LAND-WATER LINKAGES: AGENT-BASED MODELLING OF LAND USE AND ITS IMPACT ON WATER RESOURCES

Report to the
Water Research Commission

by

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EXECUTIVE SUMMARY

1. Introduction

Over the last few decades, numerous researchers have improved measurements of land-use change, the understanding of the causes of land-use change, and predictive models of land-use change, by a representation of much more complex, and sometimes intricate, processes of land-use. Understanding of the causes of land-use change has moved from simplistic representations to a much more profound understanding that involves situation-specific interactions among a large number of factors at different spatial and temporal scales (Lambin *et al*., 2003). Concerns about land-use change emerged in the research agenda on global environmental change several decades ago with the realization that land surface processes influence climate. It was recognised that land-cover change modifies surface albedo and thus surface-atmosphere energy exchanges, which have an impact on regional and global climate.

In central South Africa, agriculture, mainly commercial farming, is the economic backbone of the community in the region. The rural small-scale farmers are currently being introduced to improved agricultural practices through improved surface water (rainwater) management. The hydrological balance of any river basin is directly and indirectly influenced by the spatial and temporal distribution of land-use and land-cover changes. Changes in land cover can modify crucial hydrological processes, such as evapotranspiration and ground water recharge. Upstream land-use change could bring about a significant on-site effect on catchment water resources and off-site effect on downstream users. For instance, the introduction of IRWH in the upper Modder river basin catchment may result in a significant impact on the downstream water users and the ecological balance of the system if allowed to expand unchecked.

2. Aims of the project

The general aim of this project was to contribute to the understanding of the dynamics of human-environment interactions and decision-making processes for the sustainable use of land and water in the Modder River. The specific aims of this project were:

- To investigate the driving forces in land-use change.
- To understand the influence of the spatial and temporal distribution of land-use and land-cover changes on the hydrological balance of the river basin.
- To analyse and model both the physical environment and the human dimension of the processes of land use change and its impact on water resources.

3. Biophysical Characteristics of the Modder River Basin

Biophysical factors, such as climate, soil, topography and vegetation are some of the major factors that greatly affect runoff from a specific catchment (Peugeot *et al*., 1997; Jain *et al*., 2004). Rainfall and evapotranspiration (ET) are the main components of the climate that have major influence on the water balance of a catchment. High rainfall contributes to increased stream flow while in contrary high ET reduces the amount of overland water considered as blue water (Jewitt *et al*., 2004). Soil physical and chemical properties such as soil texture and infiltration rate affect the amount of surface water considerably. Soils with high silt and clay content and soils with low infiltration rate contribute to high surface runoff. On the other hand, sandy soils and soils with high infiltration rate reduce runoff and thereby stream flows.

In the Modder river basin seven soil series were identified. The Upper Modder river basin is dominated by soil series type Va40/Va41 including some minor ones, such as Bo and Sw forms. This series ranked second in the basin. The texture of this soil is 100% sandy clay loam to sandy clay (SaClLm to SaCl). The Middle Modder river basin is predominantly covered by soil series Cv34 and Ss16 which are first and fourth in area coverage within the basin. The soil texture of Cv34 is dominated by sand to loamy sand (Sa to LmSa) while the series Ss16 is dominated by sandy clay loam (SaClLm). The Lower Modder river basin is largely dominated by soil series Hu36. The Upper and Middle Modder river basin catchments are dominated by land type Dc17 covering an area of 225 554 ha.

The Modder river basin receives mean annual rainfall which ranges between 300 and 725 mm. The upper Modder river basin receives relatively higher mean annual rainfall which amounts to 725 mm. The lowest mean annual rainfall (300 mm) is received by the lower Modder river basin which is located in the most westerly part of the basin. The maximum mean annual temperature of the basin varies between 27°C and 29°C while the lowest varies between -2°C and 2°C. The mean aridity index (AI) estimated as 0.24 and ranges from 0.16 to 0.34 for the lower and the upper basin, respectively. Thus, the whole basin falls within the range of semi-arid climate.

Regarding land use of the basin, the upper basin is dominated by unimproved natural grassland. In this part of the basin irrigated crop land is insignificant. The middle and lower part of the basin are largely used for crop production, with commercial irrigation farming dominating the lower part of the basin. Large portion of the middle part of the basin area is used for urbanization, which consists of towns such as Bloemfontein and Botshabelo. The lower part of the basin consists of large areas of bush lands and low fynbos in addition to the croplands. Quaternary catchment C52A is located on the upper Modder River basin. Land use map of 2000 shows that 84% of C52A area covered by grassland while only about 8% was used by agriculture.

4. Socio-Economic Drivers of Land Use Change

Xie *et al*. (2005) also identifies six possible socio-economic drivers that affect land use changes. These include population increase and its level of affluence, technology, political economy, political structure, and attitudes and values. For instance, they described the impact of population increase on land use change as bringing a sequence of immediate increase in demand for land for life sustaining needs such as residence space, food and fibre. They also report that the original physical and ecological environments of the Yangtze River and the Pearl River basins have been totally altered and replaced with intensive human-transformed agricultural systems, along with highly concentrated population and socioeconomic activities. In a similar way Alberti and Waddell (2000) have coupled urban growth models with models of ecosystem processes to evaluate the impact of different demographic and economic scenarios.

The Modder River Basin includes a major city and two townships within the Free State Province, namely Bloemfontein, Botshabelo and Thaba Nchu (Figure 7). These three cities account for the biggest proportion of the province's population with a combined figure of 618 566 for the year 2001. The largest share goes to Bloemfontein with population of 375 823 (current estimate 850 000), followed by Botshabelo with population of 175 672 and Thaba Nchu 67 071. The population showed 1.3% growth rates between 1996 and 2001 (MLM IDP, 2008/9).

In terms of the economic situation in the area that comprises the Modder River basin, the average household income per annum in Bloemfontein, Thaba Nchu and Botshabelo are R76 611; R32 105 and R24 828, respectively (Urban-Econ, 2003). Approximately 15% of the household earn between R6 000 and R18 000. On the other hand, 75% of individuals earned less than R800 per month in 2001. The figures in Table 4 show that approximately half of the economically active population in the Modder River Basin are unemployed.

5. Hydrological Modelling of Land Use Impact

Numerous modelling approaches have been developed to simulate the impact of land use changes on the environment in general and water resources in particular. One of these models is called Soil and Water Assessment Tool (SWAT). The SWAT model is used to simulate the impact of land-use change and land management practices on water balance of a catchment. SWAT has also proven to be an effective tool for understanding pollutions by fertilizer applications and point sources (Arnold *et al*., 1998 and Fohrer *et al*., 2005) and for wider environmental application on the globe (Gassman *et al*., 2007).

Taking into account its wider application in assessing the impact of land use changes on water resources, SWAT model was applied in the Modder river basin of Central South Africa to evaluate the impact of land use change on water resources, with particular emphasis on the flow of water into Rustfontein dam. The model simulated several parameters among which the direct flow (DIRQ), the base flow or the ground water flow (GWQ), water yield (WY) and evapotranspiration (ET) were selected for evaluation purpose. Figure 12 in the main text shows the variation of the WY for the two land use data sets at the outlet of C52A catchment.

An assessment of the impact of land use change on the water balances of C52A catchment was also under taken by creating logically perceived land use scenarios using ArcGIS. In this study, land use data for the year 2000 was used as a benchmark against which different land use scenarios were compared. Two land use scenarios were considered. *Scenario*-1 (Agri-CON): conventional land use which represents the current land use practice in the area and *Scenario*-2 (Agri-IRWH): in-field rainwater harvesting based on the work of Hensley *et al.* (2000) which was aimed at improving the precipitation use efficiency (PUE). The 2000 land use data of C52A shows that 84% of the land is covered by pasture (PAST). This was taken as a base scenario against which the other two scenarios were compared. To create the first scenario (Agri-CON), a change was made to the original pasture (PAST) land in such a way that the land on slopes of 0 to 3% was converted to agriculture with conventional practices. This change brought about 420 km^2 (54%) of the pasture area on slopes of 0 to 3% under agricultural land. This has increased the area of the agricultural land from 8% to 53% and decreased the pasture area from 84% to 39%. The second scenario (Agri-IRWH) was obtained by changing the pasture land

(PAST) located on slopes of 0 to 3% to an agricultural land planted with maize using an infield rainwater harvesting (IRWH). In both scenarios all other land use types remained the same as in the base scenario and they both have the same area of cropland and crop type which is maize, the only difference being the tillage type, i.e. scenario-1 uses conventional row cropping while scenario-2 uses IRWH.

The scenario analysis results revealed that conventional agricultural land use scenario generates highest direct flow than the ones dominated by pasture or IRWH land use scenarios. This may not support favourable crop production on rain-fed arid areas, such as the Modder river basin, due to the decreased infiltration of water to the sub-soil which ultimately influences the soil water content within the root zone. However, in this study it is difficult to conclude whether the increased direct runoff would have been more beneficial if it was to be harnessed by small ponds or dams on-site for use as a supplemental irrigation using the Agri-CON production scenario or if used by the downstream communities from the increased stream flow.

The results also confirmed that there was improvement of water infiltration into the soil by Agri-IRWH and PAST land uses. Both resulted in higher base flow than Agri-CON land use. Both also demonstrated high deep water percolation with a significant difference in annual amounts compared to Agri-CON. The Agri-IRWH showed 105% higher base flow compared to the Agri-CON land use scenario (Table 1).

Table1. Mean monthly stream flow components in mm for the three land use scenarios over the period of 1995-2007

Month	Rainfall (mm)	Agri-IRWH			Agri-CON			PAST		
		DIRQ	GWQ	WY	DIRQ	GWQ	WY	DIRQ	GWQ	WY
Sep	16.8	0.93	0.30	1.23	1.12	0.25	1.37	0.69	0.69	1.38
Oct	53.7	2.90	0.18	3.08	3.72	0.15	3.87	2.41	0.46	2.87
Nov	73.6	6.51	0.56	7.07	8.94	0.47	9.41	9.04	1.48	10.52
Dec	78.7	4.48	1.51	5.99	6.10	0.91	7.01	3.65	2.67	6.32
Jan	96.5	6.50	1.52	8.02	10.18	0.75	10.93	6.59	1.89	8.48
Feb	93.2	8.93	4.24	13.17	18.21	1.68	19.89	12.11	2.73	14.84
Mar	88.1	8.10	9.68	17.78	13.95	4.12	18.07	10.63	5.88	16.51
Apr	41.2	3.65	9.00	12.65	4.76	4.42	9.18	4.30	6.63	10.93
May	18.2	1.34	6.45	7.79	1.84	3.25	5.09	1.33	5.53	6.86
Jun	5.3	0.34	2.89	3.23	0.36	1.40	1.76	0.24	2.64	2.88
Jul	5.1	0.20	0.94	1.14	0.23	0.51	0.74	0.12	0.98	1.10
Aug	19.8	1.34	0.27	1.61	1.43	0.16	1.59	1.42	0.31	1.73
Annual	**590.3**	**45.22**	**37.54**	**82.76**	**70.84**	**18.07**	**88.91**	**52.53**	**31.89**	**84.42**

DIRQ = Direct flow
GWQ = Ground water flow or base flow
WY = Water yield

In the past a variety of models were used for predicting land-use changes. Recently the focus has shifted away from using mathematically oriented models to agent-based modelling (ABM) approach to simulate land use scenarios. The agent-based perspective, with regard to land-use cover change, is centred on the general nature and rules of land-use decision making by individuals.

In the study of land use changes and its impact on water resources, there are several agents who have direct and indirect impact on land use decision making process. As the number of agents increase the level of model complexity also increases. However, in order to get the first glimpse of the dynamics of human-environment interaction, the number and type of agents will be limited to farmers, land owners or farm managers who are directly involved in the use of land in a catchment. In a given time, farmer's land use decision is subjected to environmental conditions, which in this study are grouped under three categories, namely biophysical, social and economic environments. It was hypothesised that based on the perception about the environment individual farmers will take action according to their goals. This action will also be supplemented with the interactions and communications with other farmers in order to arrive at a decision on land use. In this study several steps have been undertaken in the development of the ABM, such as early and late requirements, architectural and detailed design of the land use system. The outcome of this land use decision will then be linked to a hydrological model to assess the impact of a given land use scenario on water resources. It is planned that the land use scenario results from the ABM will be dynamically incorporated into the hydrological model for simulation of land use impact on water resources.

Acknowledgment

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ABBREVIATIONS AND SYMBOLS

a.m.s.l	above mean sea level
ABM	Agent based model
Agri-CON	Conventional agriculture/maize cropped
Agri-IRWH	Infield rain water harvesting cropped with maize
AGRR	Agricultural row cropping
AOSE	Agent-Oriented Software Engineering
ARC	Agricultural Research Council
ArcSWAT	SWAT integrated with ArcGIS
Cl	Clay
CN	Curve number
DEM	Digital Elevation Model
D-index	Index of determination
DIRQ	Direct flow
DoY	Day of the year
DWAF	Department of Water Affairs and Forestry
ET	Evapotranspiration
FAO	Food and Agriculture Organization
FRSE	Ever green forest
GIS	Geographic Information System
GWQ	Ground water flow or base flow
HRU	Hydrological response unit
IRWH	Infield rain water harvesting
ISCW	Institute for Soil, Climate and Water
JADE	Java Development Environment
Lm	Loam
MAE	Mean absolute error
MAS	Multi-agent system
MASE	Multi-Agent Systems Engineering
MDA	Model Driven Architecture
NS	Nash and Sutcliffe (1970) efficiency
OMG	Object Management Group
OWL	Ontology Web Language
PAST	Pasture
PUE	Precipitation use efficiency
Q	Stream flow/discharge
R^2	Regression coefficient of determination
RMSE	Root mean square error
RMSEs	Root mean square error (systematic)
RMSEu	Root mean square error (unsystematic)
RNGB	Range and brush land
Sa	Sand
Si	Silt
SURQ	Surface flow
SWAT	Soil Water Assessment Tool

TAOM4E	Tool for Agent Oriented Modelling for Eclipse
UML	Unified Modelling Language
URBN	Urban
USA	United States of America
USDA	United States Department of Agriculture
WATR	Water bodies
WETN	Wetland
WY	Water yield

1. INTRODUCTION

Understanding and predicting the impact of surface processes on water resource requires long-term historical reconstructions and projections into the future of land use changes at local and regional scales. Over the last few decades, numerous researchers have improved measurements of land-use change, the understanding of the causes of land-use change, and predictive models of land-use change, by a representation of much more complex, and sometimes intricate, processes of land-use. Understanding of the causes of land-use change has moved from simplistic representations to a much more profound understanding that involves situation-specific interactions among a large number of factors at different spatial and temporal scales (Lambin *et al*., 2003).

Concerns about land-use change emerged in the research agenda on global environmental change several decades ago with the realization that land surface processes influence climate. It was recognised that land-cover change modifies surface albedo and thus surface-atmosphere energy exchanges, which have an impact on regional and global climate.

In central South Africa, agriculture, mainly commercial farming, is the economic backbone of the society in the region. The rural small-scale farmers are currently being introduced to improved agricultural practices through improved surface water (rainwater) management. The hydrological balance of any river basin is directly and indirectly influenced by the spatial and temporal distribution of land-use and land-cover changes. Changes in land cover can modify crucial hydrological processes, such as evapotranspiration and ground water recharge. Since the demand for water and land are closely related to socio-economic development, it is necessary to analyse and model both the physical environment and the human dimension of these processes.

In the Modder river basin (Figure 1) water resource is increasingly becoming one of the critical natural resources (DWAF, 1999). The basin covers an area of about 1.73 million hectares and is divided into three reaches, namely the Upper, Middle and Lower Modder River. Generally the basin is characterised by low and erratic seasonal rainfall, receiving about 537 mm of mean annual rainfall (DWAF, 1999). Due to low rainfall and soil type which is prone to crusting and which enhances water loss by surface runoff, rainfed farmers frequently encounter scarcity of soil-water which results in low crop yields and water productivity. These climatic and environmental situations as well as lack of management skill are believed to be discouraging small-scale farmers from expanding to the crop lands (Botha *et al*., 2003).

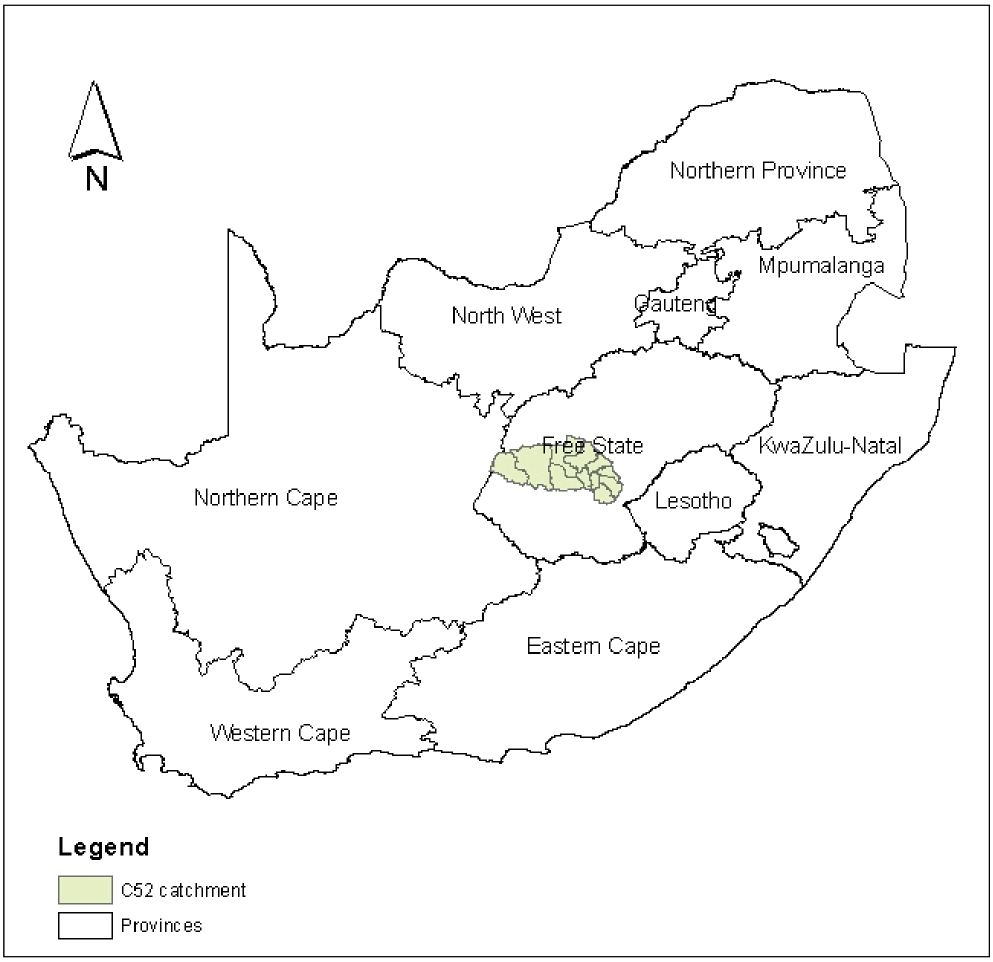

Figure 1 Location of the Modder River Basin and the Provincial boundaries of South Africa

In order to alleviate the water scarcity problem a suitable type of water conservation technology known as infield rainwater harvesting (IRWH) was introduced to the Upper Modder river basin (Hensley *et al*., 2000). After six years of research and extension work, results revealed that IRWH could improve yields of maize and sunflower up to 50% compared to the conventional farming practice (Botha *et al*., 2003). This is an example of land use change which had resulted from the interaction of physical basin characteristics (such as climate, soil, etc.) and socio-economic factors (such as population increase, food security, market, etc.).

However, upstream land-use change could bring about a significant on-site effect on catchment water resources and off-site effect on downstream users. It may increase or decreases discharge of water at the outlet of a catchment. For instance, the introduction of IRWH in the upper Modder river catchment may result in a significant impact on the downstream water users and the ecological balance of the system if allowed to expand unchecked. The aim of this project was, therefore, to contribute to the understanding of the dynamics of human-environment interactions and decision making processes for the sustainable use of land and water in the Modder river basin using hydrological and agent-based modelling.

Agent-based models (ABMs) are capable of simulating possible land-use change scenarios that can have different impacts on the water resources of an environment. Among the different land-use scenarios simulated, one may have a chance to closely evaluate the scenario which is environmentally sustainable and that may have optimum water productivity. Taking into account all the advantages of ABMs, the different and complex interactions of biophysical and socio-economic factors need to be established for use as a conceptual model for the perceived ABM. The conceptual model is a primary requirement for developing an ontological model and thereby an ABM. Parker *et al*. (2003) emphasised on the need of a conceptual model to elucidate the component parts of an ABM and potential interactions between parts.

In this report, four main aspects are presented, namely biophysical characteristics, socio-economic drivers of land use change, hydrological modelling, and ABM development.

1.1 Study area

The Modder River basin is a large basin with a total area of 1.73 million hectares. It is divided into three sub-basins, named as the Upper Modder, the Middle Modder and the Lower Modder. It is located within the Upper Orange Water Management Area to the east of the city of Bloemfontein. The water supply to the middle and lower reaches of the Modder River is stabilised by the Rustfontein and Mockes dams in the east and Krugersdrift Dam in the west of the city of Bloemfontein.

The study was carried out on the Upper Modder River Basin specifically on the quaternary catchment C52A (Figure 2). It is located between 26.48^{o} and 26.87^{o} East and; between 29.25^{o} and 29.62^{o} South. The catchment has a mean annual rainfall of 537 mm. Rustfontein dam is located in the upper part of the Modder river basin in quaternary catchment C52A (Figure 2) with a contributing area of 927.6 km^2, which is the area of C52A delineated by ArcSWAT based on the geographic coordinates of the flow gauge at the outlet of the catchment and a digital elevation model (DEM) of C52 which was obtained from the Institute for Soil, Climate and Water (ISCW). The area delineated by ArcSWAT shows about 10 km^2 less than the area delineated by South African Catchment Management Agency, which is about 937 km^2. The soil of the catchment is dominated by land type Dc17 and Db89 which have sandy clay loam and sandy clay textured soils, respectively. They are dominated by Valsrivier soil forms and have depths that vary between 400 to 800 mm. Land type Dc17 covers approximately 90.3% of the catchment area while land type Db89 covers 8.3% of the catchment area. Water bodies including the Rustfontein dam cover 1.4% of the catchment area.

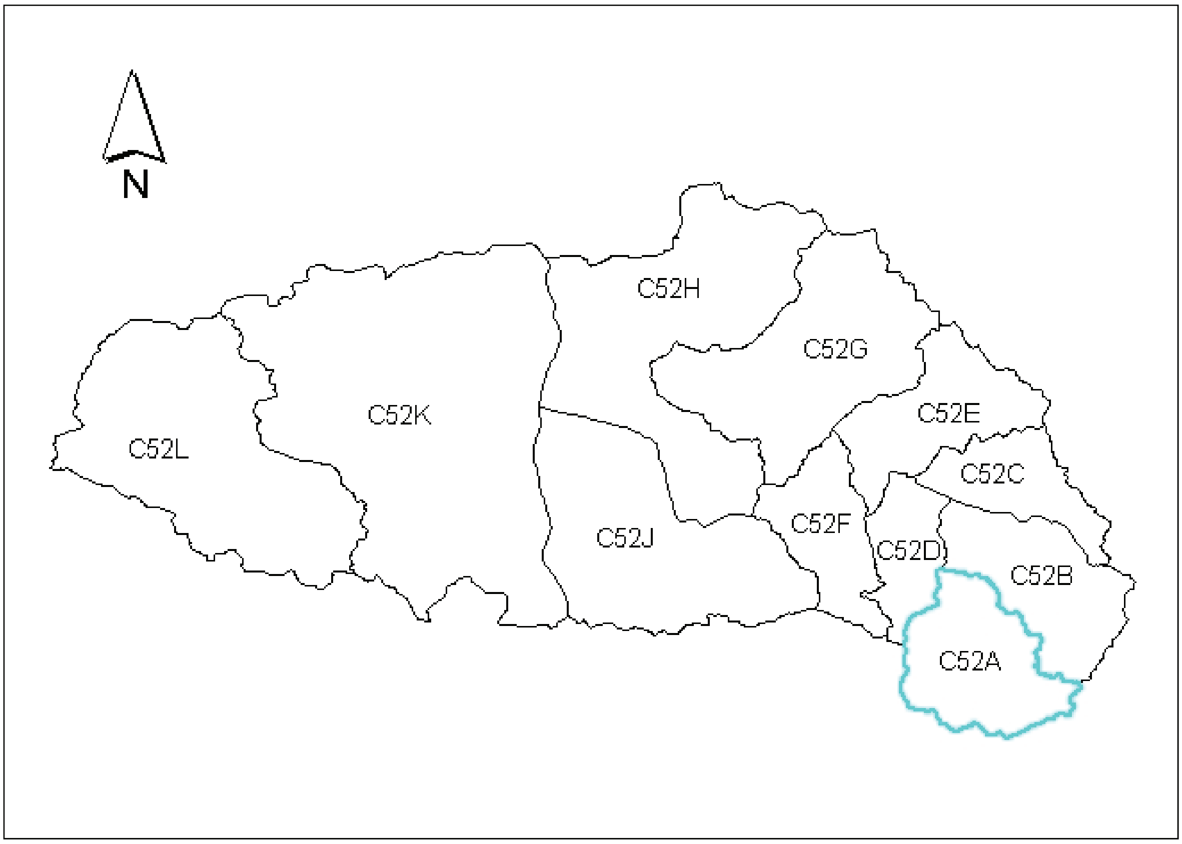

Figure 2 Location of the study area (C52A) in the Modder River Basin

2. BIOPHYSICAL CHARACTERISTICS OF THE MODDER RIVER BASIN

Biophysical factors, such as climate, soil, topography and vegetation are some of the major factors that greatly affect runoff that would be produced from a specific catchment (Peugeot *et al*., 1997; Jain *et al*., 2004). Rainfall and evapotranspiration (ET) are the main components of the climate that have major influence on the water balance of a catchment. High rainfall contributes to increased stream flow while in contrary high ET reduces the amount of overland water considered as blue water (Jewitt *et al*., 2004). Soil physical and chemical properties such as soil texture and infiltration rate affect the amount of surface water considerably. Soils with high silt and clay content and soils with low infiltration rate contribute to high surface runoff. On the other hand, sandy soils and soils with high infiltration rate reduce runoff and stream flows.

2.1 Soil

According to the soil map and GIS database obtained from the Institute of Soil Climate and Water (ISCW), seven soil series are identified in the Modder river basin (Figure 3). The Upper Modder river basin is dominated by soil series type Va40/Va41 including some minor ones like Bo and Sw forms. This series ranked second in the basin. The texture of this soil is 100% sandy clay loam to sandy clay (SaClLm to SaCl). The Middle Modder river basin is predominantly covered by soil series Cv34 and Ss16 which are first and fourth in area coverage within the basin. The soil texture of Cv34 is dominated by sand to loamy sand (Sa to LmSa) while the series Ss16 is dominated by sandy clay loam (SaClLm). The Lower Modder river basin is largely dominated by soil series Hu36. The detailed soil characteristics of these soils are presented in Tables 1 and 2.

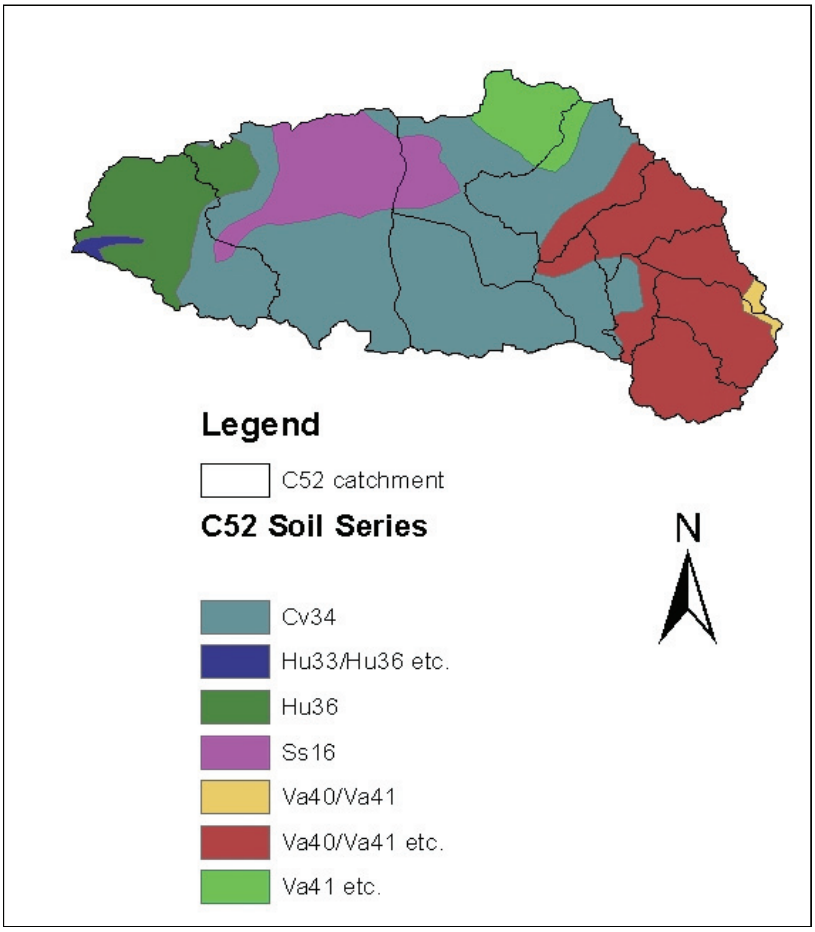

Figure 3 Soil series of the Modder river basin (C52)

Tables 1 and 2 show the dominant land types and the associated soil series in the Modder river basin. The Upper and Middle Modder river basin catchments are dominated by land type Dc17 which covers an area of 225 554 ha. The soils in this land type are of Valsrivier (Va), Arcadia (Ar), Bonheim (Bo), Sterkspruit (Ss) and Swartland (Sw) series (see Table 1) and texture dominated by SaClLm-SaCl (Table 1). The clay content ranges between 35% and 60% which contributes to high water holding capacity. This type of soil is also characterised by high susceptibility to surface crusting and shallow root depth that ranges between 400 to 700 mm (Botha et al., 2007).

Table 1 General description of the soil types of the Modder river basin

Soil Series	Series texture	Topography (a.m.s.l)	Dominant texture
Va40/Va41	100% SaClLm-SaCl	1400-1500 **Upper**	SaClLm-SaCl
Cv34	60% Sa-LmSa 35% SaLm	1250-1350 **Middle**	Sa-LmSa
Hu36	45% LmSa 50% SaClLm	1100-1200 **Lower**	SaClLm
Va40/Va41 etc	100% SaClLm-SaCl	1400-1500 **Upper**	SaClLm-SaCl
Va41 etc	25% SaLm-SaClLm; 70% SaClLm-SaCl	1200-1400 **Middle**	SaClLm-SaCl
Ss16	65% SaClLm-SaCl; 30% SaLm	1300-1450 **Middle**	SaClLm-SaCl
Hu33/Hu36 etc	40% LmSa-SaLm; 55% SaClLm-SaCl	1100-1200 **Lower**	SaClLm-SaCl

Table 2 Land types and soil series in the Modder river basin

River basin	Quaternary catchments	Land types	*Main Soil series
Upper Modder	C52A	Dc17 Db87	Sw, Ss, Va, Ar, Bo Va and Sw
Middle Modder	C52B	Dc17,	Sw, Ss, Va, Ar, Bo
		Ib99	Ms, Rock
		Ca33	We, Ss
	C52C	Dc17	Sw, Ss, Va, Ar, Bo
		Db37	Va, Sw, Ss
		Ca22	Va, We
		Ea39	Ar, Mw, Va
	C52D	Dc13	Va, Oa
		Ca22	Va We
		Ea39	Ar, Mw, Va
	C52E	Dc17 Ea39	Sw, Ss, Va, Ar, Bo Ar, Mw, Va
	C52F	Ea, Ca	NA
	C52G	Dc17, Ca, Ea, Da, Fc, Ae	NA
	C52H	Ae, Da, Fc, Db	NA
Lower Modder	C52J	Dc17, Ca, Ae	NA
	C52K	Ae, Db, Fb	NA
	C52L	Ae, Fb, Ah	NA

*Main soil types are: Va = Valsrivier, We = Westleigh, Ss = Sterkspruit, Oa = Oakleaf, Ar = Arcadia, Mw = Milkwood, Ms = Mispah, Bo = Bonheim, Sw = Swartland

2.2 Climate

The Modder River Basin rainfall distribution was analysed using ArcGIS® based on the database obtained from ISCW. The Modder river basin receives mean annual rainfall which ranges between 300 mm and 725 mm (Figure 4). The lowest mean annual rainfall (300 mm) is received by the lower Modder river basin which is located in the most westerly part of the basin. The maximum mean annual temperature of the basin varies between 27°C and 29°C while the lowest varies between -2°C and 2°C. The mean aridity index (AI) was estimated as 0.24. The basin AI ranges from 0.16 to 0.34 for the lower and the upper basin, respectively. Thus, the whole basin falls within the range of semi-arid climate. Figure 5 presents the monthly rainfall and temperature variation based on a weather station at Rustfontein dam which is situated at the outlet of C52A catchment. The annual mean rainfall (1960-1991) at the Rustfontein dam weather station is 535 mm. DWAF, 1999 reported the mean annual rainfall of C52A as 537 mm.

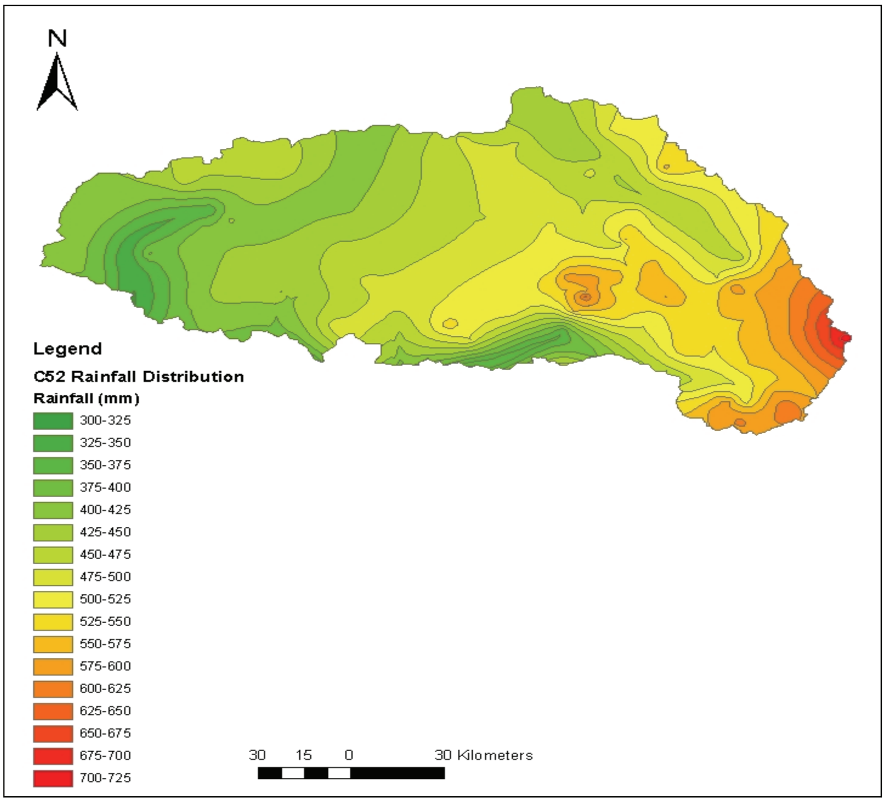

Figure 4 Mean annual rainfall distribution in the Modder River Basin

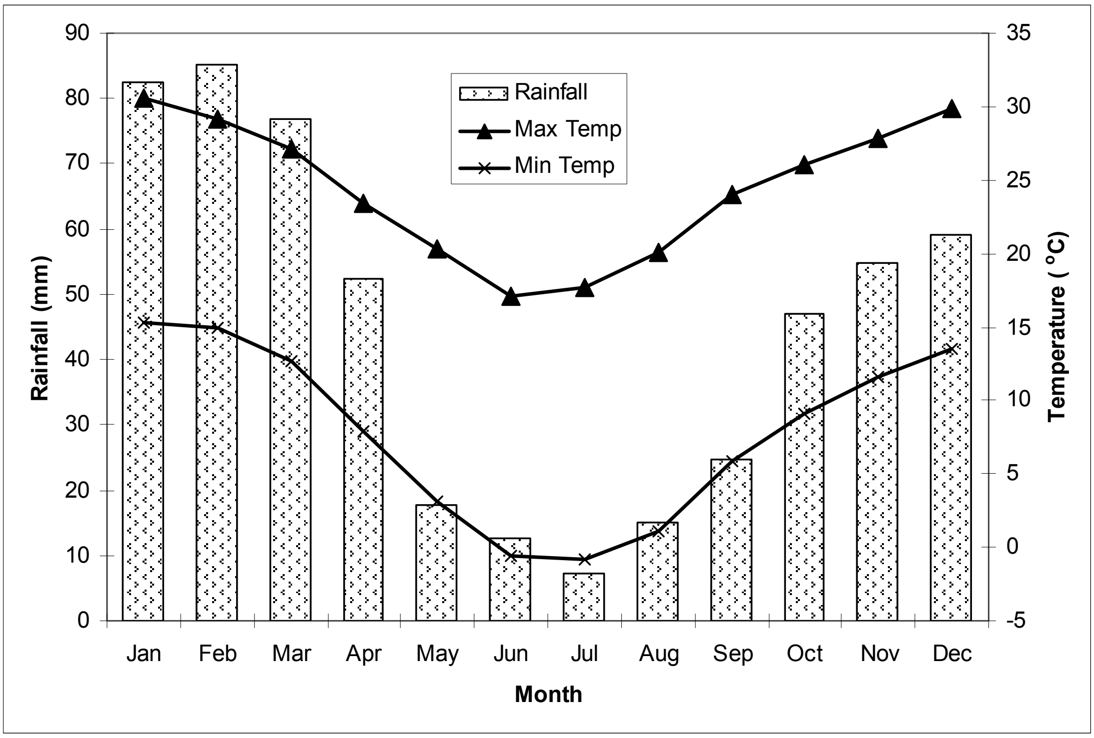

Figure 5 Mean monthly rainfall and temperature distribution at the Rustfontein dam (1960-1991)

2.3 Hydrology

The Modder river basin consists of 11 quaternary sub-catchments with a total area of 1.73 million hectares (Figure 2). The Upper Modder which consists of the quaternary catchment C52A comprises approximately 5% of the total runoff contributing area. The Middle Modder consists of the second largest portion of the basin area. It covers about 45% of the total area and includes quaternary catchments of C52B, C52C, C52D, C52E, C52F, C52G and C52H. The remaining 50% of the area, which is the largest part of the basin, belongs to the lower Modder basin with quaternary catchments C52J, C52K and C52L. In this river basin there are four dams, namely Rustfontein, Krugersdrift, Mockes and Groothoek.

The Modder River originates at the eastern hills of the quaternary catchment C52A, around the town of Dewetsdorp and routes to the Rustfontein dam, located at the outlet of the catchment C52A. The river enters into the dam at two different inlets. The dam has a total capacity of 10.33×10^6 m^3 (Table 3). The highest flow season in C52A catchment starts on the first Day of the Year (DoY 1) and ends up on the DoY 115; and followed by the second highest flow period that starts on the DoY 227 and ends up on the DoY 365. This is consistent with the highest rainy months' records at the Rustfontein dam weather station. The mean annual rainfall-runoff ratio based on data given in Table 3 is 6%.

Table 3 Hydrology of the Modder River basin (DWAF, 1999)

Flow station No.	Description	Value
C5R003 (Rustfontein Dam)	**Quaternary catchments: C52A**	
	Incremental area	937 km^2
	Contributing incremental area	937 km^2
	Area of urbanization	0 km^2
	Area of irrigation	4.5 km^2
	Total farm dam capacity	10.33x 10^6 m^3
	Mean annual evaporation (S-pan)	1600 mm
	Present day mean annual runoff (MAR)	30.67 x 10^6 m^3
	Mean annual rainfall	537 mm
C5R004 (Krugersdrift Dam)	**Quaternary catchments: C52B, C52C, C52D, C52E, C52F, C52G**	
	Incremental area	5394 km^2
	Contributing incremental area	5391 km^2
	Cumulative area	6331 km^2
	Area of urbanization	785 km^2
	Area of irrigation	23.9 km^2
	Total farm dam capacity	19.88 x 10^6 m^3
	Mean annual evaporation	1639 mm
C5H018 (Tweeriver)	**Quaternary catchments: C52H, C52J, C52K, C52L**	
	Incremental area	11029 km^2
	Contributing incremental area	2236 km^2
	Area of urbanization	0 km^2
	Area of irrigation	45 km^2
	Farm dam capacity	7.45 x 10^6 m^3
	Mean annual evaporation	1871 mm

2.4 Topography

The topography of the Modder river basin (Figure 6) gradually acquires sloppy and undulating landscape from the eastern and upper side to a flatter topography towards the western and the lower side of the basin. The altitude ranges from 1600 to 1700 m.a.s.l. in the eastern end to approximately 1100 m.a.s.l. in the western end. The quaternary catchment C52A is located in the undulating and high altitude part of the basin between altitudes of 1400 and 1500 m.a.s.l.

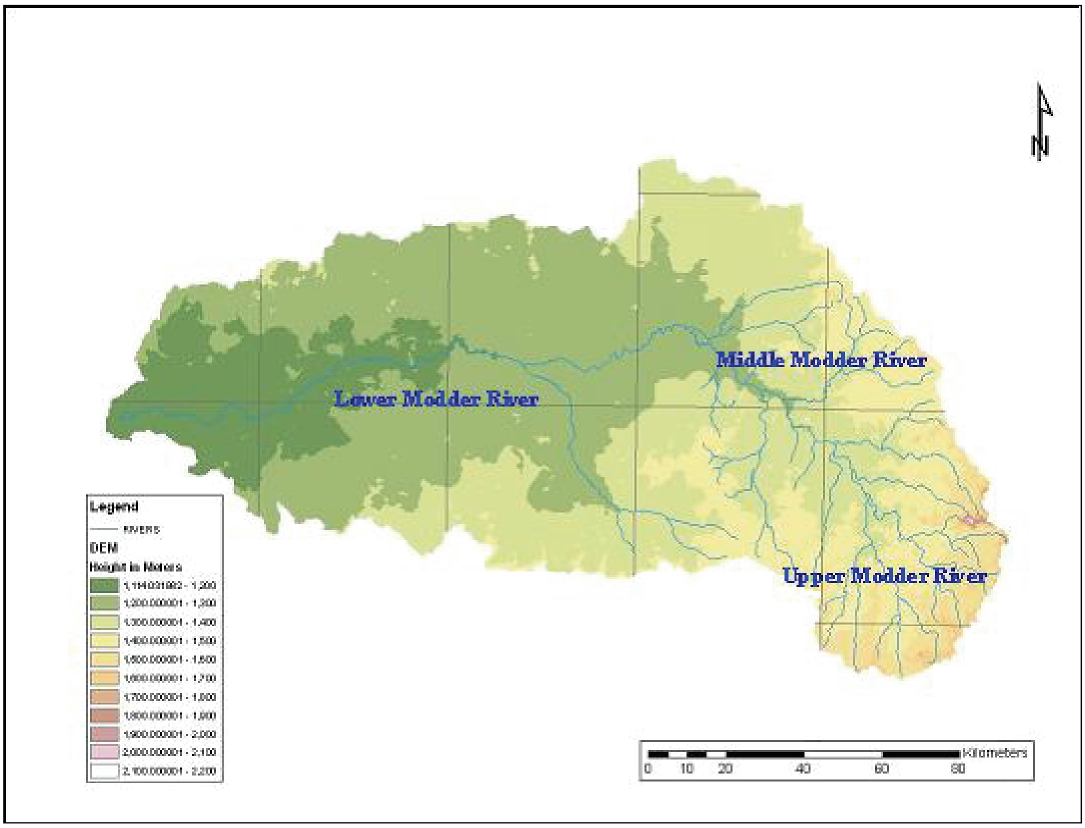

Figure 6 The topography of the Modder river basin and the three reaches

2.5 Land Use

Different vegetations and land use types affect the overland flow of water in different ways. Vegetations mainly affect the ET and runoff. Land uses for varying crop types on different slopes result in varying runoff amounts. For instance, in arid zones where rainfall amount is insufficient for crop production, water conservation techniques, such as the IRWH, used for improving soil moisture content may be responsible for decreased stream flow downstream.

Table 4, Figures 7 and 8 present the land-use of the Modder river basin based on data of 1994 and 2000 which is obtained from ISCW and reclassified by ArcSWAT (2005 version). The Upper Modder river basin where quaternary catchment C52A is located, the land use is dominated by unimproved natural grassland. In this part of the basin irrigated crop land is insignificant. The middle and lower part of the basin are largely used for crop production, with commercial irrigation farming dominating the lower part of the basin. Large portion of the middle part of the basin area is used for urbanization, which consists of towns such as Bloemfontein, Botshabelo and Thaba Nchu. The lower part of the basin consists of large areas of bush lands and low fynbos in addition to the croplands.

Table 4 Modder River Basin (C52) land uses in hectares during 1994 and 2000

Land Use	1994	2000	Difference	% Change	Conversion rate (per annum)
Agriculture	363108.4	294348.3	-68760.1	-23.4	-3%
Forest	2442.7	2036.7	-406.0	-19.9	-3%
Pasture	902122.9	1005696.0	103573.1	10.3	2%
Range & Brush	409912.2	341890.5	-68021.6	-19.9	-3%
Urban	22272.7	35423.3	13150.6	37.1	8%
Water	4859.4	2746.9	-2112.5	-76.9	-9%
Wetland	31267.6	53837.9	22570.3	41.9	9%
Total	**1737980.0**	**1737980.0**			

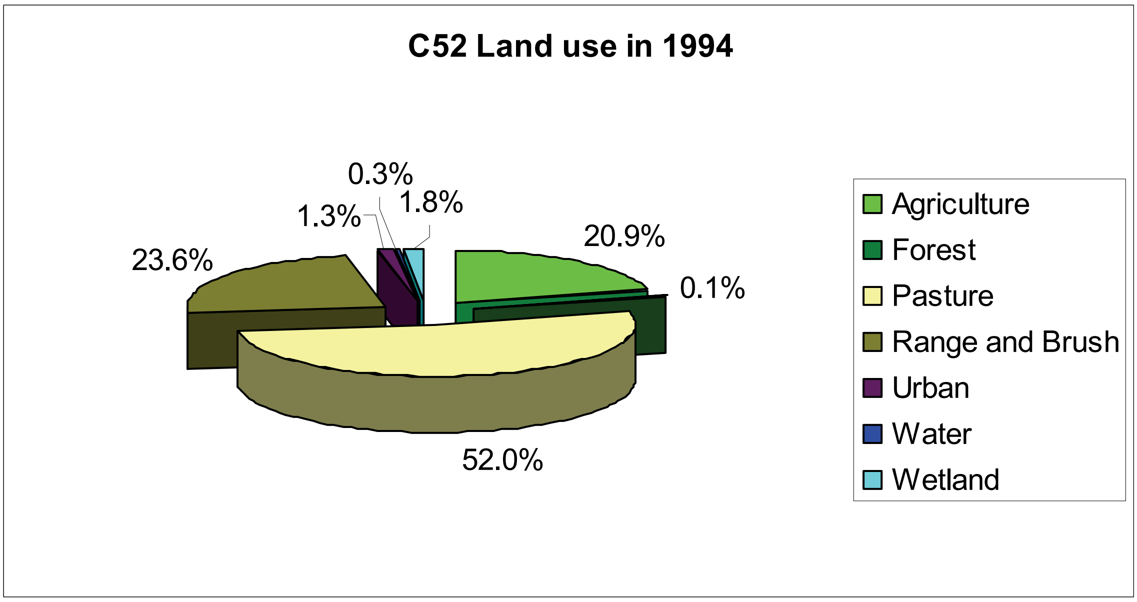

Figure 7 Percentage of land use in the Modder River Basin during 1994

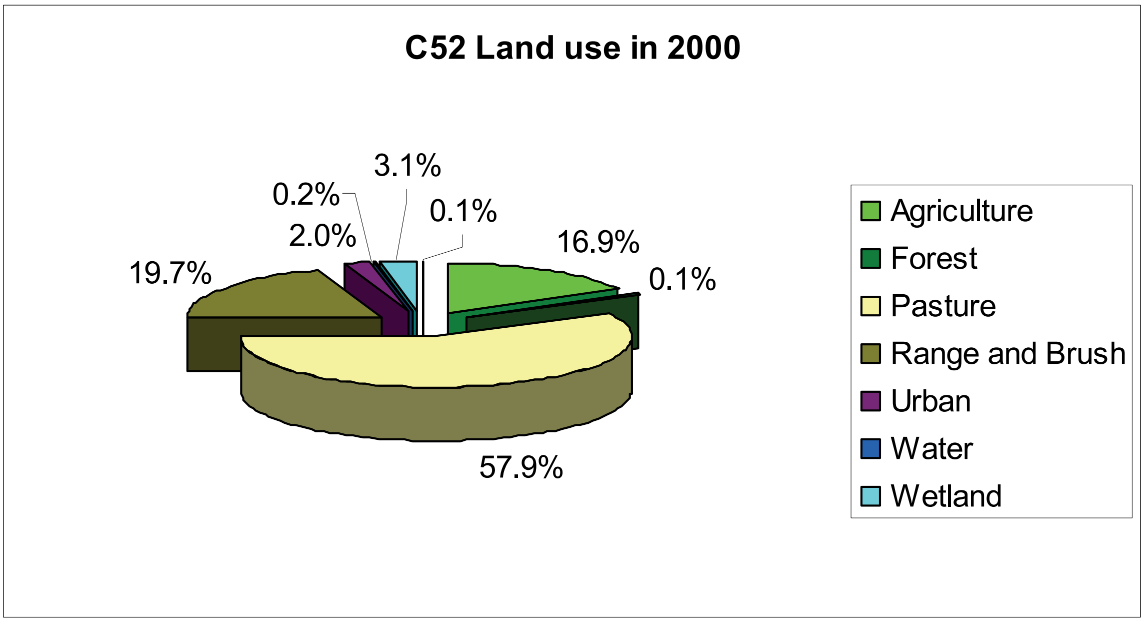

Figure 8 Percentage of land use in the Modder River Basin during 2000

The conversion rate per annum for each major land use-cover class in C52 catchment for the period 1994 to 2000 was calculated according to the following formula (FAO, 1996).

$$Rc = \left[1 - \frac{S1 - S2}{S1}\right]^{1/n} - 1 \qquad [1]$$

Where R_c is the rate of conversion process, S_1 the area of land use-cover class at the date t_1; S_2 the area of land use-cover class at the date t_2; and n the difference of years between the two dates.

Thus, according to Equation 1 the conversion rate of agricultural land between 1994 and 2000 was found to be negative (- 3% per annum). Similarly forest land decreased by 3% per annum. The other important land use change is urbanization. There was an increase of urban area by 8% per annum between 1994 and 2000. If urbanization had continued to increase at the same rate beyond 2000, then the current year (2010) projection estimate of urban occupied land would have been about 76 469 hectares. This is equal to 41 046 hectares or 116% more area compared to year 2000. In a similar scenario, the dominant land use of pasture, currently would have been 220 000 hectares or 22% more area than during 2000. Agricultural land would have decreased by 77 290 hectares or 26% less area compared to 2000. The area of land under urban and pasture might have increased in 2000 probably at the expense of decrease in forest and agricultural land. The increase of wetland by 9% may also be evidenced by the drying out of water bodies which showed an annual decline by the same rate (Table 4).

3. SOCIO-ECONOMIC DRIVERS OF LAND USE CHANGE

3.1 Introduction

Many important techniques have been developed and applied to quantify land use and land cover changes and to investigate social, political and economic forces driving the changes. Among these techniques remote sensing and agent based modelling (ABM) are the most common ones. Geographic information system (GIS) is another important technique which is often deployed to visualise land use/land cover change spatial patterns and to explore relationships between land use/land cover changes and other bio-physical factors in visual forms (Batty and Xie, 1994; Fischer *et al*., 1998; Vela´ zquez *et al*., 2003). On the other hand, census tabulation of local socioeconomic data provides statistical means for looking into negative as well as positive impacts of social, demographic and economic activities on land change dynamics (Uusivuori *et al*., 2002).

ABMs have been applied in a variety of social science domains, including economics, sociology, political science, and geography. The following are some examples of ABM usage in relation to socio-economic drivers in land use/land cover changes and water resources management. Manson (2005) considered a conceptual framework for land use change which includes five socio-economic drivers of change: population growth, economic growth, technological change, political and economic institutions and cultural attitudes and beliefs. On the other hand, Xie *et al*. (2005) showed how policy interacts with other socioeconomic factors in affecting paddy field losses in China. According to these authors, continued rural to urban migration, rural economic development and rapid urban expansion represent the primary forces that lead to the conversion of paddy fields into non-agricultural uses.

Xie *et al*. (2005) also identifies six other possible forces or socio-economic drivers that affect land use changes which includes population increase and its level of affluence, technology, political economy, political structure, and attitudes and values. For instance, they described the impact of population increase on land use change as bringing a sequence of immediate increase in demand for land for life sustaining needs such as residence space, food and fibre. They also report that the original physical and ecological environments of the Yangtze River and the Pearl River basins have been totally altered and replaced with intensive human-transformed agricultural systems, along with highly concentrated population and socioeconomic activities. In a similar way Alberti and Waddell (2000) have coupled urban growth models with models of ecosystem processes to evaluate the impact of different demographic and economic scenarios.

Robinson (2003) used an agent-based model called LUCITA to better understand how the changing composition and age structures of households in Altamira, Pārá, Brazil, affect the land use/cover within each household plot and collectively across the landscape of the region. Robinson (2003) reported as well that labour and amount of initial capital were constraining factors on the amount of forested land that a household could clear for the establishment of a household plot.

Moran (1981) also identified a number of socioeconomic factors, including credit policies, market opportunities, and inflation rates, each of which may affect the land-use decisions by individuals. On the other hand, Berger and Ringler (2002) showed how land-use patterns might change over time under different technological and market scenarios. Similarly, Monticino *et al*. (2007) in their study of land use changes in Dallas Fort Worth (Texas) region facing intense residential development reported that the principal drivers of land-use change are the land price model and the sensitivity of the landowner agents' decision about whether to sell in response to changes in land prices and neighbouring development.

Berger *et al*. (2007) underlined the specific strength of multi-agent systems (MAS) or ABM approach in representing social and institutional relations among water users, enabling researchers to fully capture social phenomena such as collective action while Balmann (1997) and Berger (2001) used agent-based modelling techniques to examine the impact of agricultural policies on the distribution of farm size. Farolfi and Bonte (2006) applied MAS in the modelling of stakeholder driven process in the development of catchment management planning and for participatory water resources management.

In this research project the different ABM applications demonstrate that spatial outputs of land-use models may play a dual role by evaluating socioeconomic and environmental/ ecological impacts.

3.2 Demography and Socioeconomic Indicators of the Modder River Basin

Although there was no information specifically on the Modder River Basin's socio-economic and demographic statistics, some of the information could be inferred from reports compiled on the Free State Province, as well as Motheo District Municipality where much of the Modder River basin is located (Figure 1). The Modder River Basin includes a major city and two townships within the Free State Province, namely Bloemfontein, Botshabelo and Thaba Nchu (Figure 9). These three cities account for the biggest proportion of the province's population with a combined figure of 618 566 for the year 2001. The largest share goes to Bloemfontein with population of 375 823 (current estimate 850 000), followed by Botshabelo with population of 175 672 and Thaba Nchu 67 071. The population showed 1.3% growth rates between 1996 and 2001 (MLM IDP, 2008/9).

In terms of the economic situation in the area that comprises the Modder River basin, the average household income per annum in Bloemfontein, Thaba Nchu and Botshabelo are R76 611, R32 105 and R24 828, respectively (Urban-Econ, 2003). Approximately 15% of the household earn between R6 000 and R18 000. On the other hand, 75% of individuals earned less than R800 per month in 2001. The figures in Table 5 show that approximately half of the economically active population in the Modder River Basin are unemployed.

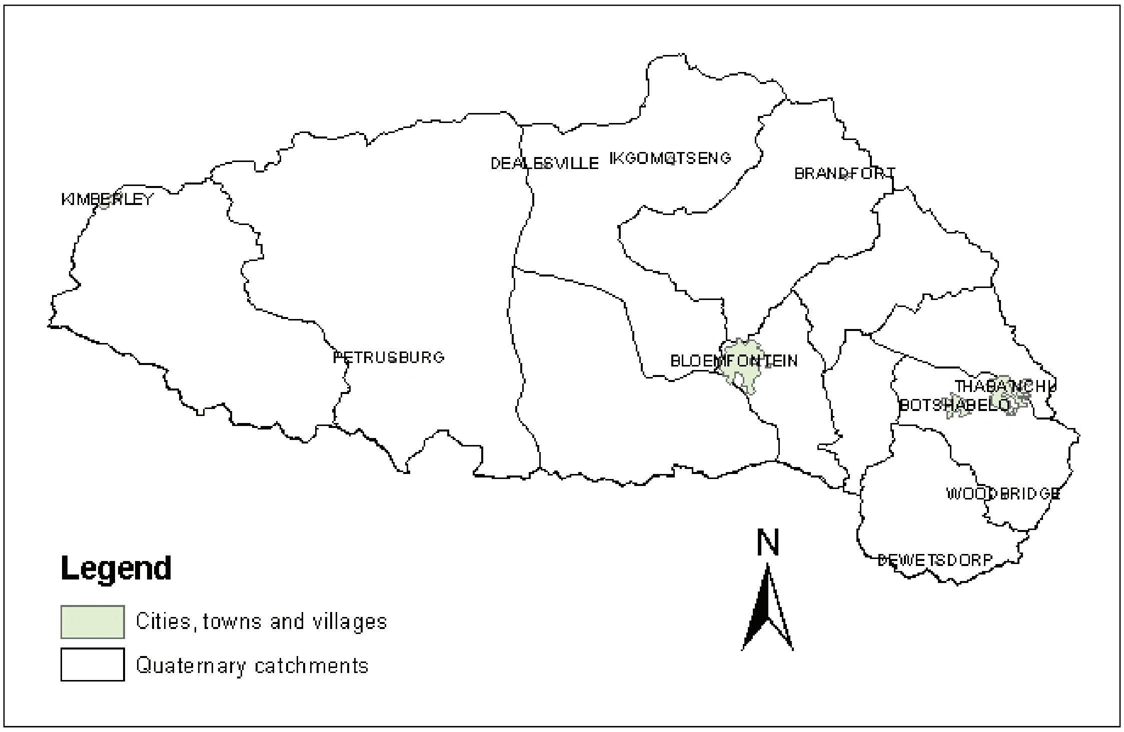

Figure 9 Cities and settlement areas in the Modder River Basin

Table 5 Informal employment data according to gender for the major population centres in the Modder River basin

Magisterial district	% of informal employment by sex	
	Males	Females
Bloemfontein	54	46
Botshabelo	31	69
Thaba Nchu	52	48
Total	**48**	**52**

In the Modder River Basin the destitute peoples are most vulnerable to crime, HIV/AIDS and drug abuse. According to Mangaung Local Municipality's Integrated Development Plan (MLM IDP, 2008/9), poor people see the government as the responsible separate entity to change their livelihoods. The apartheid system also left behind a dependency culture in these vulnerable communities. The inhabitants believe that the new democratic government should improve the resource distribution in favour of previously marginalised societies. Mangaung's development strategy therefore has the objective of making communities self-reliant, proud and strong; reduce the risks that face women, youth, the aged and the disabled.

With regard to education, 13% of the people in Mangaung have never been to school, 46% only have primary education and only 5.8% have a tertiary qualification. Literacy is around 80% (MLM IDP, 2008/9). Approximately 23% of the land area of the municipality is farmland, with a further 2% occupied by smallholders (MDB, 2002). It is estimated that 6% of the population live in the rural parts of the region. Commercial livestock farming is the economic backbone of the rural areas. Such agricultural activity is also backed by the land use type data of 1994 and 2000.

The land use of the Modder River Basin during 1994 and 2000 was dominated by grass land (Table 4; Figures 7 and 8). Urbanization shows an increase of 37% in 2000 compared to 1994. This is consistent with the population increase in urban areas. Most households in the villages are engaged in agriculture, producing livestock and crops. The major crops produced include maize, wheat and sunflower.

According to Woyessa *et al*. (2006a) 35% of the upper Modder river basin was occupied by communal farmers. The area occupied by the communal farmers is marginal for crop production as well as largely unproductive due to insufficient rainfall for rainfed agriculture. Most smallholder farmers in the communal areas report that they lack farming knowledge, especially regarding crop production (Kundhlande *et al.*, 2004). With the demise of the system after 1994 under which the homeland government prepared the land and planted for farmers, many fields have not been in use for many years. This is also evidenced by a decrease of agricultural land by about 23% in 2000 compared to 1994 (Table 4). The decrease in farm land was accompanied by an increased pasture or grasslands by about 10% in 2000 compared to 1994.

A significant portion of land in the Upper Modder River basin is communally owned, while commercial farm land dominates in the middle and lower part of the Modder river Basin. In the communally owned land part, land is distributed and allocated by a Tribal Authority under the leadership of Chief Moroka (Kundhlande *et al.*, 2004). In this area each village is assigned a fixed amount of land which is subdivided into three use categories namely residential, crop farming and communal grazing. Residential land and land for farming is allocated to individual households upon granting of approval to settle in the village by the Tribal Authority, while all members of the village have a right to graze animals in the communal pastures (Kundhlande *et al*., 2004).

According to the report by the Free State Provincial Department of Agriculture its goal is to create a better life for the people in the Free State through self-reliance and utilisation of agriculture and other resources within a sustainable living environment. Regarding smallholder farmers, the objective is to enable households to produce adequate quantities of food for own consumption, and possibly surpluses to sell and generate income. The poorest of the rural households mostly live in semi-arid and arid areas and rely on rain fed agriculture for their livelihoods, often farming on marginal and fragile soils.

3.3 Summary

Socio-economic factors such as population growth and movement, political structures, values and attitudes of the people, and growth in demand for agricultural products have an impact on land use patterns. In turn changes in land use patterns affect the quantity and quality of water resources in a catchment. Effective water resource management policies and strategies need to be underpinned by a good understanding of these factors and the pathways through they affect land use patterns and water resources.

The population within the Modder river catchment has grown rapidly in the past decade, especially in and around the city of Bloemfontein and the townships of Botshabelo and Thaba Nchu. This expansion in population has resulted in growth in demand for housing. A significant amount of agricultural land within the vicinity of

Bloemfontein, Bosthabelo and Thaba Nchu has thus been converted to residential use in order to help meet the growth in demand for housing. The impacts of this development on the water resources in the Modder catchment include the increase in demand for water for domestic use, but also an increase in run-off from built-up areas.

The growth in population and the increased levels of economic activity and the attendant growth in incomes have led to increased demand for food and changes in food consumption patterns. Farmers within the Modder catchment have over the past decade increased production of horticultural products and livestock in order to meet the growing demand for fresh produce and for meat. These production activities tend to be more water intensive and have negative impacts on water quality in the river system.

In the past decade, efforts by various levels of government and other stakeholders to increase agricultural production among the rural households in Thaba Nchu have seen the development of and expansion in the use of rainwater harvesting techniques to support crop production. The implications of wide scale application rainwater harvesting on water resources have not been fully investigated. There are concerns that if applied on a very large scale, rainwater harvesting for crop production may negatively impact stream flows.

4 HYDROLOGICAL MODELLING OF LAND USE IMPACT

4.1 Introduction

The impacts of land use changes on ecosystems and biodiversity have received considerable attention from ecologists (Turner *et al*., 2001; cited in Lin *et al*., 2007). Land use changes in a catchment can impact on water supply by altering hydrological processes such as infiltration, groundwater recharge, base flow and runoff (Lin *et al*., 2007).

One of the water supply sources in a river basin is stream flow which plays an important role in establishing the critical interactions that occur between biophysical, ecological and socio-economic processes. Socio-economic processes including population dynamics, land use transformation, migration, transportation and agricultural practices closely interact with and greatly affect ecological processes, such as vegetative growth, ecological succession, habitat formation and maintenance (Choi and Deal, 2008).

In both cases, hydrological dynamics can be used as a medium of understanding the conditions for interactions to take place and the consequences that arise from such interactions. One of the most important socio-economic processes for establishing far-reaching and long-term environmental effects is land use transformation, especially the human-induced variety termed ‘urbanization.’ The far-reaching effects of urbanization can best be described by its enormous impacts on basin hydrology and water quality. Understanding these complex socio-hydrological dynamics is imperative for planning a more sustainable future. For instance, covering large watershed areas with impervious surfaces frequently results in increased surface runoff and reduced local surface erosion rates. Moreover, watershed development changes land use patterns and reduces base flow by changing groundwater flow pathways to surface water bodies (Lin *et al*., 2007).

Based on the specific biophysical and socioeconomic requirements of IRWH, different studies were carried out to estimate the suitable areas for IRWH in the Upper Modder River Basin. For instance, Woyessa et al. (2006b) estimated 27% of the Upper Modder River Basin area (which includes quaternary catchments C52A, C52B, C52C and C52D) as suitable for IRWH while Kahindia et al. (2008a and b) estimated as 79%, for the same Upper Modder River Basin area. The suitable area for IRWH estimated by Kahinda et al. (2009) in C52A, assuming 10% adoption level of IRWH, is only 14% of the total area. Kahinda et al. (2009) also studied the hydrological impact of IRWH by considering the monthly median flow (wettest season flow) of C52A catchment when 100% of the estimated suitable areas are occupied by IRWH. In their study, they reported that a 100% adoption scenario significantly reduced the high flow compared to the actual land use of 2000 or 0% adoption. They also showed that according to their analysis, “the most likely scenario” which is about 10% area adoption level of IRWH suitable land, gave no significant difference compared to the 0% adoption. However, their study has not clearly shown the impact of the rainwater harvesting technique on the different components of the catchment water balance.

Numerous modelling approaches have been developed to simulate the impact and consequences of land use changes on the environment in general and water resources in particular. One of these models is Soil and Water Assessment Tool (SWAT). The SWAT model was developed by USDA over a period of 30 years and is used to simulate the impact of land-use change and land management practices on water balance of a catchment. Many research reports witnessed the robustness of the model in simulating satisfactorily most of the water balance components of a catchment. SWAT has also proven to be an effective tool for understanding pollutions by fertilizer applications and point sources (Arnold *et al*., 1998 and Fohrer *et al*., 2005). It also proved its wider environmental application on the globe (Gassman *et al*., 2007).

More elaborately, SWAT is a basin scale model that operates on a continuous daily time step and is designed to predict the impact of management on water, sediment and agricultural chemical yields in ungauged catchments. The model is physically based and capable of continuous simulation over long time periods. Major components of the SWAT model include weather, hydrology, soil properties, plant growth and land management. In SWAT model, a catchment is divided into multiple sub-catchments, which are then further subdivided into hydrologic response units (HRUs) that consist of homogeneous land use, management, and soil characteristics. The HRUs represent percentages of the sub-catchment area and are not identified spatially within a SWAT simulation. Alternatively, a catchment can be subdivided into sub-catchments that are characterised by dominant land use, soil type, and management (Gassman *et al*., 2007).

The model is also used as a decision support tool for assisting to take proactive measures in land use planning by analysing the impact of different land use scenarios on water resources. For instance Fohrer *et al*. (2001) used SWAT model to study two different land use scenarios as proposed by ProLand model (Moller and Kuhlmann, 1999a) on the water balance of Aar and Dietzhlze watershed in Germany. Proland is an economic model which optimises land use by minimizing agricultural income. They adapted the SWAT model for application in the peripheral region of Germany.

Similarly, Cao *et al*. (2009) used SWAT model to evaluate the impact of land cover change on total water yields, ground water flow and quick flow in the Motueka River Catchment, New Zealand. In addition to the current actual land use scenario of the catchment under study, they used two more land use scenarios (a prehistoric land cover and a potential maximum plantation pine cover) to evaluate the aforementioned water balances. They summarised that under the current land use conditions, both annual water yield and low flow are higher than was the case before human intervention in the area or in a maximum commercial reforestation scenario.

Conan *et al*. (2003b) found that SWAT model has adequately simulated when land use was changed from wetlands to dry land in the Upper Guadiana River Basin in Spain. But, they reported that SWAT was unable to capture discharge details impacted by land use alterations.

Mapfumo *et al*. (2004) tested SWAT model in simulating the soil water content of three small catchments under three different grazing intensities in Aleberta, Canada. They found that SWAT was over-predicting the soil water content in dry soil condition and *vice versa*. But, generally they found that SWAT simulated the soil water content adequately for all the three watersheds with a daily time step. In a similar study, Chanasyk *et al*. (2003) evaluated the impacts of grazing on hydrology and soil moisture of three watersheds under three different grazing intensities using SWAT in Alberta, Canada. They evaluated SWAT's ability to simulate low flow conditions that included snow-melt events.

Taking into account its wider application in assessing the impact of land use changes on water resources, SWAT model was applied in the Modder river basin of Central South Africa to evaluate the impact of land use change on water resources, with particular emphasis on the flow of water into Rustfontein dam. According to the drainage basin classification of South Africa, the Modder river basin falls within the tertiary catchment called C52. This is further divided into quaternary catchments, such as C52A, C52B, etc. Rustfontein dam is located in the upper part of the Modder river basin (Figure 10) with a contributing area of 927.6 km^2, which is the area of C52A delineated by ArcSWAT based on the geographic coordinates of the flow gauge at the outlet of the catchment and a digital elevation model (DEM) of C52. The main aim of this task was to set up and calibrate the model parameters and assess land use change impacts on the water balances of the quaternary catchment C52A.

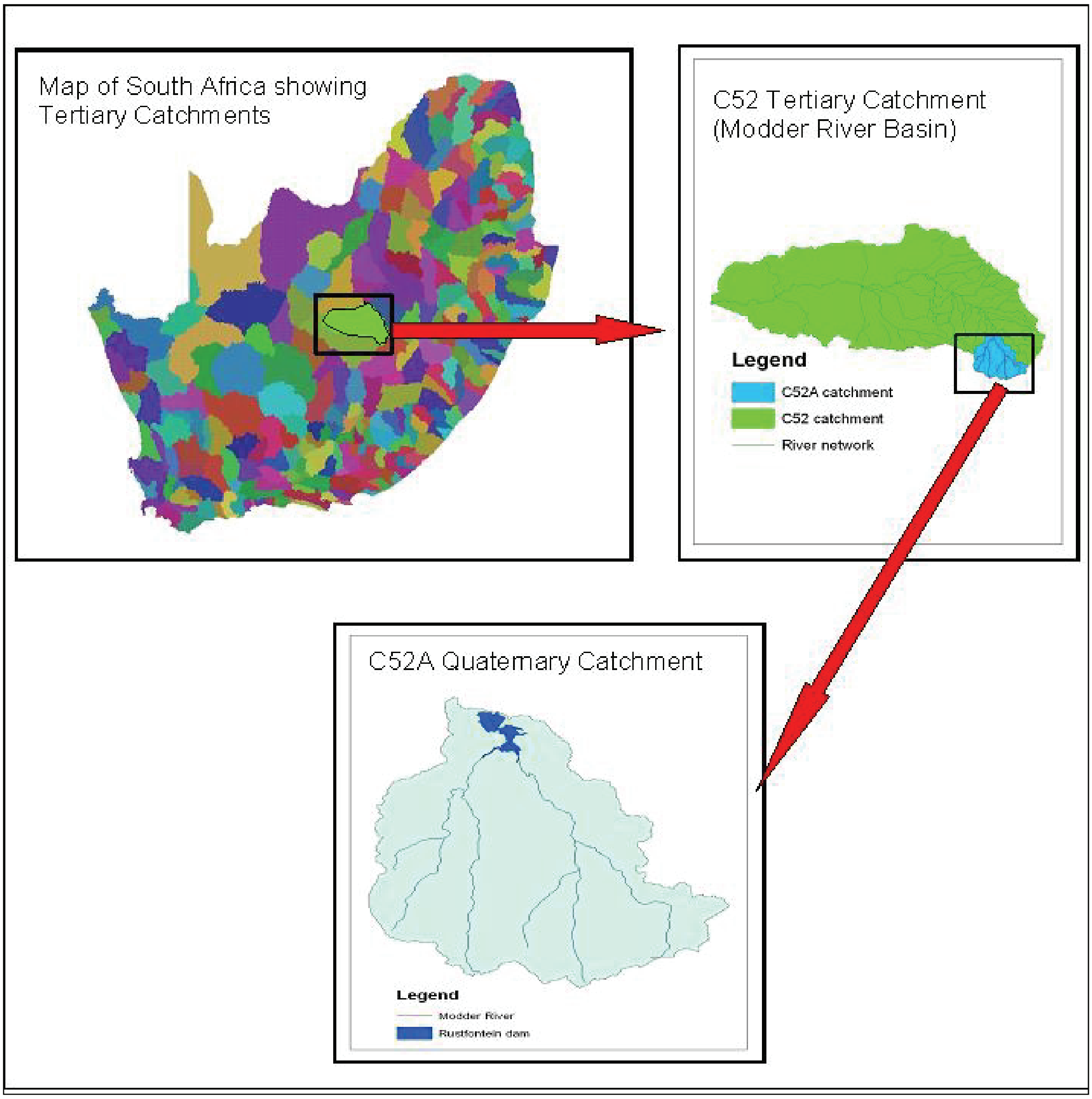

Figure 10 Location of the Modder river basin and the quaternary catchment C52A)

4.2 Sensitivity analysis

During the simulation of the water balances of the C52A catchment, using land use data of 1994 and 2000, the default and measured parameters used for simulation of the water balances were subjected to a sensitivity analysis with and without using the observed flow data. In C52A catchment there are two stream flow gauging stations measuring the total stream flow. The first one is the gauging station at the outlet of catchment C52A, designated as station C5R003 and measures the discharge draining from an area of 927.6 km^2 measured by ArcSWAT. The second gauging station (C5H056) is located upstream of the first one and at the outlet of a sub-catchment of C52A (Figure 11). This gauging station measures the stream flow from an area of 419.2 km^2. In the first case there is a record of nine years of daily average flow (1999 to 2007). In the second case the record is available for six years (2002 to 2007).

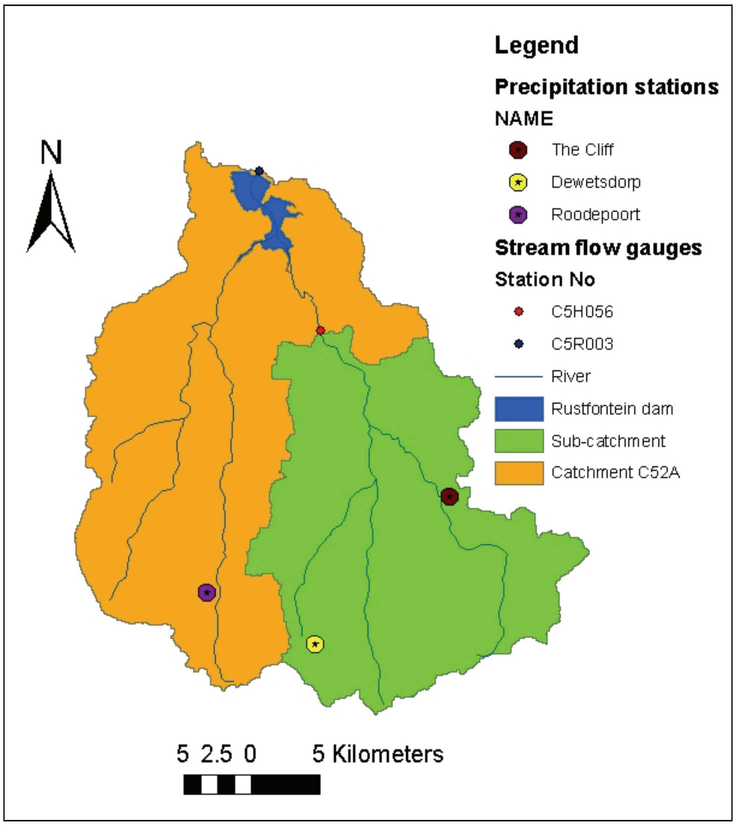

Figure 11 The sub-catchment within the quaternary catchment C52A and locations of rain and stream flow measuring gauges

In both cases, stream flow simulations were conducted using SWAT model and the parameters were analysed for their sensitivity on the total stream flow discharge using SWAT's sensitivity analysis module. The results showed consistence parameter sensitivity at both gauging stations. They are ranked as presented in Table 6.

Table 6 Results of sensitive analysis using SWAT Model

Parameter	Rank
Curve number for land use	1
Soil available water capacity	2
Threshold depth of water in the shallow aquifer required for return flow to occur	3
Soil evaporation compensation factor	4
Soil layer depth	5
Ground water 'revap*' coefficient	6
Soil saturated hydraulic conductivity	7
Average slope length of sub basin	8
Threshold depth of water in the shallow aquifer for 'revap' to occur	9
Surface lag time	10
Effective hydraulic conductivity in main channel alluvium	11
Moist soil albido	12
Average slope of sub basin	13

**Revap*: SWAT models the movement of water into overlaying unsaturated layers as a function of water demand for evapotranspiration. To avoid confusion with soil evapotranspiration this process has been termed '*revap'*.

During the simulation of the stream flow before calibration was carried out, we consistently encountered higher stream discharge values than the observed one. According to Winchell *et al*. (2008), this inconsistency between the observed and simulated data particularly occurs when the following parameter values are high: Curve number; Soil available water capacity; and Soil evaporation compensation factor, which increases the surface flow. During the sensitivity analysis, these parameters ranked on the top four positions (Table 6).

An overestimation of stream flow is also expected when there is high base flow and low evapotranspiration estimation. In this case increasing deep percolation loss or adjusting the threshold depth of water in shallow aquifer required for the base flow to occur may improve the simulation. This parameter during the analysis ranked number 3. Also increasing ground water revap (movement of water into overlaying unsaturated layers) and decreasing threshold depth of water in shallow aquifer for revap to occur will improve the simulation.

4.3 Calibration

Calibration was carried out on the most sensitive input parameters of the model, using auto-calibration module of SWAT using daily time step stream flow simulation. The observed data at gauging station C5R003 was found to have regulating discharges from the Rustfontein Dam. Thus, the calibration was done only by using the observed flow data recorded at the gauging station C5H056 during the year 2002 on parameters ranked 1 to 7 during sensitivity analysis. The calibration result gave an R^2 of 0.68 and a D-index of 0.86 (Table 7) between the simulated and observed values. The systematic and unsystematic root mean square errors (RMSEs and RMSEu) were also minimal. The ratio of the unsystematic root mean square error (RMSEu) to the root mean square error provided a value of 0.87. When this ratio approaches unity, it indicates a good correlation between the observed and simulated objective functions as well as indicates that the error is not possibly of a systematic nature (Welderufael *et al*., 2009). The Nash and Sutcliffe (1970), NS, index/efficiency revealed a value of 0.57 for the monthly stream flow calibration, describing a satisfactory correlation between the observed and simulated monthly stream discharges. According to Motovilov *et al*. (1999), simulated stream flows are considered “good” for values of NS > 0.75, while for values of NS between 0.75 and 0.36, simulated stream flows are considered “satisfactory”. Figures 12 and 13 show the satisfactory performance of SWAT.

Although satisfactory statistical performances, simulation of the daily stream flow or the water yield for the sub-basin using the calibrated parameters provided good results but failed to capture some of the peak flows (Figure 12). According to Winchell *et al*. (2008) this happens when precipitation data was obtained from non representative meteorological data or if there is a malfunctioning of flow gauges. In our study, the latter presumes to be the more likely cause. Rainfall data was obtained from South Africa Weather Service for three stations within the C52A catchment (Figure 11) and they were also cross checked with other sources and found to be acceptable.

Table 7 Calibration performance statistics

Indices	**Value**
Slope (b)	1.07
Intercept (a)	0.08
RMSE	0.18
RMSEs	0.09
RMSEu	0.16
MAE	0.12
R^2	0.68
D-index	0.86
RMSEu:RMSE	0.87
Nash & Sutcliffe (1970) efficiency, NS*	0.57

* = Value for monthly stream flow calibration

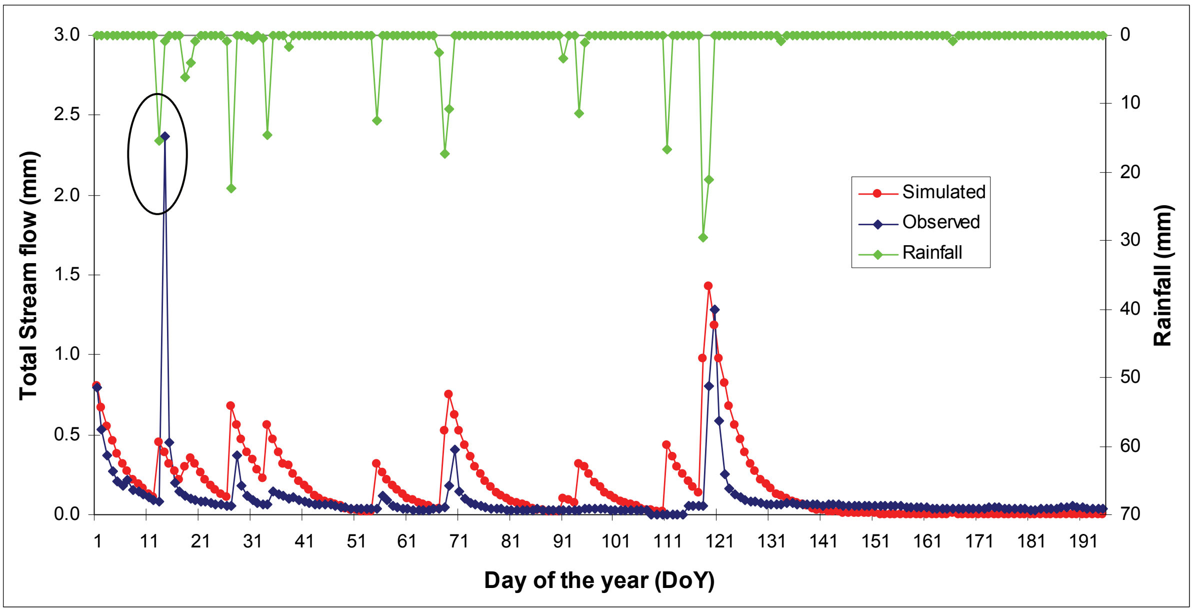

Figure 12 Observed and simulated daily stream flow (Q) after calibration at gauging station C5H056

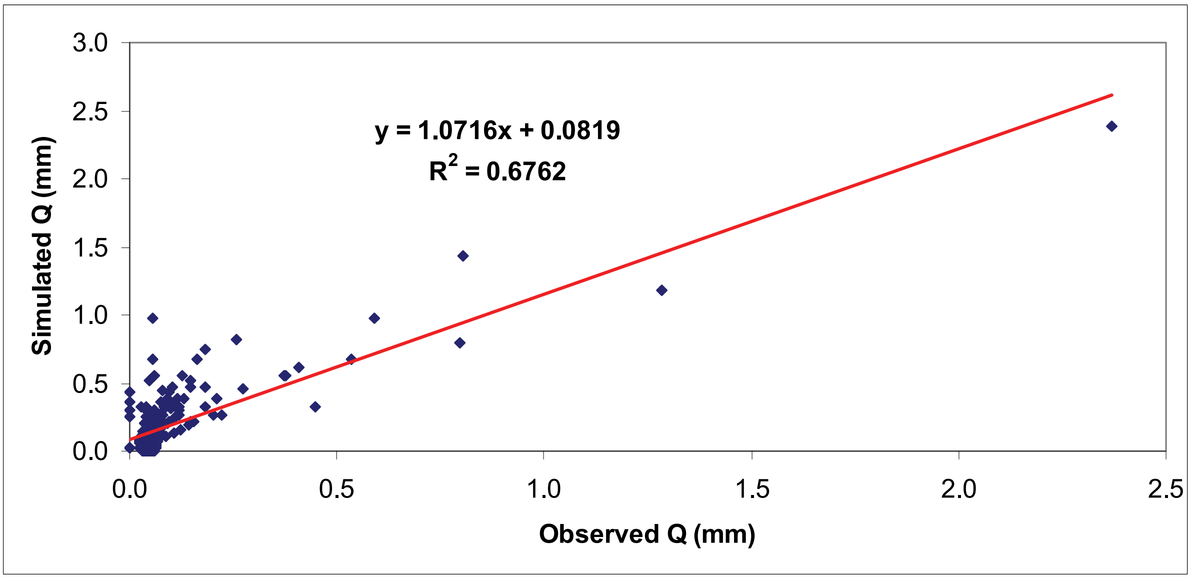

Figure 13 Linear relationships between the observed and simulated daily stream flow after calibration

4.4 Validation

Validation of the model was not conducted due to the unreliability of the observed stream flow data beyond the year 2002. The obtained observed data (i.e. 2003 to 2007) lacks consistency and reliability. This inconsistency was also observed in the relatively better part of the observed daily flow data during 2002 which was used for calibration of the model. In Figure 12 one can easily observe the high discharge amount on DoY 14 (indicated by the oval). During this event the preceding rainfall amount was 15 mm. This rainfall produced a discharge of more than 2 mm which is not in the same order of magnitude with most of the observations. In addition, it seems unrealistic when the rainfall-runoff relationship of the catchment was closely scrutinised. Thus, because of high frequencies of these types of events which questions the integrity of the data; and which most probably emerged from the inaccuracy of the observed flow data, validation process was discarded.

4.5 Simulation Results

As indicated in the preceding paragraphs, the inputs to SWAT model are land use types, (such as agriculture, both irrigated and dry land), forest, rangeland (improved and non-improved pasture, grass land, shrubs, etc); topography in the form of Digital Elevation Model (DEM); soil characteristics (such as hydrological soil group, maximum root zone depth, soil bulk density, soil saturated hydraulic conductivity, and soil available water capacity) which obtained from different literatures; and weather data (such as daily rainfall and temperature). The South Africa Weather Service provided us rainfall and temperature data of C52A for the period 1993 to 2007 for three rainfall stations inside C52A (Figure 11); and three temperature stations adjacent to C52A (Bloemfontein Stad, Bloemfontein W.O and Glen Agricultural Collage). Two sets of land use data for the years of 1994 and 2000 were obtained from the ISCW of the Agricultural Research Council (ARC). The preparation of input data for the model was one of the most demanding, but important aspect of the overall task.

Keeping all the parameters, such as soil, topography and climate, constant, the impact of land use change on water resources was evaluated using the SWAT model for catchment C52A. The comparison of land use data for both years and the percentage change in land use type and/or cover are given in Table 8.

Table 8 Land use types of catchment C52A during the year 1994 and 2000 and percentage change during these two periods.

Land Use	1994 (Ha)	2000 (Ha)	Difference (Ha)	%
Pasture (PAST)	70 854	78 044	7 190	10
Range-Brush (RNGB)	9 446	4 175	-5 271	-56
Agricultural Land Row crops (AGRR)	10 261	7 214	-3 047	-30
Evergreen forest (FRSE)	31	223	192	619
Wet land (WETN)	200	1 379	1 179	589
Water (WATR)	1 752	1 048	-704	-40
Urban (URBN)	138	599	461	334
Sum	92 682	92 682		
Note: the land use types are prepared and classified according to the input requirement of the SWAT model				

The model simulated several parameters among which the direct flow (DIRQ), the base flow or the ground water flow (GWQ), water yield (WY) and evapotranspiration (ET) were selected for evaluation purpose. Figure 14 shows the variation of the WY for the two land use data sets at the outlet of C52A catchment.

The result showed that there was an average decrease of WY by about 21% over a period of 13 years (1995-2007) when land use data of 1994 was compared to the land use data of 2000. The decrease in WY was accompanied by a slight increase in settlement areas, an increasing trend in grass land areas from 77% to 84% and a decrease in agricultural areas from 11% to 8% (Table 8).

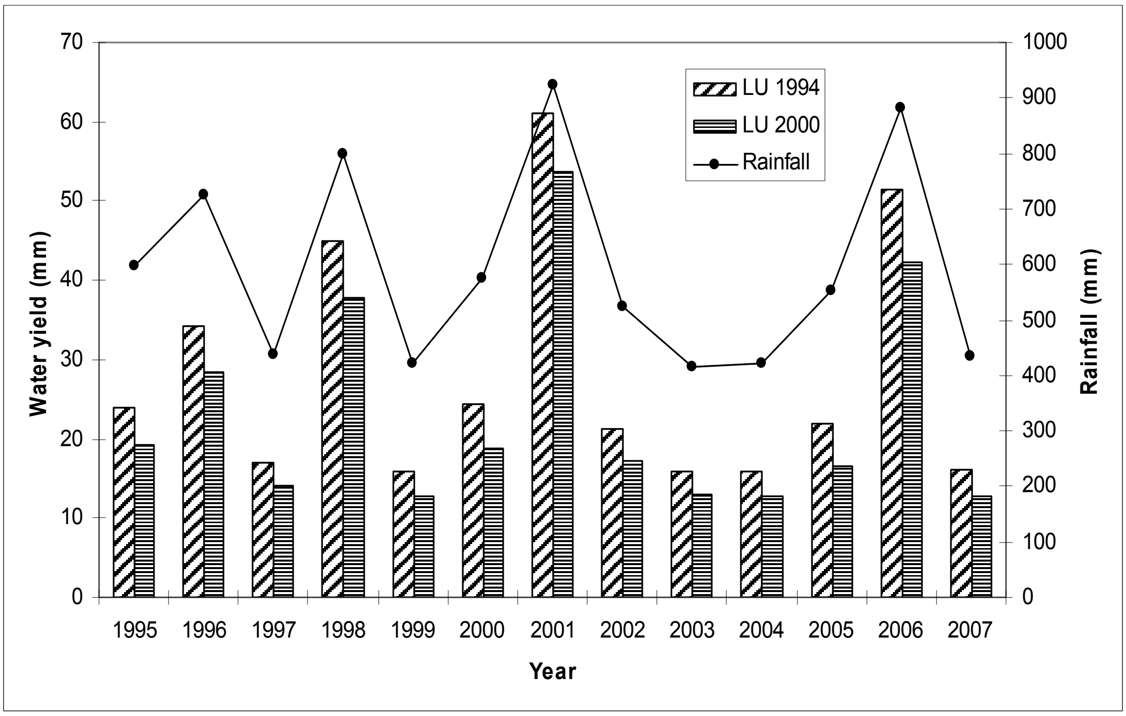

Figure 14 Comparison of the simulated annual water yields for the period of 1995 to 2007 based on the two land use data sets

The difference in WY given in millimetre per year seems very small. But due to the large area of the catchment (927.6 km^2) a millimetre difference in WY brings about a volume difference of 927 600 m^3 of water per year which is a significant amount.

An assessment of the impact land use change on the water balances of catchment C52A was also under taken by creating logically perceived land use scenarios using ArcGIS®. In this study, land use data of the year 2000 was used as a bench mark against which different land use scenarios were compared. Daily weather data from 1993 to 2007 was used for the simulations. The data from the first two years was used to warm up the SWAT model. Once the model was calibrated and set up, the water balance of C52A was simulated by changing the land use scenarios only. The simulation was done on a daily as well as monthly time steps, but the results were interpreted using mean monthly values.

Two land use scenarios were considered: (1) conventional land use which represents the current land use practice in the area (Agri-CON) and (2) in-field rainwater harvesting (IRWH) based on the work of Hensley *et al.* (2000) which was aimed at improving the precipitation use efficiency (PUE). The 2000 land use data of C52A shows that 84% of the land is covered by pasture (PAST). This was taken as a base scenario against which the other two scenarios were compared (Figure 15b and Table 9). To create the first scenario (Agri-CON), a change was made to the original pasture (PAST) land in such a way that the land on slopes of 0 to 3% was converted to agriculture with conventional practices (Figure 13d and Table 10). This change brought about 420 km^2 (54%) of the pasture area on slopes of 0 to 3% under agricultural land. This has increased the area of the agricultural land from 8% to 53% and decreased the pasture area from 84% to 39%. The second scenario (Agri-IRWH) was obtained by changing the pasture land (PAST) located on slopes of 0 to 3% to an agricultural land planted with maize using an infield rainwater harvesting (IRWH) (Fig. 15d and Table 9). In both scenarios all other land use types remained the same as in the base scenario and they both have the same area of cropland and crop type which is maize, the only difference being the tillage type, i.e. scenario-1 uses conventional tillage (row cropping) while scenario-2 uses IRWH.

The curve number for antecedent moisture condition two (CN2) and tillage management were modified for Agri-IRWH in order to satisfy the surface condition created by IRWH. The change of land use from pasture to maize conventional tillage planting and IRWH was done using ArcGIS. The slope ranges were selected in such a way that it satisfies the FAO slope classification standard (FAO, 1990) and the suitable slope range for IRWH (Kahinda *et al*., 2008).

Table 9 Actual land use of C52A in 2000 and the two land use scenarios

Land use type	Actual land use in 2000 (Area and percentage)		Area and percentage under Agri-CON or Agri-IRWH	
	Area (km^2)	(%)	Area (km^2)	(%)
Agriculture (AGRR)	72.4	7.8	492.4	53.1
Ever green forest (FRSE)	2.2	0.2	2.2	0.2
Pasture (PAST)	780.0	84.1	360.0	38.8
Range plus brush land (RNGB)	42.0	4.5	42.0	4.5
Urban (URBN)	6.1	0.7	6.1	0.7
Water bodies (WATR)	10.5	1.1	10.5	1.1
Wet land (WETN)	14.0	1.5	14.0	1.5
Total	**927.2**	**100.0**	**927.1**	**100.0**

Table 10 C52A slope ranges and area coverage

Slope range (%)	Area (km^2)	(%)
0 - 3	524.1	56.5
3 - 8	319.0	34.4
> 8	84.0	9.1
Total	**927.1**	**100.0**

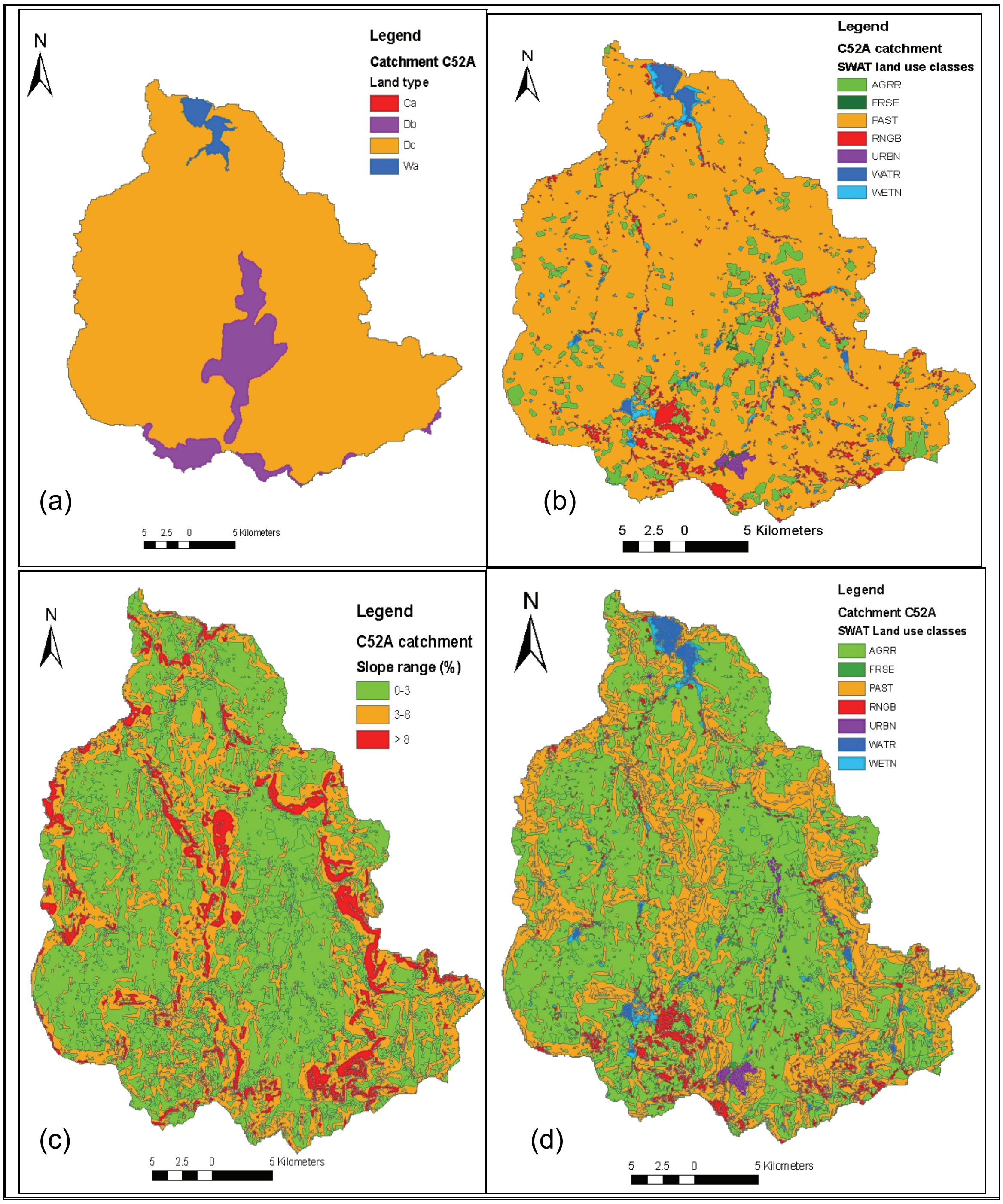

Figure 15 Land and topography information of C52A: Land type (a); Land use 2000 (b); Slope range (c); and agriculture on slopes of 0-3% (d).

The impacts of the different land use scenarios on the components of the stream flow are presented in Figure 16 and Table 11. The mean monthly WY (DIRQ + GWQ) for the period of 1995 to 2007 showed significant differences in peak flow when pasture (PAST) land on 0 to 3% slope was converted to Agri-CON and Agri-IRWH land uses. The monthly mean peak WYs were 20 mm, 18 mm and 16 mm for Agri-CON, Agri-IRWH and PAST, respectively. The mean monthly WY on the Agri-CON land use scenario was higher than the other two scenarios during the rainy months of

December to March only (Figure 14b). During the remaining months, the two land use types (Agri-IRWH and PAST) recharged the ground water better and had more WYs than the Agri-CON land use scenario. Agri-IRWH showed a higher peak WY value than PAST probably due to the high ground water contribution by the IRWH technique during the same month as the occurrence of the peak flow. The F-test for two samples variances for the monthly WYs revealed no significance differences among the three land use scenarios.

Table 11 Mean monthly stream flow components in mm for the three land use scenarios for the period 1995-2007.

Month	Rainfall (mm)	Agri-IRWH			Agri-CON			PAST		
		DIRQ	GWQ	WY	DIRQ	GWQ	WY	DIRQ	GWQ	WY
Sep	16.8	0.93	0.30	1.23	1.12	0.25	1.37	0.69	0.69	1.38
Oct	53.7	2.90	0.18	3.08	3.72	0.15	3.87	2.41	0.46	2.87
Nov	73.6	6.51	0.56	7.07	8.94	0.47	9.41	9.04	1.48	10.52
Dec	78.7	4.48	1.51	5.99	6.10	0.91	7.01	3.65	2.67	6.32
Jan	96.5	6.50	1.52	8.02	10.18	0.75	10.93	6.59	1.89	8.48
Feb	93.2	8.93	4.24	13.17	18.21	1.68	19.89	12.11	2.73	14.84
Mar	88.1	8.10	9.68	17.78	13.95	4.12	18.07	10.63	5.88	16.51
Apr	41.2	3.65	9.00	12.65	4.76	4.42	9.18	4.30	6.63	10.93
May	18.2	1.34	6.45	7.79	1.84	3.25	5.09	1.33	5.53	6.86
Jun	5.3	0.34	2.89	3.23	0.36	1.40	1.76	0.24	2.64	2.88
Jul	5.1	0.20	0.94	1.14	0.23	0.51	0.74	0.12	0.98	1.10
Aug	19.8	1.34	0.27	1.61	1.43	0.16	1.59	1.42	0.31	1.73
Annual	**590.3**	**45.22**	**37.54**	**82.76**	**70.84**	**18.07**	**88.91**	**52.53**	**31.89**	**84.42**

DIRQ = Direct flow; GWQ = Ground water flow or base flow; WY = Water yield

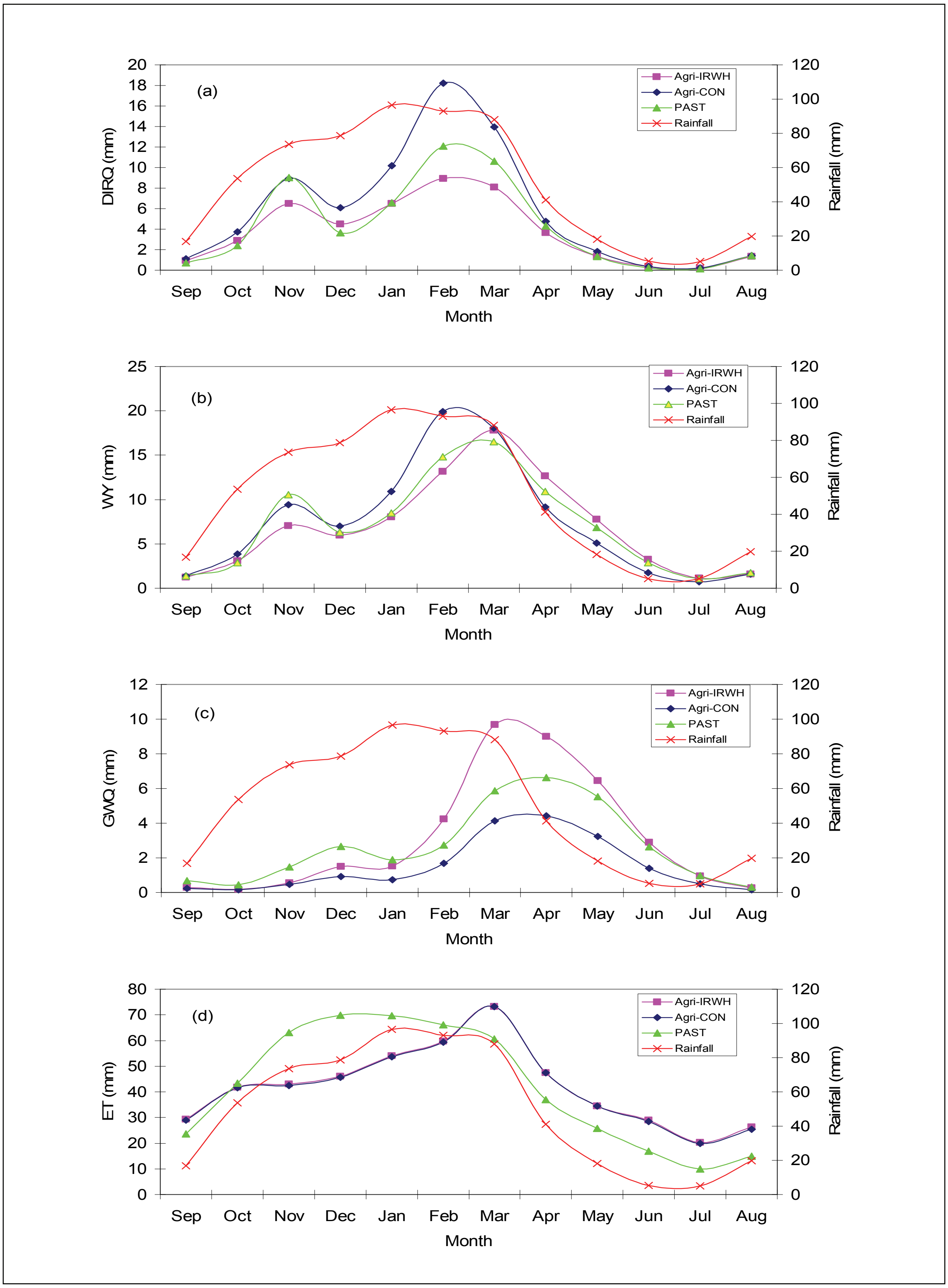

Figure 16 Water balance components of catchment C52A for three land use scenarios: Direct flow (a); Total water yield (b); Base flow (c); and Evapotranspiration (d).

The effect of the different land use scenarios on the water balance of C52A is well demonstrated by the direct flow component of the WY. The direct flow comprises the surface runoff and the lateral flow, also known as interflow. Figure 16a presents the direct flow component of the three land use scenarios. The highest mean monthly peak DIRQ was obtained on Agri-CON land use, amounting to about 18 mm followed by PAST with 12 mm. Agri-IRWH land use scenario generated the lowest DIRQ which amounted to about 9 mm. Similarly the mean annual direct flows were 71 mm, 52 mm, and 45 mm on Agri-CON, PAST, and Agri-IRWH land use scenarios, respectively (Table 11).

The F-test for the DIRQ gave a significant difference ($P < 0.02$) between Agri-IRWH and Agri-CON land scenarios while there is no significant difference between Agri-IRWH and PAST as well as between PAST and Agri-CON. All the DIRQ generated on Agri-IRWH scenario come from the lateral flow (LATQ) component of the direct flow (Table 12). The surface runoff (SURQ) component on Agri- IRWH shows literally no runoff for the whole period covered by the study (1995-2007) (Table 12). Generally, the results of the simulation demonstrated that the total annual WY was affected minimally by the different land use scenarios, which were 89 mm, 84 mm and 83 mm for Agri-CON, PAST and Agri-IRWH, respectively (Table 11). Kahinda *et al*. (2008a and b) reported, in their hydrological impact study of C52A catchment, that a 100% adoption scenario significantly reduced the high flow compared to the actual land use of 2000 or 0% adoption. They also showed that according to their analysis, “the most likely scenario” which is about 10% area adoption of IRWH, gave no significant difference compared to the 0% adoption.

As per its intended purpose, Agri-IRWH reduced the direct surface runoff by 37% and the surface runoff component almost by 100% compared with the Agri-CON land use scenario (Table 12). This obviously improves the soil water availability within the crop root zone as well as the PUE. Rain-fed agriculture using Agri-IRWH technique in this area has been reported to have increased production of maize and sunflower by about 50% compared to Agri-CON production (Hensley *et al*., 2000; Botha *et al*., 2003; Botha *et al*., 2007). Woyessa *et al*. (2006b) also reported that Agri-IRWH improved both crop production and monetary income of a farmer more than Agri-CON that uses supplemental irrigation system by harvesting the direct runoff in small dams or ponds.

The other interesting result on the impact of land use change was related to the ground water (base flow) component of the WY. Figure 16c presents the ground water discharge to the stream flow. Agri-IRWH, due to its surface runoff harnessing design, collects the runoff generated from the two meter strip and stores it in two meter long and one meter wide basin (Figure 17). By doing so it allows more water to infiltrate into the soil and to percolate further deep into the ground water table than the other two land use scenarios (Table 13).

Table 12 Components of the direct flow of the different land use scenarios

		PAST			Agri-CON			Agri-IRWH		
YEAR	PREC	SURQ	LATQ	DIRQ	SURQ	LATQ	DIRQ	SURQ	LATQ	DIRQ
	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)
1995	590.7	10.61	18.23	28.84	16.47	30.25	46.72	0.00	31.07	31.07
1996	755.5	61.18	27.46	88.64	85.93	42.50	128.43	0.00	51.40	51.40
1997	452.8	8.13	16.02	24.15	12.17	25.57	37.74	0.00	26.62	26.62
1998	811.5	75.12	28.98	104.10	86.53	45.25	131.78	0.00	54.23	54.23
1999	433.0	1.49	12.84	14.33	3.31	22.32	25.63	0.00	22.44	22.44
2000	591.3	6.40	20.41	26.81	10.94	31.43	42.37	0.00	32.15	32.15
2001	934.3	118.85	38.03	156.88	98.32	54.86	153.18	3.88	66.89	70.77
2002	531.3	14.43	18.67	33.10	26.47	29.91	56.38	0.00	32.24	32.24
2003	425.6	19.19	13.53	32.72	23.42	22.33	45.75	0.00	24.14	24.14
2004	403.7	0.08	11.98	12.06	0.72	19.65	20.37	0.00	19.67	19.67
2005	541.9	0.78	16.32	17.10	1.72	25.17	26.89	0.00	25.24	25.24
2006	910.8	104.82	42.44	147.26	112.30	58.19	170.49	0.00	70.42	70.42
2007	396.1	4.11	11.45	15.56	6.98	18.49	25.47	0.00	18.83	18.83
Sum	**7778.7**	**425.19**	**276.36**	**701.55**	**485.28**	**425.92**	**911.20**	**3.88**	**475.34**	**479.22**

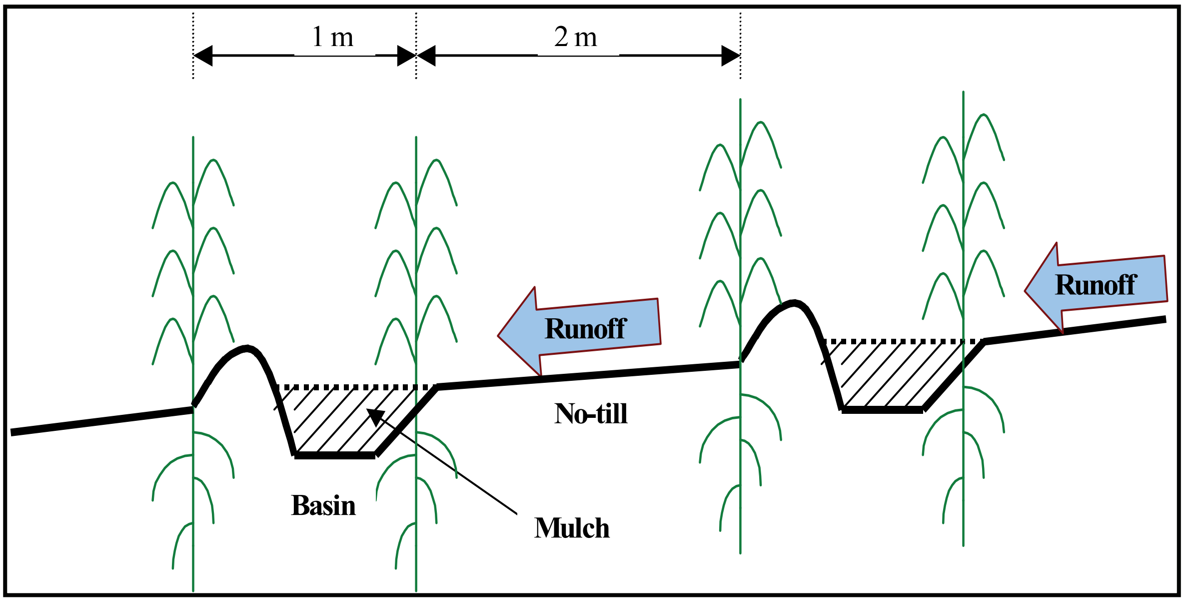

Figure 17 Diagrammatic representation of the IRWH technique (Adapted from Hensley *et al*., 2000)

Table 13 Simulated annual deep water percolation on the different land use scenarios

Year	Precipitation (mm)	Annual deep percolation in mm		
		Agri-IRWH	**PAST**	**Agri-CON**
1995	590.7	0.6	3.3	*0.6*
1996	755.5	110.3	67.1	*45.4*
1997	452.8	20.3	22.2	*11.6*
1998	811.5	78.3	59.0	*28.0*
1999	433.0	0.0	0.0	*0.0*
2000	591.3	7.9	14.2	*4.3*
2001	934.3	122.2	135.3	*70.5*
2002	531.3	28.3	21.4	*12.4*
2003	425.6	4.0	11.6	*3.1*
2004	403.7	0.0	0.0	*0.0*
2005	541.9	1.3	2.9	*1.3*
2006	910.8	168.7	174.3	*104.4*
2007	396.1	0.2	0.2	*0.2*
Mean	**598.4**	**41.7^{a}**	**39.3^{a}**	**21.7^{b}**

a = numbers followed by the same letter in the same raw are not significantly different at P < 0.05

Thus, the Agri-IRWH was found to recharge the ground water table better than the other two scenarios. The build up of the water table under the Agri-IRWH will in turn contribute to the recharge of the stream of C52A as a base flow. Thus, the highest mean monthly peak ground water flow was produced by Agri-IRWH amounting to 10 mm, followed by 7 mm and 4 mm by PAST and Agri-CON land use scenarios, respectively. The annual mean ground water flow was also found to be the reverse of the direct flow. The highest annual ground water flow was obtained from Agri-IRWH which was 37 mm, followed by 32 mm on PAST and 18 mm on Agri-CON land use scenarios. The base flow showed about 105% increase on Agri-IRWH compared to Agri-CON land use scenario. The F-test for GWQ as well revealed a significant (P < 0.03) difference between Agri-IRWH and Agri-CON. There is also a significant difference (P < 0.04) between PAST and Agri-CON. But there is no significant difference between Agri-IRWH and PAST. The results demonstrate that there was high infiltration of water on Agri-IRWH and PAST than on the Agri-CON land use. The Agri-IRWH technique creates a pond of water inside the furrow that later infiltrates into the soil profile. Moreover, Agri-IRWH and PAST scenarios were found to increase the residence time of runoff flow in a catchment which in turn had an effect on the occurrence of the monthly WY peak flows. Thus, the increased dry season WY under Agri-IRWH may have positive environmental as well as hydrological implications/impacts downstream.

With regard to evapotranspiration (ET) there was no significant difference in the total annual amount. But there is a marked difference in the monthly ET distribution of grass and maize crops (Figure 16d). The ET from Agri-CON and Agri-IRWH land use followed the same pattern due to the same type of crop (maize) considered in both cases. The annual ET of Agri-IRWH showed 4 mm more water loss than both Agri-CON and PAST land use scenarios.

4.6 Summary

The SWAT hydrological model was used to assess the impact of two possible land use scenarios, in addition to the 1994 and 2000 actual land use data, on the water resources of the quaternary catchment C52A. The 2000 actual land use scenario was used as base line scenario to asses the different water balance components of quaternary catchment C52A against the two new scenarios envisage in the study. The study used a climatic data of three weather stations within C52A that have records of 1993 to 2007. The first two years weather data were used to warm up the SWAT model. The two new possible land use scenarios are (1) Pasture on the 0-3% slope of land use 2000 changed to maize crop land using conventional tillage (Agri-CON) and (2) Pasture on the 0-3% slope of land use 2000 changed to maize crop land using IRWH (Agri-IRWH).

The result of the water balance simulation by comparing land use 1994 and land use 2000 over 13 years period (1995-2007) showed that land use 2000 gave 21% lower WY compared to land use 1994. This result demonstrates that land use types which are dominated by pasture or grassland have more negative impact on WY or total stream flow than land type dominated by conventional agriculture. This was evidenced by the fact that in 2000 agriculture land use in C52A catchment decreased by 30% while pasture covered area increased by 10% compared to 1994. Comparable results were also found when the C52A catchment water balance was analysed under different land use scenarios.

The scenario analysis results confirmed that there was improvement of water infiltration into the soil by Agri-IRWH and PAST land uses. Both resulted in higher base flow than Agri-CON land use. Both also demonstrated high deep water percolation with a significant difference ($P < 0.05$) in annual amounts compared to Agri-CON. The Agri-IRWH showed that 105% higher base flow compared to the Agri-CON land use scenario. However, there is no significant water yield difference among the three land use scenarios. But the results revealed that conventional agricultural land use type generated highest direct flow than the ones dominated by pasture or IRWH land use scenarios. This may not support favourable crop production on rainfed semi-arid areas, such as the Modder river basin, due to decreased infiltration of water to the sub-soil which ultimately influences the soil water content within the root zone. However, whether or not the increased direct runoff would be more beneficial if harnessed by small ponds or dams on-site, for use as a supplemental irrigation using the Agri-CON production scenario compared with its use by the downstream communities from the increased stream flow, could be a subject for further study.

Overall, the results suggest that the WY of C52A may not be adversely affected by the Agri-IRWH land use scenario despite its surface runoff abstraction design. It is expected that this result will assist in taking a proactive measure regarding water resources management in general and a strategic allocation and use of water in particular.

5 AGENT BASED MODELLING (ABM) OF LAND USE SCENARIOS

5.1 Introduction

Research into land-use change and its impact on the environment has been going on for several decades. The reasons for research into this field include the impact that land-use change has on society, the economy and the environment. Considering the implications, it is imperative that a deeper understanding be attained of the driving forces and the impacts of land-use change.

In the past, a variety of models were used for mapping changes in land-use and it is only recently that the focus has shifted away from using mathematically oriented models to agent-based modelling (ABM) approach. The agent-based perspective, with regard to land-use cover change, is centred on the general nature and rules of land-use decision making by individuals. Decisions are made that try to optimise profit within a set of given constraints. In applying the agent-based modelling approach to land-use change, a cellular model that represents the biological, geographical, physical, and ecological aspects of the modelled system has to be developed as well as an agent-based model to represent human decision making. In such a model, agents can interact with each other as well as their environment on a temporal scale to accurately simulate how land managers act in the real world.

The cellular model should reflect the landscape of the specific region through a lattice of congruent cells. Each cell would be of a predetermined size and should be able to transition between a finite number of states, for example specifying whether a cell is currently being used for crop production or not. The agents acting in the system should represent individual land managers, but higher-level agents such as government agencies can also be modelled. The agents acting in the model should make decisions about how to optimally make use of the land that they have at their disposal with regards to the resources that they have at hand in order to maximise their wealth.

As with traditional object oriented software development, multi-agent systems (MAS) have methodologies to aid the developer with the design of such systems. Agent Oriented Software Engineering (AOSE) is the name given to software design methodologies used to design MAS (Silaghi, 2005). In this study, Tropos methodology was adopted (Giorgini *et al*., 2004; Bresciani *et al*., 2004) for the development of the ABM's as discussed below.

Tropos is one of the most prominent methodologies in existence today. Tropos consists of several design phases that cover the entire development lifecycle, from early requirements analysis to implementation and it has some tools for developing agent systems. One such tool is the Agent Oriented visual Modelling for the Eclipse (Eclipse, 2008) platform (TAOM4E) (TAOM4E, 2008). The TAOM4E environment takes into account emerging guidelines and standards from the Object Management Group's (OMG) (OMG, 2008) Model-Driven Architecture (MDA) (OMG Model Driven Architecture, 2008) initiative which proposes an approach to software development based on modelling and automated mapping of models to code. The tool is based on the Eclipse Platform, which offers a flexible solution to the problem of component integration. TAOM4E provides a comprehensive development environment able to design agent systems with the Tropos methodology. In addition to providing functionality to draw diagrams of the agents and their interactions, goals, etc., the tool also provides agent code generation through the t2x plug-in. This comprehensive range of tools, frameworks and platforms motivated us to choose this methodology. One demerit of using TAOM4E is that Jadex, which is the implementation platform of the tool, does not make use of ontologies in the sense of OWL, for example, but uses Java classes instead. Although this is not a fatal flaw, the ontology constraint can influence future integration with other systems, be it agent or otherwise.

5.2 The Development of the ABM Using Tropos Methodology

Tropos is one of the most prominent methodologies in existence today. It is based on Eric Yu's (2009) i* framework which proposes an agent-oriented approach to requirements engineering focussed on the intentional characteristics of the agent (Bernon *et al*., 2005). Tropos consists of several design phases that cover the entire development lifecycle, from early requirements analysis to implementation. These phases are early requirements, late requirements, architectural design, detailed design and implementation (Giorgni *et al*., 2004; Bresciani *et al*., 2004). Each of these phases serves a specific function in the total design of a system:

- Early Requirements – Identify the domain stakeholders and model them as social actors. These actors depend on one another for goals to be achieved, plans to be performed and resources to be furnished. During early requirements, we identified the following actors, their goals plans and associated resources as shown in Figure 18: Farmer, Trader, Farm Worker, Bank, Researcher, Government Body and markets.

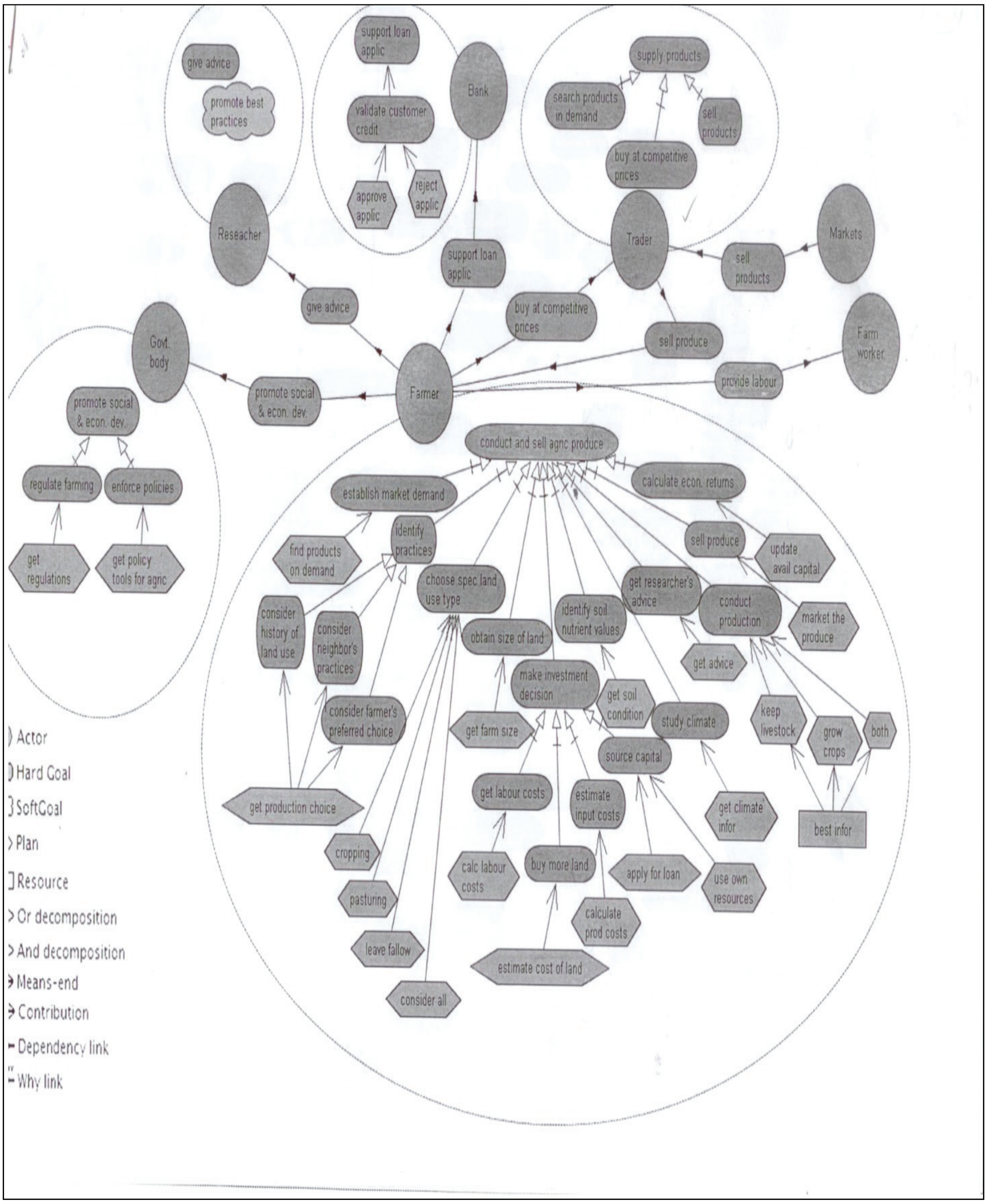

Figure 18 The early requirements diagram

- Late Requirements – The conceptual model is extended including a new actor which represents the system and a number of dependencies with other actors of the environment. During this phase, the system to be was modelled as the Land Use System linked to the actors identified in the first phase through dependencies. The internal goals of the Land Use System were also identified.
- Architectural Design – The global architecture of the system is defined in terms of sub-systems, interconnected through data and control flows. A mapping of system actors to a set of software agents, each of which is characterised by specific capabilities, was also provided by this phase. The Land Use system was

refined into the following sub-actors: Farm Manager, Finance Manager, Marketing Manager and advisor; all with their goals, plans and resources. Figure 20 shows the architectural design of the system and Figure 21 shows the architectural design of the three sub-actors of the system. Details of the Farm Manager actor are given in Figure 22.

- Detailed Design – During this phase the focus was on specifying agent, their capabilities and interactions. At this stage of the design the implementation platform is usually decided and the detailed design can then be directly mapped to the code. The detailed design of the sub-actors identified in the previous phase was then undertaken and the agents identified include: Farmer agent, Researcher agent, Marketing agent, Finance Manager agent, etc.
- Implementation – This stage follows the detailed design specification on the basis of the established mapping between the implementation platform constructs and notions determined in the detailed design phase.

Key to Design Diagrams

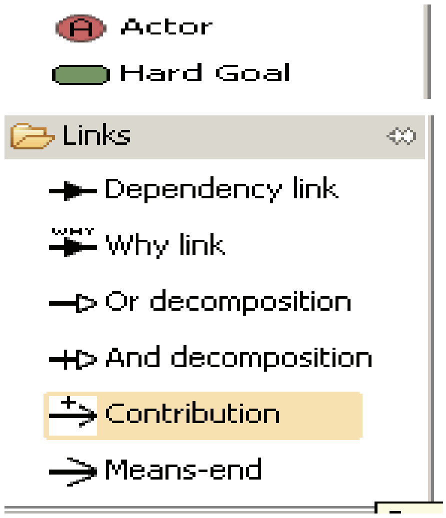

Figure 19 The Key to the Design Diagrams

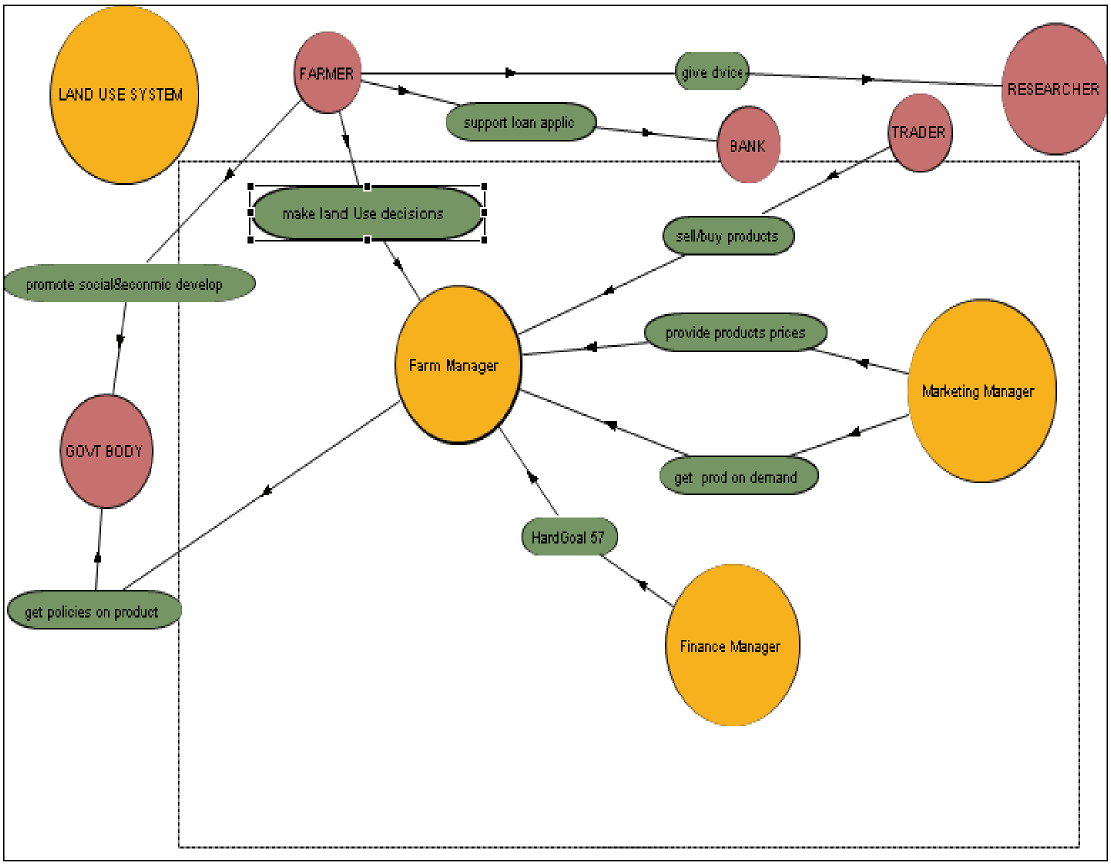

Figure 20 The Architectural design diagram of the Land Use System

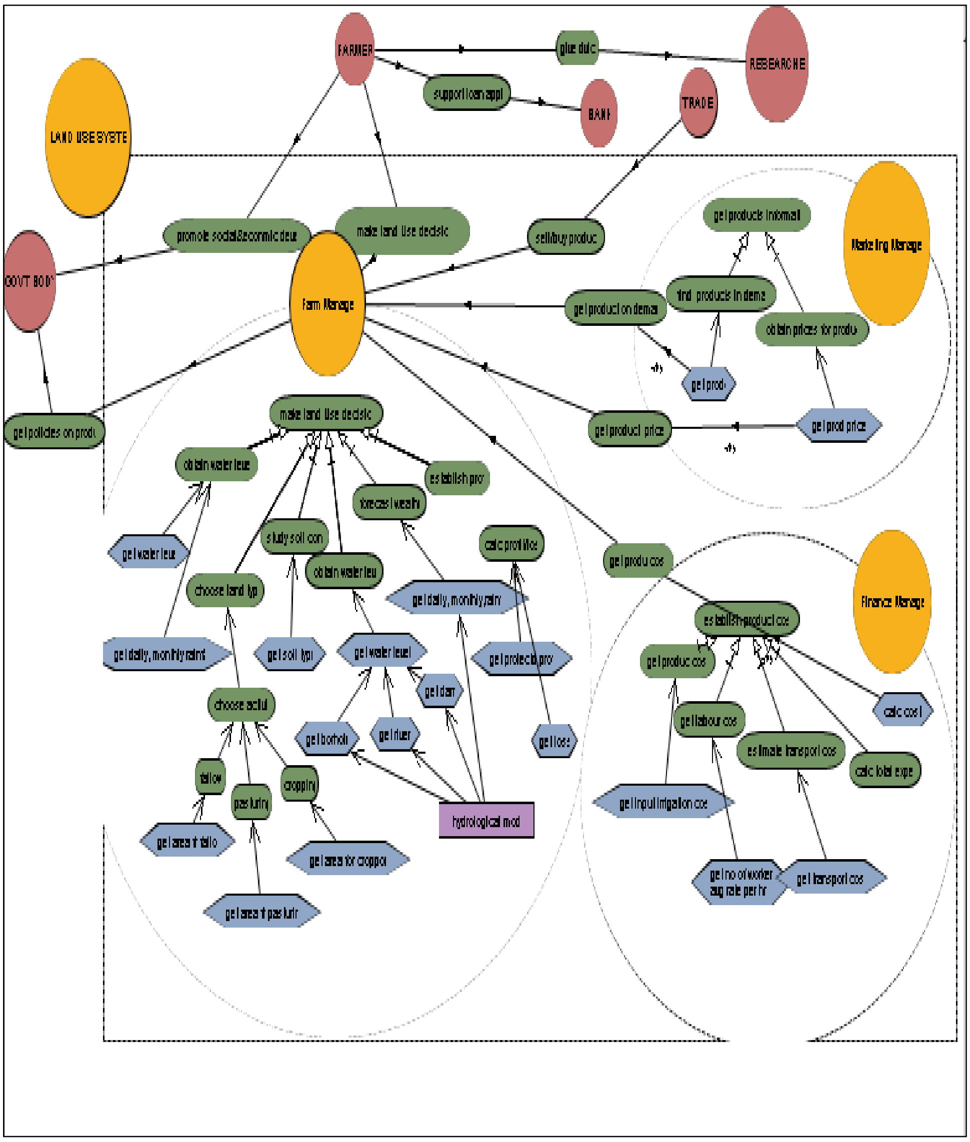

Figure 21 Architectural design decomposition: Simplified Goal model of the three Sub-actors

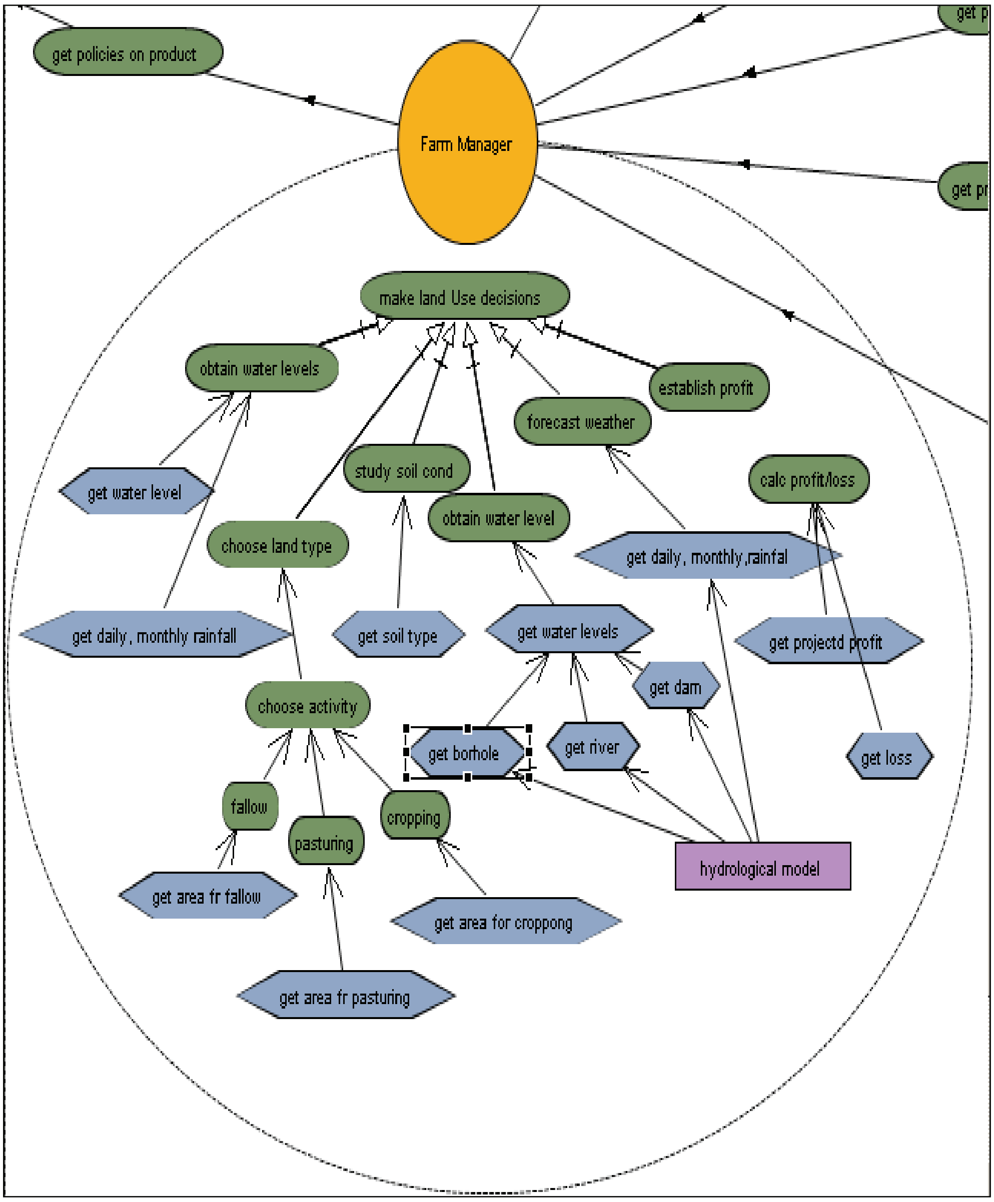

Figure 22 The Farm Manager sub-actor

5.3 Simulation of the Land Use Scenarios Using the ABM

In the study of land use changes and its impact on water resources, there are several agents who have direct and indirect impact on land use decision making process. As the number of agents increase the level of model complexity also increases. Figure 23 below shows how the ABM will be linked to the other components in the water management system. The ABM's land use scenario is fed into the SWAT model. The land use scenario recommended by the ABM has specific implications on the water resources which are captured into the biophysical database together with other GIS data. These in turn are used by the ABM together with prevailing social-economic conditions to adjust the land use scenario recommendations. It is expected that this feedback loop will improve the long term sustainability of water resources.

The implementation of the ABM is not complete in order to enable us to perform the simulations with the ABM at this stage. The major drawback was due to the unreliability of the postgraduate (PG) students who were involved in the development work. The kind of development work in this project requires the participation of PG students who will then use the appropriate tools and methodologies to develop the system under the guidance of supervisors. Two PG students who were involved in this project during the earlier phases of the project abandoned their studies and we had to get a replacement student on two occasions to continue with the development work. One student is currently doing fairly well. However, we plan to complete the ABM development followed by the simulation activities and the validation work later on.

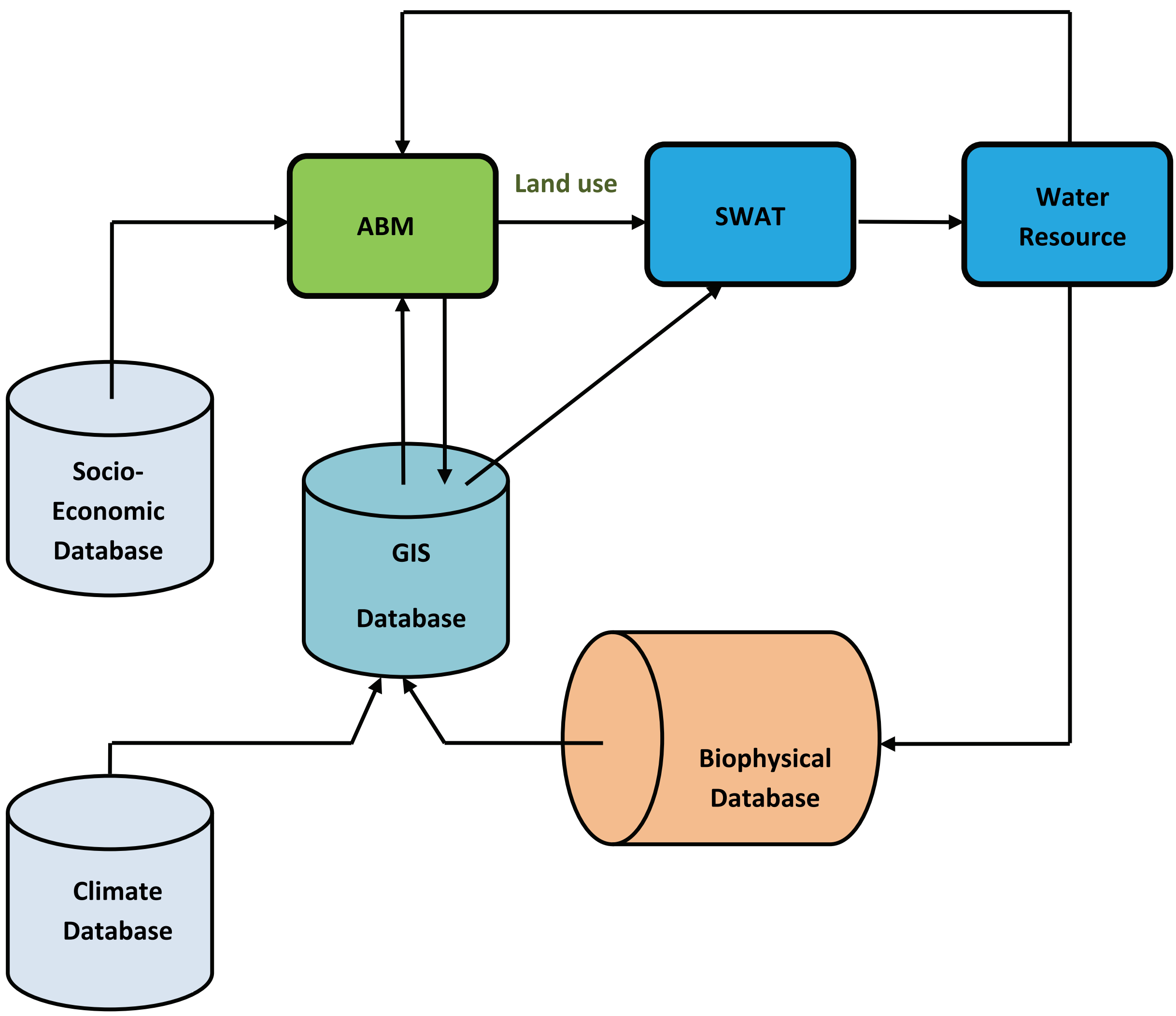

Figure 23 Dynamic incorporation of the ABM into the Land use Scenario

5.4 Linking the ABM to the Hydrological Model

In the study of land use changes and its impact on water resources, there are several agents who have direct and indirect impact on land use decision making process. As the number of agents increase the level of model complexity also increases. However, in order to get the first glimpse of the dynamics of human-environment interaction, the number and type of agents will be limited to farmers, land owners or farm managers who are directly involved in the use of land in a catchment. In a given time, farmer's land use decision is subjected to environmental conditions, which in this study are grouped under three categories, namely biophysical, social and economic environments. It is hypothesised that based on the perception about the environment individual farmers will take action according to their goals. This action will also be supplemented with the interactions and communications with other farmers in order to arrive at a decision on land use. The outcome of this land use decision will then be linked to a hydrological model to assess the impact of a given land use scenario on water resources. It is planned that the land use scenario results from the ABM will be dynamically incorporated into the hydrological model. The schematic representation of the ABM and its linkage with the hydrological model is shown in Figure 24.

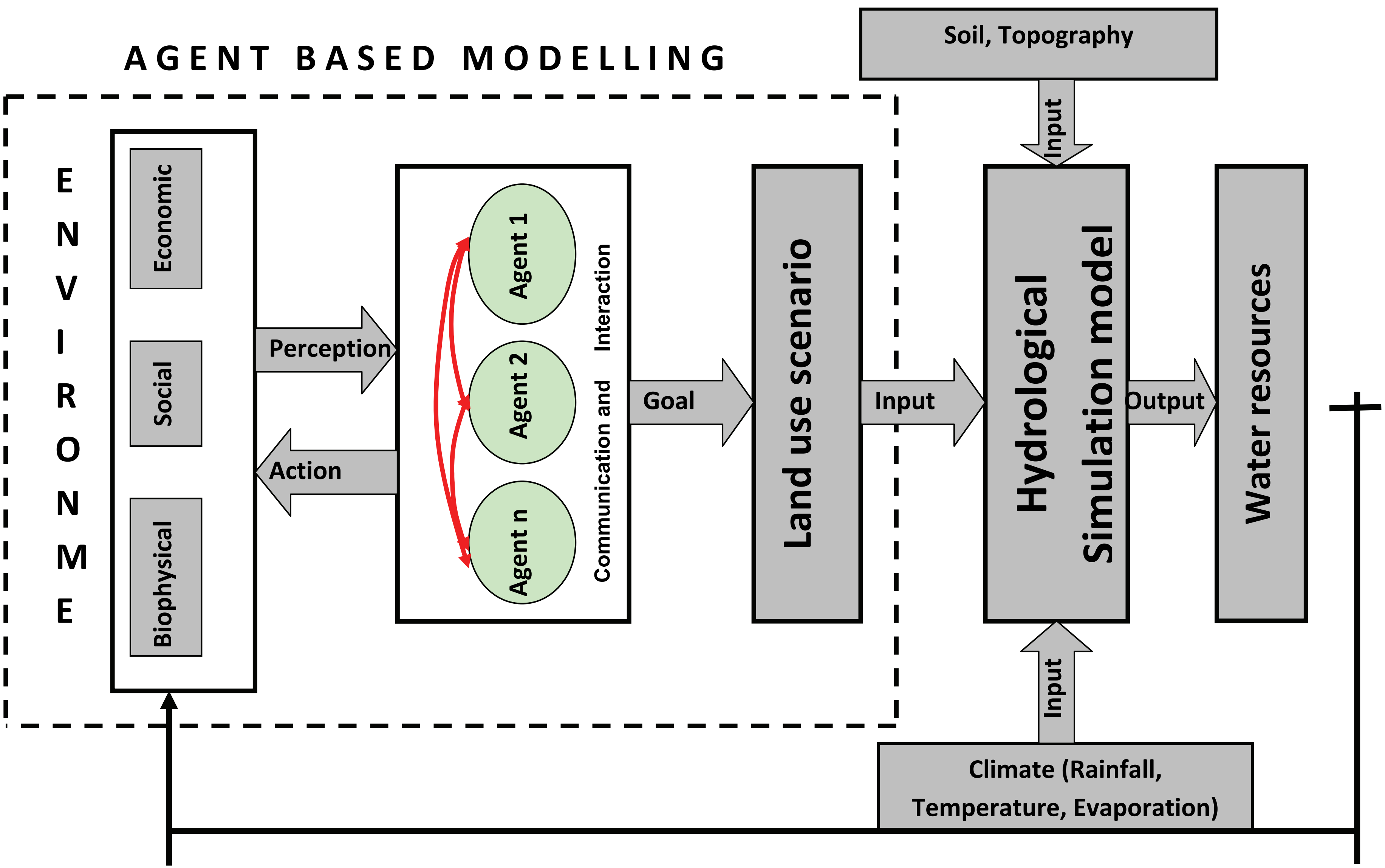

Figure 24 The Linking of the ABM with the Hydrological Model

5.5 Summary

The agent-based perspective, with regard to land-use cover change, is centred on the general nature and rules of land-use decision making by individuals. In the study of land use changes and its impact on water resources, there are several agents who have direct and indirect impact on land use decision making process. As the number of agents increase the level of model complexity also increases. It is hypothesised that based on the perception about the environment individual farmers will take actions according to their goals. These actions will also be supplemented with the interactions and communications with other farmers in order to arrive at a decision on land use. The outcome of this land use decision will then be linked to a hydrological model to assess the impact of a given land use scenario on water resources. The closed loop interaction between the environmental factors, the ABM and the hydrological model is expected to contribute to the sustainable use of water resources.

6 CONCLUSION

In the Modder river basin water resource is increasingly becoming one of the critical natural resources (DWAF, 1999). The basin covers an area of about 1.73 million hectares and is divided into three reaches, namely the Upper, Middle and Lower Modder River. Generally the basin is characterised by low and erratic seasonal rainfall, receiving about 537 mm of mean annual rainfall (DWAF, 1999). Due to low rainfall and soil type which is prone to crusting and which enhances water loss by surface runoff, rainfed farmers frequently encounter scarcity of soil-water which results in low crop yields and water productivity. These climatic and environmental factors as well as lack of management skill are believed to be discouraging small-scale farmers from expanding to the crop lands (Botha *et al*., 2003). Since the demand for water and land are closely related to socio-economic development, it is necessary to analyse and model both the physical environment and the human dimension of these processes.

The aim of this project was, therefore, to contribute to the understanding of the dynamics of human-environment interactions and decision making processes for the sustainable use of land and water in the Modder river basin using hydrological and agent-based modelling. The results were presented in four main sections, namely biophysical characteristics, socio-economic drivers of land use change, hydrological modelling, and ABM development.

Biophysical factors

Generally, biophysical factors, such as climate, soil, topography and vegetation are some of the major factors that greatly affect runoff that would be produced from a specific catchment (Peugeot *et al*., 1997; Jain *et al*., 2004). Rainfall and evapotranspiration (ET) are the main components of the climate that have major influence on the water balance of a catchment. The hydrological balance of any river basin is directly and indirectly influenced by the spatial and temporal distribution of land-use and land-cover changes. Changes in land cover can modify crucial hydrological processes, such as evapotranspiration and ground water recharge. High rainfall contributes to increased stream flow while in contrary high ET reduces the amount of overland water considered as blue water (Jewitt *et al*., 2004).

Socio-economic drivers of land use change

Research indicates six possible forces or socio-economic drivers that affect land use change, namely population increase and its level of affluence, technology, political economy, political structure, and attitudes and values (Xie *et al*., 2005). For instance, the impact of population increase on land use change could be due to immediate increase in demand for land for life sustaining needs such as residence space, food and fibre.

The population within the Modder river catchment has grown rapidly in the past decade, especially in and around the city of Bloemfontein and the townships of Botshabelo and Thaba Nchu. This expansion in population has resulted in growth in demand for housing. A significant amount of agricultural land within the vicinity of Bloemfontein, Bosthabelo and Thaba Nchu has thus been converted to residential use in order to help meet the growth in demand for housing. The impacts of this development on the water resources in the Modder catchment include the increase in demand for water for domestic use, but also an increase in run-off from built-up areas. The growth in population and the increased levels of economic activity and the attendant growth in incomes have led to increased demand for food and changes in food consumption patterns. Farmers within the Modder catchment have over the past decade increased production of horticultural products and livestock in order to meet the growing demand for fresh produce and for meat. These production activities tend to be more water intensive and have negative impacts on water quality in the river system.

Hydrological modelling of land use impact

Numerous modelling approaches have been developed to simulate the impact and consequences of land use changes on the environment in general and water resources in particular. One of these models is called Soil and Water Assessment Tool (SWAT). The SWAT model was developed by USDA over a period of 30 years and is used to simulate the impact of land-use change and land management practices on water balance of a catchment. Many research reports witnessed the robustness of the model in simulating satisfactorily most of the water balance components of a catchment. SWAT has also proven to be an effective tool for understanding pollutions by fertilizer applications and point sources (Arnold *et al*., 1998 and Fohrer *et al*., 2005). It also proved its wider environmental application on the globe (Gassman *et al*., 2007).

Taking into account its wider application in assessing the impact of land use changes on water resources, SWAT model was applied in the Modder river basin of Central South Africa to evaluate the impact of land use change on water resources, with particular emphasis on the flow of water into Rustfontein dam. According to the drainage basin classification of South Africa, the Modder river basin falls within the tertiary catchment called C52. This is further divided into quaternary catchments, such as C52A, C52B, etc. Rustfontein dam is located in the upper part of the Modder river basin with a contributing area of 927.6 km^2, which is the area of C52A delineated by ArcSWAT based on the geographic coordinates of the flow gauge at the outlet of the catchment and a digital elevation model (DEM) of C52.

The SWAT hydrological model was used to assess the impact of two possible land use scenarios, in addition to the 1994 and 2000 actual land use data, on the water resources of the quaternary catchment C52A. The 2000 actual land use scenario was used as baseline scenario (PAST) to asses the different water balance components of quaternary catchment C52A against the two new scenarios considered in the study. The two new land use scenarios were (1) Conventional agriculture on lond with 0-3%

slope (Agri-CON) and (2) Agriculture using infield rainwater harvesting on land with 0-3% slope (Agri-IRWH).

The scenario analysis results confirmed that there was improvement of water infiltration into the soil by Agri-IRWH and PAST land uses. Both resulted in higher base flow than Agri-CON land use. Both also demonstrated high deep water percolation with a significant difference ($P < 0.05$) in annual amounts compared to Agri-CON. The Agri-IRWH showed that 105% higher base flow compared to the Agri-CON land use scenario. However, there is no significant water yield difference among the three land use scenarios. The results also revealed that conventional agricultural land use type generated highest direct flow than the ones dominated by pasture or IRWH land use scenarios. This may not support favourable crop production on rainfed semi-arid areas, such as the Modder river basin, due to decreased infiltration of water to the sub-soil which ultimately influences the soil water content within the root zone. However, whether or not the increased direct runoff would be more beneficial if harnessed by small ponds or dams on-site, for use as a supplemental irrigation using the Agri-CON production scenario compared with its use by the downstream communities from the increased stream flow, could be a subject for further study.

Overall, the results suggest that the WY of C52A may not be adversely affected by the Agri-IRWH land use scenario despite its surface runoff abstraction design. It is expected that this result will assist in taking a proactive measure regarding water resources management in general and a strategic allocation and use of water in particular.

Agent based modelling of land use scenario

The agent-based perspective, with regard to land-use cover change, is centred on the general nature and rules of land-use decision making by individuals. In the study of land use changes and its impact on water resources, there are several agents who have direct and indirect impact on land use decision making process. As the number of agents increase the level of model complexity also increases. It is hypothesised that based on the perception about the environment individual farmers will take actions according to their goals. These actions will also be supplemented with the interactions and communications with other farmers in order to arrive at a decision on land use. The outcome of this land use decision will then be linked to a hydrological model to assess the impact of a given land use scenario on water resources. The closed loop interaction between the environmental factors, the ABM and the hydrological model is expected to contribute to the sustainable use of water resources.

However, the implementation of the ABM is not complete in order to enable us to perform the simulations with the ABM at this stage. The major drawback was due to the unreliability of the postgraduate (PG) students who were involved in the development work. The kind of development work in this project requires the participation of PG students who will then use the appropriate tools and methodologies to develop the system under the guidance of supervisors. Two PG students who were involved in this project during the earlier phases of the project abandoned their studies and we had to get a replacement student on two occasions to continue with the development work. One student is currently doing fairly well. However, we plan to complete the ABM development followed by the simulation activities and the validation work later on.

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8 Appendix: Monthly total water balance simulated by SWAT hydrological model

Monthly total water balance based on different land use scenarios as simulated by SWAT hydrological model

YEAR	MONTH	PREC (mm)	Agri-IRWH			Agri-CON			PAST		
			SURQ (mm)	LATQ (mm)	DIRQ (mm)	SURQ (mm)	LATQ (mm)	DIRQ (mm)	SURQ (mm)	LATQ (mm)	GWQ (mm)
1995	1	83.91	0.00	3.74	3.74	1.34	3.70	5.04	0.41	2.11	2.52
	2	52.28	0.00	2.70	2.70	0.01	2.69	2.70	0.00	1.52	1.52
	3	100.34	0.00	5.00	5.00	0.79	4.99	5.78	0.09	2.89	2.98
	4	5.31	0.00	0.68	0.68	0.00	0.68	0.68	0.00	0.64	0.64
	5	41.13	0.00	2.30	2.30	0.61	2.29	2.90	0.16	1.29	1.45
	6	0.00	0.00	0.03	0.03	0.00	0.03	0.03	0.00	0.04	0.04
	7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	9	1.93	0.00	0.03	0.03	0.00	0.03	0.03	0.00	0.03	0.03
	10	76.81	0.00	3.79	3.79	0.23	3.78	4.01	0.01	2.15	2.16
	11	64.99	0.00	3.62	3.62	0.05	3.62	3.67	0.01	2.06	2.07
	12	164.05	0.00	9.18	9.18	13.43	8.45	21.88	9.93	5.51	15.44
1996	1	117.46	0.00	7.01	7.01	6.38	6.51	12.89	3.18	3.76	6.94
	2	213.32	0.00	16.00	16.00	60.80	11.46	72.26	44.83	7.40	52.23
	3	48.59	0.00	9.63	9.63	13.63	6.07	19.70	10.16	5.56	15.72
	4	31.87	0.00	1.78	1.78	0.01	1.76	1.77	0.00	1.05	1.05
	5	11.54	0.00	0.55	0.55	0.00	0.55	0.55	0.00	0.33	0.33
	6	0.70	0.00	0.02	0.02	0.00	0.02	0.02	0.00	0.02	0.02
	7	35.47	0.00	1.55	1.55	0.50	1.55	2.05	0.06	0.82	0.88
	8	10.41	0.00	0.75	0.75	0.00	0.75	0.75	0.00	0.59	0.59
	9	11.74	0.00	0.42	0.42	0.00	0.42	0.42	0.00	0.23	0.23

	10	31.89	0.00	1.70	1.70	0.00	1.70	1.70	0.00	0.91	0.91
	11	159.30	0.00	8.17	8.17	4.60	7.93	12.53	2.95	4.51	7.46
	12	83.20	0.00	3.82	3.82	0.01	3.78	3.79	0.00	2.31	2.31
1997	1	105.35	0.00	7.21	7.21	3.70	6.85	10.55	3.94	4.28	8.22
	2	42.61	0.00	2.16	2.16	0.04	2.06	2.10	0.01	1.30	1.31
	3	106.85	0.00	6.59	6.59	7.32	6.21	13.53	3.83	3.76	7.59
	4	26.70	0.00	2.58	2.58	0.72	2.39	3.11	0.31	2.09	2.40
	5	21.62	0.00	0.88	0.88	0.00	0.88	0.88	0.00	0.47	0.47
	6	25.57	0.00	1.39	1.39	0.26	1.38	1.64	0.03	0.96	0.99
	7	16.18	0.00	0.64	0.64	0.00	0.64	0.64	0.00	0.33	0.33
	8	4.79	0.00	0.28	0.28	0.00	0.28	0.28	0.00	0.20	0.20
	9	1.58	0.00	0.10	0.10	0.00	0.10	0.10	0.00	0.09	0.09
	10	30.97	0.00	1.75	1.75	0.12	1.75	1.87	0.02	0.93	0.95
	11	36.35	0.00	1.43	1.43	0.00	1.43	1.43	0.00	0.69	0.69
	12	34.19	0.00	1.60	1.60	0.01	1.60	1.61	0.00	0.92	0.92
1998	1	139.98	0.00	7.17	7.17	6.62	7.04	13.66	4.23	4.23	8.46
	2	198.68	0.00	14.25	14.25	37.71	10.16	47.87	33.17	6.61	39.78
	3	123.86	0.00	12.14	12.14	33.74	8.62	42.36	30.69	5.90	36.59
	4	14.27	0.00	2.28	2.28	0.02	1.44	1.46	0.00	1.10	1.10
	5	1.41	0.00	0.09	0.09	0.00	0.09	0.09	0.00	0.10	0.10
	6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	7	8.62	0.00	0.33	0.33	0.00	0.33	0.33	0.00	0.18	0.18
	8	0.00	0.00	0.02	0.02	0.00	0.02	0.02	0.00	0.02	0.02
	9	28.84	0.00	1.43	1.43	0.00	1.43	1.43	0.00	0.81	0.81
	10	127.12	0.00	6.13	6.13	7.28	5.90	13.18	4.76	3.63	8.39
	11	87.44	0.00	6.35	6.35	0.98	6.19	7.17	2.27	4.22	6.49
	12	81.29	0.00	4.04	4.04	0.19	4.03	4.22	0.01	2.20	2.21
1999	1	92.83	0.00	5.27	5.27	1.26	5.21	6.47	0.73	3.17	3.90
	2	39.04	0.00	2.08	2.08	0.03	2.08	2.11	0.00	1.16	1.16

	3	42.76	0.00	2.13	2.13	0.02	2.13	2.15	0.00	1.22	1.22
	4	31.86	0.00	1.11	1.11	0.09	1.11	1.20	0.00	0.71	0.71
	5	0.00	0.00	0.43	0.43	0.00	0.43	0.43	0.00	0.41	0.41
	6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	9	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	10	33.08	0.00	1.86	1.86	0.07	1.86	1.93	0.01	0.85	0.86
	11	9.41	0.00	0.46	0.46	0.00	0.46	0.46	0.00	0.26	0.26
	12	184.05	0.00	9.09	9.09	1.84	9.05	10.89	0.75	5.05	5.80
2000	1	120.97	0.00	7.76	7.76	1.62	7.56	9.18	2.44	5.06	7.50
	2	58.29	0.00	2.49	2.49	0.19	2.48	2.67	0.02	1.82	1.84
	3	85.34	0.00	4.30	4.30	3.01	4.12	7.13	0.64	2.64	3.28
	4	53.92	0.00	2.64	2.64	0.63	2.61	3.24	0.26	1.63	1.89
	5	21.65	0.00	2.16	2.16	0.70	2.03	2.73	0.92	1.76	2.68
	6	1.76	0.00	0.03	0.03	0.00	0.03	0.03	0.00	0.03	0.03
	7	0.53	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	8	0.88	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	9	51.41	0.00	2.79	2.79	2.73	2.68	5.41	1.46	1.53	2.99
	10	30.51	0.00	1.28	1.28	0.00	1.28	1.28	0.00	0.79	0.79
	11	93.41	0.00	4.33	4.33	0.87	4.31	5.18	0.19	2.49	2.68
	12	72.68	0.00	4.36	4.36	1.19	4.33	5.52	0.48	2.67	3.15
2001	1	34.30	0.00	1.39	1.39	0.09	1.39	1.48	0.00	0.98	0.98
	2	62.79	0.00	3.25	3.25	0.00	3.24	3.24	0.00	1.69	1.69
	3	118.36	0.00	5.82	5.82	1.01	5.78	6.79	0.32	3.60	3.92
	4	145.74	0.00	12.31	12.31	17.67	10.34	28.01	22.27	7.56	29.83
	5	30.80	0.00	4.87	4.87	7.74	3.74	11.48	5.87	3.44	9.31
	6	22.70	0.00	0.86	0.86	0.00	0.86	0.86	0.00	0.45	0.45
	7	3.16	0.00	0.32	0.32	0.00	0.32	0.32	0.00	0.30	0.30

	8	30.24	0.00	1.04	1.04	0.04	1.04	1.08	0.00	0.41	0.41
	9	19.69	0.00	1.38	1.38	0.00	1.38	1.38	0.00	1.07	1.07
	10	97.58	0.00	5.14	5.14	5.17	4.84	10.01	4.71	2.77	7.48
	11	247.09	3.88	21.57	25.45	54.49	14.41	68.90	80.79	10.67	91.46
	12	121.84	0.00	8.94	8.94	12.11	7.52	19.63	4.88	5.08	9.96
2002	1	100.79	0.00	6.75	6.75	19.81	5.46	25.27	9.27	3.34	12.61
	2	45.53	0.00	3.50	3.50	1.30	2.86	4.16	0.25	1.96	2.21
	3	29.49	0.00	1.98	1.98	0.16	1.95	2.11	0.03	1.22	1.25
	4	30.05	0.00	1.82	1.82	0.00	1.82	1.82	0.00	1.08	1.08
	5	79.73	0.00	3.02	3.02	2.31	2.99	5.30	1.09	1.42	2.51
	6	0.00	0.00	1.33	1.33	0.10	1.28	1.38	0.04	1.19	1.23
	7	0.00	0.00	0.01	0.01	0.00	0.00	0.00	0.00	0.01	0.01
	8	88.55	0.00	4.77	4.77	1.59	4.65	6.24	3.26	2.74	6.00
	9	10.05	0.00	1.60	1.60	0.08	1.45	1.53	0.23	1.36	1.59
	10	33.11	0.00	1.32	1.32	0.00	1.32	1.32	0.00	0.62	0.62
	11	11.81	0.00	0.87	0.87	0.00	0.87	0.87	0.00	0.70	0.70
	12	102.22	0.00	5.29	5.29	1.11	5.26	6.37	0.27	3.03	3.30
2003	1	106.32	0.00	5.97	5.97	8.33	5.50	13.83	6.18	2.74	8.92
	2	39.80	0.00	2.66	2.66	0.00	2.50	2.50	0.00	1.71	1.71
	3	126.66	0.00	7.72	7.72	14.52	6.66	21.18	12.89	4.47	17.36
	4	18.38	0.00	1.43	1.43	0.00	1.33	1.33	0.00	0.96	0.96
	5	18.66	0.00	0.83	0.83	0.00	0.83	0.83	0.00	0.53	0.53
	6	0.00	0.00	0.02	0.02	0.00	0.02	0.02	0.00	0.02	0.02
	7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	8	6.81	0.00	0.35	0.35	0.00	0.35	0.35	0.00	0.17	0.17
	9	29.74	0.00	1.00	1.00	0.00	1.00	1.00	0.00	0.48	0.48
	10	5.51	0.00	0.55	0.55	0.00	0.55	0.55	0.00	0.39	0.39
	11	23.47	0.00	1.02	1.02	0.00	1.02	1.02	0.00	0.60	0.60
	12	50.24	0.00	2.59	2.59	0.57	2.58	3.15	0.12	1.46	1.58

2004	1	20.38	0.00	0.69	0.69	0.11	0.69	0.80	0.00	0.69	0.69
	2	72.87	0.00	3.56	3.56	0.00	3.56	3.56	0.00	1.98	1.98
	3	89.37	0.00	4.60	4.60	0.41	4.59	5.00	0.07	2.58	2.65
	4	46.08	0.00	2.63	2.63	0.13	2.62	2.75	0.01	1.83	1.84
	5	0.35	0.00	0.09	0.09	0.00	0.09	0.09	0.00	0.09	0.09
	6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	8	21.30	0.00	0.95	0.95	0.00	0.95	0.95	0.00	0.49	0.49
	9	46.78	0.00	2.33	2.33	0.07	2.32	2.39	0.00	1.36	1.36
	10	19.20	0.00	1.06	1.06	0.00	1.06	1.06	0.00	0.77	0.77
	11	33.62	0.00	1.23	1.23	0.00	1.23	1.23	0.00	0.61	0.61
	12	53.80	0.00	2.54	2.54	0.00	2.54	2.54	0.00	1.58	1.58
2005	1	92.17	0.00	3.78	3.78	0.62	3.78	4.40	0.04	2.21	2.25
	2	64.66	0.00	3.41	3.41	0.09	3.41	3.50	0.00	2.43	2.43
	3	93.70	0.00	3.94	3.94	0.18	3.94	4.12	0.09	2.33	2.42
	4	48.69	0.00	3.61	3.61	0.29	3.58	3.87	0.18	2.37	2.55
	5	27.57	0.00	1.66	1.66	0.00	1.66	1.66	0.00	0.93	0.93
	6	4.57	0.00	0.15	0.15	0.00	0.15	0.15	0.00	0.15	0.15
	7	0.00	0.00	0.02	0.02	0.00	0.02	0.02	0.00	0.02	0.02
	8	5.42	0.00	0.13	0.13	0.00	0.13	0.13	0.00	0.06	0.06
	9	10.07	0.00	0.47	0.47	0.00	0.47	0.47	0.00	0.26	0.26
	10	62.05	0.00	2.48	2.48	0.00	2.48	2.48	0.00	1.61	1.61
	11	72.91	0.00	2.73	2.73	0.40	2.72	3.12	0.08	1.51	1.59
	12	60.11	0.00	2.85	2.85	0.14	2.84	2.98	0.39	2.43	2.82
2006	1	185.66	0.00	11.28	11.28	20.12	9.73	29.85	20.63	5.98	26.61
	2	167.90	0.00	16.49	16.49	26.39	13.15	39.54	22.52	9.89	32.41
	3	162.26	0.00	14.72	14.72	35.38	11.49	46.87	29.75	8.66	38.41
	4	81.00	0.00	8.63	8.63	14.16	6.49	20.65	11.54	5.54	17.08
	5	12.46	0.00	0.99	0.99	0.01	0.85	0.86	0.00	0.76	0.76

	6	0.00	0.00	0.01	0.01	0.00	0.01	0.01	0.00	0.01	0.01
	7	9.13	0.00	0.05	0.05	0.02	0.05	0.07	0.00	0.05	0.05
	8	88.62	0.00	6.04	6.04	4.13	5.49	9.62	8.63	3.65	12.28
	9	0.88	0.00	0.56	0.56	0.00	0.45	0.45	0.00	0.56	0.56
	10	61.56	0.00	1.91	1.91	2.60	1.84	4.44	3.10	1.31	4.41
	11	83.75	0.00	7.14	7.14	8.96	6.05	15.01	8.53	4.45	12.98
	12	57.54	0.00	2.60	2.60	0.53	2.58	3.11	0.12	1.58	1.70
2007	1	24.39	0.00	1.02	1.02	0.00	1.01	1.01	0.00	0.75	0.75
	2	4.39	0.00	0.07	0.07	0.00	0.07	0.07	0.00	0.07	0.07
	3	28.70	0.00	1.10	1.10	0.00	1.10	1.10	0.00	0.73	0.73
	4	45.69	0.00	2.37	2.37	0.00	2.37	2.37	0.00	1.39	1.39
	5	1.41	0.00	0.07	0.07	0.00	0.07	0.07	0.00	0.07	0.07
	6	24.73	0.00	1.24	1.24	0.01	1.24	1.25	0.00	0.75	0.75
	7	4.00	0.00	0.08	0.08	0.00	0.08	0.08	0.00	0.05	0.05
	8	1.05	0.00	0.02	0.02	0.00	0.02	0.02	0.00	0.03	0.03
	9	39.95	0.00	1.58	1.58	0.52	1.57	2.09	0.12	0.67	0.79
	10	56.23	0.00	3.06	3.06	0.00	3.05	3.05	0.00	2.08	2.08
	11	108.95	0.00	4.07	4.07	6.19	3.91	10.10	3.87	1.95	5.82
	12	56.65	0.00	4.15	4.15	0.26	4.00	4.26	0.11	2.91	3.02
SUM			**3.88**	**475.3**	**479.2**	**485.3**	**425.9**	**911.2**	**425.2**	**276.4**	**701.6**