be directly from the river - no dams are assumed present.

In practice, water use charges for land-use will have to be expressed on a per hectare basis and paid annually. Table 40 shows the charges per hectare under the different policy options that would generate a given amount of revenue (in this case R20 per hectare for farm A). Consider first option a. The most salient point is that the charges for intensive maize and sugar irrigation are an order of magnitude higher compared to the SFRA. The example of sugar illustrates that switching from intensive to less intensive irrigation brings the charges down significantly, to a level similar to that of the SFRA.

Table 39 Annual per ha charges for key LUMPs required to generate revenue corresponding to R20/ha for Farm A

		Policies targeting annual impacts		Policies targeting low flow impacts	
Rands per ha Annual charge		Policy a	Policy b	Policy c	Policy of
Wattle		8.7	17	5.8	15
Irrigated maize (25/7)	Runoff reduction	0	-22	0	-118
	Abstraction	55	55	0	0
	Total	55	33	0	-118
Irrigated sugar (25/7)	Runoff reduction	0	-4	0	-44
	Abstraction	134	134	307	820
	Total	134	130	307	776
Irrigated sugar (15/7)	Runoff reduction	0	12	0	20
	Abstraction	11	11	180	480
	Total	11	23	180	500

Note:

Policy a: based on R0.02 per m³annual streamflow reduction – runoff impacts of irrigated and non-SFRA dryland activities excl.

Policy b: based on R0.04 per m³ annual streamflow reduction - runoff impacts of irrigated and non-SFRA dryland activities incl.

Policy c: based on R1.5 per m³ streamflow reduction during low flow months in dry years—runoff impacts of irrigated and non-SFRA dryland activities excl.

Policy c: based on R4 per m³ streamflow reduction during low flow months in dry years—runoff impacts of irrigated and non-SFRA dryland activities excl.

Shifting the focus from option a to b results in an increase in the charge for the SFRA and low intensity irrigation, while the charges for the intensive irrigation decrease. This is understandable: as farmers get credited for the runoff increases which intensive irrigation generates, one has to increase the per m<sup>3</sup> charge from R0.02 to R0.04 to meet the same revenue target. This results obviously also in a doubling of the charge for the SFRAs.

More marked differences are observed when shifting the target from mean annual impacts to average impacts during low flow months in dry years. It is important to note that charges have to be paid annually, not just during dry years. Consider first option c and compare it with option a. The charge for the SFRA is more or less the same, and even reduces slightly. Irrigated maize is now completely exempt from any charges, as it does not involve any abstraction during the low flow months. Irrigated sugar, however, experiences a sharp increase in per hectare charges as its irrigation seasons starts in August, a dry flow month. When the runoff contributions of irrigation and non-licensed LUMPs are taken into account, the charges between the various LUMPs differ even more. Irrigated maize now receives a net subsidy for its positive contribution to streamflow during the low flow months in dry years. Irrigated sugar, for both levels of intensity, sees a marked increase in the charges. It is important to note that these figures are based on the assumption of direct abstraction from the river.

The above discussion can be summarized as follows:

- Imposing a charge on average annual streamflow reduction would normally imply charges for intensive irrigation, which are significantly higher than those for SFRAs.
- Imposing a charge based on streamflow reduction during the low flow months in dry years
  would lead to vastly different charges for irrigation LUMPs: some LUMPs would remain
  uncharged, or even qualify for a subsidy, while others would be charged very heavily. For a
  given revenue objective, the charges for SFRAs would be more or less the same, irrespective
  of whether the impacts on mean annual streamflow or on low flow during dry years would be
  targeted.

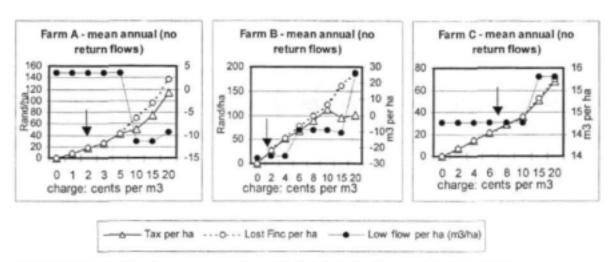
The implementation of each of the four policies was simulated and the results are discussed below. Figure 19 to Figure 22 present the impacts, which these policies would have on farm income, revenue from charges and low flow. To avoid an overload of figures, the impact on land-use decisions is not presented, but will merely be discussed.

Figure 19 presents the results for policy option a. A first observation is that a given charge leads to a different water use charge burden per hectare for different farms. A charge of say R0.02 per m<sup>3</sup> would lead to water use charge burdens of R20, R30 and R5 per hectare for farms A, B and C respectively. In other words, one would need to apply different charges per farms should one wish to have a similar water use charge burden from charges across farms. The arrows indicate the charges required to achieve a water use charge burden of about R20 per ha.

Consider now the impact of the charges for each farm. It is clear that Farmer A will not adjust his farm plan for charges below R0.05 per m<sup>3</sup>. This can be derived from the fact that the low flow

contribution of the farm is unaffected up to that point. At about R0.08 per m<sup>3</sup>, the farmer will switch from irrigated to dryland maize. He will keep his irrigated potatoes. Simulations indicated that he would switch from potatoes to dryland maize only if charges increase beyond R0.35 per m<sup>3</sup>.

An important observation is that for relatively low charges, in this case below R0.05 per m<sup>3</sup>, the loss in farm income is equal to the revenue from charges, collected by the government. As the charges increase, the farmer will at some point decide to adjust his farm plan in a quest to keep his water use charge burden down. From that point onwards, the revenue from charges collected will be smaller that the loss incurred by the farmer. The difference is a net loss to society. It is further interesting to note the impact on low flows for farm A. Given the high contribution to low flow of irrigated maize, it is not surprising that the switch from irrigated to dryland maize leads to a reduction in low flow.



Note: The low flow per ha refers to the contribution to streamflow during low flow periods on a per ha basis

Figure 19 The impacts of a water use charge on mean annual runoff reduction (excluding return flows)

Consider now Farm B. A charge of R0.02 per m³ will induce Farmer B to adjust the intensity of his sugar irrigation, while at the same time reducing the area under irrigated cane by 20 ha, in favour of irrigated seed maize. The model assumes that due to limited demand, he would not be able to expand the area under irrigated seed maize by more than that amount. This obviously leads to an improvement of the low flow contribution of the farm. At about R0.05 per m³, Farmer B will start further reducing his area under sugar cane, this time in favour of dryland maize. As the charges increase, the area under dryland maize will continue to increase, first the expense of irrigated cane, thereafter at the expense of irrigated seed maize. One can further observe that there is a ceiling on how much revenue from charges one would be able to obtain from Farmer B: with this instrument, the maximum would be about R110 per ha.

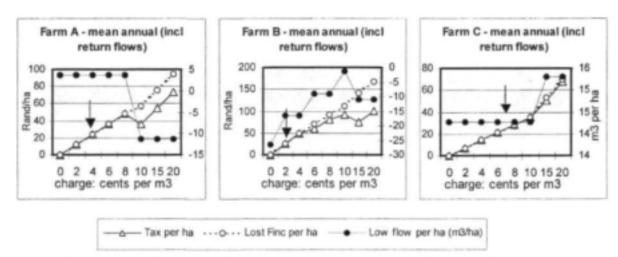
The case for Farm C is simple. Farmer C has no alternatives but to plant forests. The only strategy available is to switch species. The Figure indicates that he would only resort to this option for charges beyond R0.10 per m<sup>3</sup>, or a water use charge burden of about R35 per hectare.

The conclusion of this discussion on water use charges targeting mean annual streamflow reductions without taking into account the runoff impacts of irrigated and non-licensed dryland land-uses, can be summarized as follows:

- Charges that imply water use charge burdens lower than R40 to R50 per hectare per annum will not induce changes in farm plans. Farmers will absorb the measures as an additional cost, without changing their LUMP mix.
- · The impacts on low flow are ambiguous: they can be positive or negative.

It should be noted that these results apply to the three farm case studies, and the farm types they represent.

The next policy option to be considered is option b, which differs from a in that all hydrological impacts of all land-uses are taken into account in calculating the total water use bill for each farmer. The results are very similar. The only difference worth commenting on is the fact that for Farm B, the impact on low flow is slightly different. For relatively low charges, the low flow impact is of Farm B is slightly higher.



Note: The low flow per ha refers to the contribution to streamflow during low flow periods on a per ha basis

Figure 20 The impact of a water use charge on mean annual runoff reduction (including return flows)

Consider now options c and d. The Figure below gives the results for option c. First of all, because only flows during 4 months are considered during dry years, which are only supposed to occur 20% of

the time, it is not surprising that the charge per m<sup>3</sup> is much higher to generate similar amounts of revenue. The charges are about 100 times larger: instead of cents per m<sup>3</sup>, the unit for the charges is now Rand per m<sup>3</sup>. The actual annual per hectare charges to which these volumetric charges give rise, will not differ by a factor 100 as was illustrated in Table 40.

A look at the results for Farm A shows that the low flow now contribution of the farm increases as the charges increase. In the previous cases, the low flow contribution decreased. The reason is the following. Under option a, the farmer switched from irrigated to dryland maize. In this case, he switches from irrigated potatoes (which impacts negatively on low flows) to irrigated maize (which actually contributes to low flows). It is further clear that through this strategy the farmer avoids paying charges, although the cost in terms of lost farm income is considerable.

For Farm B the situation is seems much simpler. As the charge increases to R1, the farmer immediately switches reduces the irrigation intensity for sugarcane to a lower level during dry years. He keeps that level as the charge increase. Only at about R25 per m³ does the farmer adjust his farm plan further. The resulting contribution to low flow is considerably higher compared to that observed for similar levels of water use charge burdens under option a.

For Farm C, there is hardly any change, except for the fact that for the charges considered, no species switch seems to occur.

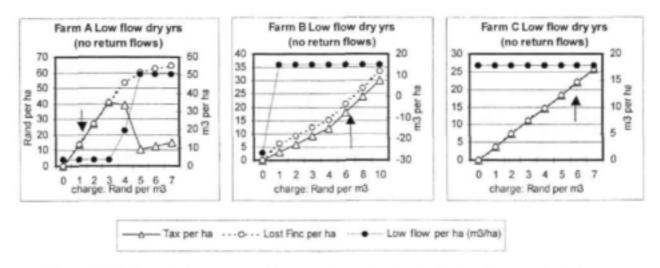


Figure 21 The impact of a water use charge on flow reduction during low flow months in dry years (excluding return flows)

Figure 22 below illustrates the results for option d. The most salient point is that as the charges increase the burden from these charges disappears altogether, and the charges lead to net subsidies for Farms A and B. The ability of such a charge to raise revenue is therefore limited compared to the

previous options. For Farm B for example, it would be impossible to create a water use charge burden that would be higher than a couple of Rand per hectare.

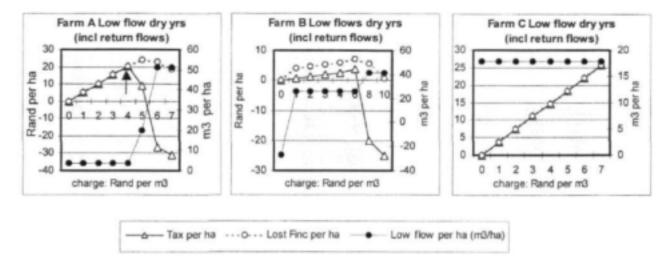


Figure 22 The impact of a water use charge on flow reduction during low flow months in dry years (including return flows)

In conclusion of this section on water use charges, the following can be said.

- Water use charges can be used to raise revenue to cover the costs for water resource management.
- The easiest application of a system of water use charges would be one, which focuses on the
  mean annual streamflow reduction of different land-uses with the proviso that the impact on
  runoff of irrigation and non-licensed dryland land-uses is ignored. With this approach
  revenue can be raised but the impact on low flow is poor at best and negative in some cases.
- Implementing charges targeting mean annual streamflow reduction in its most pure way (i.e.
  by taking into account all hydrological impacts of all land-uses) only creates a marginal
  benefit in terms of improved low flows compared to the 'impure' way. This is probably not
  worth the extra cost of implementation.
- Targeting water use charges on the impact of LUMPs on the streamflow during low flow
  months in dry years would have the advantage of improving low flows while at the same time
  generating revenue. This holds even if the charges are implemented in a way, which ignores
  the impact on runoff of irrigation and non-licensed dryland land-uses.

- If the latter impact is not ignored, the ability of the water use charge to raise significant
  amounts of revenue is impaired as is some cases the charge would be negative, i.e. the farm
  would receive a net subsidy.
- For relatively low charges (water charges of R0.30 per hectare and lower), farmers will not
  adjust their farm plans significantly. Changes, if any, would only involve reducing the
  irrigation intensity for some crops. This is true for whatever approach towards the
  implementation is chosen. The implication of this is that for relatively low charges, it does
  not matter much which implementation approach is adopted.

# 10.9 Trading Opportunities

The marginal cost curves in Figure 15 in Section 10.5 suggest that farmers face radically different marginal costs, which it comes to increasing their contribution to low flows during dry years. This idea was further expanded in Section 10.6. This implies an opportunity for trade in water use entitlements within the agricultural sector, e.g. between irrigation and forestry operations.

For trade in water use entitlements to be possible three conditions should ideally be fulfilled. Firstly, the licence holder must be certain of the quantity, quality, location and timing of the water availability. In the case of water use entitlements for irrigation, the quantity and timing of the water availability is often not known with certainty. At most, an irrigation farmer has an indication of how often drought conditions will apply, and how much he realistically can expect during these periods. He has further no legal recourse if the actual availability is below what he expected. Section 31 of the NWA explicitly states in this respect that a licence does not imply a guarantee of relating to the statistical probability of supply, the availability of water, and the quality of water.

In the case of licences for SFRAs, holders also do not have certainty regarding the availability of water (in this case in the form of rainfall) for their crops. However, on the basis of rainfall records, they however can have an exact idea regarding the statistical probability of supply, unlike a holder of irrigation rights.

It thus appears that water use licences in the agricultural sector do not fulfil this first trading condition completely. However, as will be clear from the example below, this does not have to mean that some form of trade in water rights is not possible.

A second condition for water markets is that water use must not affect, or be affected by water use of third parties. This will in many cases be a possibility. This externality issue will have to be assessed in each context. A third condition, related to the second, is that the right should be enforceable. The government should be able to observe and ensure that the licence holder does not exceed the amount allocated to him in a given time period.

The above discussion suggests that it could be conceivable for Farmer B to sell some of his rights to water during low flow periods, to Farmer C who would ideally like to plant more wattle. Farmer B could either make more low flow rights available by sticking to his current crop mix and reduce the irrigation application intensity, or by switching from a crop which has a negative impact on low flow (e.g. irrigated sugar cane) to one that has a positive impact on low flow (e.g. irrigated seed maize).

Making more water available by reducing irrigation intensities is possible but is difficult with respect to enforcement. Switching irrigation crops seems much more straightforward in that respect.

To illustrate this point, a trading opportunity is discussed. It is not a direct selling of a licence from one holder to another rather it is a licence conversion: Water managers would allow Farmer C to expand his forestry plantations in return for Farmer B's downward adjustment of his irrigation water use entitlements,. Farmer C would compensate Farmer B for this move.

Table 41 below suggests that if Farmer B switches from irrigated sugar to irrigated cane on 12.3 hectares, he would create on average about 67 700 m<sup>3</sup> more streamflow during normal years. During low flow months in dry years, he would create and additional flow of 2950 m<sup>3</sup>.

Table 40 An example of land-based water use licence conversions

	From	From To	Area	Change in	stream flow	Minimum compensation /
				Average annual Normal years	Average low flow Dry years	payment required
Farmer B reducing his water use entitlements	Irr cane	Irr seed maize	12 ha	+64700	+2950	R8667 for 12.3 ha
Farmer C increasing his water use entitlements	Veld	Wattle	144 ha	-64700	-2732	R60/ha

This additional annual and low flow, would allow the water manager to approve licences for other types of water use elsewhere in the catchment, as long as environmental reserve considerations would not be violated. If Farmer B would apply for an additional licence for planting wattle, the water manager could approve 144 hectares without any negative impact on the overall water balance. The Table shows that, in fact, he could approve slightly more if only low flows are his concern. Implicitly this means that for the proposed landuse swaps at both farms, a hydrological conversion ratio of (144/12=) 12 would apply. The water manager would be fully acting within the ambit of the NWA as such licence conversions are allowed under Section 25 of that Act.

By allowing this conversion, the water manager would unlock significant economic benefits. The combined additional labour wages for both farms would amount to over R300 000 per annum. Farmer income for the two farms combined would see a net increase of close to R150 000 per annum.

Obviously, Farmer B would require compensation. The minimum compensation required to cover his reduction of future income is estimated at a once-off payment of R8 667. In terms of the cost per hectare for the new wattle plantations, this would come to about R60. This is well below the market price of forestry permits, which range from R700 to R2 000 per ha.

To promote market forces to take advantage of such opportunities, water resource managers could publicize conversions ratios at a Quaternary Catchment level. Figure 23 below illustrates such a matrix of trading ratios.

These conversion ratios would stipulate the ratios at which the water manager would approve the conversion of water use entitlements. A ratio  $a_{\eta}^{kl}$  would minimally be defined on the basis of the following information:

- The land-uses which the seller like to switch from (p<sub>i</sub>) and to (p<sub>i</sub>).
- The land-uses, which the buyer would like to switch from (pk) and to (pl).

When it comes to irrigation land-uses, one has to make a distinction on whether the abstraction happens directly from the river, from a private farm dam that is off or on channel, or from a large government owned water scheme. In each of these cases, it may be difficult to define in advance one specific ratio. Instead, one could also define ranges of ratios, with  $a_{ij}^{M}$  as a lower bound, and  $a_{ij}^{M}$  as an upper bound. Interested trading parties can then approach the water resource manager with their specific case after which the latter can make a judgement on a which specific ration he will accept.

	[	Seller	
		 Change p <sub>i</sub> to p <sub>i</sub>	
		į	
Buyer	Change pk to pi	 $a_y^{\mathcal{U}}$ or $a_y^{\mathcal{U}} - a_y^{\mathcal{U}}$	
	14		

Figure 23 An example of a matrix hydrological conversion ratio to promote trading of water use licences in the agricultural sector

# 10.10 Meeting the Reserve Requirements

When this research was conducted, the Reserve had not yet been determined for the Mvoti River catchment. This, together with the fact that the model focuses on selected farm case studies rather than the upper catchment as a whole implies that the issue of meeting Reserve requirements cannot be dealt with comprehensively. Nevertheless, it is possible to offer a meaningful discussion of this issues based on the results that were obtained with the HEAM.

Consider therefore a simplified presentation of the catchment in Table 42. This table is based on Table 1, but concentrates only on the major landuses. The focus is further on streamflow reduction during low flow months in dry years. Although Reserve requirements are much more complex this focus on low flows will at least provide some indication of the costs of meeting Reserve requirements.

Table 41 An overview of the main current streamflow reductions in the upper Mvoti catchment

		Streamflow during low flow months in dry years	
	ha	Flow per ha	Total flow (mcm)
Virgin streamflow			
Natural veld	64800	29	1,9
Streamflow reduction		Flow reduction per ha (m³)	Total flow reduction - mem (% of total virgin flow)
Forestry	38700	15*	0.58 (31%)
Irrigation	2400	200 <sup>b</sup>	0.48 (26%)

Total Reduction	64800		0.74 (39.5%)
Grassland	13100	0	0 (0%)
Maize	10600	-30	-0.32 (-17%)

Notes:

a: This is an average for various forestry species.

The table shows that forestry as well as irrigation are responsible for a significant reduction of the virgin flow in the case study area, the 2 upper quaternary catchments. Their combined effect implies a streamflow reduction of about 57%. The positive impact on streamflow of dryland maize compensates almost one third of that reduction. The overall reduction stands at about 40%.

To reduce the current streamflow reduction a number of options are open:

- Disallowing renewals of forestry permits.
   It was seen earlier that this is an expensive route, with a marginal annual cost as high as R45 per m3 of water in low flow months during dry years.
- Changing irrigation intensities and crops
  In section 10.6 it was shown that the 260 heactare of irrigation on farms A and B could liberate a maximum of about 75 000 m³ of water during low flow months in dry years, at a rather low marginal cost of 7 cents per m³. This extra low flow corresponds to about 300 m³ per ha per annum. If a conservative figure of 100 m³ pa per ha is used for extrapolation to the total irrigation in the study area, about 0.24 mcm could be liberated during the critical low flow period at a negligible annual cost of less than R20,000. In other words, the current streamflow reduction could be reduced by a third at a very low cost. There figures are, however, purely indicative and one would need data on other irrigation activities in the

#### Clearing riparian zones.

catchment to make definitive statements.

During the course of the research no specific attention was paid to riparian zones. For the current context Umgeni Water (1997) is used as a reference. The study estimates a cost with a PV in 1996 Rand of about R1.1m for the clearing of 6000 ha of riparian zones. In 1999 Rand and translated to annual values, this would amount to about R50 per hectare annually. As far as the streamflow reduction is concerned, Umgeni Water (1997) estimated a annual streamflow reduction that was about 5 to 6 times that of forestry plantations outside riparian zones. If this ratio is extrapolated to the reduction during low flow months in dry years one

b: This is an estimate. Table 21 suggests that the impact of various irrigated crops and irrigation intensities can vary widely. The 200 m³ pa is purely used as an estimate. The real average impact of irrigation will depend on the actual mix of crops and irrigation intensities in the catchment.

would have a reduction of on average 80m<sup>3</sup> per ha per annum. This would represent an annual cost of 62 cent per m<sup>3</sup> reduction during low flow months in dry years.

Overall it is clear that this study cannot provide definitive estimates of the cost meeting reserve requirements. It is clear that this cost will be influenced by the strategy adopted. Irrigation seems to harbour the most cost-effective options to generate more streamflow during critical dry periods (dry months during dry years). Pushing back forestry on non-arable land is prohibitively expensive. Clearing riparian zones seems to be a relatively cost-effective option but more economic and hydrological data would be required to conclude this with more certainty.

#### 11 CONCLUSIONS

In this document, the development of a Hydrological Economic Agricultural Model (HEAM) is discussed. The results of its application to case studies in the Mvoti Catchment are included.

Each of the 6 key reseach objectives will be reported on.

Research objective 1: Development of a hydrological economic model for the Mvoti Catchment.

Initially, the project was set to focus on the Mvoti Catchment in its entirety. The focus was scaled down to the Upper Mvoti catchment. The idea of creating one single model for that upper catchment was abandoned as it was felt that this would fail to capture the diversity of farm types, each of which might be responding very differently to policy changes. The modelling scale was therefore set at the farm level. Three different farm types were selected, which in a way reflected the diversity of farms occurring in the area:

- · A small mixed farming operation (Farm A),
- A larger mixed farming operation (Farm B) and
- A farm with timber only (Farm C).

The HEAM was developed as a mathematical linear programming (LP) model using GAMS (General Algebraic Modelling System). Like any LP model, the model captured the activities available to the farmer as well as the resource constraints. The key resources available to the farmer include the land and (where applicable) the water that can be abstracted from the irrigation (sometimes with temporary storage in a farm dam). The farmer's impact on the water resources available to downstream users is measured by the streamflow reduction caused by his operation. The streamflow reduction is the sum of two impacts:

- water abstraction from the river
- runoff reduction on the land (i.e. the change in the runoff from the land compared to Acocks)

A key characteristic of the model is that four hydrological periods are considered:

- wet months during dry years,
- · dry months during dry years,
- · wet months during normal years, and
- dry months during normal years

The wet months cover the period September through to April. The months May to August constitute the dry months. The dry years are the 20% driest years in terms of annual runoff from land under natural conditions. Normal years were taken to be years that are centred around the year with median annual runoff.

The introduction of these hydrological periods means that there are four water commodities, each of which has a different scarcity value. This also implies that there are four streamflow, four abstraction and four runoff variables.

The integration of the LP model with the hydrological Acru model was as follows. Acru was used to simulate daily figures for a number of hydrological variables over for the past 45-year period using observed rainfall data. These variables include:

- the streamflow in the river passing through farms A and B, which would be available for abstraction,
- · the amount of water applied per hectare for all of the irrigated LUMPs, and
- the runoff from one hectare of each of the LUMPs.

From daily figures for each of these variables, monthly averages were calculated. These monthly averages were further used to create averages for the four hydrological periods mentioned earlier, which were in turn fed into the LP model.

With respect to the integration of the hydrological and LP model the following can be noted:

- The ACRU model is not seamlessly integrated into or with the LP model. The hydrological model is invoked independently to prepare the hydrological input data for the LP model.
- The LP model then mimics the farmer's maximisation of the enterprise net margin taking into
  account risk. The hydrological impact (streamflow reduction) of the resulting LUMP mix is
  determined within the LP model, and not using the hydrological model. In other words,
  assuming linearity of response, the hydrological impact of the entire farm during each of the
  four hydrological periods is calculated through a linear combination of the simulated impacts
  for 1 hectare.
- The LP model is not a dynamic model but a static model. The results of a static model can be
  interpreted as what would happen in the long run, if current conditions prevailed. Within a
  dynamic model short term factors that influence farm decisions, such as capital constraints, or
  more broadly, financial risk, can be modelled.

Research objective 2: Evaluation of the use of permits and licences as water resource management tools

The first policy evaluated was the use of licences for SFRAs and irrigation activities to guarantee enough water for the environment and the economy downstream.

- The old policy, the Afforestation Permit System, was evaluated in this respect. It was found
  that this approach was an inefficient way of trying to meet low flow objectives since:
  - It forced some farmers such as farmer A to adopt inefficient farm plans. Indeed, the same contribution to low flow could be met in a more cost efficient manner.
  - It forced certain farmers to release more low flow at a high marginal cost, while ignoring the farms that could make the same contribution at a fraction of the cost.
  - o It was found that reducing forestry on non-arable land costs at least R9 per m³ of water liberated during low flow months in dry years. Switching irrigated LUMPs to less intensive irrigation regimes may potentially increase low flow at a cost of about R0.07 per m³ of water during low flow months in dry years. In other words, for the case studies in question, it is much cheaper to liberate water from irrigation (by moving to a lower irrigation intensity) than from forestry.
  - The above figures can be used to estimate the extra cost that the APS implicitly imposed on the farmers in the catchment when compared to the most cost-effective approach. In terms of annual farm and labour income for the three farms combined this difference was estimated to amount to R100 000 and R140 000 respectively. An extrapolation to the catchment as a whole suggests that the same flow during low flow months in dry years could have been achieved with annual farm and labour incomes up to R3.7 to R4.9 million higher respectively than they are currently.

Another policy option considered was the use of water use licences for irrigation, in particular the reduction of these licences, as a strategy to guarantee low flows.

It was shown that unless abstraction rights are defined for different relevant hydrological
periods, including low flow months during dry years, this strategy might be costly as well. If
annual rights for farm B are reduced with the idea of increasing low flow during dry years,
one sees in the first place an increase in annual flows. Low flows only increase marginally.
The cost per m³ of water liberated during low flow months in dry years amounts to about R3.

- Defining water use licences in more detail, i.e. by specifying not just rights to annual
  amounts, but also rights to water during low flow months during dry years, would open op
  more efficient options. Reducing such rights would liberate low flow at a cost of R0.07 per
  m³ for farm B. Obviously, such a more refined definition of water use licences would be
  more costly from an administrative point of view, but given the significant efficiency gains,
  this should not be insurmountable.
- Ensuring a certain level of low flows by reducing existing water use licences across the board, or placing a moratorium on the issuing of new licences is unlikely to be efficient, even if water rights are defined in a detailed way. Decision-makers do not have the information, which would allow them to allocate the burden of generating contributions to low flow efficiently within the agricultural sector. An efficient situation would be one in which all farms would face the same marginal costs when it comes to generating contributions to low flow. Indeed, imposing a blanket (say 10%) reduction in water use entitlements during low flow months in dry years, would ignore the fact that for some farmers this reduction is much more costly than for others.
- Through the facilitation of trade in water use entitlements, this problem could be addressed.
  Not only would this trade require a great deal of detailed information regarding the
  hydrological impact of LUMPs, it would also require detailed monitoring of land-use and
  abstraction. The cost of such a system is likely to be significant. These costs obviously
  would have to be covered by the trading parties. It is therefore imperative to investigate in
  more detail the potential gains from trade.

Research objective 3 Assessment of the cost of meeting the Reserve requirements.

The exact requirements for the Reserve have not yet been established in the Mvoti catchment. Reserve requirements are generally a complex set of conditions. In the context of this study the Reserve requirements were simplified to minimal flow requirements during low flow months in dry years. In other words, assessing the cost of meeting Reserve requirements was translated into assessing the cost of generating extra flow during low flow months in dry years.

Furthermore, the fact that this study focused on 3 selected farm case studies rather than on a full sample representative farms in the catchment means that only indicative extrapolations can be made regarding the cost of meeting Reserve requirements.

The results generated by the study show that this cost will be influenced by the strategy adopted. Irrigation seems to harbour the most cost-effective options to generate more streamflow during critical dry periods (dry months during dry years). Pushing back forestry on non-arable land is prohibitively expensive. Clearing riparian zones seems to be a relatively cost-effective option but more economic and hydrological data would be required to conclude this with more certainty.

Research objective 4 Assessment of the impact of water use charges targeting streamflow reduction.

The conclusions from this assessment are as follows.

- Water use charges can be used to raise revenue for CMAs to cover the cost of water resource management.
- The easiest application of a system of water use charges would be one that targets the mean annual streamflow reduction of different land-uses with the proviso that the impact on runoff of irrigation and non-licensed dryland land-uses is ignored. With this approach revenue can be raised, but the impact on low flow is poor at best and negative in some cases.
- Implementing charges targeting mean annual streamflow reduction in its most pure way (i.e. by taking into account all hydrological impacts of all land-uses) only creates a marginal benefit in terms of improved low flows, which is probably not worth the extra cost of implementation.
- Targeting water use charges on the impact of LUMPs on the streamflow during low flow months in dry years would have the advantage of improving low flows while at the same time generating revenue. This holds even if the charges are implemented in a way, which ignores the impact on runoff of irrigation and non-licensed dryland land-uses.
- If the latter impact is not ignored, the ability of the water use charge to raise significant
  amounts of revenue is impaired as is some cases the water use charge would be negative, i.e.
  the farm would receive a net subsidy.
- For relatively low charges (water use charges of R0.30 and lower), farmers will not adjust
  their farm plans significantly. Changes if any would only involve reducing the irrigation
  intensity for some crops. This is true for whatever approach towards the implementation is
  chosen. The implication of this is that for relatively low charges, it does not much which
  implementation approach is adopted.

Research objective 5 Assessment of the options for a system of transferable water rights

The conclusions from this assessment are as follows.

- Farms face significantly different marginal costs in producing low flows. This indicates that
  there are trading opportunities (or licence conversion opportunities).
- An example was given. The seller, an irrigator, could convert a crop with a lower impact on annual flow and low flows. The buyer could in return, expand his forestry operations by converting land currently under say veld. A conversion ratio would have to be set stating how many hectares the buyer can convert for every hectare converted by the seller so that the overall water balance would not be negatively impacted upon.
- In practice, it was shown that a conversion from irrigated sugar cane to irrigated seed maize on 12 ha could allow the switch from veld to wattle on about 144 ha. The net effect of this conversion was estimated to be about R300 000 per annum in terms of labour income, and about R150 000 per annum in terms of farm income. The minimum compensation Farmer C would have to pay Farmer B would come to a payment for a forestry licence of about R60 per ha. Currently, afforestation licences are implicitly valued at between R700 and R2200 in the market place.
- The HEAM's estimate of the economic costs and benefits of the above conversion are approximations. Only the farmers themselves have the perfect information to calculate these. However, a critical determinant in evaluating the potential for licence conversions is the conversion ratio. Farmers have no information whatsoever on this. The water manager could promote such conversions, which lead to a more efficient use of water, by publicising conversion ratios. This could be a matrix with elements a<sub>ij</sub><sup>M</sup> or a<sub>ij</sub><sup>M</sup> a for a buyer wishing to convert from land use k to land use l, and for a seller, prepared to convert from land use i to j, a<sub>ij</sub><sup>M</sup> denote the number of hectares the buyer can convert for every hectare converted by the seller. As conversion ratios will be dependent on how water is abstracted (directly from river, from off or on channel dam, from large public water scheme), a lower bound a<sub>ij</sub><sup>M</sup> and upper bounds a<sub>ij</sub><sup>M</sup> could be stated.

## 12 RECOMMENDATIONS AND FURTHER RESEARCH

A first set of recommendations focuses on improvements in the model.

#### Farm gate prices

The authors of this research acknowledge the importance of the forward and backward linkages to the economy, which in certain instances may result in large societal benefits that in fact exceed the benefits accruing from the production of the raw product on the farm. This is a topic for further research, which can potentially be built into the HEAM.

### Upscaling from the farm level to the catchment level

This study focuses on selected farm case studies. To the extent that they are representative and operate independently hydrologically, one could upscale to the catchment level in a relatively straightforward manner. One would simply multiply the results for each farm by the number of farms of that type in the catchment, and add the results of the different farm types together.

The assumption of hydrological independence will however not hold in a context of water scarcity. Decisions by upstream farmers will affect the opportunities open for downstream farmers. In that case, one may have to model the farms that are hydrologically linked as one system.

#### GIS automation of land categories

The use of GIS to assess land-categories in catchments, in order to assist in the extrapolation of farm level simulations to the catchment level needs to be explored further.

### Hydrological and yield impacts associated to different irrigation intensities

Key findings of the report are based on the fact that farmers can modify the intensity with which they irrigate their crops. More information is needed on how different irrigation intensities impact on runoff and yield, and on how this impact differs in dry versus normal or wet years. This is an area of research that is believed to be of great importance due to the fact that 50% of South Africa's water is held by the irrigation section and ways of moving this water to other sectors, without negatively impacting the economy or society, need to be explored.

### Runoff impacts of non-licensed dryland land-uses and irrigation activities

The costs and benefits of ignoring the runoff impacts of non-licensed Dryland (i.e. non-SFRAs) land-uses and irrigation activities needs to be further evaluated.

#### Improving forestry simulation accuracy

The comments in Table 18 illustrate that there are considerations, such as site species matching, as well as other practical considerations, such as wattle being used as fire-breaks as it does not burn as easily as the other forestry species, which make certain forestry species more attractive on certain lands than others. These considerations require a detailed delineation of the farm, as well as special algorithms in the LP model to capture the forestry related working rules. Due to time constraints, this level of detailed modelling was not undertaken, and the three coarsely defined LCs were used. This may be an area for future model development

#### Testing the accuracy of the hydrological output generated by the LP model

The hydrological output of the model, results from some simple linear calculations, which were described in Section 9. One would have to use ACRU to test the accuracy of generating hydrological outputs using this linear approach.

#### Dynamic versus static modelling

The current model is a static model. Apart from the fact that financial risk cannot be taken into account, it is also limited in dealing with the impact of water storage facilities. One should strive to link the LP algorithm more closely with the hydrological simulation model. However, there will be limits to this due to the different nature of optimisation and simulation models: optimisation models require simplicity – simulation models thrive in complexity. A dynamic model monthly over 45 years would probably have too many choice variables to allow an LP algorithm to find a solution in a reasonable amount of time.

A more modest approach may be to integrate the economic simulation model such as the one developed for this project in Excel, into ACRU. Apart from the economic modules, the hydrological modules from ACRU would also require further development to allow for the specification of allocation/operating rules for water from dams, and the calculation of system yield.

Apart from the above technical improvements of the model, it is recommended that the following issues should be targeted by further research, possibly through the use of this or related models.

## o Trading

The cost required to facilitate trading or conversion of water use entitlements, and the potential gains from the trade and conversions should be further explored. The idea of a matrix of conversion ratios could be tested out in the Mvoti Catchment as a pilot project.

## 13 REFERENCES

BKS Consulting Engineers, 1999, Water Resources Yield Model User Guide: Release 4.1.1, South Africa

COMBUD, 1997 & 1999, Combud Crop Budgets, KwaZulu-Natal Department of Agriculture, South Africa

CSIR, 1994, CRAM: the Catchment Resource Assessment Model, Users Guide β Version, South Africa.

Dallimore, A., Ferrar, S., Pott, A.J., Thompson, D., and Ashburner, B.J., 2000, Water Use and Dependency in the Mhlathuze Catchment: a Macro Economic and Sectoral Analysis (a report by DRA Development to the Strategic Environmental Assessment team of DWAF), South Africa

Dent, M.C., Lynch, S.D., and Schulze, R.E., 1989, Mapping Mean Annual and Other Rainfall Statistics Over Southern Africa, Water Research Commission, Pretoria, Report 109/1/89, South Africa

DWAF, 1996, Mvoti River: Dam Feasibility Study. Supporting Report No. 4, Environmental, Volume 3: Supplementary Documents. Prepared by Ninham Shand Consulting Engineers, South Africa

DWAF, 1999a, Water Conservation and Demand Management National Strategy Framework (Draft), Pretoria, South Africa

DWAF, 1999b, Establishment of a Pricing Strategy for Water Use Charges in Terms of Section 56(1) of the National Water Act, 1998, Pretoria, South Africa

DWAF, 1999c, Water-Use Licensing: The Policy and Procedure for Licensing Stream Flow Reduction Activities, Pretoria, South Africa

DWAF, 2000a, Water Conservation and Demand Management Strategy for the Forest Sector in South Africa, Pretoria, South Africa

DWAF, 2000b, Water Conservation and Demand Management Strategy for the Agricultural Sector, Pretoria, South Africa

Forestry Economic Services, 1997, Forestry Costs in South Africa, 1996: The Green Gold Crop, Pietermaritzburg, South Africa Fulcher, C., Prato, T. and Zhou, Y., 1996, Economic and Environmental Impact Assessment Using a Watershed Management Decision Support Tool. Proceedings of the Seventeenth annual ESRI User Conference, San Diego, July 8-11, United States of America

Geringer, J., 2000, Personal Communication, DWAF, South Africa

Grové, B., 1997, Modellering Van Die Ekonomiese Effekte Van Wisselvallige Waterbeskikbaarheid Vir Besproeingsboere In Die Wintertongebied Met Inagneming Van Minimum Binnestroomvloeivoorsiening, Department of Agriculture, University of the Orange Free State, South Africa

Hazell, P.B.R. and R.D. Norton, 1986. Mathematical programming for economic analysis in agriculture. Macmillan Publishing Co., New York.

Jewitt, J.P.W., Horan, M.J.C., Meier, K.B. and Schulze, R.E., 2000, A Hydro-Economic Assessment of a Compensatory Forest Approach to Clearing Alien Vegetation from Riparian Zones in A South African Catchment, School of Bioresources Engineering and Environmental Hydrology, University of Natal – Pietermaritzburg

Jewitt, G.P.W. and Schulze, R.E., 1999, Verification of the ACRU model for Forest Hydrology Applications. Water SA 25(4), South Africa

MBB Consulting Engineers Incorporated, 1997, Umgeni Water Upper Mvoti Catchment Riparian Zone Rehabilitation Study, South Africa

Muller, M., 1999. Transforming Water Law to Achieve South Africa's Development Vision: A Case Study In National Law, South Africa

National Water Act, 1998, Act No. 36 of 1998

Olbrich, B.W. and Hassan, R., A Comparison of the Economic Efficiency of Water Use of Plantations, Irrigated Sugarcane and Sub-tropical Fruits: A Case Study of the Crocodile River Catchment, Mpumalanga Province, WRC Report No 666/1/99, South Africa

Perkins, J., 2000. The Assessment of Water Use Authorisations and License Applications in terms of Section 27(1) of the National Water Act, 1998, DWAF, South Africa

Schulze, R.E., 1995, Hydrology and Agrohydrology: A Text to Accompany The ACRU 3.00 Agrohydrological Modelling System, Department of Agricultural Engineering, University of Natal, South Africa Schulze, R.E., Horan, M.J.C., Shange, S.N., Ndlela, R.M., Perks, L.A., 1998, Hydrological Impacts of Land-use Practices In the Pongola-Bivane Catchment: A report to Forest Industries Association and Department of Water Affairs and Forestry, ACRUcons Report 26 August 1998, South Africa

Scott, D.F. and Smith, R.E., 1997, Preliminary empirical models to predict reductions in total and low flows resulting from afforestation. Water SA, 23 (2): 135-140, South Africa

Summerton, M. J., 1995, Process and Modelling Studies in Forest Hydrology. M.Sc dissertation. University of Natal, Pietermaritzburg, Department of Agricultural Engineering, South Africa

Umgeni Water, 1997, Upper Mvoti Catchment riparian zones rehabilitation study. Report MO/505/1.Prepared by MBB Consulting Engineers, ACER Africa and PPRI (Plant Protection Research Institute)

## HYDROLOGICAL MODEL INPUTS

#### A. Rainfall

There are three rain gauge sites, located in or just outside the Upper Mvoti catchment, at which adequate rainfall records have been kept. These include rainfall stations: 269611W (30.35 longitude, -29.19 latitude), 270164A (30.60 longitude, -29.23 latitude) and 270219A (30.63 longitude, -29.15 latitude). The most representative rainfall station for each of the 67 HHEZ was selected giving consideration to the distance of each HHEZ from the respective rainfall stations, as well as the mean altitude of each HHEZ compared to the altitude of each rainfall station. The representative median monthly precipitation was estimated for each of the 67 HHEZ, using the GIS gridded median monthly precipitation coverages for the Upper Mvoti, (Dent et al., 1989). ACRU rainfall correction factors were derived for each of the 67 zones, by comparing the median monthly rainfall of each HHEZ with the median monthly rainfall of each respective rainfall driver station, i.e. the rainfall station most representative of each HHEZ.

With respect to HHEZ 24, the following monthly rainfall adjustment factors were calculated for rainfall station 269611A, the rainfall station most representative of HHEZ 24: An observed rainfall record of 45 years, ranging from 1950 to 1995, was used in ACRU for each of the three driver rainfall stations. The daily rainfall in a given month is multiplied by the rainfall correction factors, as shown below, to generate a 45-year daily rainfall record for each of the 67 zones.

#### ACRU rainfall correction factors for HHEZ 24

PERMIT	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Rainfall Correction Factor.	1.05	0.93	0.99	0.90	0.93	0.67	0.67	1.25	1.05	0.91	1.05	0.98

As can be seen from the rainfall correction factors, only small adjustments need to be made to the driver stations rainfall record in the wetter months, however, quite substantial adjustments (33% reduction) needs to be made to the daily rainfall during the dry months of June and July.

#### HYDROLOGICAL MODEL INPUTS

#### B. Irrigation

Modes of irrigation scheduling depend on, amongst other considerations, the irrigation system (equipment), level of management, climatic conditions, water availability, the type of crop, and its stage of growth. Five modes of scheduling are currently available in ACRU (Schulze, 1995) including:

- i. Demand mode scheduling according to soil water depletion levels
- ii. Irrigation with a fixed cycle and in fixed amounts of water application
- iii. Irrigation with a fixed cycle and in varying amounts of water
- iv. Irrigating according to a predetermined schedule, and
- v. Deficit irrigation (Schulze, 1995)

The five ACRU modes of irrigation are not discussed in detail in this report. Irrigation mode used to simulate the hydrological impact of irrigation LUMPs is the irrigation cycle with a fixed cycle and in fixed amounts of water. In this mode of irrigation, commonly in use with center pivot systems, either a pre-selected or otherwise predetermined amount of irrigation water is applied in a fixed cycle. In ACRU the selected cycle length is assumed to continue throughout the growing season, regardless of smaller amounts of rainfall occurring, except that the entire cycle is interrupted and restarted when the rainfall on a given day exceeds a selected threshold amount (Schulze, 1995). The threshold amount selected for this study was 12mm of rainfall. This mode of irrigation is commonly used in practice because it is easily managed.

A few important points that need to be made regarding the simulation of irrigated LUMPs include:

i. In the ACRU model, there are currently three options from which irrigation can take place, including, irrigation from an unlimited supply of water (usually used for planning purposes, such as dam sizing), irrigation from a dam subject to water availability, and irrigation from a river subject to water availability. Due to the modelling methodology adopted, i.e. simulating only one hectare of each HHEZ with each LUMP respectively (67 HHEZ \* 10 LUMPs = 670 runs), it would not have been possible to irrigate from the river, or from a dam, as there would not have been water available. Consequently, water was irrigated from an unlimited supply of water. This is not a true reflection of reality, as not only may there not be enough water to irrigate during dry periods, but water use allocations may be considerably curtailed during these dry periods. In other words, there

may be a physical and/or legal constraint limiting the amount of water available for a farmer to irrigate. However, interviews with Farmer A and Farmer C revealed that only once were they constrained by water. Consequently, curtailments are not considered in the LP model, however, an variable has been included in the LP model, representing the water right of the irrigator.

ii. An irrigation schedule of 25mm of water applied once every seven days was selected, after discussions with the farmers. The application of 25mm every 7 days was simulated fro all irrigated LUMPs, i.e. maize, sugarcane, potatoes and pasture. The months in which irrigation takes place for each of the four irrigation LUMPs is shown in the table below. The grey-shaded areas represent months in which irrigation occurs.

The irrigation LUMPs, and the months in which irrigation takes place.

Irrigated crops	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Sugar	\$20	450	SEX	(Ca)				250	300	10000	150	160
Potato								EVEL)	574	BAY.	100	100
Pasture	150 M	5.803	-394	62-5	GESS:	136	327	22	9/50	15/0/5	ALC:	300
Maize	Miles.	219	2808								2535	EC BE

iii. Of the four irrigation LUMPs selected for this study, only irrigated pastures require irrigation during all four critically dry months of May-August. Both irrigated sugarcane and irrigated potatoes require water to be used for irrigation for one of the 4 months representative of the 4 dry months, i.e. August. The point to be made is the abstraction of water during low flow periods has a high impact on water availability, in that the streamflow is reduced when the river is critically low.

There are parameters in the ACRU model that account for water losses associated with various forms of irrigation. These losses include conveyance losses and spray evaporation and wind drift losses.

#### C. Evaporation

The importance of discussing evaporation is that the ACRU agro-hydrological model is essentially a total evaporation based model (Schulze, 1995). With respect to the hydrological impact of the various LUMPs, the amount of streamflow reduction is primarily due to the evapotranspiration of a given land under different LUMPs compared to the evapotranspiration of the land covered by natural veld (Acocks). Put differently, when simulating the hydrological impact of the various LUMPs for each of the 67HHEZ in ACRU, use was made of a given rainfall record, given soil characteristics and given temperature records. The reduction in streamflow relates to how much water each crop uses directly (transpiration by the plant), as well as the impact of each LUMP on the evaporation from the soil surface (evaporation). The term evapotranspiration refers to both the evaporation from the soil surface, as well as the transpiration from the crops.

However, the amount of water that can be evaporated by each crop on a given day, is dependent on the characteristics of that day, including, amongst others, temperature, wind speed and humidity. Use is made in ACRU of an evaporation reference, referred to as the potential evaporation, which reflects the aforementioned conditions that influence LUMP evaporation. The amount of water that each crop uses relative to the potential evaporation, referred to as the crop coefficient, is determined from experimental observations.

The reference evaporation used by ACRU is daily A-pan equivalent evaporation values (Schulze, 1995). Month by month subcatchment averages, shown in the table below, of mean A-Pan equivalent potential evaporation were determined from one minute by one minute grid values of reference potential evaporation. The grid values were derived on a regional basis by multiple regression analysis from observed A-Pan evaporation values, giving consideration to factors such as, maximum temperature, day length, distance from the sea and altitude. These values were converted internally, by a Fourier Analysis to daily values (Schulze, 1995).

Monthly averages of A-Pan equivalent potential evaporation

FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	Total
155	148	126	109	97	106	133	149	161	160	180	1701

## HYDROLOGICAL MODEL INPUTS

## D. Temperature (minimum and maximum)

As with estimates of evaporation, monthly minimum and maximum temperature values are derived on a regional basis from one minute by one minute grid values. The monthly minimum and maximum estimates are shown in the table below.

Maximum and Minimum Monthly Temperatures For HHEZ 24

	10 AC 9			Maxin	num mon	thly temp	erature	100			10-
JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
24.5	25.5	24.5	22.5	20.5	18.5	18.5	20.5	21.5	22.5	23.5	25.5
	44.	0.00		Minin	num mont	hly temp	erature				
JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
14.5	14.5	13.5	10.5	7.5	4.5	4.5	6.5	9.5	10.5	11.5	13.5

### HYDROLOGICAL MODEL INPUTS

## E. Landcover (LUMPs)

Land cover and land-use affect hydrological responses through canopy and litter interception, infiltration of rainfall into the soil and the rates of evaporation and transpiration of soil water out of the soil. Land cover/use input into ACRU therefore includes:

- An interception loss value, which can change from month to month during a plant's annual growth cycle, to account for the estimated interception of rainfall by the plant's canopy on a rainy day,
- ii. A monthly consumptive water use (or "crop") coefficient (converted internally in the model to daily values by Fourier Analysis), which reflects the ratio of water use by vegetation under condition of freely available soil water to the evaporation from a reference potential evaporation (e.g. A-pan or equivalent), and
- iii. The fraction of plant roots that are active in extracting soil moisture from the topsoil horizon in a given month, this fraction being linked to root growth patterns during a year and senescence brought on, for example, by lack of soil moisture or by frost (Schulze et al., 1998).

A further variable that can change seasonally is the coefficient of initial abstraction, which accounts for vegetation, soil surface and climate influences on stormflow generation. In ACRU this coefficient takes cognizance of surface roughness (e.g. after ploughing) and initial infiltration before stormflow commences. Higher values of crop coefficients under forests, for example, reflect enhanced infiltration (Schulze et al., 1998). The table below shows the abovementioned ACRU landcover parameters for each of the 10 LUMPs selected for the project.

Month-by-month input parameters for the LUMPs selected for this project.

7 - 15 - 7	Natural			Highland		e Sourve	eld [Basel	ine land o	cover]			
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oet	Nov	Dec
Water use coeff	0.7	0.7	0.65	0.6	0.5	0.3	0.25	0.25	0.35	0.45	0.55	0.65
Interception loss	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3
Roots in topsoil	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85
Coeff of initial abstraction	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
1 7 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1	10	4 10		Dryland	Maize (No	ov 10)						
Water use coeff	1.07	1.02	0.62	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.37	0.79
Interception loss	0.94	1.3	1.23	0.99	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.37
Roots in topsoil	0.76	0.75	0.82	0.94	1	1	1	1	1	1	0.97	0.84
Coeff of initial abstraction	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
				Irrigated	Maize (N	ov 10)						
Water use coeff	1.09	0.96	0.45	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.38	0.85
Interception loss	1.07	1.3	1.23	0.99	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.39
Roots in topsoil	0.75	0.76	0.87	0.95	1	1	1	1	1	1	0.97	0.82
Coeff of initial abstraction	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
1 1 13 - 12 - 1 to 1 to 1	0		Sugar	Cane - G	eneralize	d (drylan	d)					
Water use coeff	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
Interception loss	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8
Roots in topsoil	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75
Coeff of initial abstraction	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
		Gur	n interm	ediate (In	termediat	e site pre	paration	)				
Water use coeff	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95
Interception loss	2.60	2.60	2.60	2.60	2.60	2.60	2.60	2.60	2.60	2.60	2.60	2.60
Roots in topsoil	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Coeff of initial abstraction	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
		Pin	e interme	ediate (Int	ermediat	e site pre	paration)					
Water use coeff	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85
Interception loss	3.50	3.50	3.50	3.50	3.50	3.50	3.50	3.50	3.50	3.50	3.50	3.50
Roots in topsoil	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60
Coeff of initial abstraction	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
Coci oi illinii acanacioni	0.00			rediate (Ir					0.52	0.30	0.55	0.55
Water use coeff	0.90	0.90	0.90	0.89	0.86	0.87	0.89	0.90	0.92	0.92	0.90	0.90
Interception loss	1.80	1.80	1.80	1.80	1.75	1.70	1.70	1.70	1.75	1.80	1.80	1.80
Roots in topsoil	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Coeff of initial abstraction	0.25	0.25	0.25	0.25	0.3	0.3	0.3	0.3	0.3	0.3	0.25	0.25
COCH OF HIMMER BUSINESSON	0.40	0.20		o (PD = A				0.5	0.5	0.5	0.20	0.20
Water use coeff	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.40	0.65	0.90	1.00	0.20
Interception loss	0.50	0.50	0.50	0.50	0.50	0.50	0.00	0.50	1.00	1.50	1.50	0.50
Roots in topsoil	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.92	0.70	0.60	0.50	1.00
Coeff of initial abstraction	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.92	0.70	0.00	0.30	0.2
Coeff of initial abstraction	0.2	0.2						0.2	0.2	0.2	0.2	0.2
Water and soul	0.40	0.80		es - Peren			0.50	0.40	0.60	0.70	0.00	0.80
Water use coeff	0.80	0.80	0.80		0.60	0.50		0.50	0.60		0.80	
Interception loss	1.40	1.40		1.40	1.20	1.00	1.00			1.40	1.40	1.40
Roots in topseil	0.80	0.80	0.80	0.90	1.00	1.00	1.00	1.00	0.90	0.90	0.80	0.80
Coeff of initial abstraction	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
35 75 767				-	Plantati							
Water use coeff	0.95	0.95	0.95	0.80	0.20	0.20	0.20	0.20	0.40	0.80	0.90	0.95
Interception loss	2.70	2.70	2.70	2.00	1.00	1.00	1.00	1.00	1.00	1.50	2.00	2.50
Roots in topsoil	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70
Coeff of initial abstraction	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2

The following can be noted from the above table:

- iv. ACRU Land-use parameters clearly reflect the "life cycle" of land-uses that are planted and harvested intra annually (i.e. within a year), such as potatoes, and maize, and irrigated sugarcane. In other words, the cycle of the hydrological impact can be observed in the above table for intra-annual crops. However, the "life cycle" of inter-annual crops is not reflected above as the table reflects average conditions for inter-annual crops.
- v. ACRU does have the facility to represent the full "life cycle" of inter-annual crops, using what is referred to as a dynamic land-use parameter file (Schulze, 1995). However, in order to be consistent in modelling approach, it was decided to use the "static" monthly land-use parameters for all LUMPs.
- vi. The natural veld for HHEZ, to be used as the baseline against which comparisons are to be made, consists of Highland and Dohne Sourveld

#### HYDROLOGICAL MODEL INPUTS

#### F. Soil parameters

Soils play a crucial role in the hydrological responses of an area by facilitating the infiltration of precipitation, by acting as a store of water which makes soil water available to plants and by redistributing water, both within the soil profile and out of it, by evaporation and transpiration processes and by drainage below the root zone (Schulze et al., 1998).

A GIS coverage of soil Land Types for the Upper Mvoti, from the Institute for Soil, Climate and Water (ISCW), provided by Umgeni Water, was "translated" into hydrological variables for use in ACRU using the AUTOSOIL Program (Schulze, 1995). AUTOSOIL output includes the thickness of the topsoil and subsoil horizons, values of the soil water content at permanent wilting point, drained upper limit (field capacity) and saturation (porosity) for both soil layers and saturated drainage redistribution rates (Schulze, 1995). Values of the aforementioned variables were determined each HHEZ, which was delineated on soil Land Types, rainfall and temperature. In other words, there was no need to area-weight soils, as each HHEZ is an independent soil Land Type, individually simulated in ACRU for each of the ten LUMPs.

The table below illustrates the ACRU soil hydrological parameters for HHEZ 24. Note that adjustments were made to the soil parameters to reflect forest LUMPs, with the depth of the B-soil horizon being increased, and LUMPs in which tillage occurs, with the porosity of the A-soil horizon being increased. The B-soil horizon depth was increased by 0.25m for forestry crops to account for the trees' deeper rooting patterns, following recommendations by Summerton (1996). Where tillage occurs, the porosity of the A-Horizon is increased by 8%.

With respect to land-uses requiring tillage practices, such as maize, sugarcane and potatoes (irrigated and dryland), an adjustment was made to the ACRU translated soils data to reflect the impact the tillage has on the soil characteristics, which in turn influences rainfall-runoff processes.

	Land	Type soils i	inform	ation "	transla	ted" in	to variab	oles for u	se in A	CRU	
	No Forests	Forestry		T	T	T	No Till	Tillage	4	T	
DEPAHO	DEPBHO	DEPBHO	WP1	WP2	FC1	FC2	PO1	PO1	PO2	ABRESP	BFRESP
(m)	CALL BOOK	15/3/4	(m.m <sup>-1</sup>	)	350		5.500	19.15		Fraction.d	ay <sup>-1</sup>
0.26	0.40	0.65	0.153	0.170	0.244	0.261	0.434	0.469	0.413	0.32	0.32

Adjunct Impervious Area	Disjunct Impervious Area
(Fraction)	(Fraction)
0.018	0.07

With,

DEPAHO = THICKNESS OF THE A SOIL HORIZON (M)

DEPBHO = Thickness of the B-soil horizon (m)

WP1 and 2 = Permanent wilting point of the A- and B-soil horizons (m.m<sup>-1</sup>)

FC 1 AND 2 = DRAINED UPPER LIMIT OF THE A- AND B-SOIL HORIZONS (M.M.)

PO 1 and 2 = Porosity of the A- and B-soil horizons (m.m<sup>-1</sup>)

ABRESP = Saturated redistribution from the A- to the B-soil horizon, (fraction.day')

BFRESP = Saturated redistribution from the B to the F- soil horizon, (fraction.day')

The adjunct and disjunct impervious areas are also derived from Land Type information. Adjunct impervious areas represent the fraction of adjunct impervious areas within a subcatchment, constituting the areas around channel zones assumed to be permanently wet and from which direct overland flow is hypothesized to occur after rain, and disjunct impervious areas such as rock outcrops, from which rainfall running off infiltrates into surrounding areas and influences their water budgets (Schulze et al., 1998).

## SIMULATED HYDROLOGICAL OUTPUT

## RUNOFF SIMULATED WITH ACRU (m³/ha)

1966 1 500 1	1	NORMAL YEAR	S		DRY YEARS	
LUMP	Annual	Dry months	Wet Months	Annual	Dry months	Wet Months
Acocks	1153	104	1049	610	29	581
Gum	586	63	523	213	10	203
Wattle	717	67	650	298	10	288
Pine (30 yr)	691	85	606	238	16	222
Pine (18 yr)	691	85	606	238	16	222
Poplar	885	90	795	407	21	386
Dry Maize	1304	135	1169	783	59	724
I. Seed Maize1	2256	238	2018	1908	176	1731
I. Seed Maize2	1683	144	1539	1354	76	1278
1. Seed Maize3	952	45	907	892	39	854
I. Maize 1	2256	238	2018	1908	176	1731
I. Maize 2	1683	144	1539	1354	76	1278
1. Maize 3	952	45	907	892	39	854
I. Sugar 1	960	101	859	560	85	475
I. Sugar 2	657	43	614	313	16	297
1. Sugar 3	554	31	523	267	5	262
I. Potato	2643	456	2188	1965	352	1613

## SIMULATED IRRIGATION ABSTRACTION

(m3/ha)

	NO	DRMAL YEAR	RS	- 1 Age	DRY YEARS	by 14
LUMP	Annual	Dry months	Wet Months	Annual	Dry months	Wet Months
Acocks						
Gum						
Wattle						
Pine (30 yr)						
Pine (18 yr)	-					
Poplar						
Dry Maize						
1. Seed Maize1	2750		2750	3275		3275
I. Seed Maize2	2040		2040	2360		2360
I. Seed Maize3	550		550	750		750
l. Maize 1	2750		2750	3275		3275
I. Maize 2	2040		2040	2360		2360
I. Maize 3	550		550	750		750
I. Sugar 1	6700	1000	5700	7150	1025	6125
I. Sugar 2	5160	800	4360	5380	820	4560
1. Sugar 3	3720	660	3060	3840	600	3240
I. Potato	4250	1100	3150	4175	1000	3175

# VARIABLE COSTS FOR VARIOUS LUMPS

DRYLAND MAIZE		
Allocated costs:		
		1999 Rand/ha
Maize seed		153
Fertilizer	L.A.N	142
	M.A.P	285
	K.C.L	149
	LIME	114
Chemicals	MONOCROTOPHOS	30
	BULLDOCK 050	8
	EPTAM SUPER	136
	GESAPRIM	126
	PUNCH EXTRA	98
Pesticides	CONTRACT AERIAL SPRAY	100
Crop	Maize insurance	154
Insurance		
Mechanical	Machineryrepairs	250
Maintenance	Implements repairs	54
Harvest:	Contracting harvesting maize	200
	Transport	150
	Labour	48
TOTAL ALLOCATED COST	TS PER HA	2195

## IRRIGATED SEED MAIZE

#### Allocated costs: 1999 Rand/ha Preharvest: Maize seed 0 Fertilizer LAN 1415 Equip hire 32 Tools 26 Chemicals 584 Pesticides Aerial spray 131 Crop insurance 200 Mechanical maintenance 1362 Irrigation Electricity, machinery repairs, motor & pump repairs 1432 Irrigation labour + labour 686 40 Cartage from land to dryer Harvest: 172 Detasselling 859 Hoeing 192 Reaping 621 Transport to PANNAR 132 Maize Drying - Fuel (R37) 299 288 Dryer Repairs 8471 Total allocated costs 7338

Appendix 3

IRRIGATED MAIZE		
Allocated costs	:	
		1999 Rand/ha
Maize seed		192
Fertilizer	L-A.N	575
	M.A.P	221
	K.C.L	149
	LIME	95
	GYPSUM	26
Chemicals	MONOCROTOPHOS	30
	BULLDOCK 050	8
	EPTAM SUPER	136
	GESAPRIM	126
	PUNCH EXTRA	98
Pesticides	CONTRACT AERIAL SPRAY	100
Crop	Maize insurance	247
Insurance		
Mechanical	Machineryrepairs	171
Maintenance	Implements repairs	54
Irrigation	Electricity	589
	Motor & Pump Repairs	29
	Machinery repairs	56
	Irrigation labour	155
Harvest:	Contracting harvesting maize	240
	Maize drying	200
	Transport	120
	1.abour	86
Total allocated costs per I		3702

WRC project K890 Appendix 3 173

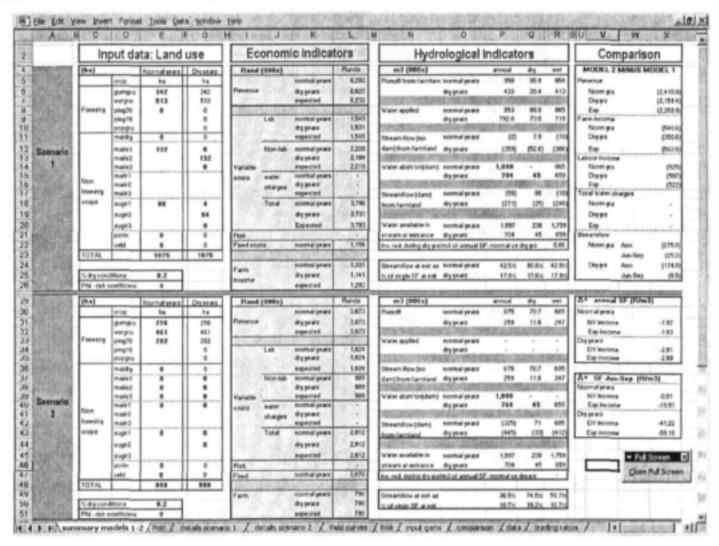
IRRIGATED SUGAR CANE		
Allocated costs		
		1999 Rand/ha
LAND PREPARATION:	Consumables - planting	26
	Consumables - annual	35
Seed		156
Chemicals:	(1) At planting	235
	(2) Maintenance	363
Plant Fertilizer:	(1) At Planting	849
	(2) Maintenance (top dress)	619
Fuel & Lube + Mech Maintenance		961
Contract/Plant hire		0
Transport:	Seed transported to farm	290.4
	Cut cane transported (per/ha)	1700
Crop Insurance		0
Levies		0
Labour		1434
Irrigation Electricity		478
Other:	Aerial Spray	135
	Rep irrigation	177
	Rep radio	21.2
Total allocated costs		7479

IRRIGATED POTATOES Allocated Costs		
:		1999 Rand/ha
Potato Seed		5879
Fertilizers:	L.A.N (28)	221
	2.3.4. (30) + 1% ZN	2295
Chemicals:	Guardian	163
	Eptam	153
	Karate	14
	Bravo	282
	Dithane M45	586
	Gramoxone	62
Labour Planting		360
Fuel		163
Mech Maintenance		384
Harvest:	Labour Harvesting	1800
	Pockets 10kg	6000
	Tranport 100 km	1500
	Electricity	558
	Motor & Pump Repairs	28
	Machinery repairs	56
	Irrigation labour	155
TOTAL ALLOCATED COST	S PER HA	20657

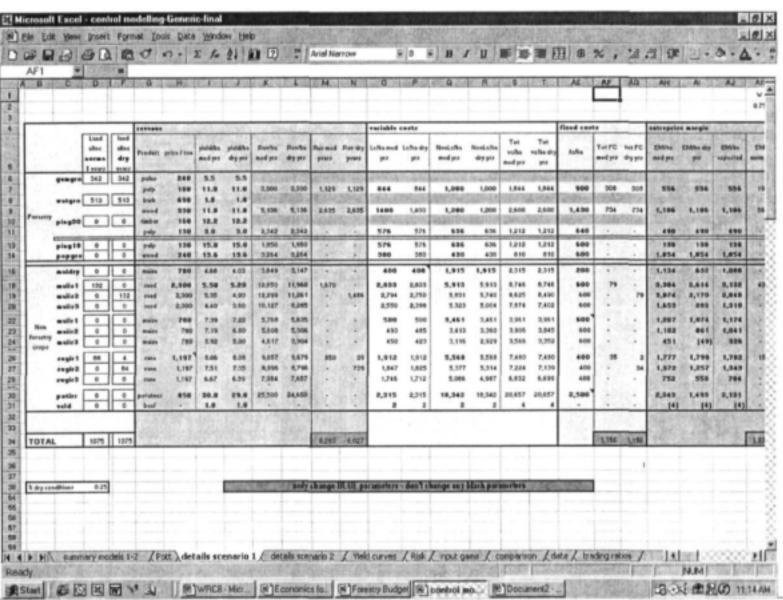
## FORESTRY SPECIES

PORESTRIST	DC125			attle P	ine [timber] I Rand	Pine [pulp] Rand	Poplar Rand
Establishment	Labour		37	134	18	17	82
	Machinery		0	23	2	2	19
	Other		80	249	26	21	50
	Total	117	406	4	7 41	1 1	52
Tending	Labour		6	87	91	84	181
	Machinery		0	1	0	0	8
	Other		32	246	9	8	41
	Total	38	334	10	00 92	2 1	48
Harvesting	Labour		0	823	146	253	116
	Machinery		0	224	242	350	190
	Other		942	0	0	6	0
	Total	942	1047	38	88 60	9 3	06
Transport	Labour		23	12	21	48	0
	Machinery		221	191	143	268	204
	Other		503	610	609	154	0
	Total	747	813	7	73 47	70 2	04
Total allocatabl	e costs		1844	2600	1212	1308	810

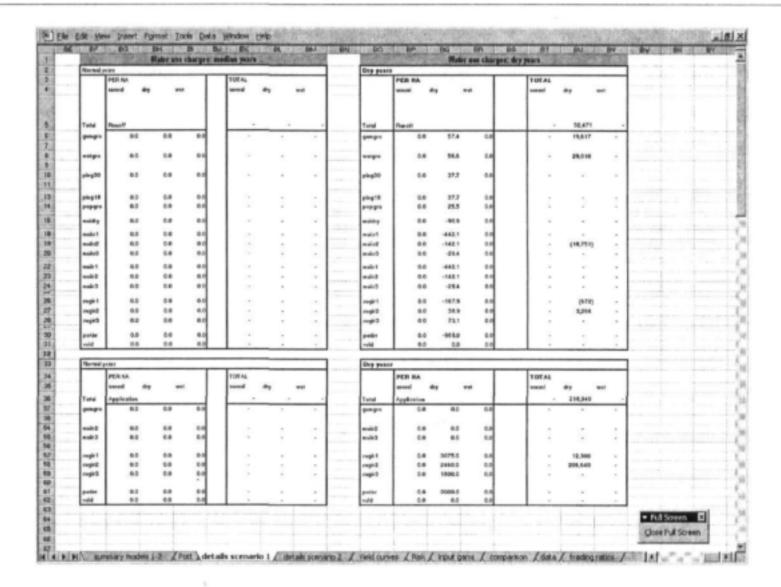
## APPENDIX 4 STRUCTURE OF THE EXCEL MODEL



1023	SENAL E	B C	0	AMERIE (NY	F G F	HIBIE	Sold St	BOOK KILL	OPPLICATION M	LAND NOON	0	P	0	R	SU V	NEW VI	X
25	MANAGE TO	X dry con		0.2		income	90.569	dypears	1,141	ox of wirgin SF at exit	dypears	17.8%	17.6%	17,500		Jun-Sep	
26	STATE OF	Phi-risk i	poefficient	0				expected	1,290			-					_
28	85534677	(ha)		Normal years	Drugears	Rand	[1000]	23/3/3/3/3/	Rands	m3 (000s)		annual	dry	wet	A+ annual	SF (Rim.)	)
30	SECTION 1		erep	ha	ha	923340	54.113.14	normal years	3,873	Punoff	normal years	675	79.7	605	Moemal years		
31			gumgro	256	256	Revenue	P8[50]	dypears	3,873		degreats	259	11.8	247	NY income		-15
32	100001-004		weigro	461	461	3797.5	9351.03	expected	2,870	TOWN YOUR DESIGNATION	BY PANEL PLAN	THE REAL PROPERTY.	355/30	9577	Exp income		-1.0
33	\$6537S	Forestry	ping30	282	292	25vc0	2553-251	April Hause Co.	S-346512	Water applied	normal years				Dry gears		
34	<b>把戶面</b>	1	ping18 popgro		0	100.50	Lab	dry years	1,024	PERSONAL PROPERTY.	dypears	Martine	one of	inima.	DY income Expirecme		-2.0
38	(KOE 20)	_	maidre	0	0	1,30		espected	1,024	Stream flow ino	normal years	625	70.7	605	Cap anicona		-6.1
31	850000U		mais 1			2267	Non-lab	the state of the state of the state of		damit from farmland		258	11.0	247	Δ+ SF Jun	See (Div	-71
38	STATE OF	1	malis2	0	0	<b>解胶</b>	26773	dypeus	909	PERMANENTAL	CONTRACTOR OF THE PARTY OF THE	B00 7719	MARKET .	SECON	Normal years	and there	
53	Scenario	1	maks3		0	Variable	11685	espected	903	Water abotr'on(dam)	normal years	1,000			NY income		-0.0
411	acertainu 4	Non	mair1		0	costs	water	normal years	10000	-	dig pears	704	45	659	Exp Income		-19
41	BOOK DIE	forestry	mair2 mair3			TA	charges	espected	505	Street of the Street	normal years	(325)	71	605	Dry gears DY income		41.
43	SECTION .	trops	sugir1		0	1,333	Total	normalyrars	2,012	Streamfow (dam) from (armland	dypas	[445]	(33)		Exp Income		-59
44	69/8/97		rugir2	'	0	10000		dygras	2,012	1.1-23630-10-00-0	245V2335E960	SH 267 Y	DATE	SHOW			
45	DEPART	1	rugir3	1 1	1	300		espected	2,012	Water available in	normal years	1,997	238	1,750			
46	300000	1	poter	0	0	Plick.	S-18 7 (F)	reprosent	100.27	stream at entrance	dypens	704	45	689			
41	BOD STORY		weld		0	Fined	S401773	normal years	1,070	inc. red. during drugs							
48	BEG-2015	TOTAL		993	999	1000	SCHOOL S	12431066	(3.05 C)								
450	19695959					Fam		normal years		Streamflow at eet as		36.500	74,500				
50	4209/2005	11 dry con		0.2		(C) (8		dillens	790	35 of virgin SF at enit.		10.7%	10.2%	10,750			
51	DESCRIPTION	P16 - 850, I	coefficient	0	CONTRACTOR OF THE PARTY OF THE	-	-	expected	790	Mary I manufacture in the last	CONTRACTOR OF THE PARTY OF THE	Name of Street	-	-	-		-
54			1			1	1	-	71. 1	Virgin streamflow at	normal years	3,342	302	2,041			-
55										entrance	dry sears	1,769	84	1,005			
57										Virgin runoff from	normal years	1,239	112	1,127			
58									-	farm	drygears	156	21	625	1-1-1-1		
59																	
60								-	(discount)	Vater Charges	THE STREET	annual /	dy	UHL			
61									135000	Panoli reduction in	normal prace	d. offices	114110	100			
62						1			Scenario 1	28904995	dygens	CONTRACTOR OF STREET	0.00	999	+		
64		1							1651490	Water abot action	THE PERSON NAMED IN	10.00		100	100		
85								and the second second	1500 9530	WANT ROTE BOOKS	tormal pears	92 BE	終榜	STOUR B			
5-3									No. of Concession, Name of Street, or other party of the Concession, Name of Street, or other pa	The second second second	dilber	-		110	+		
66									20 20 20 7	Tat applies to non-li	genced kanys (bd	to 1,7+e/fg	STATE OF				
67									-	-					-		
68									GE 1898	Vater Charges	THE PERSON NAMED IN	annual	dy	WHE			
70	-								(\$ (358) F	Pursel reduction	normal years	MC 199	90.09	858	++	▼ Full S	cteen
71								-	Scenario 2	THE RESERVE	qilhes	DE CONTRACTO	100	0		STATE OF THE PARTY	7,000
72					1				23/5/289:	Vieter abort action	hormal years	100.0	20 100	1.00	++	Glose F	ul 50
73									14:280.2	5877923556	dis practs	60 <b>4</b> 600	7 (6)	199	4-1		
					1				SERVICE.	Tax applies to non-to		-	10000	STATE OF	+		
									Secretary of the	at appear to non-to	STREET STREET STREET	pr. (Jine 9)	-	1000			
74																	



	SIAHUS	, Al	CALC	LAK	- ALC	-AM	AN :	10	J.M.	AQ /		(ATO	AU	AV	Y.II	-A6.	AY.	AZ:	DA DE	10 BC	80
3				~	D				Hydro	impact no	mal years						Hy	dro impa	t dry years		
d				0.75	0.25		Mormal							Deg	****						
d				_	_			PER MA			TOTAL				- 1	PER BA			TOTAL		
d	catropris	e margin	130064	-	207	-	_	searcd	dry	wet	twent	dry	wel	_	-	several	dry	work	unned	dy	wel
1	PMN6	thin by	EMA	250	200					- 1			- 1		- 1						
9	nerpi	100	imported	seemed	the day					- 1					- 1				11		
3	PROMPT.		250	200	7207		Tetal	Resett			950,411	95,927	654,465	Tel	w L	Result			411,022	20,351	412,57
Ц	(ALC: A)	\$250M	9229	1325	1000		deside.	506	63	523	200,364	21,362	178,982	946	410	218	10	203	72,849	3,379	6/9,47
1	556	554	354	190	190	-									-1				1		
d	1,196	1,106	1,104	567	567		andie	717	47	650	267,759	34,217	333,542	wut	400	298	10	288	152,643	5,207	147,63
i	Contract	1,144	33-50	3200	Sant.		play30	691	85	606	1	-		pine		228	16	222			
i	490	490	810	1900	2500				-				-		-				1	-	-
i	110	1138	134	1.00	1,760	7.4	ping 18	691	85	806				play		258	16	222			
1	1,854	1,854	1,854	170	300		paper.	885	90	795	1			P+0		407	21	205		-	
		***	1										-								
	1,134	612	1,008	100	UTY.	-	maidry	1304	135	1169				made	-1	765	59	724			
Į	3,584	2,614	3,132	456	200		mellet	2256	238	2018	297,771	31,429	266,342	mult		1905	176	1731			
į	5,074	2,170	2,848	950	285		melie2	1603	144	1539				-	_	1954	76	1278	176,772	10,078	196,65
ı	1,455	242	1,510	3743	100		melie3	952	45	907		-	- 1	well	13	892	39	854	· ·		
	1,007	1,074	1,174	1300	2533		medic f	2256	808	2018				made		1908	176	1721			
ļ	1,102	861	1,041	100	220		metic2	1683	166	1539				mail		1354	76	1278			
ij	200	(44)	50.5	1230	1000		melie 2	952	45	907					٠.	812	39	854			
ij	1,777	1,799	1,782	154	7		regir1	968	101	859	84,517	1,899	75,510	119	11	560	85	475	2,240	340	1,900
9	1,572	1,857	1,343	2,500	106-	-	angie 2	657	43	614				119	re l	313	16	297	26,317	1,547	24,97
į	752	554	704	15.50	250		ragir3	554	31	529	-			119	13	267	5	262			
ij	2,040	1,495	2,151	See	350		petier	2643	456	2188				pati		1965	352	1613	1 .		
ı	(4)	(4)	(4)	140			weld	1153	104	1049				reld		610	29	581		-	
1	弘明				K00.1		_								_						
			Bisc,	-	100	-	Morand y			_	_			Bry	pen			_			
	12,0%	MINIS	1000	1,001	1,10			PER BA			TOTAL				_ !	PER HA			TOTAL		
1								uned	dy	947	second	dry	test		4	sarvesi	dry	wit	seems	dy	wet
Н							Total	Application			952,600	88,000	864,600	Tol	al l	Applicati	lon		792,040	72,900	719,068
							gampe.			-				gen	-			-			-
U																					
H						_	maile? maile3	2,040		2,040 550				auti	_	2,360		2,360			
H						- 1		150		250	1	-		- auti	"	750		750			
ĺ							empir 1	6,700	1,000	5,700	589,600	88,000	501,600	199		7,150	1,025	6,125	21.500	4,100	24,50
ı							regir2	5,160	800	4,960				regi		5,310	820	4,560	451,920	68,880	283,04
Ø							regir3	3,729	660	3,060				regi	13	3,840	500	9,240			
ı								4 455							. 1						
d							petire	4,250	1,100	3,150	1	- :	- :	pati		4,175	1,000	2,175	-	-	
3														1.44	-						-1
Ì																			* Full S	icreen k	4
g																			Close I	rul Screen	
ı																			The State of	COLUMN TO SERVE	



## GAMS CODE OF THE LP MODEL

```
SET
               Lumps (land use and management practices) /
                     gum plantation (10yr rotation)
       gumgro
                      wattle plantation (10yr rotation)
       watgro
                     pine plantation (30yr rotation for pulp a
pine plantation (18yr rotation for pulp only)
       ping30
                                                        for pulp and timber)
       pingl8
       popgro
                     poplar plantation (18yr rotation)
                     dry maire
       maidry
       maiirl
                      irrigated maize (25mm in 7 days)
       maiir2
                     irrigated maize (20mm in 7 days)
                     irrigated maize (20mm in 14 days)
irrigated seed maize (25mm in 7 days)
       maiir3
       maiinl
                   irrigated seed maize (20mm in 7 days)
irrigated seed maize (20mm in 14 days)
       maiis2
       maiin3
                      irrigated sugarcane (25mm in 7 days)
       sugirl
                      irrigated sugarcane (20mm in 7 days)
       sugir2
       sugir3
                     irrigated sugarcane (20mm in 14 days)
       potirr
                      irrigated potatoes (25mm in 7 days)
       velgro
                      veld
--
       Note
             Pinegro30 and 18 use same hydrology, but have different economic costs
C
       products /
                      Telkom poles
       apo
                      wattle bark
       wba
       pti
                      pine sawn timber
                     poplar wood
       DOD
                      pulp gum
       pug
                   pulp wattle
       DUM
                     pulp pine
       pup.
       sug
                      sugar cane
       mai
                      maize grain
       mas
                      maize seed
       pot
                      potatoes
       vel
                      natural veld
       land types /
***Bracken and Mason farms
                      nar, ir /
***Meier farm
                     narlf, ar1, arirl, narirl, narir2, arir2f, arir3, arir4, nar2 /
.
       variable costs /
U
                      labour costs
       lab
                      nonlabour variable costs /
       nlab
       hydrological exceedence level
z
                     20 percent driest acocks low flow years
                      median years acocks low flow years
IRP(P)
              irrigation lumps
                                               / maiirl, maiisl, sugirl, potirr,
                                          maiir2, maiir3, maiis2,
                                          maiis3, sugir2, sugir3
AFP(P)
               afforestation landuses
                                              / gumgro, watgro, ping30,
                                              ping18, popgro
                                          / maiirl, maiisl, sugirl, potirr, maiir2, maiir3, maiis2,
NAFP(P)
               non-forestry landuses
                                          maiis3, sugir2, sugir3, velgro
                                              / gpo, wba, pti, pop, pug, puw, pup /
/ sug, mai, mas, pot, vel /
/ sugirl, sugir2, sugir3 /
AFC(C)
               afforestation products
NAFC(C)
               non-forestry products
ISP(P)
               irrigated sugar lumps
                                              / maiirl, maiir2, maiir3 /
IMP(P)
               irrigated maize lumps
IMSP(P)
               irrigated seed maize lumps
                                              / maiis1, maiis2, maiis3 /
NL(P)
               non licenced land uses
                                              / maidry
```

```
***Bracken and Mason farms
IRS(S) irrigable lands
                                       / 15
                                       / ir
ARS (S)
            arable lands
***Meier farm
*IRS(S)
             irrigable lands
                                        / arirl, narir2, arir3, arir4
                                        / arl, arirl, arir3, arir4
/ nar2
*ARS(S)
             arable lands
*GRS(S)
             grazing non-arable lands
*AFS(S)
             afforested lands
                                        / narlf, arir2f
                                        / ann, dry, wet
TP
            time periods
TS(TP)
             seasons
                                        / dry, wet
                                        / ann, dry
/ 1988*1998
REL (TP)
            relevant periods
TV
             year
ALIAS (P, KP);
ALIAS (S,SP);
PARAMETER
             ALPHA(Z)
                          percentage of the time that normal and dry conditions apply
            dryyrs =
                         0.2
                        0.8/
            normyrs =
PARAMETER
             product reference prices (1999 Rand per ton)
PRICE(C)
             -240
      apo
            =690
      wba
            =160
      pti
            =240
      pop
            =180
      pug
      puw
            =330
      pup
            =130
      sug
            =1197
      mai
            =780
      mas
            =2000
      pot
            =850
            =0
••
      **** PRICES CHECKED BY AJP 16/8/2000
      ....
           REFERENCE: FARM BUDGETS & DISCUSSION WITH FARMERS ****
                        sensitivity factor price of product
PARAMETER
            SENSPR(C)
      gpo
            -1
            -1
      wba
      pti
            =1
      pop
            =1
            -1
      pug
      puw
            -1
      pup
            -1
      sug
            =1
      mai
            -1
      mas
            -1
            -1
      pot
      vel
TABLE VCOST(P, Z, U)
            1ab
                  nlab
gumgro.normyrs 844
                   1000
            844
                    1000
gumgro.dryyrs
watgro.normyrs 1400
                    1200
watgro.dryyrs
            1400
                   1200
ping30.normyrs 576
                    636
ping30.dryyrs 576
                   636
ping18.normyrs 576
                    636
ping18.dryyrs
            576
                    636
popgro.normyrs 380
popgro.dryyrs 380
                    430
                    430
maidry.normyrs 400
                    1915
maidry.dryyrs
             400
                    1915
maiisl.normyrs 2833
maiisl.dryyrs 2833
                    5913
                    5913
maiisl.dryyrs
                   5831
maiis2.normyrs 2794
```

Creemers and Pott

```
maiis2.dryyrs
               2750
                       5740
maiis3.normyrs 2550
                       5323
mails3.dryyrs
               2398
                       5004
maiirl.normyrs
               500
                       3461
maiirl.dryyrs
              500
                       3461
maiir2.normyrs 493
                       3413
maiir2.dryyrs
               485
                       3360
maiir3.normyrs 450
                       3116
maiir3.dryyrs
               423
                       2929
sugirl.normyrs
               1912
                       5568
augirl.dryyrs
               1912
                       5568
sugir2.normyrs
               1847
                       5377
sugir2.dryyrs
               1825
                       5314
sugir3.normyrs
               1746
                       5086
               1712
sugir3.dryyrs
                       4987
potirr.normyrs 2315
                       18342
potirr.dryyrs
               2315
                       18342
velgro.normyrs
velgro.dryyrs
..
       pingl8 costs are higher because pulp needs to be transported to Richards Bay
       **** VALUES CHECKED BY AJF 16/8/2000 ****
**** REFERENCE: FARM BUDGETS 6 DISCUSSION WITH FARMERS ****
..
SCALAR UNITEC
                       unit pumping cost (R per m3)
                                                             /0.02
SCALAR SENSVC
                      sensitivity factor variable costs
                                                             /1/
** Fixed cost per ha
PARAMERTER FCOST(P)
gumgro =900
watgro =1430
ping30 =640
ping18 =600
       =600
popgro
       =200
maidry
       =600
maiirl
maiir2 =600
maiir3 =600
maiis1 =600
maiis2 =600
maiis3 =600
sugirl =4000
sugir2 =400
sugir3 =400
potirr =2500
velgro =0;
** conversion possibilities
PARAMETER
               CVC(S)
                              annualised conversion cost Rand per ha
***Bracken and Mason farms
              /nar= 1000
               ir = 0
***Meier farm
        narlf
                        0
                      0
       arl
              .
       arirl
                      0
       narirl
              -
                      0
       narir2
              *
                      0
       arir2f
              -
                      1000
       arir3
               *
                      0
       arir4
                      0
                      0
*Total conversion cost is about R10 000 per ha. This is depreciated over 10 years in a
straight
*depreciation
PARAMETER
             AFFOR(S)
                            total area afforested on given land category S
```

```
***Bracken
            /par= 855
            ir = 0
***Mason
             /nar= 999
              ir = 0
***Meier
+/
       narlf =
                     100
            -
                   0
     arl
      arirl
                   0
                   0
      narirl =
      narir2 =
                   0
      arir2f =
                   -
     arir3
            -
                    0
      arir4
            -
                   0
      nar2
            -
                   0
SCALAR SENSFC sensitivity factor fixed costs
SCALAR SENSTC sensitivity factor total costs
TABLE YIELD(P,C,Z,S) yield per ha (ton per ha per annum)
                   nar
                          ir
                          5.5
                   5.5
gumgro.gpo.normyrs
                          5.5
                   5.5
gumgro.gpo.dryyrs
                   11.0
                          11.0
gumgro.pug.normyrs
                        11.0
                   11.0
gumgro.pug.dryyrs
watgro.wba.normyrs 1.8
                         1.8
watgro.wba.dryyrs
                   1.8
                          1.8
watgro.puw.normyrs
                   11.8
                         11.8
watgro.puw.dryyrs
                   11.8
                          11.8
ping30.pti.normyrs
                   12.2
                          12.2
ping30.pti.dryyrs
                   12.2
                          12.2
ping30.pup.normyra
                   3.0
                          3.0
ping30.pup.dryyrs
                   3.0
                          3.0
ping18.pti.normyrs
                  0.0
                         0.0
ping18.pti.dryyrs
                   0.0
                          0.0
                15.0
15.0
                        15.0
ping18.pup.normyrs
ping18.pup.dryyrs
                          15.0
popgro.pop.normyrs
                   0
                          0
popgro.pop.dryyrs
                          4.7
                   0
maidry.mai.normyrs
                   0
                          4.0
maidry.mai.dryyrs
                          5.5
maiisl.mas.normyrs
                   0
                   0
                          5.2
maiisl.mas.dryyrs
maiis2.mas.normyrs
                   0
                          5.3
maiis2.mas.dryyrs
                   0
                          4.9
maiis3.mas.normyrs
                   0
                          4.4
maiis3.mas.dryyrs
                   0
                          3.6
maiirl.mai.normyrs
                   0
                          7.4
maiirl.mai.dryyrs
                   0
                          7.2
maiir2.mai.normyrs
                   0
                          7.2
maiir2.mai.dryyrs
                   0
maiir3.mai.normyrs
                   0
                          5.9
mailr3.mai.dryyrs
                   0
                          5.0
sugirl.sug.normyrs
                   0
                          8.1
sugirl.sug.dryyrs
                   0
                          8.1
                   0
sugir2.sug.normyrs
                          7.5
                          7.3
sugir2.sug.dryyrs
                   0
                   0
                         6.7
sugir3.sug.normyrs
                   0
                          6.4
sugir3.sug.dryyrs
                   0
potirr.pot.normyrs
                          30.0
potirr.pot.dryyrs
                          29.0
velgro.vel.normyrs
                   0
                         0.0
velgro.vel.dryyrs
                   0
                         0.0;
                               arirl
                  narlf
                        arl
                                      narirl narir2 arir2f
                                                          arir3
                                                                 arir4
                  5.5
                                5.5 5.5
                         5.5
                                              5.5 5.5
                                                           5.5 5.5
                                                                         5.5
*gumgro.gpo.normyrs
                            5.5
                                  5.5
                                         5.5
                                                5.5
                                                       5.5
                                                              5.5
                                                                     5.5
                                                                           5.5
                     5.5
*gumgro.gpo.dryyrs
                                  11
                                         11
                                                11
                                                       11
                    11
                                                             11
                                                                    11
                            11
*gumgro.pug.normyrs
                                  11
                                         11
                                                11
                                                       11
                                                             11
                                                                    11
                                                                           11
*gumgro.pug.dryyrs
                     11
                            11
                     1.8
                            1.8
                                  1.8
                                         1.8
                                                1.8
                                                       1.8
                                                              1.8
                                                                    1.8
                                                                           1.8
*watgro.wba.normyrs
                                  1.8
                                         1.8
                                                              1.8
                            1.8
                                                1.8
                                                       1.8
                                                                           1.8
                     1.8
*watgro.wba.dryyrs
```

*watgro	.puw.no	rnyra	11.0	11.8	11.8	11.8	11.8	11.8	11.8	11.8	11.8
	.puw.dr		11.8	11.8	11.8	11.8	11.8	11.8	11.8	11.6	11.8
	.pti.no		12.2	12.2	12.2	12.2	12.2	12.2	12.2	12.2	12.2
	.pti.dr		12.2	12.2	12.2	12.2	12.2	12.2	12.2	12.2	12.2
	.pup.no		3	3	3	3	3	3	3	3	3
	.pup.dr		3	3	3	3	3	3	3	3	3
	.pti.no		0	0	0	0	0	0	0	0	0
	.pti.dr		0	0	0	0	0	0	0	0	0
	.pup.no:		15	15	15	15	15	15	15	15	15
	.pup.dr		15	15	15	15	15	15	15	15	15
	.pop.no		0	13.6	0	13.6	0	0	0	13.6	0
	.pop.dr	-	0	13.6	0	13.6	0	0	0	13.6	0
	.mai.no		0	4.7	4.7	0	0	4.7	4.7	4.7	0
	.mai.dr		0	4	4	0	0	4	4	4	0
	.mai.no		0	0	7.4	0	0	0	7.4	7.4	0
	.mai.dr		0	0	7.2	0	0	0	7.2	7.2	0
	.mai.no		0	0	7.2	0	0	0	7.2	7.2	0
	.mai.dr		0	0	6.8	0	0	0	6.8	6.8	0
	.mai.no		0	0	5.9	0	0	0	5.9	5.9	0
	.mai.dr		0	0	5.0	0	0	0	5.0	5.0	0
			0	0	0	0	0	0		0	0
	.nai.no:		0	0	0		0		0		
	.mai.dr					0		0	0	0	0
	.mai.no:		0	0	0	0	0	0	0	0	0
	.mai.dr		0	0	0	0	0	0	0	0	0
	.mai.no:		0	0	0	0	0	0	0	0	0
	.mai.dr		0	0	0	0	0	0	0	0	0
	.sug.no:		0	0	0	0	0	0	0	0	0
	.sug.dr		0	0	0	0	0	0	0	0	0
*sugir2	.sug.no:	rmyrs	0	0	0	0	0	0	0	0	0
*sugir2	.sug.dr	yyrs	0	0	0	0	0	0	0	0	0
*sugir3	.sug.no:	cmyrs	0	0	0	0	0	0	0	0	0
*sugir3	.sug.dr	yyrs	0	0	0	0	0	0	0	D	0
*potirr	.pot.no:	cmyrs	0	0	30	0	0	0	30	30	0
*potirr	.pot.dr	yyrs	0	0	28.5	0	0	0	28.5	28.5	0
*velgro	.vel.no:	rmyrs	0	0	0	0	0	0	0	0	0
*velgro	.vel.dry	yra	0	0	0	0	0	0	0 -	0	0 ;
** I.6		TAPES SE	N. J. B. 40								
*******		TIME SE	********								
TABLE	REV (P.	TY)									
TABLE	REV(P,	TY)	998 rand						•••	1997	1998
TABLE * Reven	REV(P, ue figu:	TY) res in 1	998 rand	1991	1992	1993	1994	1995	1996	1997	1998
TABLE * Reven	REV(P, ue figu: 1988 3234	TY) res in 1: 1989 3080	998 rand: 1990 3185	1991 3700	1992 3360	1993 3234	1994 3150	1995 3325	1996 3150	3590	2940
TABLE * Reven gumgro watgro	REV(P. ue figu: 1988 3234 5264	TY) res in 1: 1989 3080 5580	998 rand: 1990 3185 4883	1991 3700 5270	1992 3360 5425	1993 3234 4960	1994 3150 4805	1995 3325 5425	1996 3150 6000	3590 5270	2940 5270
TABLE * Reven gumgro watgro ping30	REV (P. ue figu: 1988 3234 5264 2808	TY) res in 1: 1989 3080 5580 2880	998 rand: 1990 3185 4883 2450	1991 3700 5270 2960	1992 3360 5425 2640	1993 3234 4960 2800	1994 3150 4805 2920	1995 3325 5425 2680	1996 3150 6000 2920	3590 5270 2560	2940 5270 2920
TABLE * Reven gumgro watgro ping30 ping18	REV(P, ue figu: 1988 3234 5264 2808 1931	TY) res in 1: 1989 3080 5580 2880 1980	998 rand: 1990 3185 4883 2450 1870	1991 3700 5270 2960 2035	1992 3360 5425 2640 1815	1993 3234 4960 2800 1925	1994 3150 4805 2920 2008	1995 3325 5425 2680 1843	1996 3150 6000 2920 2008	3590 5270 2560 1760	2940 5270 2920 2008
TABLE Reven gumgro watgro ping30 ping18 popgro	REV (P. ue figu: 1988 3234 5264 2808 1931 3436	TY) res in 1: 1989 3080 5580 2880 1980 3477	998 rand: 1990 3185 4883 2450 1870 3599	1991 3700 5270 2960 2035 3172	1992 3360 5425 2640 1815 3233	1993 3234 4960 2800 1925 3538	1994 3150 4805 2920 2008 3599	1995 3325 5425 2680 1843 3416	1996 3150 6000 2920 2008 3508	3590 5270 2560 1760 3325	2940 5270 2920 2008 3477
TABLE * Reven gumgro watgro ping30 ping18 popgro maidry	REV (P. ue figu: 1988 3234 5264 2808 1931 3436 2150	7Y) res in 1: 1989 3080 5580 2880 1980 3477 2494	998 rand: 1990 3185 4883 2450 1870 3599 2838	1991 3700 5270 2960 2035 3172 3010	1992 3360 5425 2640 1815 3233 3440	1993 3234 4960 2800 1925 3538 3578	1994 3150 4805 2920 2008 3599 4128	1995 3325 5425 2680 1843 3416 4128	1996 3150 6000 2920 2008 3508 4300	3590 5270 2560 1760 3325 4472	2940 5270 2920 2008 3477 4730
TABLE * Reven gumgro watgro ping30 ping18 popgro maidry maiisl	REV (P. ue figu: 1988 3234 5264 2808 1931 3436 2150 9500	7Y) res in 1: 1989 3080 5580 2880 1980 3477 2494 10450	998 rand: 1990 3185 4883 2450 1870 3599 2838 10925	1991 3700 5270 2960 2035 3172 3010 10930	1992 3360 5425 2640 1815 3233 3440 10970	1993 3234 4960 2800 1925 3538 3578 11400	1994 3150 4805 2920 2008 3599 4128 11400	1995 3325 5425 2680 1843 3416 4128 11400	1996 3150 6000 2920 2008 3508 4300 11400	3590 5270 2560 1760 3325 4472 11875	2940 5270 2920 2008 3477 4730 12350
TABLE * Reven gumgro watgro ping30 ping18 popgro maidry maiis1 maiis2	REV(P, ue figu: 1988 3234 5264 2808 1931 3436 2150 9500 9100	TY) rea in 1: 1989 3080 5580 2880 1980 3477 2494 10450 9100	998 rands 1990 3185 4883 2450 1870 3599 2838 10925 9555	1991 3700 5270 2960 2035 3172 3010 10930 9600	1992 3360 5425 2640 1815 3233 3440 10970 10000	1993 3234 4960 2800 1925 3538 3578 11400 10920	1994 3150 4805 2920 2008 3599 4128 11400 10920	1995 3325 5425 2680 1843 3416 4128 11400 10920	1996 3150 6000 2920 2008 3508 4300 11400 10920	3590 5270 2560 1760 3325 4472 11875 11375	2940 5270 2920 2008 3477 4730 12350 11830
TABLE * Reven gumgro watgro ping30 ping18 popgro maidry maiis1 maiis2 maiis3	REV (P, 1988) 3234 5264 2808 1931 3436 2150 9500 9100 6500	TY) res in 1: 1989 3080 5580 2880 1980 3477 2494 10450 9100 6900	998 rands 1990 3185 4883 2450 1870 3599 2838 10925 9555 7500	1991 3700 5270 2960 2035 3172 3010 10930 9600 7900	1992 3360 5425 2640 1815 3233 3440 10970 10000 8100	1993 3234 4960 2800 1925 3538 3578 11400 10920 8100	1994 3150 4805 2920 2008 3599 4128 11400 10920 8500	1995 3325 5425 2680 1843 3416 4128 11400 10920 8700	1996 3150 6000 2920 2008 3508 4300 11400 10920 8700	3590 5270 2560 1760 3325 4472 11875 11375 11000	2940 5270 2920 2008 3477 4730 12350 11830 11500
TABLE * Reven gumgro watgro ping30 ping18 popgro maidry maiis1 maiis2 maiis3 maiir1	REV (P. 1988 3234 5264 2808 1931 3436 2150 9500 5133	7Y) res in 1 1989 3080 5580 2880 1980 3477 2494 10450 9100 6900 5307	998 rand: 1990 3185 4883 2450 1870 3599 2838 10925 9555 7500 5655	1991 3700 5270 2960 2035 3172 3010 10930 9600 7900 5742	1992 3360 5425 2640 1815 3233 3440 10970 10000 8100 5829	1993 3234 4960 2800 1925 3538 3578 11400 10920 8100 5629	1994 3150 4805 2920 2008 3599 4128 11400 10920 8500 5829	1995 3325 5425 2680 1843 3416 4128 11400 10920 8700 5829	1996 3150 6000 2920 2008 3508 4300 11400 10920 8700 5916	3590 5270 2560 1760 3325 4472 11875 11375 11000 6003	2940 5270 2920 2008 3477 4730 12350 11830 11500 6264
TABLE * Reven gumgro watgro ping30 ping18 popgro maidry maiis1 maiis2 maiis3 maiir1 maiir2	REV (P. 1988 3234 5264 2808 1931 3436 2150 9500 5133 4250	7Y) res in 1 1909 3080 5580 2880 1980 3477 2494 10450 9100 6900 5307 4845	998 rand: 1990 3185 4883 2450 1870 3599 2838 10925 9555 7500 5655 5015	1991 3700 5270 2960 2035 3172 3010 10930 9600 7900 5742 5100	1992 3360 5425 2640 1815 3233 3440 10970 10000 8100 5829 5185	1993 3234 4960 2800 1925 3538 3578 11400 10920 8100 5829 5270	1994 3150 4805 2920 2008 3599 4128 11400 10920 8500 5829 5355	1995 3325 5425 2680 1843 3416 4128 11400 10920 8700 5829 5610	1996 3150 6000 2920 2008 3508 4300 11400 10920 8700 5916 5695	3590 5270 2560 1760 3325 4472 11875 11375 11000 6003 5695	2940 5270 2920 2008 3477 4730 12350 11830 11500 6264 5780
TABLE * Reven gumgro watgro ping30 ping18 popgro maidry maiis1 maiis2 maiir1 maiir2 maiir3	REV (P. use figu: 1988 3234 5264 2808 1931 3436 2150 9500 9500 6500 6500 6500 2835	7Y) res in 1 1989 3080 5580 2880 1980 3477 2494 10450 9100 6900 5307 4845 3402	998 rand: 1990 3185 4883 2450 1870 3599 2838 10925 9555 7500 5655 5015 3969	1991 3700 5270 2960 2035 3172 3010 10930 9600 7900 5742 5100 4131	1992 3360 5425 2640 1815 3233 3440 10970 10000 8100 5829 5185 4617	1993 3234 4960 2800 1925 3538 3578 11400 10920 8100 5629 5270 4860	1994 3150 4805 2920 2008 3599 4128 11400 10920 8500 5829 5355 5103	1995 3325 5425 2680 1843 3416 4128 11400 10920 8700 5829 5610 5103	1996 3150 6000 2920 2008 3508 4300 11400 10920 8700 5916 5695 5346	3590 5270 2560 1760 3325 4472 11875 11375 11000 6003 5695 5427	2940 5270 2920 2008 3477 4730 12350 11830 11500 6264 5780 5427
TABLE * Reven gumgro watgro ping30 ping18 popgro maidry maiis1 maiis2 maiis3 maiir1 maiir2 maiir3 sugir1	REV(P, ue figu: 1988 3234 5264 2808 1931 3436 2150 9500 9100 6500 5133 4250 2835 9000	TY) res in 1 1989 3080 5580 2880 1980 3477 2494 10450 9100 6900 5307 4845 3402 9300	998 rand: 1990 3185 4883 2450 1870 3599 2838 10925 9555 7500 5655 5015 3969 9800	1991 3700 5270 2960 2035 3172 3010 10930 9600 7900 5742 5100 4131 10000	1992 3360 5425 2640 1815 3233 3440 10970 10000 8100 5829 54617 10000	1993 3234 4960 2800 1925 3538 3578 11400 10920 8100 5829 5270 4860 10000	1994 3150 4805 2920 2008 3599 4128 11400 10920 8500 5829 5355 5103 10000	1995 3325 5425 2680 1843 3416 4128 11400 10920 8700 5829 5610 5103 10000	1996 3150 6000 2920 2008 3508 4300 11400 10920 8700 5916 5695 5346 10000	3590 5270 2560 1760 3325 4472 11875 11375 11000 6003 5695 5427 10000	2940 5270 2920 2008 3477 4730 12350 11830 11500 6264 5780 5427
TABLE * Reven gumgro watgro ping30 ping18 popgro maidry maiis1 maiis2 maiis3 maiir1 maiir2 maiir3 sugir1 sugir2	REV(P, ue figu: 1988 3234 5264 2808 1931 3436 2150 9500 9100 6500 5133 4250 2835 9000 8100	TY) rea in 1: 1989 3080 5580 2880 1980 3477 2494 10450 9100 6900 5307 4845 3402 9300 8300	998 rands 1990 3185 4883 2450 1870 3599 2838 10925 9555 7500 5655 5015 3969 9800 8400	1991 3700 5270 2960 2035 3172 3010 10930 9600 7900 5742 5100 4131 10000 8700	1992 3360 5425 2640 1815 3233 3440 10970 10000 8100 5829 5185 4617 10000 8700	1993 3234 4960 2800 1925 3538 3578 11400 10920 8100 5629 5270 4860 10000 8700	1994 3150 4805 2920 2008 3599 4128 11400 10920 8500 5829 5355 5103 10000 8700	1995 3325 5425 2680 1843 3416 4128 11400 10920 8700 5829 5610 5103 10000 9000	1996 3150 6000 2920 2008 3508 4300 11400 10920 8700 5916 5695 5346 10000 9200	3590 5270 2560 1760 3325 4472 11875 11375 11000 6003 5695 5427 10000 9400	2940 5270 2920 2008 3477 4730 12350 11830 11500 6264 5780 5427 10000 9600
TABLE * Reven gumgro watgro ping30 ping18 popgro maidry maiis1 maiis2 maiir3 maiir1 maiir2 maiir3 sugir1 sugir2 sugir3	REV (P, use figu: 1988 3234 5264 2808 1931 3436 2150 9500 6500 5133 4250 2835 9000 6900	TY) res in 1: 1989 3080 5580 2880 1980 3477 2494 10450 9100 6900 5307 4845 3402 9300 8300 7100	998 rands 1990 3185 4883 2450 1870 3599 2838 10925 7500 5655 5015 3969 9800 8400 7100	1991 3700 5270 2960 2035 3172 3010 10930 9600 7900 5742 5100 4131 10000 8700 7300	1992 3360 5425 2640 1815 3233 3440 10970 10970 10000 8100 5829 5185 4617 10000 8700 7500	1993 3234 4960 2800 1925 3538 3578 11400 10920 8100 5829 5270 4860 10000 8700 7700	1994 3150 4805 2920 2008 3599 4128 11400 10920 8500 5829 5355 5103 10000 8700 7700	1995 3325 5425 2680 1843 3416 4128 11400 10920 8700 5829 5610 5103 10000 9000 7800	1996 3150 6000 2920 2008 3508 4300 11400 10920 8700 5916 5695 5346 10000 9200 8000	3590 5270 2560 1760 3325 4472 11875 11375 11000 6003 5695 5427 10000 9400 8400	2940 5270 2920 2008 3477 4730 12350 11830 11500 6264 5780 5427 10000 9600 8500
TABLE * Reven gumgro watgro ping30 ping18 popgro maidry maiis1 maiis2 maiis3 maiir1 maiir2 maiir3 sugir1 sugir2 sugir3 potirr	REV (P. 1988) 3234 5264 2808 1931 3436 2150 9500 9500 5133 4250 2835 9000 8100 6900 27260	7Y) res in 1: 1989 3080 5580 2880 1980 3477 2494 10450 9100 6900 5307 4845 3402 9300 8300 7100 0	998 rands 1990 3185 4883 2450 1870 3599 2838 10925 9555 7500 5655 5015 3969 9800 8400 7100 27200	1991 3700 5270 2960 2035 3172 3010 10930 9600 7900 5742 5100 4131 10000 8700 7300 27000	1992 3360 5425 2640 1815 3233 3440 10970 10000 8100 5829 5185 4617 10000 8700 7500 27500	1993 3234 4960 2800 1925 3538 3578 11400 10920 8100 5829 5270 4860 10000 8700 7700 26800	1994 3150 4805 2920 2008 3599 4128 11400 10920 8500 5829 5355 5103 10000 8700 7700 27600	1995 3325 5425 2680 1843 3416 4128 11400 10920 8700 5829 5610 5103 10000 9000 7800 27200	1996 3150 6000 2920 2008 3508 4300 11400 10920 8700 5916 5695 5346 10000 9200 8000 27200	3590 5270 2560 1760 3325 4472 11875 11375 11000 6003 5695 5427 10000 9400 8400 27200	2940 5270 2920 2008 3477 4730 12350 11830 11500 6264 5780 5427 10000 9600 8500 27200
TABLE * Reven gumgro watgro ping30 ping18 popgro maidry maiis1 maiis2 maiir3 maiir1 maiir2 maiir3 sugir1 sugir2 sugir3	REV (P. 1988) 3234 5264 2808 1931 3436 2150 9500 9500 5133 4250 2835 9000 8100 6900 27260	TY) res in 1: 1989 3080 5580 2880 1980 3477 2494 10450 9100 6900 5307 4845 3402 9300 8300 7100	998 rands 1990 3185 4883 2450 1870 3599 2838 10925 7500 5655 5015 3969 9800 8400 7100	1991 3700 5270 2960 2035 3172 3010 10930 9600 7900 5742 5100 4131 10000 8700 7300	1992 3360 5425 2640 1815 3233 3440 10970 10970 10000 8100 5829 5185 4617 10000 8700 7500	1993 3234 4960 2800 1925 3538 3578 11400 10920 8100 5829 5270 4860 10000 8700 7700	1994 3150 4805 2920 2008 3599 4128 11400 10920 8500 5829 5355 5103 10000 8700 7700	1995 3325 5425 2680 1843 3416 4128 11400 10920 8700 5829 5610 5103 10000 9000 7800	1996 3150 6000 2920 2008 3508 4300 11400 10920 8700 5916 5695 5346 10000 9200 8000	3590 5270 2560 1760 3325 4472 11875 11375 11000 6003 5695 5427 10000 9400 8400	2940 5270 2920 2008 3477 4730 12350 11830 11500 6264 5780 5427 10000 9600 8500
TABLE * Reven gumgro watgro ping30 ping18 popgro maidry maiis1 maiis2 maiis3 maiir1 maiir2 maiir3 sugir1 sugir2 sugir3 potirr velgro PARAMET	REV(P, ue figu: 1988 3234 5264 2808 1931 3436 2150 9500 9100 6500 5133 4250 2835 9000 8100 6900 27260 500	TY) rea in 1: 1989 3080 5580 2880 1980 3477 2494 10450 9100 6900 5307 4845 3402 9300 8300 7100 0 500	998 rands 1990 3185 4883 2450 1870 3599 2838 10925 9555 7500 5655 5015 3969 9800 8400 7100 27200	1991 3700 5270 2960 2035 3172 3010 10930 9600 7900 5742 5100 4131 10000 8700 7300 27000 500	1992 3360 5425 2640 1815 3233 3440 10970 10000 8100 5829 5185 4617 10000 8700 7500 27500 500	1993 3234 4960 2800 1925 3538 3578 11400 10920 6100 5629 5270 4860 10000 8700 7700 26800 500	1994 3150 4805 2920 2008 3599 4128 11400 10920 8500 5829 5355 5103 10000 8700 7700 27600 500	1995 3325 5425 2680 1843 3416 4128 11400 10920 8700 5829 5610 5103 10000 9000 7800 27200 500	1996 3150 6000 2920 2008 3508 4300 11400 10920 8700 5916 5695 5346 10000 9200 8000 27200	3590 5270 2560 1760 3325 4472 11875 11375 11000 6003 5695 5427 10000 9400 8400 27200	2940 5270 2920 2008 3477 4730 12350 11830 11500 6264 5780 5427 10000 9600 8500 27200
TABLE Reven gumgro watgro ping30 ping18 popgro maidry maiis1 maiis2 maiis3 maiir1 maiir2 maiir3 sugir1 sugir2 sugir3 potirr velgro PARAMET REVDEV(	REV(P, ue figu: 1988 3234 5264 2808 1931 3436 2150 9500 9100 6500 5133 4250 2835 9000 8100 6900 27260 500	TY) rea in 1: 1989 3080 5580 2880 1980 3477 2494 10450 9100 6900 5307 4845 3402 9300 8300 7100 0 500	998 rand: 1990 3185 4883 2450 1870 3599 2838 10925 9555 7500 5655 5015 3969 9800 8400 7100 27200 500	1991 3700 5270 2960 2035 3172 3010 10930 9600 7900 5742 5100 4131 10000 8700 7300 27000 500	1992 3360 5425 2640 1815 3233 3440 10970 10000 8100 5829 5185 4617 10000 8700 7500 27500 500	1993 3234 4960 2800 1925 3538 3578 11400 10920 8100 5629 5270 4860 10000 8700 7700 26800 500	1994 3150 4805 2920 2008 3599 4128 11400 10920 8500 5829 5355 5103 10000 8700 7700 27600 500	1995 3325 5425 2680 1843 3416 4128 11400 10920 8700 5829 5610 5103 10000 9000 7800 27200 500	1996 3150 6000 2920 2008 3508 4300 11400 10920 8700 5916 5695 5346 10000 9200 8000 27200	3590 5270 2560 1760 3325 4472 11875 11375 11000 6003 5695 5427 10000 9400 8400 27200	2940 5270 2920 2008 3477 4730 12350 11830 11500 6264 5780 5427 10000 9600 8500 27200
TABLE Reven gumgro watgro ping30 ping18 popgro maidry maiis1 maiis2 maiis3 maiir1 maiir2 maiir3 sugir1 sugir2 sugir3 potirr velgro PARAMET REVDEV( RAVG(P)	REV(P, ue figu: 1988 3234 5264 2808 1931 3436 2150 9500 6500 5133 4250 2835 9000 6900 27260 500	TY) res in 1: 1989 3080 5580 2880 1980 3477 2494 10450 9100 6900 5307 4845 3402 9300 8300 7100 0 500	998 rand: 1990 3185 4883 2450 1870 3599 2838 10925 7500 5655 5015 3969 9800 8400 7100 27200 500	1991 3700 5270 2960 2035 3172 3010 10930 9600 7900 5742 5100 4131 10000 8700 7300 27000 500 ions for e for la	1992 3360 5425 2640 1815 3233 3440 10970 10000 8100 5829 5185 4617 10000 8700 7500 27500 500	1993 3234 4960 2800 1925 3538 3578 11400 10920 8100 5629 5270 4860 10000 8700 7700 26800 500	1994 3150 4805 2920 2008 3599 4128 11400 10920 8500 5829 5355 5103 10000 8700 7700 27600 500	1995 3325 5425 2680 1843 3416 4128 11400 10920 8700 5829 5610 5103 10000 9000 7800 27200 500	1996 3150 6000 2920 2008 3508 4300 11400 10920 8700 5916 5695 5346 10000 9200 8000 27200	3590 5270 2560 1760 3325 4472 11875 11375 11000 6003 5695 5427 10000 9400 8400 27200	2940 5270 2920 2008 3477 4730 12350 11830 11500 6264 5780 5427 10000 9600 8500 27200
TABLE Reven gumgro watgro ping30 ping18 popgro maidry maiis1 maiis2 maiis3 maiir1 maiir2 maiir3 sugir1 sugir1 sugir2 sugir3 potirr velgro PARAMET REVDEV( RAVG(P) RAVG(P)	REV(P, 1988) 3234 5264 2808 1931 3436 2150 9500 6500 5133 4250 2835 9000 6900 27260 500	7Y) res in 1: 1989 3080 5580 2880 1980 3477 2494 10450 9100 6900 5307 4845 3402 9300 8300 7100 0 500 revenua	998 rand: 1990 3185 4883 2450 1870 3599 2838 10925 9555 7500 5655 5015 3969 9800 8400 7100 27200 500	1991 3700 5270 2960 2035 3172 3010 10930 9600 7900 5742 5100 4131 10000 8700 7300 27000 500 ions for e for la: TY))/CA	1992 3360 5425 2640 1815 3233 3440 10970 10000 8100 5829 5185 4617 10000 8700 7500 27500 500	1993 3234 4960 2800 1925 3538 3578 11400 10920 8100 5629 5270 4860 10000 8700 7700 26800 500	1994 3150 4805 2920 2008 3599 4128 11400 10920 8500 5829 5355 5103 10000 8700 7700 27600 500	1995 3325 5425 2680 1843 3416 4128 11400 10920 8700 5829 5610 5103 10000 9000 7800 27200 500	1996 3150 6000 2920 2008 3508 4300 11400 10920 8700 5916 5695 5346 10000 9200 8000 27200	3590 5270 2560 1760 3325 4472 11875 11375 11000 6003 5695 5427 10000 9400 8400 27200	2940 5270 2920 2008 3477 4730 12350 11830 11500 6264 5780 5427 10000 9600 8500 27200
TABLE Reven gumgro watgro ping30 ping18 popgro maidry maiis1 maiis2 maiis3 maiir1 maiir2 maiir3 sugir1 sugir2 sugir3 potirr velgro PARAMET REVDEV( RAVG(P)	REV(P, 1988) 3234 5264 2808 1931 3436 2150 9500 6500 5133 4250 2835 9000 6900 27260 500	7Y) res in 1: 1989 3080 5580 2880 1980 3477 2494 10450 9100 6900 5307 4845 3402 9300 8300 7100 0 500 revenua	998 rand: 1990 3185 4883 2450 1870 3599 2838 10925 7500 5655 5015 3969 9800 8400 7100 27200 500	1991 3700 5270 2960 2035 3172 3010 10930 9600 7900 5742 5100 4131 10000 8700 7300 27000 500 ions for e for la: TY))/CA	1992 3360 5425 2640 1815 3233 3440 10970 10000 8100 5829 5185 4617 10000 8700 7500 27500 500	1993 3234 4960 2800 1925 3538 3578 11400 10920 8100 5629 5270 4860 10000 8700 7700 26800 500	1994 3150 4805 2920 2008 3599 4128 11400 10920 8500 5829 5355 5103 10000 8700 7700 27600 500	1995 3325 5425 2680 1843 3416 4128 11400 10920 8700 5829 5610 5103 10000 9000 7800 27200 500	1996 3150 6000 2920 2008 3508 4300 11400 10920 8700 5916 5695 5346 10000 9200 8000 27200	3590 5270 2560 1760 3325 4472 11875 11375 11000 6003 5695 5427 10000 9400 8400 27200	2940 5270 2920 2008 3477 4730 12350 11830 11500 6264 5780 5427 10000 9600 8500 27200
TABLE Reven gumgro watgro ping30 ping18 popgro maidry maiis1 maiis2 maiis3 maiir1 maiir2 maiir3 sugir1 sugir2 sugir3 potirr velgro PARAMET REVDEV( RAVG(P) RAVG(P) REVDEV(	REV(P, ue figu: 1988 3234 5264 2808 1931 3436 2150 9500 9100 6500 5103 4250 2835 9000 8100 6900 27260 500	TY) res in 1 1989 3080 5580 2880 1980 3477 2494 10450 9100 6900 5307 4845 3402 9300 8300 7100 0 revenua averag = SUM(' = REV()	998 rand: 1990 3185 4883 2450 1870 3599 2838 10925 9555 7500 5655 5015 3969 9800 8400 7100 27200 500 e deviatue TY, REV(PP, TY)-RA	1991 3700 5270 2960 2035 3172 3010 10930 9600 7900 5742 5100 4131 10000 8700 7300 27000 500 ions for e for la: TY))/CA	1992 3360 5425 2640 1815 3233 3440 10970 10000 8100 5829 5185 4617 10000 8700 7500 27500 500	1993 3234 4960 2800 1925 3538 3578 11400 10920 8100 5629 5270 4860 10000 8700 7700 26800 500	1994 3150 4805 2920 2008 3599 4128 11400 10920 8500 5829 5355 5103 10000 8700 7700 27600 500	1995 3325 5425 2680 1843 3416 4128 11400 10920 8700 5829 5610 5103 10000 9000 7800 27200 500	1996 3150 6000 2920 2008 3508 4300 11400 10920 8700 5916 5695 5346 10000 9200 8000 27200	3590 5270 2560 1760 3325 4472 11875 11375 11000 6003 5695 5427 10000 9400 8400 27200	2940 5270 2920 2008 3477 4730 12350 11830 11500 6264 5780 5427 10000 9600 8500 27200
TABLE Reven gumgro watgro ping30 ping18 popgro maidry maiis1 maiis2 maiis3 maiir1 maiir2 maiir3 sugir1 sugir2 sugir3 potirr velgro PARAMET REVDEV( RAVG(P) RAVG(P) REVDEV( ***Brac	REV(P, ue figu: 1988 3234 5264 2808 1931 3436 2150 9500 9100 6500 5133 4250 2835 9000 8100 6900 27260 500 ER P,TY)	TY) rea in 1: 1989 3080 5580 2880 1980 3477 2494 10450 9100 6900 5307 4845 3402 9300 8300 7100 0 revenue average = SUM(: = REV()	998 rand: 1990 3185 4883 2450 1870 3599 2838 10925 9555 7500 5655 5015 3969 9800 8400 7100 27200 500 e deviat. e revenus TY, REV (P.	1991 3700 5270 2960 2035 3172 3010 10930 9600 7900 5742 5100 4131 10000 8700 7300 27000 500 ions for e for la: TY))/CA	1992 3360 5425 2640 1815 3233 3440 10970 10000 8100 5829 5185 4617 10000 8700 7500 27500 500	1993 3234 4960 2800 1925 3538 3578 11400 10920 8100 5629 5270 4860 10000 8700 7700 26800 500	1994 3150 4805 2920 2008 3599 4128 11400 10920 8500 5829 5355 5103 10000 8700 7700 27600 500	1995 3325 5425 2680 1843 3416 4128 11400 10920 8700 5829 5610 5103 10000 9000 7800 27200 500	1996 3150 6000 2920 2008 3508 4300 11400 10920 8700 5916 5695 5346 10000 9200 8000 27200 500	3590 5270 2560 1760 3325 4472 11875 11375 11000 6003 5695 5427 10000 9400 8400 27200	2940 5270 2920 2008 3477 4730 12350 11830 11500 6264 5780 5427 10000 9600 8500 27200
TABLE Reven gumgro watgro ping30 ping18 popgro maidry maiis1 maiis2 maiis3 maiir1 maiir2 maiir3 sugir1 sugir2 sugir3 potirr velgro PARAMET REVDEV( RAVG(P) RAVG(P) REVDEV( ***Brac SCALAR	REV (P. ue figu: 1988 3234 5264 2808 1931 3436 2150 9500 9100 6500 5133 4250 2835 9000 8100 6900 27260 500 ER P, TY) P, TY) ken and PHI	TY) res in 1 1989 3080 5580 2880 1980 3477 2494 10450 9100 6900 5307 4845 3402 9300 8300 7100 0 revenua averag = SUM(' = REV()	998 rand: 1990 3185 4883 2450 1870 3599 2838 10925 9555 7500 5655 5015 3969 9800 8400 7100 27200 500 e deviat. e revenus TY, REV (P.	1991 3700 5270 2960 2035 3172 3010 10930 9600 7900 5742 5100 4131 10000 8700 7300 27000 500 ions for e for la: TY))/CA	1992 3360 5425 2640 1815 3233 3440 10970 10000 8100 5829 5185 4617 10000 8700 7500 27500 500	1993 3234 4960 2800 1925 3538 3578 11400 10920 8100 5629 5270 4860 10000 8700 7700 26800 500	1994 3150 4805 2920 2008 3599 4128 11400 10920 8500 5829 5355 5103 10000 8700 7700 27600 500	1995 3325 5425 2680 1843 3416 4128 11400 10920 8700 5829 5610 5103 10000 9000 7800 27200 500	1996 3150 6000 2920 2008 3508 4300 11400 10920 8700 5916 5695 5346 10000 9200 8000 27200 500	3590 5270 2560 1760 3325 4472 11875 11375 11000 6003 5695 5427 10000 9400 8400 27200	2940 5270 2920 2008 3477 4730 12350 11830 11500 6264 5780 5427 10000 9600 8500 27200
TABLE Reven gumgro watgro ping30 ping18 popgro maidry maiis1 maiis2 maiis3 maiir1 maiir2 maiir3 sugir1 sugir2 sugir3 potirr velgro PARAMET REVDEV( RAVG(P) RAVG(P) REVDEV( ***Brac SCALAR ***Meie	REV(P, use figu: 1988   3234   5264   2808   1931   3436   2150   9500   6500   5133   4250   2835   9000   6900   27260   500   ER P, TY)   ken and PHI r farm	TY) rea in 1: 1989 3080 5580 2880 1980 3477 2494 10450 9100 6900 5307 4845 3402 9300 8300 7100 0 revenue average = SUM(' = REV()	998 rand: 1990 3185 4883 2450 1870 3599 2838 10925 7500 5655 5015 3969 9800 8400 7100 27200 500 e deviat. e revenu TY, REV(P P, TY) - RA'	1991 3700 5270 2960 2035 3172 3010 10930 9600 7900 5742 5100 4131 10000 8700 7300 27000 500 ions for e for la: TY))/CA	1992 3360 5425 2640 1815 3233 3440 10970 10000 8100 5829 5185 4617 10000 8700 7500 27500 500	1993 3234 4960 2800 1925 3538 3578 11400 10920 8100 5629 5270 4860 10000 8700 7700 26800 500	1994 3150 4805 2920 2008 3599 4128 11400 10920 8500 5829 5355 5103 10000 8700 7700 27600 500	1995 3325 5425 2680 1843 3416 4128 11400 10920 8700 5829 5610 5103 10000 9000 7800 27200 500	1996 3150 6000 2920 2008 3508 4300 11400 10920 8700 5916 5695 5346 10000 9200 8000 27200 500	3590 5270 2560 1760 3325 4472 11875 11375 11000 6003 5695 5427 10000 9400 8400 27200	2940 5270 2920 2008 3477 4730 12350 11830 11500 6264 5780 5427 10000 9600 8500 27200
TABLE Reven gumgro watgro ping30 ping18 popgro maidry maiis1 maiis2 maiis3 maiir1 maiir2 maiir3 sugir1 sugir2 sugir3 potirr velgro PARAMET REVDEV( RAVG(P) RAVG(P) REVDEV( ***Brac SCALAR	REV(P, use figu: 1988   3234   5264   2808   1931   3436   2150   9500   6500   5133   4250   2835   9000   6900   27260   500   ER P, TY)   ken and PHI r farm	TY) rea in 1: 1989 3080 5580 2880 1980 3477 2494 10450 9100 6900 5307 4845 3402 9300 8300 7100 0 revenue average = SUM(' = REV()	998 rand: 1990 3185 4883 2450 1870 3599 2838 10925 9555 7500 5655 5015 3969 9800 8400 7100 27200 500 e deviat. e revenus TY, REV (P.	1991 3700 5270 2960 2035 3172 3010 10930 9600 7900 5742 5100 4131 10000 8700 7300 27000 500 ions for e for la: TY))/CA	1992 3360 5425 2640 1815 3233 3440 10970 10000 8100 5829 5185 4617 10000 8700 7500 27500 500	1993 3234 4960 2800 1925 3538 3578 11400 10920 8100 5629 5270 4860 10000 8700 7700 26800 500	1994 3150 4805 2920 2008 3599 4128 11400 10920 8500 5829 5355 5103 10000 8700 7700 27600 500	1995 3325 5425 2680 1843 3416 4128 11400 10920 8700 5829 5610 5103 10000 9000 7800 27200 500	1996 3150 6000 2920 2008 3508 4300 11400 10920 8700 5916 5695 5346 10000 9200 8000 27200 500	3590 5270 2560 1760 3325 4472 11875 11375 11000 6003 5695 5427 10000 9400 8400 27200	2940 5270 2920 2008 3477 4730 12350 11830 11500 6264 5780 5427 10000 9600 8500 27200
TABLE Reven gumgro watgro ping30 ping18 popgro maidry maiis1 maiis2 maiis3 maiir1 maiir2 maiir3 sugir2 sugir3 potirr velgro PARAMET REVDEV( RAVG(P) RAVG(P) REVDEV( ***Brac SCALAR ***Meie *SCALAR	REV(P, ue figu: 1988 3234 5264 2808 1931 3436 2150 9500 9100 6500 5133 4250 2835 9000 8100 6900 27260 500 ER P,TY)  P,TY)  ken and PHI r farm PHI	TY) rea in 1: 1989 3080 5580 2880 1980 3477 2494 10450 9100 6900 5307 4845 3402 9300 8300 7100 0 revenue average = SUM(' = REV() Mason frisk farisk farisk :	998 rand: 1990 3185 4883 2450 1870 3599 2838 10925 9555 7500 5655 5015 3969 9800 8400 7100 27200 500 e deviat. e revenus TY, REV (P P, TY) - RA'	1991 3700 5270 2960 2035 3172 3010 10930 9600 7900 5742 5100 4131 10000 8700 7300 27000 500 ions for e for la ,TY))/CA	1992 3360 5425 2640 1815 3233 3440 10970 10000 8100 5829 5185 4617 10000 8700 7500 27500 500	1993 3234 4960 2800 1925 3538 3578 11400 10920 8100 5829 5270 4860 10000 8700 7700 26800 500	1994 3150 4805 2920 2008 3599 4128 11400 10920 8500 5829 5355 5103 10000 8700 7700 27600 500	1995 3325 5425 2680 1843 3416 4128 11400 10920 8700 5829 5610 5103 10000 9000 7800 27200 500	1996 3150 6000 2920 2008 3508 4300 11400 10920 8700 5916 5695 5346 10000 9200 8000 27200 500	3590 5270 2560 1760 3325 4472 11875 11375 11000 6003 5695 5427 10000 9400 8400 27200	2940 5270 2920 2008 3477 4730 12350 11830 11500 6264 5780 5427 10000 9600 8500 27200
TABLE  Reven  gumgro watgro ping30 ping18 popgro maidry maiis1 maiis2 maiis3 maiir1 maiir2 maiir3 sugir2 sugir3 potirr velgro PARAMET REVDEV( RAVG(P) RAVG(P) REVDEV( ***Brac SCALAR ***Meie *SCALAR **** **** **** **** **** **** ****	REV(P, ue figu: 1988 3234 5264 2808 1931 3436 2150 9500 9100 6500 5133 4250 2835 9000 8100 6900 27260 500 ER P,TY)  P,TY)  ken and PHI r farm PHI HYDROLOU	TY) rea in 1: 1989 3080 5580 2880 1980 3477 2494 10450 9100 6900 5307 4845 3402 9300 8300 7100 0 revenue average = SUM(' = REV() Mason for risk factorisk fa	998 rand: 1990 3185 4883 2450 1870 3599 2838 10925 7500 5655 5015 3969 9800 8400 7100 27200 500 e deviat. e revenu TY, REV(P P, TY) - RA'	1991 3700 5270 2960 2035 3172 3010 10930 9600 7900 5742 5100 4131 10000 8700 7300 27000 500 ions for e for la, ,TY))/CA	1992 3360 5425 2640 1815 3233 3440 10970 10000 8100 5829 5185 4617 10000 8700 7500 27500 500	1993 3234 4960 2800 1925 3538 3578 11400 10920 8100 5629 5270 4860 10000 8700 7700 26800 500	1994 3150 4805 2920 2008 3599 4128 11400 10920 8500 5829 5355 5103 10000 8700 7700 27600 500	1995 3325 5425 2680 1843 3416 4128 11400 10920 8700 5829 5610 5103 10000 9000 7800 27200 500	1996 3150 6000 2920 2008 3508 4300 11400 10920 8700 5916 5695 5346 10000 9200 8000 27200 500	3590 5270 2560 1760 3325 4472 11875 11375 11000 6003 5695 5427 10000 9400 8400 27200	2940 5270 2920 2008 3477 4730 12350 11830 11500 6264 5780 5427 10000 9600 8500 27200

```
.................
TABLE WAVAIL(2,TP)
                   total water available (1000m3)
                  dry
                         wet
***Bracken
            1997 238
                          1759
normyrs
dryyrs
            704
                  45
                          659:
***Mason
                  29
             241
*normyrs
                          212
*dryyrs
             8.5
                          802
***Meier
             9777
                          8614
*normyrs
                    1163
             3447
*dryyrs
                   220
PARAMETER WAVAIL2(Z,TP);
                          WAVAIL2(Z, TP)=1000*WAVAIL(Z, TP);
            DAMCAP
                                                                  / 700000
SCALAR
                         dam capacity in m3 BRACKEN
*SCALAR
             DAMCAP
                           dam capacity in m3 MASON AND MEIER
                                                                   101
SCALAR BETA percentage of dam avaible in dry years trhough traf from wetter yrs/0.25 /
..................
TABLE RUNOFF(P, Z, TP)
                           simulated RUNOFF (m3 per ha)
                  dry
            ann
                         wet
gumgro.normyrs 586
                   63
                          523
                    10
                          203
gumgro.dry, 717
watgro.normyrs 717
298
gumgro.drvyrs
                    67
                           650
                    10
                          288
ping30.normyrs 691
                   8.5
                           606
                          222
ping30.dryyrs
            238
                    16
pingl8.normyrs 691
                    85
                           606
pingl8.dryyrs
            238
                    16
                          222
popgro.normyrs 885
                    90
                          795
popgro.dryyrs
             407
                    21
                          386
maidry.normyrs 1304
                    135
                          1169
maidry.dryyrs
             783
                    59
                           724
maiirl.normyrs 2256
                    238
                          2018
maiirl.dryyrs
             1908
                    176
                           1731
maiir2.normyrs 1683
                   144
                          1539
maiir2.dryyrs
             1354
                    76
                           1278
maiir3.normyrs 952
                   45
                           907
maiir3.dryyrs
                           854
             892
                    39
maiisl.normyrs 2256
                    238
                          2018
maiisl.dryyrs
             1908
                    176
                           1731
maiis2.normyrs 1683
                    144
                          1539
             1354
                    76
                           1278
maiis2.dryyrs
maiis3.normyrs 952
                           907
                    45
             892
                           854
                    39
maiis3.dryyrs
sugirl.normyrs 960
                    101
                           859
sugirl.dryyrs
             560
                   85
                          475
sugir2.normyrs 657
                    43
                           614
sugir2.dryyrs
             313
                    1.6
                          297
                           523
sugir3.normyrs 554
                    31
sugir3.dryyrs
            267
                    5
                          262
potirr.normyrs
             2643
                   456
                           2188
potirr.dryyrs
             1965
                    352
                          1613
velgro.normyrs
             1153
                    104
                           1049
velgro.dryyrs
             610
                   29
                          581;
..............
TABLE WAP(P, Z, TP)
                     average water applied per ha per month (at various levels of
exceedence) (m3 per ha)
                         dry
                  ann
                               wet
                                 0
                   0
Gumgro.normyrs
                          0
                                 0
                   0
Gumgro.dryyrs
                    Ö
                          0
watgro.normyrs
                                 - 0
watgro.dryyrs
                   0
                          0
                                 0
ping30.normyrs
                    0
                           0
                                 0
ping30.dryyrs
                    0
                           0
                                 0
pingl8.normyrs
                    0
                          0
```

```
ping18.dryyrs
                   0
                         0
popgro.normyrs
                    0
                         0
popgro.dryyrs
                    0
                         0
              0
                    0
                         0
maidry.normyrs
maidry.dryyrs
                    D
                         0
                         2750
maiirl.normyrs
               2750
                    0
maiirl.dryyrs
              3275
                    0
                         3275
maiir2.normyrs
               2040
                    0
                         2040
              2360
maiir2.dryyrs
                   0
                         2360
maiir3.normyrs
               550
                    0
                         550
                         750
2750
                    0
maiir3.dryyrs
               750
maiisl.normyrs
               2750
                    0
              3275 0
2040 0
2360 0
                         3275
maiisl.dryyrs
maiis2.normyrs
                         2040
maiis2.dryyrs
                         2360
               550
                    0
                         550
mails3.normyrs
              750
                         750
maiis3.dryyrs
              6700 1000
7150 1025
5160 800
5380 820
sugirl.normyrs
                         5700
sugirl.dryyrs
                         6125
sugir2.normyrs
                         4360
sugir2.dryyrs
                         45-60
              3720 660
3840 600
sugir3.normyrs
                          3060
                         3240
sugir3.dryyrs
              4250 1100
4175 1000
0 0
                         3150
potirr.normyrs
potirr.dryyrs
                         3175
               0
velgro.normyrs
                         0
velgro.dryyrs
               0
                    0
                         0:
PARAMETER
***BRACKEN
              land data (ha)
    AREA(S)
                  nar=855,
                   ir=220 /
***MASON
    AREA(S)
               land data (ha)
                   nar=1342,
                    ir=0 /
***MEIER
*AREA(S)
          land data (ha)
     narlf=100,
*/
    ar1=40,
   arir1=25,
narir1=35,
narir2=10,
    arir2f=9,
    arir3=10,
    arir4=13,
    nar2=18 /
         total land available ;
AREATOT
AREATOT
        = SUM(S, AREA(S));
PARAMETER
         VIRGINRO(Z, TP)
VIRGINRO(Z,TP) = AREATOT*RUNOFF('VELGRO',Z,TP);
* SEE SECTION II.1
TABLE ROREDTAX(Z,TP)
               water charges per volume of RUNOFF reduc (R per
     ann dry wet
0 0 0
0 0 0;
normyrs
dryyrs
```

```
TABLE WABTAX (2, TF)
                         charge per volume of abstraction(R per m3)
           ann
                 dry
                       wet
                0
                      0
normyrs
            0
dryyrs
            0
                 0
                      0;
SCALAR
            SUB
                        subsidy per Rand (Rand per 1000Rand)
SCALAR GAMMA Switch to turn application of rored tax on NL lumps onl or off0 / 0
SCALAR DELTA switch to turn application of rored tax on return flows on or off / 0
***BRACKEN
SCALAR
           AFPERMIT
                       afforestation permit (ha)
SCALAR
           AFPERC
                       maximum allowable affor percentage
***MASON
*SCALAR
           AFPERMIT
                        afforestation permit (ha)
                                                        / 1342
                                                       / .75 /
*SCALAR
            AFPERC
                        maximum allowable affor percentage
***MEIER
*SCALAR
            AFPERMIT
                        afforestation permit (ha)
                                                         / 210
            AFPERC
                                                         / 0.80
*SCALAR
                         maximum allowable affor percentage
TABLE IFR(2, TP)
                  ifr MAR target (% of virgin runoff of catchment of farm incl farm)
           ann
                 dry wet
                 0
normyrs
            0
                        0
            0
                 0
dryyrs
                        0.5
TABLE IFRSFLOW(2, TP) minimum streamflow required (m3)
                    dry
-1000000
            -1000000
                                    -10000000
DOEMYES
dryyrs
            -1000000
                        -1000000
                                    -1000000
TABLE WRIGHT (2, TP)
                 total abstr right (m3)
               dry
                      wet
          ann
***Bracken
           1997000238000 1759000
normyes
         704000 45000 659000;
dryyrs
***MEIER
            154700 16600 138100
*normyrs
            170800 15100 156700;
*dryyrs
           170800 170800 170800
170800 170800 170800;
*normyrs
*dryyrs
TABLE PERCWR(Z, TP)
                 total abstr right (m3)
           ann
                 dry wet
normyrs
                        17
dryyrs
TABLE SFRRIGHT(Z,TP) total streamflow reduction right (m3)
            nn dry wet
3000000 3000000 3000000
           ann
normyrs
dryyrs
            3000000 3000000 3000000;
VARIABLES
*** landuse and production variables *********
     CROP(Z, P, S)
                        landuse activities
                                                 (ha)
                      total ha of landuse activity p
     TOTCROP(Z, P)
                                                     (ha)
     XPROD(Z,C)
                       crop production
                                                 (ton)
```

Creemers and Pott 2001

```
...........
TROREDT (Z.TP)
                total tax during tp
TWART (Z, TP)
                total tax during tp
TOTS(Z)
             total subsidy
TOTWTAX(2)
                total water tax
RUNOFFT (Z, TP)
                RUNOFF (m3 per ha)
WAPT (Z, TP)
                water application (m3)
   WABT (Z, TP)
                water abstraction (m3)
RUNOFF reduction (m3)
   ROREDT (Z, TP)
                RUNOFF reduction by non licenced lumps (m3)
   ROREDNLT(Z, TP)
                RUNOFF reduction by irr lumps (m3)
   ROREDRFT (Z, TP)
SFLOWT (Z, TP)
                STREAMFLOW (m3 )
SFREDT (Z, TP)
                STREAMFLOW reduction (m3 )
TOTREV(2)
             total revenue
                           (R)
PUMPC(2)
             total pumping costs
                        (R)
             total variable cost excl labour (R)
   TOTVCOST(Z)
TOTFCOST(Z)
         total fixed cost
   CVCPOS(S)
   CVCNEG(S)
   TOTCVC
         total converstion cost
** V.4.4 Risk variables
   RISK(Z)
             risk variable
         positive price deviations
negative price deviations
   PDEV(Z, TY)
                           (B)
   NDEV(Z, TY)
YZ(Z)
          farm income during period Z
   YEXP
          expected farm income
                           (R)
POSITIVE VARIABLES CROP, TOTCROP, PDEV, NDEV, XPROD, WABT, CVCPOS, CVCNEG ;
```

```
EQUATIONS
  LANDBAL(2,S)
        land balance
  USETOT(2)
        use of total land
TOTCROPEQ(Z,F) total ha of landuse p
       crop production
  PRODEQ(Z,C)
TOTREVEO(Z)
        accounting: total revenue definition
PUMPCEQ(Z)
           accounting: total pumping cost equation
  TOTVCOSTEQ(2)
            accounting: total labor cost definition
FCOSTEQ
            fixed cost
CVCEO(S)
           accounting: conversion cost
        total conv costs
  TOTCVCEO
TROREDTEQ(Z, TP)
            tax on RUNOFF red per t
  TWABTEQ(Z, TP)
            tax on abstraction per t
   SEQ(Z)
            accounting: total subsidy generated
   TOTWTAXEQ(2)
            total water taxes paid minus subsidies received
RUNOFFTEQ (Z, TP)
            RUNOFF equations
   WAPCALCEQ(Z, TP)
            water application equation
   ROREDTEQ(Z, TP)
            RUNOFF reduction equations
  ROREDNLTEQ(2, TP)
            RUNOFF reduction by non licenced lumps
  ROREDRFTEQ(Z, TP)
            Runoff reduction by irrigation - return flows
   SFLOWTEQ(2,TF)
               STREAMFLOW equations
   SFREDTEO(Z, TP)
               STREAMFLOW reduction equations
```

```
WRIEQ(S, TP)
              water right constraint
              streamflow reduction right constraint
    SFRRTEQ(Z, TP)
    WAVTEQ(Z, TP)
              water availabilty constraint
    DAMIED
              dam equation 1
    DAM2EQ
              dam equation 2
    WABRECONC (Z)
              water abstraction reconciliation constraint
RISKEQ(Z)
              risk definition
    DEVEQ(Z, TY)
              deviations definition
IFREQ(Z,TP)
              maximum streamflow reduction requirement
    IFRSFEQ(Z,TP) minimum streamflow requirement
forestry permit equation forestry permit equation
    AFPERCEQ(Z)
SUGEO
              irr sugar equation
              irr maize equation
    MAIEO
              irr maize equation
    POTEO
    MASEO
              irr seed maize equation
    AFEQ
              afforestation equation
YZEQ(2)
              farm income definition for period Z
              expected farm income
    YEXPEQ
    CONSTRIEQ(Z) control equation 1
    CONSTRIEQ(Z)
              control equation 2
    CONSTR3EQ(Z,P) control equation 3
             control equation 4
control equation 5
    CONSTR4EQ(2)
    CONSTRSEQ(2)
    CONSTREEQ(2)
             control equation 6
..............
LANDBAL(2,S)..
             SUM(P, CROP(Z, P, S)) =L= AREA(S);
USETOT(Z) ..
             SUM((P,S),CROP(Z,F,S)) =E=AREATOT;
TOTCROP(Z,P) =E= SUM(S,CROP(Z,P,S));
TOTCROPEQ(2, P) ..
PRODEQ(Z,C)...
              XPROD(Z,C) = E = SUM((P,S), YIELD(P,C,Z,S) *CROP(Z,P,S));
TOTREV(Z) =E= SUM(C, SENSPR(C)*PRICE(C)*XPROD(Z,C));
TOTREVED(Z) ...
** VII.4.1 Variable Labour and non-labour costs
              PUMPC(2) =E= SUM(TP$TS(TP),UNITPC*WABT(2,TP));
PUMPCEQ(2).
TOTVCOSTEQ(Z)..
                  TOTVCOST(Z) =E= SENSVC*SUM((P,U), VCOST(P, Z, U)*TOTCROP(Z, P)) +
PUMPC(E);
TOTFCOSTEQ. .
                TOTFCOST =E= SENSFC*SUM(P, FCOST(P) *TOTCROP('normyrs', P));
```

```
CVCEQ(S) ..
          CVCPOS(S)+CVCNEG(S)=E= CVC(S)*(AFFOR(S)-SUM(P$AFP(P),CROP('NORMYRS',P,S)));
TOTCVCEO...
         TOTCVC=E=SUM(S, CVCPOS(S));
** VII.6.1 RUNOFF ****
RUNOFFTEQ(Z, TP)..
              RUNOFFT(Z,TP) =E= SUM(P,TOTCROP(Z,P)*RUNOFF(P,Z,TP)) ;
ROREDTED(Z.TP) ...
              ROREDT(Z,TP) =E= VIRGINRO(Z,TP)-SUM(P,TOTCROP(Z,P)*RUNOFF(P,Z,TP)) ;
ROREDNLTEQ(Z, TP) ...
               ROREDNLT(Z,TP)-E- SUM(PSNL(P),TOTCROP(Z,P)*(RUNOFF('VELGRO',Z,TP)-
RUNOFF(P, Z, TP)));
ROREDRFTEQ(Z, TP) ...
               ROREDRFT(Z, TP) = E = SUM(PSIRP(P), TOTCROP(Z, P) * (RUMOFF('VELGRO', Z, TP) -
RUNOFF(P, Z, TP)));
WAPT(2, TP) =E= SUM(P, WAP(P, Z, TP) *TOTCROP(Z, P)) ;
WAPCALCEO(Z.TP) ...
SFLOWTEQ(Z,TP)..
              SFLOWT(Z,TP) =E= SUM(P,TOTCROP(Z,P)*RUNOFF(P,Z,TP))-WABT(Z,TP);
SFREDT(Z,TP) =E= VIRGINRO(Z,TP)-SFLOWT(Z,TP);
SFREDTEO(Z.TP) ...
TROREDTEQ (Z, TP) . .
               TROREDT(Z, TP) =E= ROREDTAX(Z, TP)*( ROREDT(Z, TP)
             - (1-GAMMA) *ROREDNLT(Z, TP)
             - (1-DELTA) *ROREDRFT(Z, TP));
TWART(Z,TP) =E= WARTAX(Z,TP)*WART(Z,TP) ;
TWABTEQ(Z, TP) ...
TOTS(Z) =E= SUM(P, SUB*RAVG(P)*TOTCROP(Z, P));
SEQ(2) ...
TOTWTAXEQ(Z) . .
               TOTWTAX(2) =E= SUM(TP, TROREDT(2, TP)+TWABT(2, TP)-TOTS(2));
.........
WRTEQ(I,TP) ...
              WABT(2, TP) =L= PERCWR(2, TP) *WRIGHT(2, TP);
              SFREDT(Z,TP) =L= SFRRIGHT(Z,TP);
SFRRIEQ(2, TP) ...
WAVTEQ(Z, TP)..
              WAST(Z, TP) =L= 1000*WAVAIL(Z, TP);
              WABT(Z,'WET')+WABT(Z,'DRY') =E= WABT(Z,'ANN');
WAPT(Z,TP) =L= WABT(Z,TP);
WABRECONC(Z) ...
*DAM1EQ(Z,TP)..
*Bracken
DAM1EQ..
        WAFT('DRYYRS', 'ANN') =L= WABT('DRYYRS', 'ANN') + BETA*DAMCAP;
              WABT('NORMYRS','ANN') =E=
Alpha('DRYYRS')/(1-Alpha('DRYYRS'))*BETA*DAMCAP
+WAPT('NORMYRS','ANN');
DAMZEQ..
SUM(P$AFP(P), TOTCROP(Z, P)) =L= AFPERMIT
AFPERMEQ(2)..
AFPERCEQ(Z) ..
              SUM(PSAFP(P), TOTCROP(Z, P)) =L= AFPERC*AREATOT ;
............
```

Creemers and Pott 2001

```
SFLOWT(2,TP) =G= IFRSFLOW(2,TP);
IFRSFEQ(Z,TP)..
                    (1000*WAVAIL(Z,TP)+SFLOWT(Z,TP))/(1000*WAVAIL(Z,TP)+
IFREQ(Z,TP)...
                         VIRGINRO(2, TP)) =G= IFR(2, TP);
DEVEQ(Z,TY) ...
                    SUM(P, REVDEV(P, TY) *TOTCROP(2, P)) =E= PDEV(2, TY) - NDEV(2, TY);
RISKEQ(Z) ..
                    RISK(Z) =E=PHI*SUM(TY, PDEV(Z, TY)+NDEV(Z, TY))/CARD(TY);
***Bracken and Mason farms
SUGEQ. .
                   SUM(ISP, CROP('normyrs', ISP, 'IR')) =E=SUM(ISP, CROP('dryyrs', ISP, 'IR')) ;
***All farms
MAIEQ..
             SUM((IMP,S),CROP('normyrs',IMP,S)) =E-SUM((IMP,S),CROP('dryyrs',IMP,S));
             SUM((IMSP,S),CROP('normyrs',IMSP,S)) =E=SUM((IMSP,S),CROP('dryyrs',IMSP,S));
TOTCROP('normyrs','POTIRR') =E= TOTCROP('dryyrs','POTIRR');
TOTCROP('normyrs',P)$AFP(P) =E= TOTCROP('dryyrs',P)$AFP(P);
MASEQ..
POTED ..
AFEO(P) ...
***Bracken and Mason farms
CONSTRIEQ(Z)..
                   SUM(P$IMSP(P), TOTCROP(Z, P)) =L= 1*AREA('IR');
CONSTR2EQ(Z).
                   SUM(PSISP(P), TOTCROP(Z, P)) =L= 1*AREA('IR');
CONSTR3EQ(Z,P)SAFP(P)..
                           TOTCROP(Z, P) =L= 0.6*SUM(KP$AFP(KP), TOTCROP(Z, KP));
CONSTRAEQ(Z)..
                 TOTCROP(2, 'POTIRR')=L=0;
TOTCROP(2, 'POPGRO')=L=0;
SUM(IMSP, TOTCROP(2, IMSP))=L=147;
CONSTRSEQ(Z)..
CONSTR6EQ(Z)..
                    TOTCROP('MORMYRS', P) $ (TOTCROP('NORMYRS', P) > 0) = G=10;
.....
Y2EQ(Z) ..
             YZ(Z) -E- TOTREV(Z)-SENSTC*(TOTVCOST(Z)+TOTFCOST(Z))-TOTWTAX(Z)-RISK(Z);
YEXPEQ..
             YEXP =E= SUM(Z, ALPHA(Z)*YZ(Z));
MODEL SIMPLE1 / ALL /;
SOLVE SIMPLE! MAXIMIZING YEXP USING LP;
SET SCENARIO different scenarios
/SC01*SC04/;
TABLE LOOPSCEN(Z, TP, SCENARIO) different resource availabilities
                               SC04
                   SC02
                          SC03
            SC01
normyrs.ann
            1
                   1
                         .7
                               .5
                                     .5
normyrs.dry
                               .7
                   . 7
                         .7
normyrs.wet
            1
                         1
dryyrs.ann
                  1
                               .25
dryyrs.dry
             . 5
                         . 3
dryyrs.wet
             .7
                         .7
                               .71
             LOOPPRM (SCENARIO)
                               different APS levels
      SC01-900
      SC02=900
      SC03=900
      SC04=900
            CIdryA, CIdryD, CImedA, CImedD, CRdryA, CRdryD, CRmedA, CRmedD;
SCALAR
FILE OUTPUT / OUTPUT.OUT /;
OUTPUT.PC = 0;
```

```
OUTPUT. NJ-2;
                 column number
row number
total revenue
SCALAR COL
                                                           / 22 /:
SCALAR ROW
                                                           /-999/1
SCALAR R
SCALAR Y
                                                           /-999/:
                   income
             labour income
risk variable
conversion cost variable
marginal cost variable
SCALAR LC
                                                           /-999/:
SCALAR RS
                                                           /-999/1
                                                           /-999/;
SCALAR CC
SCALAR MC
                                                           /-999/;
SCALAR WABdryA abstraction
SCALAR WABdryD abstraction
                                                           /-999/:
                                                           /-999/;
SCALAR WABmedA abstraction
                                                           /-999/:
SCALAR WABmedD abstraction
                                                           /-999/;
SCALAR WAPdryA application
                                                           /-999/1
SCALAR WAPdryD application
                                                           /-999/;
SCALAR WAPmedA application
                                                           /-999/1
SCALAR WAPmedD application
                                                           /-999/;
                                                           /-999/:
SCALAR SFRdryA abstraction
SCALAR SPRdryD abstraction
                                                           /-999/1
SCALAR SFRmedA abstraction
                                                           /-999/;
                                                           /-999/1
SCALAR SFRmedD abstraction
SCALAR WCHARGE total water charges
                                                          /-999/:
                  CIdryA, CIdryD, CImedA, CImedD,
SCALAR
                 CRdryA, CRdryD, CRmedA, CRmedD;
PUT OUTPUT:
PUT LOOP (SCENARIO, PUT @COL, SCENARIO.TL; COL-COL+15)
PUT /:
PUT LOOP((Z,TP), PUT Z.TL, 05, '.',TP.TL /)
PUT "APS SC" /;
PUT "rev (R000s)"
PUT "finc (R000s)" /;
PUT "linc (R000s)" /;
PUT "risk (R000s)" /;
PUT "convc (R000s)" /;
PUT "wch (R000s)"
PUT "wch (R000s)" /;
PUT "mcost (R/m3)" //;
POT "wabdryA(000m3)" /;
POT "wabdryD(000m3)" /;
POT "wabmedA(000m3)" /;
PUT "wabmedD(000m3)" //:
PUT "wapdryA(000m3)" /;
PUT "wapdryD(000m3)" /;
PUT "wapmedA(000m3)" /;
PUT "wapmedD(000m3)" //;
PUT "sfrdryA(000m3)" /;
PUT "sfrdryD(000m3)" /:
PUT "sfrmedA(000m3)" /:
PUT "sfrmedD(000m3)" //:
PUT "sflow dryA" /:
PUT "sflow dryD" /;
PUT "sflow medA" /;
PUT "sflow medD" //;
COL-COL-60;
LOOP (SCENARIO,
                    change RHS to new values in table loopscenario
                  IFRSFLOW(Z, TP) =LOOPSCEN(Z, TP, SCENARIO);
                  WRIGHT(Z,TP)=LOOPSCEN(Z,TP,SCENARIO);
PERCWR(Z,TP)=LOOPSCEN(Z,TP,SCENARIO);
                  AFPERMIT=LOOPPRM (SCENARIO);
                  WABTAX(Z, TP) = LOOPSCEN(Z, TP, SCENARIO);
                  ROREDTAX(Z, TP) = LOOPSCEN(Z, TP, SCENARIO);
```

```
solve model
                  SOLVE SIMPLE1 MAXIMIZING YEXP USING LP ;
                  R=SUM(Z, ALPHA(Z) *TOTREV.L(Z))/1000;
                  Y=YEXP.L/1000;
                  LC= SUM(Z, ALPHA(Z)*SUM(P, SENSVC*VCOST(P, Z, 'LAB')
                   *TOTCROP.L(Z,P)))/1000;
                  RS= SUM(Z, ALPHA(Z)*RISK.L(Z))/1000;
                  CC= TOTCVC.L/1000;
                  MC= WRTEQ.M('DRYYRS', 'DRY');
                  WABdryA=WABT.L('dryyrs','aNN')/1000;
WABdryD=WABT.L('dryyrs','DRY')/1000;
WABmedA=WABT.L('normyrs','ANN')/1000;
                  WABmedD=WABT.L('normyrs','DRY')/1000;
                  WAPdryA=WAPT.L('dryyrs','ANN')/1000;
WAPdryD=WAPT.L('dryyrs','DRY')/1000;
WAPmedA=WAPT.L('normyrs','ANN')/1000;
WAFmedD=WAPT.L('normyrs','DRY')/1000;
                  SFRdryA=SFREDT.L('dryyrs','ANN')/1000;
                  SFRedryD=SFREDT.L('dryyrs','DRY')/1000;
SFRmedA=SFREDT.L('normyrs','ANN')/1000;
                  SFRmedD=SFREDT.L('normyrs','DRY')/1000;
                  WCHARGE-SUM(Z, ALPHA(Z)*TOTWTAX.L(Z))/1000;
                   write specific output to output file
                  LOOP((Z,TP), PUT #ROW @COL LOOPSCEN(Z,TP,SCENARIO);
                  ROW=ROW+1 )
                  PUT #ROW @COL LOOPPRM(SCENARIO) ; ROW-ROW+1;
                  PUT #ROW @COL R ; ROW-ROW+1;
                  PUT #ROW @COL Y ; ROW-ROW+1;
PUT #ROW @COL LC ; ROW-ROW+1;
                  PUT #ROW @COL RS ; ROW-ROW+1;
                  PUT #ROW @COL CC ; ROW-ROW+1;
                  PUT #ROW @COL WCHARGE ; ROW=ROW+1;
                  PUT #ROW @COL MC ; ROW-ROW+2;
                  PUT #ROW @COL WABdryA ; ROW-ROW+1;
                  PUT #ROW @COL WABdryD : ROW-ROW+1:
                  PUT #ROW @COL WABmedA ; ROW-ROW+1;
                  PUT #ROW @COL WABmedD ; ROW=ROW+2;
                  PUT #ROW @COL WAPdryA : ROW-ROW+1;
                  PUT #ROW @COL WAPdryD ; ROW-ROW+1;
                  PUT #ROW @COL WAPmedA ; ROW-ROW+1;
                  PUT #ROW @COL WAPmedD ; ROW-ROW+2;
                  PUT #ROW @COL SFRdryA ; ROW-ROW+1;
                  PUT #ROW @COL SFRdryD ; ROW-ROW+1;
                  PUT #ROW @COL SFRmedA ; ROW-ROW+1;
                  PUT #ROW @COL SPRmedD ; ROW-ROW+2;
                  PUT #ROW @COL SFLOWT.L('dryyrs','ann') ;ROW=ROW+1;
PUT #ROW @COL SFLOWT.L('dryyrs','dry') ;ROW=ROW+1;
PUT #ROW @COL SFLOWT.L('normyrs','ann') ;ROW=ROW+1;
                  PUT #ROW @COL SFLOWT.L('normyrs', 'dry') ; ROW-ROW+2;
                  COL=COL+15;
                  ROW-ROW-35;
                   next scenario until it is done
1:
FILE OUTPUT2 / OUTPUT2.OUT /:
OUTPUT2.PC = 0;
OUTPUT2.NJ=2;
```

```
COL-COL-60;
ROW-3;
PUT OUTPUT2;
PUT LOOP (SCENARIO, PUT *ROW @COL, SCENARIO.TL; COL=COL+15)
PUT /1
PUT '-
ROW=7:
PUT #5 @1, "fine (RO00s)" //;
POT LOOP(P, LOOP(Z, POT #ROW @1 , P.TL, @7, '.', Z.TL; ROW-ROW+1; );
ROW-ROW+1; );
COL=COL-60;
ROW=51
LOOP (SCENARIO,
                change RHS to new values in table loopscenario
               IFRSFLOW(2, TP) = LOOPSCEN(2, TP, SCENARIO);
               WRIGHT (Z, TP) = LOOPSCEN(Z, TP, SCENARIO);
               PERCWR(Z, TP) = LOOPSCEN(Z, TP, SCENARIO);
               AFPERMIT=LOOPPRM (SCENARIO);
               WABTAX (Z, TP) =LOOPSCEN(Z, TP, SCENARIO);
               ROREDTAX(Z,TP)=LOOPSCEN(Z,TP,SCENARIO);
                solve model
               SOLVE SIMPLE! MAXIMIZING YEXP WSING LP ;
               Y=YEXP. L/1000;
               PUT #ROW #COL Y ; ROW-ROW+2;
               LOOP (P,
               LOOP(Z, PUT #ROW @COL TOTCROP.L(Z,P); ROW=ROW+1;) ;
               ROW=ROW+1; );
               COL=COL+15;
               ROW-ROW-53;
                next scenario until it is done
```

# Other related WRC reports available:

Guidelines for financing catchment management agencies in South Africa

G Pegram & I Palmer

The National Water Act (Act 36 of 1998) provides for the progressive establishment of Catchment Management Agencies (CMAs) throughout South Africa. The intention is for CMAs to be largely financed at a WMA scale, through appropriate "user charges", which enable CMAs to be financially self-supporting and sustainable. This document is aimed at supporting those people involved in assessing the financial viability of a proposed CMA (as part of the proposal to the Minister for establishment of a CMA), as well as those involved in preparing the annual business plan (required of every CMA, once established). It provides background and interpretation to the relevant policy and legislation, with an emphasis on the user charges for water resource management that are set and recovered to cover the CMA costs. The document is supported by a financial model, that assists in the calculation of CMA costs and water use charges.

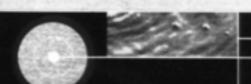
The document provides a useful background reference to financing CMA establishment and functioning, and highlights areas where the Pricing Strategy needs to be engaged. The CMA financial model provides a valuable tool to support the CMA business planning process and the calculation of user charges for water resources management.

Report Number: 1044/1/01 ISBN 1 86845 800 8

TO ORDER: Contact Rina or Judas - Telephone No: 012 330 0340

Fax Number: 012 331 2565

E-mail: publications@wrc.org.za



Water Research Commission

Private Bag X03, Gezina, 0031, South Africa

Tel: +27 12 330 0340, Fax: +27 12 331 2565

Web: http://www.wrc.org.za

