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Evaluating the role of market based policy instruments in managing trade-offs between ecosystem services supply and human welfare: case of Uluguru water catchment, Tanzania

By

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Submitted in partial fulfilment of the requirements for the degree of

Doctor of Philosophy (PhD): Environmental Economics

In the
Department of Agriculture Economics, Extension and Rural Development
Faculty of Natural and Agricultural Sciences
University of Pretoria

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May, 2017

Dedication

To my sons, Nelson and Nixon, daughter, Grace, and wife, Tumaini.

Declaration

I declare that this thesis submitted for the degree of Doctor of Philosophy in Environmental Economics at the University of Pretoria is my own work and has not been submitted anywhere else for the award of a degree or otherwise.

Parts of the thesis have been published in ecological economic journal.

Any errors in thinking and omissions are entirely my own responsibility.

Signed…………………………… Date………………………
Name: Gody Jonathan Sanga

Month……………

Acknowledgements

I would like to express my gratitude to numerous institutions and individuals that have helped me in the course of writing this thesis. My first inspiration in the field of environmental economics came from Professor Joseph Hella, who was from the Agriculture Economics and Agribusiness Department, Postgraduate coordinator and my Master's Degree supervisor at Sokoine University of Agriculture in Tanzania. He linked me with the Centre for Environmental Economics and Policy for Africa (CEEPA) for the first time in 2005. For this, I would like to say *Akhsante Sana* Prof. Hella.

I joined PhD programme in 2008, thanks to Professor Hella and Dr Kilima, who wrote excellent recommendation letters that helped me make my way to the University of Pretoria. Since then, I have been receiving continuous support and encouragement from Dr Eric D. Mungatana, Professor Rashid Hassan, Dr Wellington Jogo, Professor Christern, Professor Greg Hetzelar and other staff members of the Department of Agriculture Economics, Extension and Rural Development of the University of Pretoria and visiting Professors. These not only were my colleagues, but also they introduced me to the field of resource and environmental economics.

My supervisor, Dr Eric Dada Mungatana, deserves special thanks for his untiring support throughout my PhD programme. I acknowledge his high intellectual guidance and patience throughout the course of this work. His valuable comments and suggestions have shaped me to who I am today and this work to what it is. I received unfailing contributions and support, guidance and moral boosts from him since I started this journey at the University of Pretoria. I cannot thank you enough, Dr Mungatana, but I am looking forward to working with you in the future. I also received numerous comments, suggestions and moral support from Dr Hawasi, Dr Albino Tenge, Dr Adam Mwakalobo, Professor Abiud Kaswamila and Professor Joseph Hella especially on the paper submitted for publication from this work. To all of you, I say thank you very much.

The environmental economics unit of the University of Pretoria is a wonderful family that I am proud to have belonged to. I thank all of my friends in the PhD room who have been and will continue to be part of this great force in natural resource and environmental economics in Africa and the world at large. I benefited a lot from individual and group discussions in the PhD room, coffee/tea breaks, lunch meetings and seminars. My fellow friends with whom I enjoyed the first year of course work are: Mr Abbas Taloddi Magbul, Dr Mulatu, Dr Sikweni Dyadibha, Dr Mariam Mapila, and Mr Jingulula. Other members in the unit that I feel connected to and received support from over the last 3 years include Ms Chilot Hewort, and Dr Jethro Zwarime. I thank you all for your moral support throughout this work.

My fieldwork would not have been possible without enormous support from WWF and CARE International Morogoro office. The group consisted of charming, hard-working people who made the difficult task of travelling hundreds of kilometres in the Uluguru water catchment area and mobilising hundreds of people so much easier. Special thanks go to Mr Deustatus Lopa, the EPWS project manager, and his team mates Mr Masoro, Ms Aqulina Wamba and the driver, Mr Bakari. I am also grateful to Uluguru water catchment village leaders, agricultural officers and farmers who responded well to my questions. Special thanks go to Mr Banzi and his colleague for providing us with the logistical support throughout the fieldwork.

I would like to thank Mr Mwaluko Mpangwa, Mr Rajabu Msangi, Mr Arbogats Moshi, and Ms Gladness Thomas for assisting me during fieldwork. I thank Dr Hepelwa for reviewing the thesis. In a special way, I also thank Ms Zakia Bakari for the kind of support and comfort she offered my family throughout this work. My two little boys and daughter, who are very naughty and inquisitive, were always taken care of by this young lady who dedicated her time to assist my wife to raise him. For her I say, *Akhsante Sana* Zakia.

My study at the University of Pretoria offered me an opportunity to meet my fellow countrymen: Mr Mbawala, Dr Kitundu, Mr Mayson Rwangisa, and Dr Chacha. Our life together was full of joy, encouragement and support; I enjoyed their company. To all of them, I say *Akhsanteni Sana*.

In the course of writing this thesis, I lost three very important persons who bestowed their love for education upon me and resulted in my reaching this level. My grandmother, Matha M. Vilumba, uncle Jackson M. Mwikombe and brother Romanus

Mwikombe, who passed away when I was in the middle of this journey. May the Almighty God place their souls in eternal peace. I would like to thank my brothers and sisters: Mbodile W. Mwikombe, Frinday W. Mwikombe, Albert W. Sanga, Godrey J. Mwikombe, Neema J. Mwikombe and other members of my extended family for their tireless support and love. I would like express my special thanks to my parents, Mr Jonathan Mwikombe and Mrs Paulina M. Mwikombe, who initiated this journey when I was 11 years old. Last but not least, I would like to express my heartfelt thanks and love to my best friend and wife, Tumaini Jongo Sanga, for her great patience, love and support. She played the dual role of father and mother to our sons, Nelson and Nixon Mwikombe Sanga, who were born while I was still on the journey. As for Nelson and Nixon, I can only hope that one day they will understand why I was always on the move, coming home late at night and having time for the computer and not them when I was at home.

Finally, I cannot forget to express my gratitude to the people and institutions that made this study possible. First and foremost, I want to thank my first employer, the University of Dodoma (UDOM), for granting me three years' study leave that facilitated the early stages of this study and financial support for fieldwork and data analysis. I would like to thank CEEPA for funding my study at the University of Pretoria. I wish to thank Professor Rashid Hassan, the director of CEEPA, and Dalene Duplensis, the coordinator of CEEPA, for making my life so smooth all the time in South Africa and outside.

As with every other achievement in my life, I owe this to the Almighty God, without whom this work would never have been realised. Despite all the help I have received throughout the years, any mistakes or errors that remain in this work are entirely mine.

Abstract

This study uses the Uluguru water catchments in Tanzania to assess whether market-based policy instruments can secure internalisation of externalities in such complex socio-economic-ecological systems which are not only characterised by uncertain long-term responses to perturbations, but also intense competition between upstream and downstream beneficiaries for their limited ecosystem services.

Although several studies have shown that market-based policy instruments perform better than their command and control counterparts in a variety of socio-economic-ecological configurations, their relevance to the management of water catchments raises some concerns. First, although there is general consensus that such instruments exploit the potential of upstream landholders and downstream ecosystem services beneficiaries to achieve catchment-wide conservation goals without compromising the welfare of the former, the robustness of this conclusion is questionable. Second, the literature also acknowledges the unpredictable long-term benefit flows from managing water catchments, their inequitable distribution, and the divergence between private and social objectives facing upstream decision makers as a major challenge to the long-term sustainability of using market-based policy instruments to manage water catchments.

This research was thus designed to answer the following questions on the relevance of market-based policy instruments in securing management of water catchments: (1) is it necessarily true that market-based policy instruments can secure catchment-wide conservation without compromising the welfare of upstream decision makers? (2) Can market-based policy instruments address the incentive incompatibility faced by individual upstream decision makers? (3) Can market-based policy instruments simultaneously provide sufficient ecological, hydrological, and private economic and benefits to make them acceptable to private land users and other decision makers? (4) Which policy and economic scenarios are important in ensuring that they provide equitable long-term benefit flows?

A system dynamics framework was used to develop an integrated ecological economic model to evaluate the long-term response of the Uluguru catchment to five management regimes hypothesised to internalise upstream land use externalities: (1) taxing crop output and inputs, (2) tax cuts on inputs used in fruit production, (3) tax cuts on basic domestic goods (i.e. sugar, salt, soap, kerosene, maize and wheat flour), (4) enhancing economic growth, and (5) compensating upstream land decision makers who adopt fruit tree production on land left to fallow through payment for ecosystem services (PES) arrangement. The framework was also used to assess the distribution of benefits between upstream decision makers and downstream ecosystem services beneficiaries. Data were collected from Uluguru water catchment upstream land users, the Bank of Tanzania, Dar-es-Salaam Water and Sewage Company (DAWASCO), Ruvu Basin Water Office, and CARE International between January and December 2011.

An integrated ecological economic model was selected based on its ability to link different components that build the system into a single model that simplifies system response to exogenous factor analysis. Systems are made of elements which are tightly interwoven into one system with direct interactions and feedbacks between them. To quantify the effect of interactions and feedbacks, both biophysical and economic data are used and the model built in STELA software links all the elements through equations generated from biophysical and economic data. The linked series of equations quantify the behavioural response of complex systems upon interaction with other systems over time, a feature which gives the model the ability to predict the future state (or response) of the systems under a given management or treatment option.

Simulation results indicate that although taxing crop output will reduce the area converted to crop cultivation and increase the area planted with fruit trees on land left to fallow, the policy will skew the distribution of benefits in favour of downstream ecosystem services beneficiaries in the long run. It will reduce income accrued to upstream land holders by 26.35%; 68.48% and 11.26%; 70.64%, and the cost of producing portable water for domestic use by 18% and 0.66% when the tax is applied to banana and paddy outputs, respectively. But the policy will have different effects on the total social welfare; it will increase per capita income to both by 4.41 % and lower it by 0.57 % when the tax is applied to banana and paddy outputs, respectively

A tax cut on inputs to fruit tree production will have double dividends in the long run: it will improve the quality of water flowing downstream by reducing the sediment load by 13.21 % and by increasing social welfare measured as income per capita by 3.22 %.

This is because such reduced sediment load will reduce the cost of producing portable water downstream by 4.33%. This is because tax cut on inputs will encourage investment in fruit production; hence expansion of area under fruit production and increased fruit production will increase income. The increased income from fruit production plus the reduced cost of producing portable water downstream will give a positive social welfare accrued to both upstream and downstream communities.

Negative social welfare is obtained when taxes are applied to crop input and out prices despite the reduced sediment load and costs of producing portable water downstream. Results indicate that social welfare measured as income per capita will decrease by 2.46% and 3.44% when banana and paddy inputs, and 0.11% and 1.81% when banana and paddy outputs are taxed respectively. This is because the income accrued from increased production of fruits and reduced costs of producing portable downstream will not be enough to cover the loss from the reduced production of the two crops. This indicates how important are the two crops to upstream land holders and the effect of the policy on the total social welfare.

Tax cut on domestic goods not only decreases sediment load and cost of producing portable water for domestic use by 49.09 % and 12.67% respectively, but also increases the social welfare measured as income per capita by 4.88 %. This indicates that the policy will induce equitable distribution of benefits to both upstream land holders and downstream ecosystem services beneficiaries. This could be attributed to the fact that nearly 70 % of rural household income is spent on food and other domestic goods, and cutting down the tax to them will reduce the need for income to spend on domestic good, hence cutting down catchment detrimental economic activities such as crop production and expansion of environmentally friendly land use practices such as fruit production. Such shift in land use results in reduction of sediment load, hence reducing the cost of producing portable water for domestic use.

Improving economic growth by 7 % decreases sediment load by 4.56 %, cost of producing portable water by 2.95% and increases social welfare measured as income per capita by 1.62 % in the long run, meaning that it favours both upstream and downstream beneficiaries.

Subsidising inputs to fruit tree production through downstream upstream markets (PES) achieves the goal of reducing sediment load in water flowing downstream without compromising the well-being of upstream landholders and that of downstream ecosystem services users in the long run. In the long run, the policy will induce a decrease in the total area converted to crop production by 2.02 % per annum, and an increase in the total area left to fallow planted fruit trees and natural vegetation by 26.62 % and 0.8 % per annum, respectively. Such a trade-off in land use will decrease sediment load by 5.24 % and cost of producing portable water for domestic use by 3.33% per annum. Such induced shift in land use will improve the total social welfare measured as income per capita by 1.49 % per annum, respectively.

Change in climatic conditions also will induce land use shift in the long run; a 10% decrease in rainfall will induces a decrease in the total area converted to crop production by 36.42 % and area planted with fruit trees by 48.36 % per annum respectively. It will induce an increase in the total area left for natural vegetation to occupy by 57.62 % per annum. The overall impact of these trade-offs is to decrease the sediment load by 15.16 % and cost of producing portable water for domestic use downstream by 5.31% per annum. However, this shift in land use will not improve the social welfare to both upstream land holder and downstream ecosystem beneficiaries because the volume of water flowing downstream will decrease reducing the social welfare measured as income per capita by 1.2 % per annum.

These results demonstrate the potential for securing catchment conservation goals (i.e. reducing sediment load in the streams and rivers draining the water catchment) using taxes on crop inputs and outputs, tax cuts on inputs to fruit production, tax cuts on basic domestic goods to catchment dwellers, and downstream-upstream compensation schemes. The results also show the differential impacts of these policies on benefits distribution. Tax cuts, subsidies and economic growth achieve internalisation of land use externalities without skewing the distribution of benefits, suggesting they are likely to be sustainable in the long run. Taxing crop inputs and outputs achieves conservation goals at the expense of upstream landholders, making them amenable to rejection by upstream decision makers. The two approaches lower the social welfare in the long run something which engender rejection by policy markers.

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List of Acronyms and Abbreviations

BMP	Best Management Practice
BOD	Biochemical Oxygen Demand
BOT	Bank of Tanzania
CARE	Cooperative for American Remittances to Europe
COD	Chemical Oxygen Demand
CPI	Consumer Price index
DAWASCO	Dar-es-salaam Water and Sewerage Corporation
EAMCEF	Eastern Arc Mountains Conservation Endowment Fund
EPWS	Equitable Payment for Water Services
FBD	Forest and Beekeeping Division
FWG	Forest Working Group
GDP	Gross Domestic Product
GIS	Geographic Information System
LRDC	Land Resources Development Centre
MEA	Millennium Ecosystem Assessment
MNRT	Ministry of Natural Resources and Tourism
MoA	Ministry of Agriculture
MoW	Ministry of Water
MORUWASA	Morogoro Urban Water Supply and Sanitation Authority
NBS	National Bureau of Statistics
PCA	Principal Component Analysis
PES	Payment for Ecosystem Services
SUR	Seemingly Unrelated Regression
TAFORI	Tanzania Forestry Research Institute
TEEB	The Economics of Ecosystems and Biodiversity
TZS	Tanzania Shilling
ULUS	Uluguru Land Usage Scheme
UMBCP	Uluguru Mountains Biodiversity Conservation Project
UNEP	United Nations Environmental Program
URT	United Republic Tanzania
USA	United States of America
USA-NAS	United Sates of America-National Academic Science
USD	United State Dollar
WA	Water Atlas
WUA	Water User Association
WCST	Wildlife Conservation Society of Tanzania
WEO	Ward Executive Officer
WRBO	Wami/Ruvu Basin Office
WWF	World Wildlife Fund

CHAPTER 1

INTRODUCTION

1.1. Background to the problem

The decline in the quality and quantity of ecosystem services that society derives from the management of water catchments is of growing global concern (TEEB, 2010; Ortega-Pacheco *et al*., 2009; Costanza *et al*., 2002). Water catchments play a significant role in the livelihoods of communities living upstream and downstream. Their ability to retain water during wet seasons and release it slowly downstream provides farmers living in the catchment and downstream opportunities to grow crops throughout year (Boyd & Banzhaf, 2007). Besides crop production, water catchments provide other ecosystem services such as livestock grazing, water for irrigation, water supply for domestic and industrial use, fishing and landscape for recreation, which support human wellbeing (Lele, 2009).

Despite their demonstrated importance, water catchments continue to be plagued by problems such as water pollution, habitat destruction, intensive water abstraction, increased sedimentation in rivers draining them, changes in water flows, inadequate socio-environmental flows, land degradation, inefficient water allocation, and conflicts between water users (UNEP, 2007). For example, the Millennium Ecosystem Assessment (MEA) reports that nearly 50 per cent of water catchments worldwide deteriorated during the twentieth century and the rate of deterioration is increasing in developing countries (MEA, 2005). Overall results from the literature indicate that patterns of demographic, social and economic change generate intensive and extensive exploitation of ecosystems for production of consumption goods (Dasgupta, 2008). This problem is more profound in developing countries where people are confronted with poverty and food insecurity. In such countries, exploitation of ecosystems is characterised by high rates and low investment in internalisation of externalities (Skoufias, 2012; Swallow *et al*., 2009). The overall result of this situation is the alteration of the long-term capacity of ecosystems to provide provisioning, regulating, supporting and cultural ecosystem services at levels that can sustain current and future welfare.

Water catchments are extremely complex and dynamic systems which make the prediction of their response to human exploitation (perturbations) of ecosystem services delivery and distribution unpredictable (Kremen, 2005). The ecosystems services they supply result from interactions of interconnected components linked by complex stabilising and reinforcing feedback loops, which determine the pattern and pace of system functioning, response and resilience to external stresses (Margolis & Naevdal, 2008; Wagener *et al*., 2007). Apart from the system interaction complexity limitations, divergence in the incentives faced by individual decision makers (upstream landholders) present another limitation to the prediction of response. According to van Noordwijk *et al*. (2004), there is some divergence between what is privately and socially optimal among upstream landholders.

To slow down the harm done on such extremely complex ecosystems, scientists have been testing models that base their management on integrating ecological knowledge with economics (Costanza *et al*., 2002). The argument here is that currently, policies for the management of such systems are crafted with little attention being paid to their multi-scale impacts on ecological, hydrological and economic welfare (Voinov *et al*., 1999; Bockstael *et al*., 1995). Scientists have also proposed using economically viable mechanisms for internalisation of externalities to hurdle the chronic poverty and food security constraints facing the majority of poor and resource-constrained developing country land users (Molua, 2005). The literature argues that such mechanisms have the potential to produce both private and social benefits, and by so doing, address the survival needs of poor upstream land users, while concurrently producing public goods which addresses the externality effects downstream. Partly as result of these insights, in recent years there has been an increase in research interest and activity among economists and ecologists on integrating knowledge about ecosystems and economics in deriving policies for managing complex ecosystems and landscapes, and in using economically viable ecosystem management practices for internalisation of externalities (see Meadows, 2008; Polasky *et al*., 2005; Costanza *et al*., 2002; Robles-Diaz-de-Leon and Nava-Tudela, 1998).

Equally, attention has recently begun to be given to market-based incentives to complement the traditional command and control policy instruments in the management of water catchments (Pagiola, 2008; Claassen *et al*., 2008). The argument here is that the latter instruments, acting on their own, have not been sufficient to address the problems facing the management of water catchments (Dobbs & Pretty, 2008). In particular, command and control instruments said to have not been able to exploited the potential of upstream landholders and downstream ecosystem services beneficiaries in achieving conservation goals (Engel *et al.*, 2008; Pagiola *et al.*, 2005). The literature argues that establishing a market link between upstream landholders and downstream beneficiaries will motivate upstream landholders to take into account the effects of their actions when making decisions about their own land use (Muñoz-Piña *et al.*, 2008). The market-based approach is also considered ideal in developing countries contexts, given its potential to address the survival needs of upstream landholders, who are relatively poorer than downstream ecosystem services users, by covering their economic loss/costs incurred (Pagiola, 2008). Equally important, the literature argues that price (market) based (taxation) instruments can induce behavioural change among upstream land users by rewarding those who practise sustainable land use practices and reducing the share of the market price of products produced from destructive land use practices (TEEB, 2010).

Despite the convincing arguments put forward for basing the management of extremely complex systems like water catchments on economically viable mechanisms and market based instruments, some key empirical questions relating to the policy relevance of this approach in water catchments management remain unresolved: is it necessarily true that they can simultaneously exploit the potential of upstream land holders and downstream ecosystem services users in achieving internalization of externalities without compromising their benefits, given that water catchments are extremely complex with unpredictable dynamic responses to interventions? Will they address the challenges facing the management of water catchments, given the existence of divergence in the incentives faced by the individual decision maker? Can they simultaneously provide sufficient ecological, hydrological, private and social economic benefits to make them acceptable to private land users and other decision makers? Is it necessarily true that PES for farmers to practice fruit tree production as a way of internalising land use externalities will be relatively better than other approaches that can be used to achieve the same with fruit tree production?

1.2. The uluguru water catchment: are there land use externalities to be internalized?

The Uluguru water catchment presents a compelling case for an empirical analysis of the long-term economics, hydrological, and ecological response of the catchment system to PES and other comparative management interventions. The catchment is extremely important, given the critical role it plays in the supply of ecosystem services to the 151 000 residents in the catchment and nearly 6 million others living downstream in Dar-es-Salaam, Coastal and Morogoro cities(Yanda & Munishi, 2007; Hartley & Kaare, 2001). It supports the production of temperate vegetables and fruits (cabbages, carrots, peas, beans, potatoes, leeks, plums and peaches) in the high altitude areas (Hymas, 2001). Water from the catchment supports both small- and large-scale irrigation in the flood plains of the Uluguru Mountain where nearly 2 400 hectares of rice and vegetable fields are irrigated (Nnunduma, 2005). It plays a regulatory role in that its canopy cover reduces runoff and by so doing controls soil erosion, sediment discharge to streams and rivers, and flooding downstream. The catchment is also a major biodiversity reserve, hosting the Tanzania–Malawi endemic bird species, as well as primate species which include the black and white colobus monkey, which attracts visitors and researchers from all over the world (Doggart *et al*., 2005).

Considering the catchment's remarkable biodiversity value, the effect of upstream land use externalities to downstream ecosystem users and the economic role it plays in the economy of Tanzania, efforts to conserve it can be traced back to the colonial period. For example in 1909, measures were enacted which aimed at ending shifting cultivation in the catchment by demarcating it into areas reserved for conservation and areas reserved for agriculture use, and in 1945 the Uluguru Land Usage Scheme was enacted which introduced sustainable land use practices like bench terraces and tree planting (Temple, 1972). However, these interventions failed to slow down catchment degradation, as evidenced by the increase in cultivated area from 7 to 32 per cent, with a concomitant decline in areas under natural forests, open woodland and bush land from 8 to 6 per cent, 40 to 20 per cent, and 23 to 11 per cent, respectively, between1960 and 2010 (Yanda & Munishi, 2007). The most recent statistics show that land use in the catchment consist of the following major types: crop cultivation, natural forests, open woodland, and bush land (PREM, 2006).

Such a change in land cover affected communities living in the catchment differently economically, and the quality of ecosystem services flowing downstream (Table 1). For example, the level of sediment load in the main Ruvu River has increased from 0.13 tons per m^3 to 0.4 tons per m^3 between 2005 and 2011 (Table 1). Basing on turbidity trends and projections of population growth in the catchment and economic growth in Tanzania indicate increase in turbidity between 1.5% and 3% annually (figure 1). The cropping pattern has changed significantly with some crops dominating the others. Data for the 2010/2011 cropping season indicates that 40 per cent of the cultivated area was under banana, followed by paddy at 24.5 per cent, fruit trees at 15.3 per cent and cassava at 11.7 per cent, making these the major cash and food crops (CARE and WWF, 2010).

Table 1: State of the catchment area cover, private benefits, downstream cost of cleaning water, and the net welfare before interventions

Selected indicators for analysis	Current state
Area covered by paddy (ha)	5663.00
Area covered by banana (ha)	4187.00
Area covered by orange (ha)	251.00
Area covered by mango (ha)	24.00
Area covered by natural vegetation (ha)	10366.00
Net income from paddy crop (TZS in millions)	27534.00
Net income from banana crop (TZS in millions)	79819.12
Net income from orange fruit production (TZS in millions)	1906070.00
Net income from mango fruit production (TZS in millions)	1319230.00
Sediment loads in Ruvu river (in tons/m3)	0.45
Total cost of producing portable water downstream (TZS/m3)	35.248
Net benefit (TZS in millions)	254036.00

Source: CARE baseline survey and Eastern Arc Mountains Conservation Endowment Fund (EAMCEF) (2011).

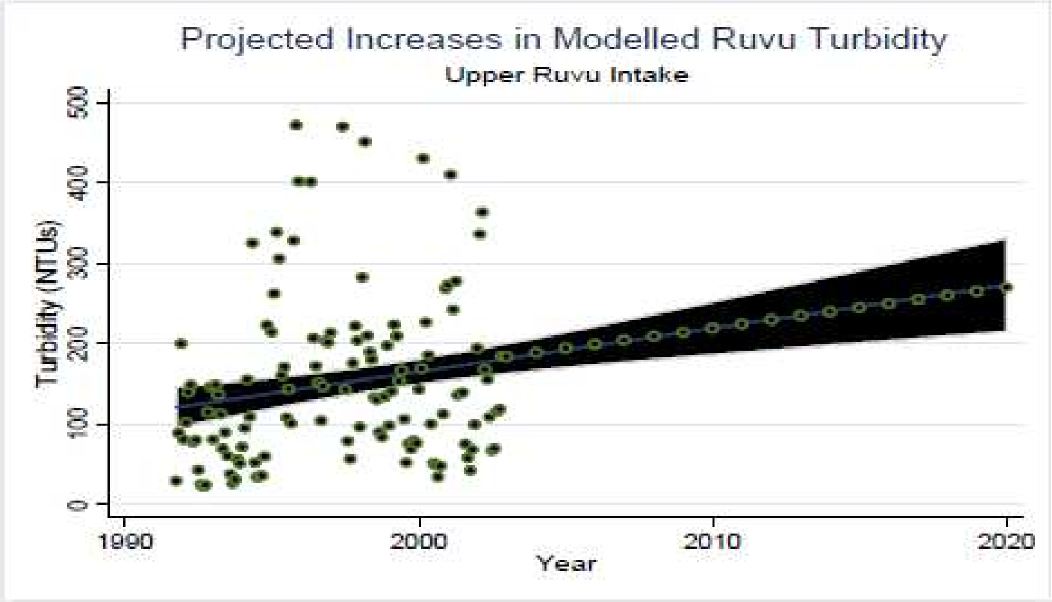

Figure 1.1: Projected increase in turbidity in Ruvu river measured at upper Ruvu intake by year 2020 (Source: CARE & WWF, 2010).

Such increase in turbidity due increase in sediment load has caused streams and rivers draining the catchment to change their courses during rainy season, which has increased flooding downstream that destroys irrigation structures every year (CARE & WWF, 2010). It is estimated that irrigation structures destroyed by flood in Ruvu river basin to cost around 800,000USD every year (Yanda & Munishi, 2007). Equally important, sediment loading also increases the cost of producing potable water for domestic use downstream; the projections of water treatment costs indicate that water treatment costs increases by 0.3% annually (figure 2).

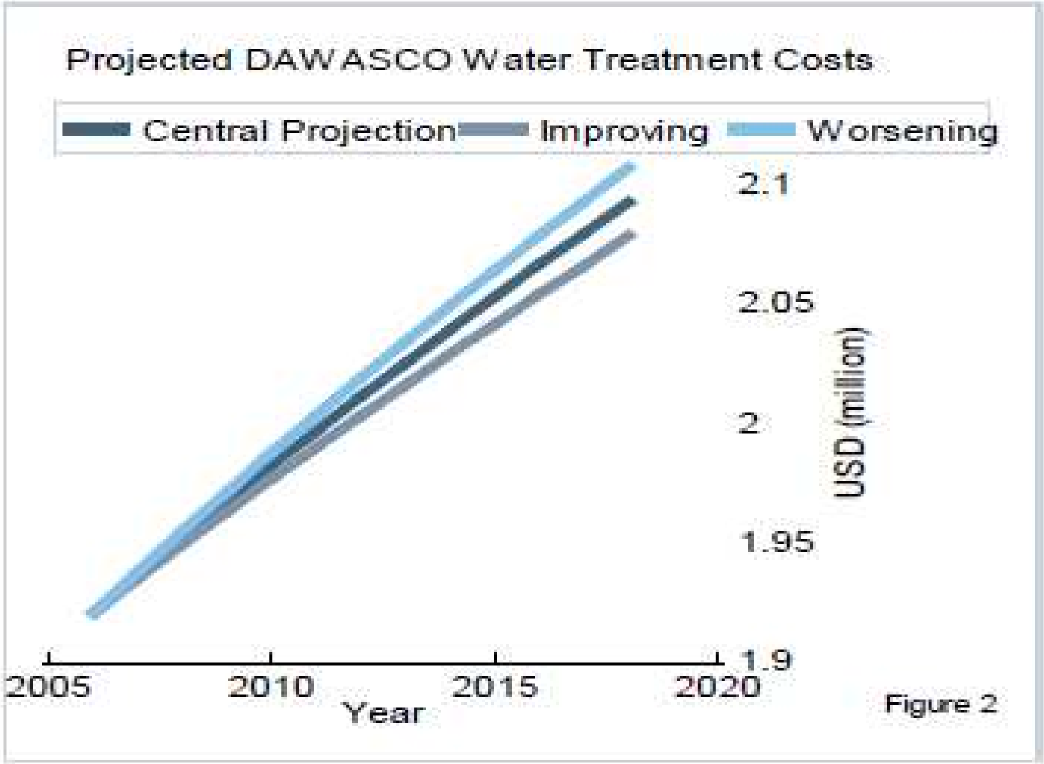

Figure 1.2: Projected trend of water treatment costs from Ruvu river (Source: Dar-es-Salaam Water Supply Company (DAWASCO))

A number of studies attribute the root cause of catchment deterioration to land use choices made by upstream landholders (Hess *et al*., 2008; Hymas, 2001). In the Uluguru water catchment, upstream land use is characterised by abandoning land parcels which are declining in agricultural productivity in favour of clearing natural vegetation cover, with disastrous consequences on downstream ecosystem services supply (Yanda & Munishi, 2007). The abandoned land is left to fallow until it becomes productive again. To address the effect of catchment deterioration on ecosystem services supply, CARE, WWF and the Wildlife Conservation Society of Tanzania initiated a series of interventions, beginning in 2006, with the key objective of motivating behavioural change among upstream landholders.

However, these initiatives are threatened by lack of information on the long-term economic, hydrological, and ecological response of the catchment and its effects on upstream and downstream socio-economic objectives as well as quality of ecosystem services flowing downstream. To enhance the efforts made by these organisations and government, this study developed an integrated ecological economic model and subsequently applied it to simulate the economic, hydrological, and ecological response of various interwoven components of the catchment to PES and other comparative policy regimes. The model was also used to simulate the long-term effect of these policy regimes on certain important socio-economic objectives of upstream landholders and downstream ecosystem services users over time. The information derived from this model is meant to inform upstream landholders, downstream ecosystem services users, policy makers, and social development planners on the long-term effects of PES to farmers practicing fruit tree production in comparison to other policy regimes in securing upstream land use externalities internalisation.

1.3. Objectives of the study

(i) To establish the physical and economic impacts of upstream land use externalities to downstream water users.

(ii) To construct an integrated ecological-economic model and subsequently use it to evaluate the long-term impacts of fruits trees on ecological, hydrological, private economic and social welfare.

(iii) To identify the land use trade-offs involved between fruit trees, natural vegetation and crop production in water catchments when fruit trees planting in abandoned farm plots is employed to internalise land use externalities.

(iv) To verify if fruit tree planting under PES scheme will be Pareto optimal to both parties involved compared to other management regime.

1.4. Hypotheses

The study tested the null hypothesis:

H_1: “Market Based Policy Instruments and Economically Viable Land Use Practice cannot achieve Land Use Externalities Internalization in complex Water Catchment systems that face conflicting incentives without compromising private and social welfare”

1.5. Contribution of the study

This study has made three important contributions; (1) as a concept, (2) providing policy implications from empirical results, and (3) providing a methodology. Conceptually, the study developed and implemented an integrated model which integrates ecological, hydrological and economic components of the water catchment upland farming system (including the relevant feedbacks). In our view, this will enhance our understanding on how agriculture can be intensified while at the same time providing environmental services, which count as a contribution to sustainable agriculture in the water catchments. Empirically, this is the first study of its kind in this specific catchment, the results of which have policy importance for sustainably managing the catchment. To the best of the author's knowledge, there is no integrated study that has been implemented in this catchment before. Also, by investing in this study, some new results and parameters have been estimated, which at minimum are unique to this catchment, but which also have potential applications for other catchments in Tanzania. Methodologically, the study has estimated the different parameters required to make the model work for this catchment.

1.6. Approaches of the study

This study employed an integrated approach, based on the system dynamics framework. This framework allows for linkage between the elements of complex systems that are tightly interwoven into one system, with direct linkages and feedbacks between them. The framework captures the inter-temporal effects of system components interactions. The model was developed and subsequently employed to identify policy and economic scenarios that are needed to ensure sustainability of fruit tree buffer strips in managing water catchments.

1.7. Organisation of the thesis

The rest of this thesis is organised as follows. Chapter 2 highlights the definition of water catchments and difficulties in defining them. It further presents an overview of the Uluguru water catchment, its ecological, hydrological and economic importance, the deterioration of the catchment, its impacts to downstream users, and efforts to combat the deterioration. Chapter 3 presents a review of the concept of ecosystems, water catchments as ecosystem providers, economically viable management practices and their linkage with human well-being. Chapter 4 reviews the literature on the concept of ecological-economic modelling. Chapter 5 presents the conceptual framework and general methodology of the study. Chapter 6 presents the results from the analysis and detailed discussion. A summary of key findings and policy implications, conclusions of the results and areas for further research are presented in Chapter 7.

CHAPTER 2

AN OVERVIEW OF THE ULUGURU WATER CATCHMENTS

2.1. Introduction

This chapter begins by defining water catchment. It further describes the Uluguru water catchment by providing details of the geographical location, topography, vegetation and hydrological distribution. It follows by providing a detailed view of the ecological, hydrological and economic importance of the water catchment. The chapter also provides a detailed review of the current state of the catchment deterioration, its impact on downstream users of ecosystems from the catchment, and efforts to combat the deterioration. The chapter ends with a conclusion on the matters raised in the chapter.

2.2. Definition of water catchment

Defining water catchment has always been difficult in all sciences related to the natural world (Harte, 2002). The difficulties in defining water catchments arises partly from our inability to 'see' the subsurface of a catchment, in which much of the hydrologic processes remains hidden from our current measurement techniques (Beven, 2000). This is due to the fact that the water catchments are self-organised systems, whose form, drainage network, ground and channel slopes, channel hydraulic geometries, soils, and vegetation, are all a result of adaptive ecological, geomorphic, and land-forming processes (Sivapalan, 2005). These difficulties have resulted in different definitions of the term water catchment. For example, the Department of Environmental Protection of New Jersey, USA, defines a water catchment as an area of land, separated from others by high points that are either hills or mountains, that drain into a body of water such as a river, lake, stream or bay (Wagener *et al.*, 2007). It includes not only the waterway itself but also the entire land area that drains into a water body (Wagener *et al.*, 2004).

The Watershed Atlas (WA) defines water catchment as a basin-like landform defined by highpoints and ridgelines that descend into lower elevations or stream valleys (WA, 2012). The landform carries the water "shed" from these lands after rain falls and snow melts, and channels it either as surface water (mainly streams), groundwater, and creeks making its way to larger rivers and eventually the sea (OECD, 2005).

Water catchments have also been defined in many ways by hydrologists. For example, Sivapalan (2005) defines a water catchment as the drainage area that contributes water to a particular point along a channel network (or a depression), based on its surface topography. Wagener *et al* (2004) define water catchment as a landscape element that integrates all aspects of the hydrologic cycle within a defined area that can be studied, quantified, and acted upon. Dooge (2003) also defines water catchments as typically open systems (complex environmental systems with some degree of organisation) of fluxes of water (both input and output) and other quantities.

In Tanzania, a water catchment is defined as an area of land, separated by ridges and hills, which drain all the streams and rainwater to a common outlet such as the outflow of a reservoir, mouth of a bay, or any point along a stream channel (Schösler & Riddington, 2006). In the country, the phrase “water catchment” is sometimes used interchangeably with drainage basin or watershed (Kulindwa *et al.*, 2006).

From these definitions, it is clear that a water catchment is an area of land that drains down the slopes until it reaches a common outlet. It is also clear that it can be distinguished from other water features on land surface by the outflow point; all of the land that captures rainwater and drains slowly to one outflow point is a water catchment. Larger water catchments contain many smaller water catchments all draining to one point, which normally are the lower points of the area. These lower points are bodies of water such as rivers, lakes, and the ocean. The easiest way to picture it is to consider it as a giant funnel that catches and directs all of the water that falls into it towards the lowest point of the area. It is also clear that the term “water catchment” is synonymous with other terms such as “drainage basin” and “watershed area”. Therefore, a simpler way of defining and distinguishing it from other surface water features is by saying that is an area of land where all of the water that falls in it ends up in the lower point outlet. All precipitation that falls within a water catchment and not used by existing vegetation, will ultimately seek the lowest points (rivers, lakes and ocean).

2.3. Uluguru water catchment: geographical, physical and climatic characterisation

2.3.1. Geographical location

Uluguru water catchments are found in Uluguru Mountain blocks, which are part of thirteen (13) isolated ancient crystalline mountains (also known as the Eastern Arc Mountains) running from the Taita Hills in Southeast Kenya to the Udzungwa Mountains in Tanzania (URT, 2010; Lovett *et al*., 1995). The Uluguru mountains are situated 07°00' south and 37°40' east of the main Eastern Arc Range, as depicted in Figure 2.1 below (Fjeldså *et al*, 1995). In Tanzania, the mountains are situated 180 km from the coast of the Indian Ocean, and are isolated from the Udzungwa and Robeho mountains by 70 km of low plains, which include the Mikumi National Park (Burgess *et al*., 2002; Munishi, 1998; Lovett, 1996).

Figure 2.1: Location of Uluguru in Easter Arc Mountains (Cource: FBD, 2005).

2.3.2. Physical characteristics

As noted in section 2.3.1, the catchment is situated in the mountains series that form a 45.5 km-long chain characterised by very rugged topography, with the tops having steep slopes above 70° (Lovett *et al.*, 1995). The mountains rise steeply from Mgeta and Mvuha floodplains which are 150 m above sea level to a peak of 2 638 m above sea level (Mbilinyi & Kashaigili, 2005). Although the mountains form a continuous ridge or chain, they are physically divided by the gap or depression called "Bunduki" into the Northern Uluguru which is 20.5 km long and 8 km wide, running towards the north-south direction and the Southern Uluguru which is 25 km long and 15.5 km wide, as depicted in Figure 2.2 below (van Donge, 1992). To the south of the mountain chain lies the Lukwangule Plateau and Kimhandu hill which rise abruptly from the lowland plains to 2638 and 2634 m above sea level, respectively (URT, 2010; Lovett *et al.*, 1993). In the north there are Mnyanza (2140 m asl), Magari (2340 m asl), Nziwane (2270 m asl) and Lupanga (2138 m asl) (Doggart *et al.*, 2004). On the east, the mountains drop steeply to 500 m above sea level, and there is then a band of gentle hills about 10–26 km wide (Griffiths, 1993).

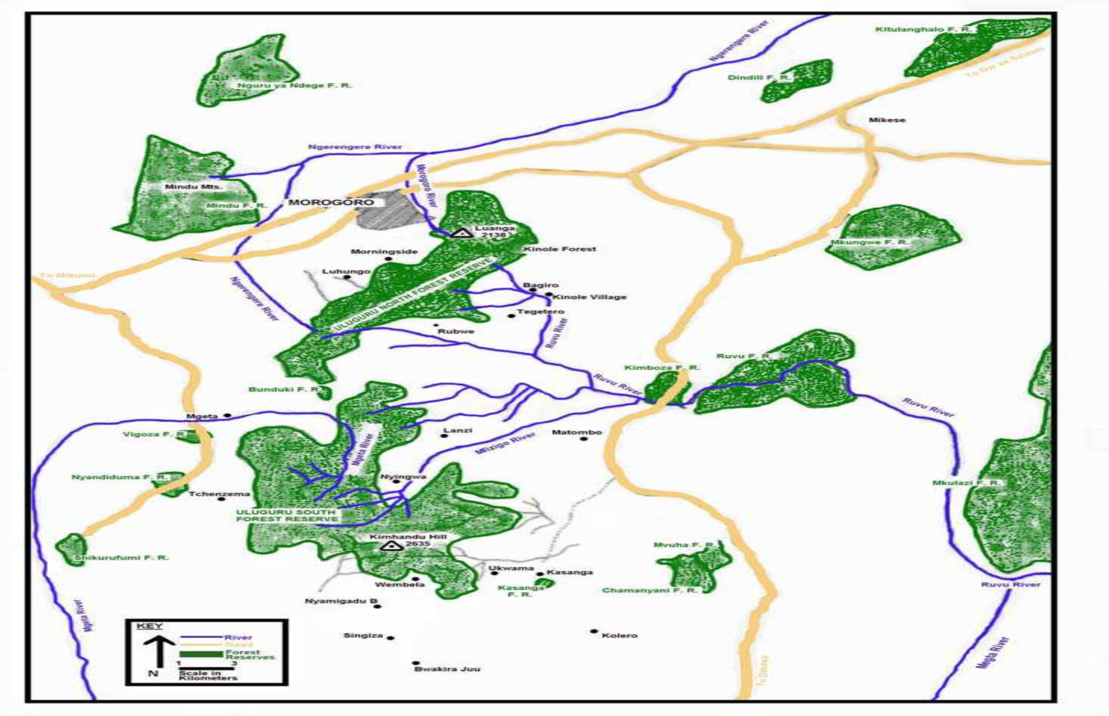

Figure 2.2: Physical characteristics of uluguru (Source: URT report on forest area change in Eastern Arc Mountains, 2010).

To the south-east there is a sudden drop in altitude towards the Mbakana River, beyond which there is an extensive complex of low hills dropping towards the Great Ruaha and Rufiji flood plains (Lyamuya *et al*., 1994). To the north of the range, the mountains drop from 2 000 m to 580 m above sea level within 4 km (Burgess & Clarke, 2000). A lowland plain extends beyond this precipitous; it drops and rises again to 1 260 m above sea level at Mindu Mountain. The foothills are between 200 to 500 m above sea level, with peaks at Mkungwe and Luhakwe which rise up to 1 100 and 900 m above sea level, respectively (Lovett *et al.*, 1995). The foothills divide the main mountain range from the lowland plains that reach the Selou game reserve, Mikumi National Park and the coast (Lovett, 1998). The main lowland includes Kimboza, Ruvu forests and flood plains, and Mgeta flood plains (Pócs, 1976).

2.3.3. Climatic characteristics

The water catchments are under the direct climatic influence of the Indian Ocean from where winds loaded with moisture arrive at the eastern slopes. Apart from winds from the ocean, temperatures also change with altitude. Temperatures range from 26 °C in the lowlands to below zero at the higher altitudes of the mountain chain (Yanda & Munishi, 2007). On average, the tops of the mountains are characterised by cold temperatures between 15 to 18 °C. The temperatures also change over the year, for example at Morogoro, the town just at the northern foothill, the average temperatures are 21.1 °C and 26.5 °C during the coolest months (June and July) and warmest months (October, November and December), respectively (Hall *et al*., 2009).

The water catchments are also characterised by three main seasons; a long rain season between January and May, with high rainfall between April and May, a dry period from June to September, and a short rain season between October and December (Burgess *et al*., 2002; Lyamuya *et al*., 1994). The length of the rain season depends greatly on location and height of the area. For example, the eastern side slopes which are windward receive rainfall between 2000 and 4000 mm per year, which decreases towards the western side of the mountains chain (Mayers *et al*., 2000). The western area receives rainfall between 890 and 2392 mm per year (URT, 2010). The foothills and lowland receives low rainfall, between 600 and 1 000 mm, compared with the high altitudes (Mittermeier *et al*., 1998; Lovett *et al*., 1995).

2.4. Uluguru water catchment: agro-ecological zones and vegetation distribution

An agro-ecological zone is an important element in describing land use and canopy cover (vegetation) distribution in a water catchment. It is an important element for explaining the observed land use patterns and canopy cover distribution. Climatic conditions (rainfall and temperature) and altitude determine the distribution of agro-ecological zones (World Bank, 1994). A stream of literature indicates that several methods have been used to classify Tanzania into different agro-ecological zones. For example, Moris (1981) identified eight (8) zones, based on geographical divisions and constituent production systems. Samki and Harrop (1984) subdivided the country into 20 zones, based on soil types, mean annual rainfall, rainfall pattern and the length of the crop growing period. In addition, Mowo *et al* (1993) divided it based on farming systems.

The most-used classification is that of the Land Resource Development Centre (LRDC). This centre has divided the country into six major zones, which can be further subdivided into 18 sub-zones according to soil type, altitude, mean annual rainfall and distribution of the growing period (Senkondo, 2000). According to LRDC classification, Tanzania is crop comprised of (i) Coast, (ii) Arid lands, (iii) Semi-arid, (iv) Plateaux, (v) Southern and western highlands and (vi) northern highlands and isolated mountains (LRDC, 1987). LRDC classification is considered appropriate because of its consideration of farming systems as a consequence of the physical environment, rather than its defining characteristics (Food Studies Group, 1992).

According to LRDC, the Uluguru catchment falls under sub-humid tropical savannah (Sharma, 1987). Although the catchment is classified as sub-humid tropical savannah land by LRDC, Svendsen and Hansen (1995) and Lovett and Pócs (1993), based on temperature, rainfall and vegetation distribution, have identified six agro-ecological zones, which include low altitude dry forest or savannah woodland, lowland semi-evergreen rain forest zone (the limestone karst areas); sub-montane dry forest, sub-montane evergreen and semi-evergreen forest zone, and upper montane or upper forest edge.

2.4.1. Low altitude dry forest or savannah woodland

This is found in the western and northern foothills of the mountains, below 600 m above sea level. The zone is characterised by annual rainfall between 700 and 900 mm, mean temperatures between 24 and 26 °C, and the dry period lasts for 4 to 6 months (URT, 2011a). Vegetation in these areas is dominated by *Acacia* tree species and grasslands which are extensive on the drier foothills of the area, and *Brachystegia* tree spp which are extensive in the moistened areas (Burgess & Clarke, 2000). These areas include the Lukwangule plateau which has the extensive natural grasslands of all the plateaus in the mountains chain, dominated by the endemic grass called *Panicum lukwangulense* (Yanda & Munishi, 2007). The larger part of this area has already been converted into farmland; therefore, natural vegetation is only seen in fragmented matrix (URT, 2010).

2.4.2. Lowland semi-evergreen rain forest zone (the limestone karst areas)

This vegetation lies between 250 and 500 m above sea level in the eastern foothills of the central part of the mountains (Burgess e*t al*., 2002). These areas receive annual rainfall between 1700 and 2400 mm, with a dry season of 1–2 months, and mean temperatures between 24 to 25 °C (Yanda & Munishi, 2007). The area is under intensive land use; therefore, much of it has been converted to farmland, with only few fragments of natural vegetation left today (Madoffe *et al*., 2006).

2.4.3. Sub-montane dry forest

This is the area which today is being replaced by open woodland of *Pterocarya angolensis, Combretum and Terminalia* species or by dry secondary grassland because of intensive cultivation characterised by burning and shifting cultivation (URT, 2006; Doggart *et al*., 2004). The area is found on the drier slopes of the eastern foothills that are up to 800 m above sea level, and spread widely on the western, northern and southern slopes which rise as high as up to 1500, 1600 and 1700 m above sea level, respectively (Burgess & Clarke, 2000). The areas receive rainfall between 950 and 1300 mm per annual and mean temperatures are between 19 and 23 °C. The dry season in this area is between 2 and 6 months.

2.4.4. Sub-montane evergreen and semi-evergreen forest zone

This is a continuous belt on the eastern slopes between 500 and 1500 m above sea level. The areas are characterised by an average rainfall of over 1800 mm per year, without being interrupted by a dry season. Occasionally, the rainfall exceeds 2500 mm and 3000 mm (Hymas, 2000a). The area is also characterised by temperatures between 23 and 17 °C at the lower and upper zones, respectively. Because of the reliable rainfall, the area is under intensive land use, which in turn has affected the distribution of natural vegetation. In the area the vegetation is fragmented, with forests being found in small patches, mainly in protected valleys at the lower edge of the evergreen forest belt (URT, 2010; Hymas, 2000b).

2.4.5. Montane evergreen forest zone

This vegetation forms a broad belt around both sides of the mountains (URT, 2010). It is found at the altitudes between 1500–2100 and 1600–2400 m above sea level in the Uluguru North and South, respectively (Hall *et al*., 2009). The area is characterised by a relatively high rainfall, with the annual precipitation ranging between 2300 and 3000 mm per year (Yanda & Munishi, 2007). The upper edge of this zone receives higher amounts of rainfall (more 3500 mm per year) without seasonal interruption than the lower edge does (URT, 2006). The area is also characterised by low temperatures that lead to occasional frosts. Annual temperatures in the area range between 12 and 17 °C, with very small changes, and the area is always under cloud (FBD, 2005). The natural vegetation, which is dominated by natural forests, is in relatively good condition compared with other areas described in previous sections (sections 2.4.1 to 2.4.4). This is attributed to the fact that most of them are inside the protected forest area (Mbilinyi & Kashaigili, 2005).

2.4.6. Upper-montane or upper forest edge

This natural vegetation cover is found between 2100 and 2400 m above sea level in the Uluguru North and South. The area receives relatively high precipitation, ranging between 2500 and 3000 mm per year, and is covered by cloud most of the time (Burgess *et al*., 2007). The area is characterised by low annual temperatures, ranging between 5 °C and 18 °C, and much higher diurnal changes reaching to more than 15 °C, and most of the time the temperature is below zero or sinks to zero (Hymas, 2000a). The vegetation is comprised of elfin woodlands, bamboo thickets, peat bogs and secondary grasslands that are modified to adapt against the strong eradiation during cold nights when the belt temperature sinks to zero (Svendsen *et al*., 1995; Lovett & Pócs, 1993).

2.5. Importance of Uluguru water catchments

The importance of water catchments to people cannot be over-emphasised. The Uluguru water catchments comprise one of the most important catchment areas nationally, regionally and globally. Their location, climatic condition and altitude enable them to provide a range of ecosystem services benefiting people within the catchment, outside (downstream) and worldwide. Generally, the services provided by the catchments can be categorised into three major groups, namely ecological, hydrological and economic (Burgess *et al*., 2007).

2.5.1. Ecological importance

The Uluguru water catchments contain a wide range of altitudinal forests (see section 2.4) that provide habitat to a unique biodiversity of exceptional biological importance globally. Analyses of the biological values rank the catchment as one of the three most important Eastern Arc mountains water catchments (Doggart *et al*., 2004). The catchments are also ranked as one of the Africa's top 20 biodiversity habitat sites (Burgess *et al*., 2002). The catchment forest hosts the three Tanzania–Malawi endemic bird species: the Uluguru Bush Shrike (*Malaconotus alius)*, the Loveridge's Sunbird (*Nectarinia loveridgei)* and the Greenbul complex (*Andropadus neumanii*) (see table 2.2) (Doggart, 2002; WCST, 2004). They also hold important populations of other bird species that are endemic to Eastern Arc Mountains. In addition to the birds, the catchment also supports a number of unique animal species. It is believed that there are about 15 species of vertebrate animal and more than150 species of invertebrate animal found in the catchment, together with 100 endemic plant species (see Table 2.1 below).

Table 2.1: Unique species of birds, mammals, reptiles and amphibians found in Uluguru water catchment

Species	Alt Distribution (m asl)	Most recent records, plus notes on abundance
BIRDS		
Malaconotus alius	1320-1710	2000, pop c.1 150 pairs
Nectarinia loveridgei	1200-2580	2000, pop 10 000 plus pairs
Andropadus neumanii		
MAMMALS		
Crocidura telfordi		1990s collected by W. Stanley
Myosorex geata		1990s collected by W. Stanley
Colobus angolensis		2000 collected by UMBCP
REPTILES		
Prosymna ornatissima	700-1000	2000 collected by UMBCP
Rhampholeon uluguruensis	650-900	2000 collected by UMBCP
Typhlops uluguruensis	750	2000 collected by UMBCP
AMPHIBIANS		
Nectophrynoides cryptus	1500 Plus	Collected 2000, U. South.
Nectophrynoides minutus	1500 plus	Collected 2000, U. South
Probreviceps uluguruensis	1500 plus	Collected 2000, U. South
Scolecomorphus uluguruensis	1500 plus	Collected 2000, U. North
Hyperolius tornieri	1500 plus	Taxonomically problematic

Source: WCST (2004).

Apart from the forest plants mentioned in section 2.4, the catchment also hosts a number of unique plant species which are wholly or semi-endemic to the catchment (see Table 2.3 below). The plants are of regional and global importance. The plant species are of importance for scientific research, attracting medical, biological, cultural and hydrological researchers from all around the world.

Table 2.2: Plant species found in Uluguru water catchment

Plant species	**Alt distribution (m asl)**	**Life form**
ACANTHACEAE		
Brillantaisia stenolepis	200 – 600	Shrub
Mellera lobulata	600 – 1000	Shrub
APOCYNACEAE		
Carvalhoa campanulata	350	Shrub
BALSAMINACEAE		
Impatiens walleriana	0-2000	Succulent perennial
CUCURBITACEAE		
Zehneria scabra	80 – 3350	Herb climbing or trailing
CYPERACEAE		
Cyperus cyperoides	150 – 2150	
DICHAPETALACEAE		
Dichapetalum madagascariense	0 – 2400	Liana
ICACINACEAE		
Leptaulus holstii	700 – 1200	Shrub or small tree
MALVACEAE		
Wissadula rostrata	700	Herb
MARANTACEAE		
Marantochloa leucantha	750 – 1200	Herb
MELASTOMATACEAE		
Warneckea amaniensis	40 – 600	Shrub or small tree
MELIACEAE		
Trichilia emetica	10 – 1300	Tree
MORACEAE		
Mesogyne isignis	500 – 1300	Shrubs or trees.
RUBIACEAE		
Aidia micrantha	1140 – 1800	Shrub or small tree
Aoranthe penduliflora	250 – 960	Shrub or small tree
Pauridiantha paucinervis holstii	500 – 2400	Shrub or small tree
Pavetta crebrifolia var. kimbozensis	400 – 460 (600)	Shrub or small tree
TILIACEAE		
Grewia goetzeana		Tree
URTICACEAE		
Obetia radula	700 – 2000	Tree

Source: WCST (2004).

2.5.2. Hydrological importance

The forests of the Uluguru Mountain ranges also provide the water catchment areas for the streams and rivers which join to form the Ruvu River, which discharges its water into the Indian Ocean (Hall *et al*., 2009). The catchment is divided into three main sub-catchments; (i) Kibungo juu which is the catchment of Mbezi, Mvuha, Mngazi, Mmanga and Mvizingo Rivers; (ii) Mgeta which is the catchment of main Mgeta, Mzinga and Mbakana Rivers; and (iii) Ngerengere which is the catchment of Main Ngerengere, Mzinga, Morogoro and Kiroka Rivers (see Figure 2.3 below) (Lovett *et al.*, 1995).

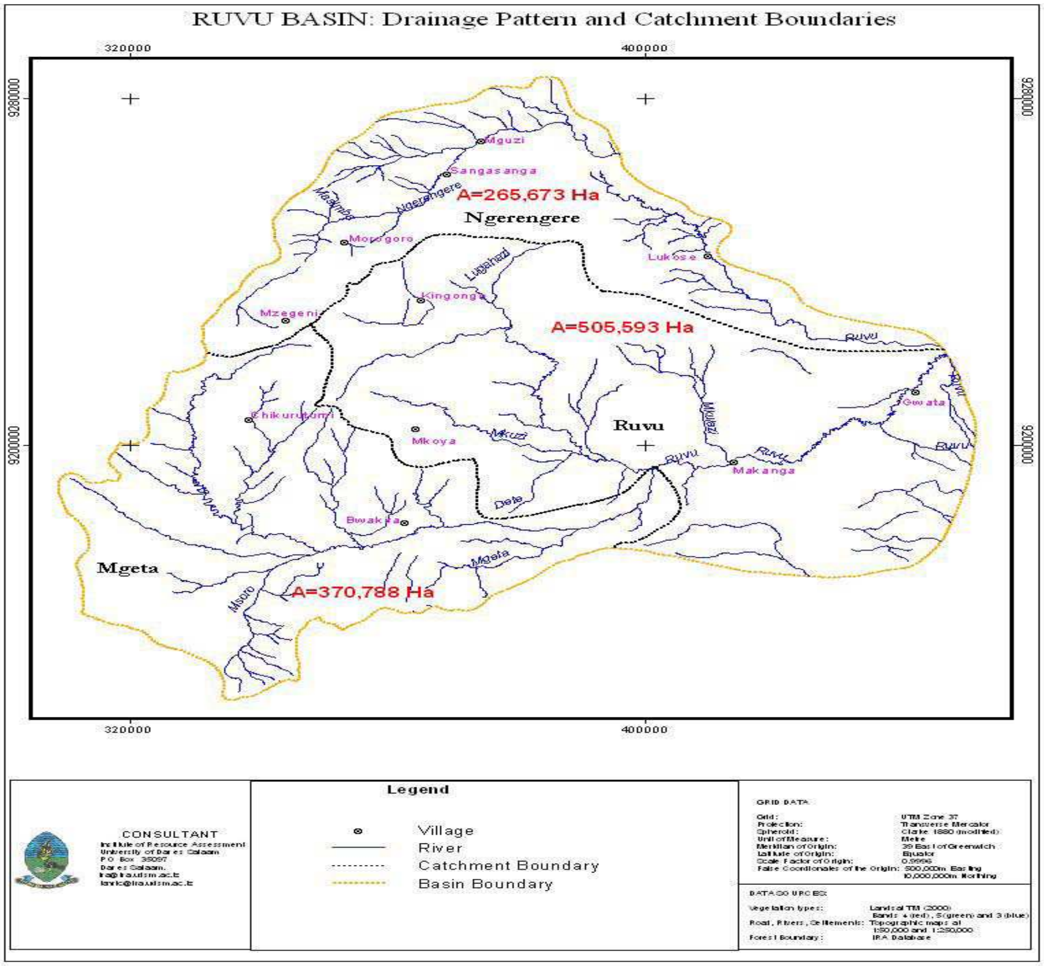

Figure 2.3: Uluguru water catchment drainage pattern (Source: Yanda and Munishi, 2007).

The Uluguru water catchment is one of the most important catchments nationally, regionally and globally for hydrological services. At national level, catchments support the need of water for domestic and industrial use in Dar-es-Salaam (the largest city in Tanzania), and other urban centres found in Morogoro and Coastal regions. Huge amounts of water are abstracted from the Ruvu River and piped to Dar-es-Salaam to serve nearly 6 million people and 1.5 million others living along the pipe line (Hartley

& Kaare, 2001). Other areas abstract water from rivers before they join to form the main Ruvu River. For example, the Ngerengere River is the major source of water for the sisal estates in Morogoro Rural District, and the Morogoro and Mzinga Rivers supply water to Morogoro Municipality (Svendsen *et al*., 1995).

2.5.3. Agricultural importance

Apart from supplying water for domestic and industrial use, the catchment is popular for supplying tropical and temperate agricultural crops to the nearby towns and cities. The favourable climatic conditions (high temperature and cold in the low and high altitudes, respectively), reliable rainfall and the ability of the catchment to supply water throughout the year (see sections 2.3.3 and 2.5.2) have made farming of both temperate and tropical crops possible (Doggart *et al*., 2004). Crops grown in the catchment vary with climatic conditions, with tropical crops being grown in the low altitudes and temperate crops in the high altitudes (Nnunduma, 2005). Tropical crops, such as pineapples, rice, bananas, sugar cane, spices, coconuts, and oranges, are grown in the lowland, while cabbages, carrots, peas, beans, potatoes, leeks and temperate fruits, such plums and peaches, are grown in the high altitudes (Hymas, 2000a). Farming in most high altitudes of the eastern part of the catchment is rain fed, while in the lowland and western part (Mgeta upland and foot plains) is mainly through irrigation. This is because the lowlands and western side are characterised by low rainfall (see section 2.3.3) (Hymas, 2001). In these areas nearly 3 400 hectares of the catchment are irrigated, comprising 1000 ha of rice and vegetable fields in the lowland of the eastern side, and 2 400 ha of vegetables, maize, beans and temperate fruits on western side (Mgeta upland and foot plains) (Masawe, 1992; WCST, 2004).

2.6. The major threats to Uluguru water catchments

Globally, water catchments are facing enormous and ongoing threats from human activities which reduce their ability to play the role of provisioning and supporting regulatory and cultural services over the coming decades (Che-Ngah & Othman, 2010). Ecosystem assessment reports show that, worldwide, nearly 50 % of water catchments have deteriorated during the last 20 years and the rate of deterioration is alarming in developing countries (MEA, 2005; 2003; Moss, 2004). The literature attributes the high deterioration rates observed in catchments found in developing countries to the excessive dependence on natural resources and very low levels of investment in internalising land use externalities by land users (Swallow *et al.*, 2009; Barrett & Swallow, 2006; Jalan & Ravallion, 2002). This is especially true when one considers that the majority of catchment inhabitants in developing countries are very poor subsistence farmers who depend on agriculture to sustain their livelihoods.

2.6.1. The status of Uluguru water catchments

The Uluguru water catchments present a compelling case of this global trend of deterioration. Over the last 50 years, the catchment has been extensively (and intensively) exploited for agricultural production and expansion. Agriculture in the catchment is characterised by poor land use practices which involve clearing natural vegetation for crop production. Cleared land is then abandoned when it loses productivity (Yanda & Munishi, 2007). Data on land cover changes for the entire catchment indicates that between 1955 and 2000 the area under cultivation increased from 7 to 32 per cent, with a concomitant decline in the areas under natural forests, open woodland, and bush land from 8 to 6 per cent, 40 to 20 per cent, and 23 to 11 per cent, respectively (Table 2.3) (Yanda & Munishi, 2007).

Table 2.3: Uluguru water catchment land use change for the period between 1955-2000

Type of land use	1955		2000	
	Area (ha)	Percentage	Area (ha)	Percentage
Natural forest	93454	8	70101	6
Woodland	451788	40	231124	20
Bushland	259145	23	129052	11
Grassland	253179	22	331938	29
Permanent swamp	1307	0.001	0	0
Cultivated land	79793	7	366486	32
Urban	1365	0.001	11571	2
Water	241	0.0002		0.0001
Total	1140272	100.0023	1140272	100.0001

Source: Yanda and Munishi (2007).

More recent data on the land use mosaic in the catchment indicates that agriculture production in the catchment is dominated by banana, followed by paddy, cassava, maize, and vegetables, with little tropical and temperate fruits. Land use data collected during the 2010/2011 cropping season indicate that 40 per cent of the area under cultivation was covered by banana, followed by paddy at 24.5 per cent and cassava at 11.7 per cent, making these the major cash and food crops in the catchment (URT, 2011b). Fruit trees covered only 15.3 per cent of the area (Table 2.3).

Table 2.4: Land use mosaic in Uluguru water catchment for crop season 2010/2011

Crop/fruit name	Area covered (ha)	Percentage
Banana	259.00	40.0
Paddy	158.83	24.5
Cassava	75.50	11.7
Orange trees	48.77	7.5
Mango	41.25	6.4
Spices	18.50	2.9
Maize	16.18	2.5
Pineapple	12.62	2.0
Coconut	9.25	1.4
Vegetable	4.05	0.6
Beans	3.29	0.5
Total area	**647.00**	**100.0**

Source: URT (2011).

2.6.2. Impacts of Uluguru water catchment deterioration to downstream

The multiple values of the catchment have deteriorated rapidly, resulting in undesirable socio-economic and environmental outcomes. Such loss in natural vegetation cover, a dynamic land use mosaic dominated by crop production (mainly paddy and banana crops), and low investment in internalising land use externalities have altered the quantity and quality of ecosystem services (particularly hydrological services) in the catchment. Some recent hydrological data on water quality indicate that over the past 20 years (1990–2010) the quantity and quality of water has deteriorated considerably. Hydrological data indicate that 50 % of the streams that used to flow throughout the year are now seasonal, with water flowing in the streams during the rainy season only (Yanda & Munishi, 2007). Over the same period of time, there has been a considerable increase in sediment load per cubic metre of water flowing in the streams and rivers draining the catchment. For example, the level of sediment load in the main Ruvu River has increased from 0.13 tons per m^3 to 0.4 tons per m^3, increasing the cost of producing drinking water and other domestic uses downstream (URT, 2011a).

Uluguru water catchment deterioration has not only affected the quality of water, but has also increased the risk of flooding downstream. Over the same period, the flood plains of Uluguru Mountains have experienced increased floods during rainy seasons. Streams and rivers draining the catchment have frequently been changing their courses during the rainy season, thus increasing flooding risks and costs of dredging irrigation channels downstream (MNRT, 2005). It is estimated that nearly 100 hectares of irrigated fields are destroyed each year by these floods during the rainy season (URT, 2011b; Ponte, 2001). This has affected the production of vegetables and paddy cultivation downstream, and hence the economy of downstream users of Uluguru water catchment hydrological services.

2.6.3. Efforts to combat the deterioration of Uluguru water catchment

Efforts to combat the harm done in the Uluguru water catchment have a long and intricate history. It dates back to 1909 when the German colonial administration enforced, for the first time, conservation measures to put to an end to shifting cultivation in the catchment. An area of 277 km^2 was declared Forest Reserve and its boundary demarcated at the top of the mountain range. The aim of this step was to safeguard perennial stream flow in the surrounding lowlands. However, the effect of this conservation measure was to intensify the exploitation of the remaining non-reserved land and to accelerate its deterioration; land was cleared before vegetation regeneration had fully restored the soil fertility and a greater proportion of steep slopes were cultivated, leading to increased soil erosion by sheet wash (Savile, 1945).

In 1920 the British took over the administration from the Germans and during this period limited conservation measures were put into operation, both by local action and through legal pressure (Platt *et al.*, 1945). In 1930 the administration became alarmed by the Land Development Commissioner's Report, which informed the British administration that a number of those expelled from the Forest Reserve, steep slopes and hot spots for hydrological services by the Germans had returned to these areas (Bagshawe, 1930). The report also noted that there were shortages of fuel wood and building poles and that the quantity and quality of hydrological services were deteriorating. Following this report, different measures were put forward and these included setting aside 100 hectares of forest to be managed by the community (commonly known as community forests), promoting planting exotic trees, such as wattle, along the tops and bottoms of farms in the western side of the catchment (the Mgeta sub-catchment), but nothing was implemented (Baldock & Hutt, 1931).

The first agricultural conservation work of significance came in 1936 and 1937, with the establishment of trial plots and experimental bench terraces for vegetable and potato growing in the Mgeta sub-catchment (Page-Jones & Soper, 1955). During this period, sustainable land use practices, such as the ladder or step terrace (in Swahili, *matuta ya ngazi*), planting of live grass barriers at the ages of farm plots, and regulations against burning (e.g. a metre-wide fire-break) were introduced and reinforced (Temple, 1972). Intensive conservation efforts implemented between 1937 and 1943 followed after the recognition of the scientific fact that the chief function of the catchment highlands is not to provide a short-lived subsistence or profit for their excessive exploiters, but to maintain a regular run-off from the climatically favoured more humid heights into the thirsty surrounding arid low lands (Harrison, 1937). During this period, demonstrations of storm draining, terracing and tie-ridging were set up at Kienzema, Kibuku and Mgeta, and these plots were said to have achieved their purpose, which was identified as the prevention of runoff and increased crop yields objectives (Platt *et al.*, 1945).

In the 1950s the British colonial government attempted a comprehensive soil conservation and land use improvement scheme, named the Uluguru Land Usage Scheme (ULUS) (Platt *et al.*, 1945; Jones, 1996). The initiative emphasised terracing cultivation and contour tie-ridging on steep slopes, and the re-enforcement of regulations against burning of grass and bush in the hilly areas, while stressing planting of trees outside the forest limits for the provision of fuel wood and poles for construction purposes (Temple, 1972). The approach was different from the aforementioned conservation measures; under this approach, land owners were supported technically and subsidised for implementing the proposed mechanisms (Rutatora *et al.*, 1996). However, the scheme did not last long; it collapsed five years after its commencement and abandoned; it was in 1955 (Duff, 1961).

Several reasons were raised for the collapse of the scheme. Among others, the widespread corruption among headmen and instructors, who could ignore breaches of rules and permit burning if bribed, was pointed out as one of the reasons (Page-Jones & Soper, 1955). On the northern and eastern slopes, the heavy labour required for constructing bench terraces was raised as the main factor, while in the east, yields were bad in bench terraces because the construction of bench terraces on steep slopes with thin soil cover exposed infertile subsoil. In the same area it was also pointed out that field officers and instructors were incompetent. In the eastern part, which is the heart of the Waluguru tribal traditions, the scheme threatened their traditional social and cultural system, particularly over the authority to allocate land (Young & Fosbrooke, 1960).

After independence, the government of Tanzania inherited the Uluguru Mountains which were under very weak conservation; most parts of the reserved forest were being encroached on and converted to farm land (Mbegu and Mlenge, 1983). To reverse the situation, the government introduced the so-called nationwide conservation policy, which involved redefining the reserved areas and the introduction of new land use regulations (Rutatora *et al*., 1996). In the Uluguru Mountains, terracing cultivation on steep slopes, regulations against burning of grass and bush in the hilly areas, planting of trees on abandoned land, and establishment of permanent settlements in the newly formed villages were emphasised and intensified (Temple & Rapp, 1972). However, these approaches were not successful, and the multiple values of the catchment continued to decline, with bush fires being intensified.

Following the continuing degradation of the water catchment, and considering the role the catchment plays to the economy and as a habitat to unique biodiversity, the Government of Tanzania in 2002 revised its 1998 water, forestry and environmental policies to harmonise conservation activities and remove conflicts of interests (URT, 2002). The new policy recognises the roles of local communities living in the catchments and of the private sector in conserving water catchments (Scurrah-Ehrhart, 2006; Vihemäki, 2005). In other words, the policy has widened recognition of the key players in conserving water catchments by allowing full involvement of the local communities and other stakeholders in planning and implementing conservation programmes. This has attracted a number of conservation activities in the catchments throughout the country, promoting different sustainable land use practices. Following this, therefore, there has been a flurry of conservation activities being imitated and implemented in Uluguru water catchment. A good example of such programmes is represented by that of CARE and WWF, which, following the recommendations from the ecological and hydrological study by Yanda and Munishi (2007), initiated a joint project called Equitable Payment for Watershed Services (EPWS). The project has been operating in the catchment for the past 6 years (i.e. since 2007). Through the project, the organisations have mainly been encouraging farmers to adopt best land use practices that can sustain agricultural productivity without compromising the catchment's ecological and hydrological value and sell the services to downstream users. Specifically, the project has been encouraging farmers to plant on-farm fruit trees (among other interventions, like bench terracing and high value crops) and continue to retain the remaining natural trees on the cleared plots.

The project administration has served as a vehicle for linking the upstream land managers (as suppliers of ecosystem services) and downstream users (as buyers of ecosystem services) by collecting the payments from downstream users and ensuring that upstream suppliers comply with the contractual terms with the downstream users for implementing sustainable land use practices. Basically, the project facilitated the conditions required for an emergence of a market linkage between the many upstream ecosystem services suppliers and two major downstream catchment ecosystem services beneficiaries (Coca-Cola Kwanza Ltd and DAWASCO), whose profitability to a large extent is influenced by the quality of the water used as inputs in producing their consumable water and beverage drinks. Based on the 2009 Water Act, CARE and WWF launched the EPWS programme, upon which a memorandum of understanding (MoU) was signed between the upstream land holders and the two major downstream ecosystem services beneficiaries. The MoU obligates upstream land holders to undertake sustainable land use practices, and downstream water users to compensate upstream land holders for such best practices (Mwanyoka *et al.*, 2010). To strengthen the bargaining power of the many upstream land holders and ensure their compliance with obligations under the MoU, CARE and WWF also facilitated the formation of the community-based organisation "*Wakulima wa Kuhifadhi na Kutunza Vyanzo vya Maji*"[1] in 2012.

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1 Translated, means "Farmers for the conservation and care of natural water sources".

Despite the good work done by CARE and WWF to combat the harm done in the catchment, the challenges which similar programmes faced in the past are still threatening the sustainability of the current interventions. These challenges stem from the fact that upstream land managers and decision makers on the ground are not certain of the long-run response of the catchment to interventions, given the fact that the catchment is extremely complex. It is also not clear to beneficiaries what the long-run distribution of benefits (both private and social) will be. In the case of policy makers and development planners, it is not clear what policies need to be in place to support the management activities going on in the catchment that would lower the burden for upstream land managers, and so attract many of them to participate after the project phases out. This is true when someone looks at the historical background of efforts to manage the Uluguru water catchment by using the same mechanisms some years back. To resolve the dilemma, this study is designed to simulate the likely long-term impacts of fruit tree buffer strips on the flow of hydrological, economic and social benefits.

2.7. Concluding summary

This chapter briefly reviewed the meaning of catchments and showed that it is difficult to define and classify them in all sciences dealing with natural world because they are self-organising systems, with much of the hydrologic processes being hidden for our current measurement techniques of observation. The chapter also highlighted the geographical location, physical (topographical) characteristics, climate, and natural vegetation distribution of the Uluguru water catchment. The review has shown that natural vegetation distribution in the catchment is highly influenced by altitude, climatic conditions and human interference. It has shown that most of the natural vegetation has disappeared owing to intensive and extensive land use, characterised by shifting cultivation and burning. Furthermore, the chapter reviewed the importance of the catchment, where it has been made clear that the catchment plays four major roles; provisioning, regulating, supporting and cultural roles. Specifically, the catchment provides multiple ecosystem services of hydrological, ecological and economic values. It is home to a significant population of people who harvest natural products and cultivate different food and cash crops; it is a habitat to unique plants, amphibians, reptiles, and mammals; and provides scenic beauty for recreation.

Nonetheless, the chapter highlighted the threats facing the role the catchment plays in providing valuable ecosystem services. It has been made clear that the multiple values of the Uluguru water catchment have deteriorated considerably over the last 50 years and continue to deteriorate over time, at an increasing rate. The major threats to the catchment are the increased conversion of natural vegetation to agriculture, continuing and growing dependence on natural vegetation for livelihood, and low investment in best land use practices that internalise externalities. This threatens not only the health of the catchment, but also the livelihoods of the population living downstream.

The chapter also reviewed the efforts to combat the harm done in the catchment. It has also been made clear that efforts to combat the harm done in the catchment can be traced from the colonial period to the current time. The review clearly shows that it has not been easy to achieve this objective. Many conservation initiatives collapsed owing to various reasons. Given the known behaviour of land managers in the catchment of clearing natural vegetation for agriculture and abandoning it when it declines in productivity, it is therefore critical that the catchment is sustainably managed so that it continues to provide services in good quality and quantity. This will eventually ensure meeting the needs of the current generation without compromising the future generations and will reduce the costs of accessing ecosystem services from the catchment to downstream users.

CHAPTER 3

REVIEW OF THE CONCEPTS OF ECOSYSTEMS, WATER CATCHMENT, ECONOMICALLY VIABLE MANAGEMENT PRACTICES AND THEIR LINKAGE WITH HUMAN WELL-BEING

3.1. Introduction

This chapter reviews literature on the concept of ecosystems, and their structure and functioning. The chapter also reviews the concept of ecosystem services, its linkage with human well-being and how human actions interfere with ecosystem functioning, and hence, the flow of services. Equally important, the chapter reviews why ecosystems are currently a topic of concern. Furthermore, the chapter reviews water catchment as concerns ecosystem service providers and the relation between its condition and service provision. The chapter ends by reviewing the concept of best management practices (BMPs); it reviews in detail fruit tree buffers strips as comprising the best management practice recommended for agricultural landscape management and its application. The chapter ends with a conclusion.

3.2. The concept of ecosystems and ecosystem services

3.2.1. Definition and composition of ecosystems

The term ecosystem (or ecological system) was coined in 1930 by Roy Clapham to denote the physical and biological components of an environment considered in relation to each other as a unit (Vreugdenhil *et al*., 2003). British ecologist Arthur Tansley later refined the term, by describing it as the interactive system established between bio-coenosis (a group of living creatures) and their biotope (the environment in which they live) (Odum, 1971). Currently, ecosystems are defined as any unit that includes all of the organisms in a given area interacting with the physical environment (Brenner *et al*., 2010). In other words, it is a community of plants, animals and smaller organisms that live, feed, reproduce and interact in the same area or environment**.** Central to the ecosystem concept is the idea that living organisms are continually engaged in a set of relationships with every element constituting the environment in which they exist (Farber *et al*., 2006).

All ecosystems, whether terrestrial or aquatic, have four basic biotic components: producers (autotrophs or green plants), the primary consumers (herbivores), secondary consumers (carnivores) and the decomposers (micro-organisms) (Figure 3.1) (Kimmins, 2004). Producers are the only group within the community that can produce food for the community through photosynthesis by combining inorganic and organic compounds with help of energy from the sun (Figure 3.1; lines 1 and 7) (Townsend *et al*., 2003). In terrestrial ecosystems, this process is carried out by higher plants, while in aquatic or large water bodies like lakes and oceans it is carried out by microscopic plankton algae (Obsorne, 2000). The primary consumers feed on producers (see Figure 3.1; line 2) and secondary consumers (carnivores) feed on primary consumers for their energy needs (Smith & Smith, 2001). Finally, the decomposers – micro-organisms, mainly bacteria or saprophytic fungi – feed on producers, primary and secondary consumers (Figure 3.1; lines 3 and 4). The decomposers are the final stage in the food chain (or energy cycle); they break down all the components in the ecosystem into nutrients and energy, which are then released to the environment and the atmosphere (Figure 3.1; line 5) (Molles, 2002). Some of the energy remains in the soil as natural gas or fossil fuel (see Dajoz, 1977).

The biotic components in Figure 3.1 normally exist as populations (or groups of interbreeding organisms of the same kind occupying a particular space) that assemble into communities (e.g. naturally occurring assemblages of plants and animals that live in the same environment) (Chapman & Reiss, 2003). Biotic communities normally have a definite functional unity within feeding structures and patterns of energy flow. According to Chapman and Reiss (2003), a key quality of communities is that organisms making it somehow interact as a society does. As Clapham (1983) puts it, “communities have a structure at all times and in all situations that is reflected in the roles played by the constituent populations, their ranges and types of areas they inhabit, the diversity of species in the community and the spectrum of interactions among them and the precise flow patterns of energy and nutrient through the community”. Thus, the interactions that occur among the individuals in their habitats define their exact role in the community and their structures.

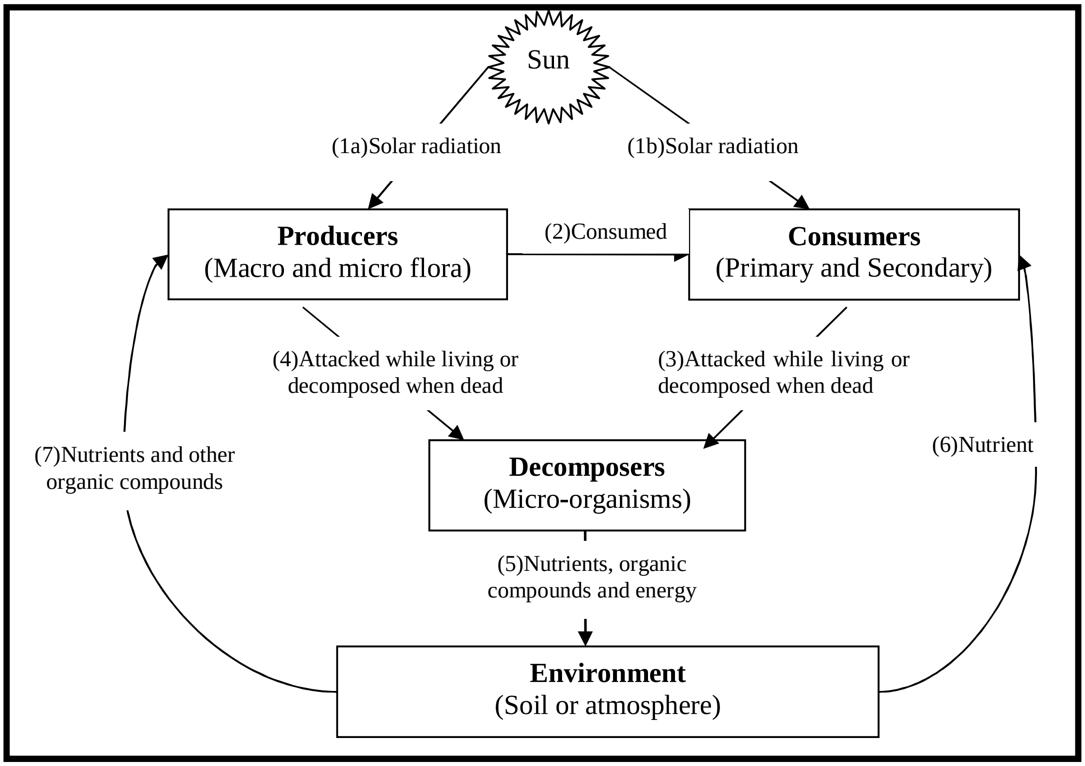

Figure 3.1: Schematic presentation of the composition of an ecosystem and relationships of element constituting it (adopted from vreugdenhil et al., 2003).

3.2.2. Characterising ecosystems

Ecosystems are characterised by components structures and the interactions involved. These together define the role of the ecosystem and services provided. Ecological systems (ecosystems) are largely characterised with regard to feeding relationships; they are divided in terms of the trophic roles (Combes, 2001). The feeding relationships are by far the most common route of interaction between different organisms of the community that lead to production of ecosystem services (Sukhdeo & Hernandez, 2004). Such relationship may be “commensal” (i.e. one organism deriving benefits from the other while the other neither gains nor loses), “mutualistic” (i.e. both organisms gain from the relationship), “parasitic” (i.e. one organism feeding upon the other, to the benefit of itself at the expense of it host), or “holozoic” (i.e. animals feeding directly one upon the other or on plants) (Lafferty *et al.*, 2006). Thus, ecosystems such as water catchments, lakes and lake basins, forests and wetlands are bound to be characterised by definite trophic structures determined by the food chains and the metabolism relationship among its organisms. Communities having high numbers of different species usually have complex structures, as do the systems composed of these communities (Vander Zanden *et al*., 1999).

The structure of an ecosystem is not only affected by feeding relationships among species, but also by the relative number of organisms in those different species (Balvanera *et al*., 2005). The diversity of species within a community reflects in part the diversity in the physical environment in which the organism is found, which in totality makes up an ecosystem and in species. Species diversity can be defined on the basis of the number of species in a community (species richness) or on the basis of relative abundance of species (species evenness) (Kremen, 2005; Luck *et al*., 2003). In general, species diversity increases with environmental complexity of heterogeneity. Accordingly, the greater the variation in the physical environment, the more numerous are the species, because there are more microhabitats available. In water catchments, the more diverse a plant community is, the more it reduces runoff, and hence the more it supports water percolation, as there will be diverse plant density with diverse root types and penetration in the soil (Neitsch *et al.*, 2002).

Finally, ecosystems are also characterised by the nature and functioning of the system, which is largely determined by composition of the community. Not all organisms in the communities are equally important in determining the nature and function of the whole community and hence the ecosystem (Lafferty, 2006). For instance, out of hundreds of thousands of kinds of organisms that might be present in a community, a relatively few species or species groups exert a major controlling influence by virtue of their numbers, size, and distribution over a large area (Kimmins, 2004). These are called ecosystem drivers species (Molles, 2002). The removal of dominant species would result in important changes, not only of the biotic community, but also in the physical environment of the ecosystem, whereas a removal of a non-driver species would produce much less change (Chapman & Reiss, 2003). This, however, does not necessarily mean that the non-dominant communities do not have important roles in the community.

3.2.3. The ecosystem services: definition

Ecosystem services are the results of complex interactions between biotic and abiotic components of the ecosystem through the universal forces of matter and energy (de Groot *et al*., 2002). According Daily (1977), ecosystems services are the conditions and processes through which ecosystems and their constituents sustain and fulfil human life. They are the benefits that human populations derive directly or indirectly from ecosystem functions (Costanza *et al*., 1997). To date, ecosystems are widely known as natural capital from which members of a human community derive their livelihood in different ways (Greiner *et al*., 2009). Boyd and Banzhaf (2007) define ecosystem services as the components of natural capital, directly enjoyed, consumed, or used to yield human well-being. Natural capital is 'an economic metaphor for the stock of physical and biological natural resources that consist of renewable natural capital (living species and ecosystems); non-renewable natural capital (sub-soil assets, e.g. petroleum, coal, diamonds); replenishable natural capital (e.g. the atmosphere, potable water, fertile soils); and cultivated natural capital (e.g. crops and forest plantations)' (Aronson *et al*., 2007).

The Millennium Ecosystem Assessment (MEA) (2005) defines ecosystem services as the benefits people obtain from ecosystems. These include provisioning, regulating, and cultural services, which directly affect people, and supporting services that are important in maintaining the other services (MEA, 2003). Changes in these services affect human well-being through impacts on security, the necessary material for a good life, health, and social and cultural relations. Generally, ecosystem services are natural goods and services which influence human freedom and available economic choices (Duraiappah, 2002).

3.2.4. Classification of Ecosystem Services

While there are some overlaps in classifications used by various authors, there is no universally agreed classification of ecosystem services (Wallace, 2007). The complexities of ecological functions underpinning ecosystem service provision militate against a single taxonomy. Following this classification of ecosystem services into various groups is often author-specific and it depends on the purpose of the classification. Because of this, several ways have been used to classify ecosystem services (de Groot *et al*., 2002; MEA, 2005). The MEA (2003) summarised approaches to ecosystem service classification into four main categories: functional (e.g. de Groot *et al*., 2002), organisational (e.g. Norberg 1999), descriptive (e.g. Moberg and Folke, 1999) and output-based groupings (e.g. Ojea *et al*., 2010).

The functional approach to ecosystem service classification is the one most widely adopted. For example, de Groot *et al*. (2002), based on this approach, assigned ecosystem services to regulation, habitat, production and information functions. Daily (1999, 2000) used a similar approach and came up with five categories: production of goods, regeneration processes, stabilising processes, life fulfilling and preservation functions. The MEA (2005), also based on this approach, classified ecosystem services into four categories: provisioning, regulating, supporting and cultural services (see figure 3.2).

Norberg (1999) developed an organisational approach to classify ecosystem services but it has not been widely adopted. Norberg's classification was based on three questions: (1) Are the goods or the object of the service internal to the ecosystem? (2) Are the goods or object of the service of biotic or abiotic origin? (3) At what level of ecological hierarchy are the goods or services maintained? Based on these criteria, Norberg derived three categories of ecosystem services: (1) those associated with certain species or a group of similar species constituting what is called community, (2) those that regulate exogenous chemical or physical inputs and are reliant on the entire community or ecosystem, and (3) those related to the organisation of biotic entities such as gene sequences through the networks of energy and material flows. Norberg's classification draws heavily on ecological theory and therefore does not include services of a social nature. However, to produce the services, ecosystems not only interact with ecological systems but also with human systems. Therefore, ecosystem services are produced as results of ecological and social interactions. Hence, Norberg's approach is considered incomplete on this respect.

Moberg and Folke (1999) classified ecosystem services using a descriptive approach based on how they are generated. Goods and services were classified separately as renewable or non-renewable. According to Moberg and Folke (1999), non-renewable goods and services are comprised of physical structures; abiotic services, biogeochemical services, information services and social and cultural services, and renewable services comprised of clean air, biotic, biochemical and water.

More recently, Lele (2009), focusing on the consequences of not taking into account the impact of change in an ecosystem on the benefits flow to human systems, applied an output-based classification in which he classified ecosystem services in terms of their benefits (outputs) to human systems. In this line, Lele (2009) highlights the point that structural changes in ecosystems can influence several processes. For example in water catchments, changes in natural vegetation cover influence erosion rates, increase/decrease water flow, or increase/decrease in groundwater recharge. These changes can result in different kinds of human impacts that can be negative, such as decreased reservoir capacity due to siltation, or positive, such as increased fertilisation of floodplain lands. These impacts can affect different beneficiaries (farmers, drinking water users, livestock owners, floodplain residents, and hydropower companies) and can be positive or negative (e.g. increase in groundwater recharging can imply more water availability; while increase in sediment load represents a negative impact, such as reduced water for hydropower generation). According to Lele (2009), the ‘process’ should not be the focus of classification, rather it is the outcome of the process which has economic meaning, as it represents an impact on human welfare (benefit or cost).

Lele (2009) therefore classified ecosystem services into five classes: (i) ecosystem extractive improvement services; (ii) ecosystem supply improvement services; (iii) ecosystem damage mitigation services; (iv) ecosystem provisioning of cultural-related services; and (v) ecosystem supporting associated services. Under this classification, the ecosystem extractive and supply improvement service is a provisioning service describing ecosystems modification for extraction purposes. Ecosystem damage mitigation service is a regulating service; it includes ecosystem mitigation of flood damage and of sedimentation of water bodies, saltwater intrusion into groundwater and of dry-land salinisation. Ecosystem cultural-related services include spiritual uses, aesthetic appreciation and tourism. Finally, ecosystem supporting associated services include, for example, terrestrial ecosystems for the provision of water for plant growth and creation of habitat for aquatic organisms such as estuaries.

The classification of ecosystems is crucial in understanding and specifying the impact of a given ecosystem management option on service flow and hence on human well-being. It helps to avoid overestimating of the value of ecosystems, especially those with complex multistage processes. Complex ecosystems like water catchments provide multiple ecosystem services, some of which are just outcomes of a stage process (e.g. regulation of the base flow that eventually affects final use of water, such as irrigation). In this case, valuing the capacity of a catchment to provide regulation control over base flow and the value of irrigation which is the outcome of the stream flow stability process may lead to overestimation of the actual value of the ecosystem (Lele, 2009). It also helps in identifying the linkages between the services and humans and the feedback loops involved (Costanza *et al*., 2002). As noted by MEA (2005), the consequences of ecosystem changes on human well-being are better understood when ecosystem services are properly categorised and the strength of linkages between the service categories and components of human well-being are identified. Ecological-economic models make use of these linkages and feedback loops to project the magnitude of the long-term impacts of ecosystem management options on human well-being, as well as on the flow of ecosystem services.

3.3. Ecosystems and human well-being

The fact that ecosystems support human well-being through its provisioning, regulation, cultural and supporting services is well known. This surfaced as early as 1864 through a publication, *Man and Nature,* by George Perkins Marsh and the subsequent 1874 revision, *The Earth as Modified by Human Action: Man and Nature* (Mooney & Ehrlich, 1997). The concept of this relationship received further attention in the late 1970s and early 1990s when ecosystem scientists started to investigate the role of environmental services on human well-being (Costanza *et al*., 1997). The concept gained further momentum awareness from the two most recent publications: the 1997 publication by the World Meteorological Organization and Stockholm Environment Institute report on the “Comprehensive Assessment of the Freshwater Resources of the World: Assessment of Water Resources and Water Availability in the World” and the 2005 MEA report to the Ramsar convention, entitled “Ecosystem and Human Well-being: Wetlands and Water synthesis”.

The linkages between ecosystems and human well-being are complex and diverse. Some relationships are immediate; others are lagged. The linkages between ecosystem and human well-being are shown in Figure 3.2 below. For instance, in water catchment ecosystems, an immediate relationship can arise when too much clearing of natural vegetation impairs the soil erosion reduction capacity, hence excess food and sediment production causes deteriorating water quality and causes siltation in water reservoirs. These damages increase the cost of producing a unit of drinking water downstream (Turner *et al*., 2000). Examples of longer time lags relationships include the clearing of natural vegetation that impairs soil formation and nutrient cycling, which reduce soil productivity that causes hunger today and malnutrition thereafter, bringing lassitude, impaired ability to concentrate and learn, and increased vulnerability to infectious diseases in the long run (Hein *et al*., 2006).

In addition, the strength of the linkages between ecosystems and human well-being varies across communities. People in poor rural communities, whose lives are directly affected by the availability of ecosystem products, such as food, medicinal plants, water, and firewood and have limited substitutes, have stronger linkages than privileged communities do (Scholes & Biggs, 2004).

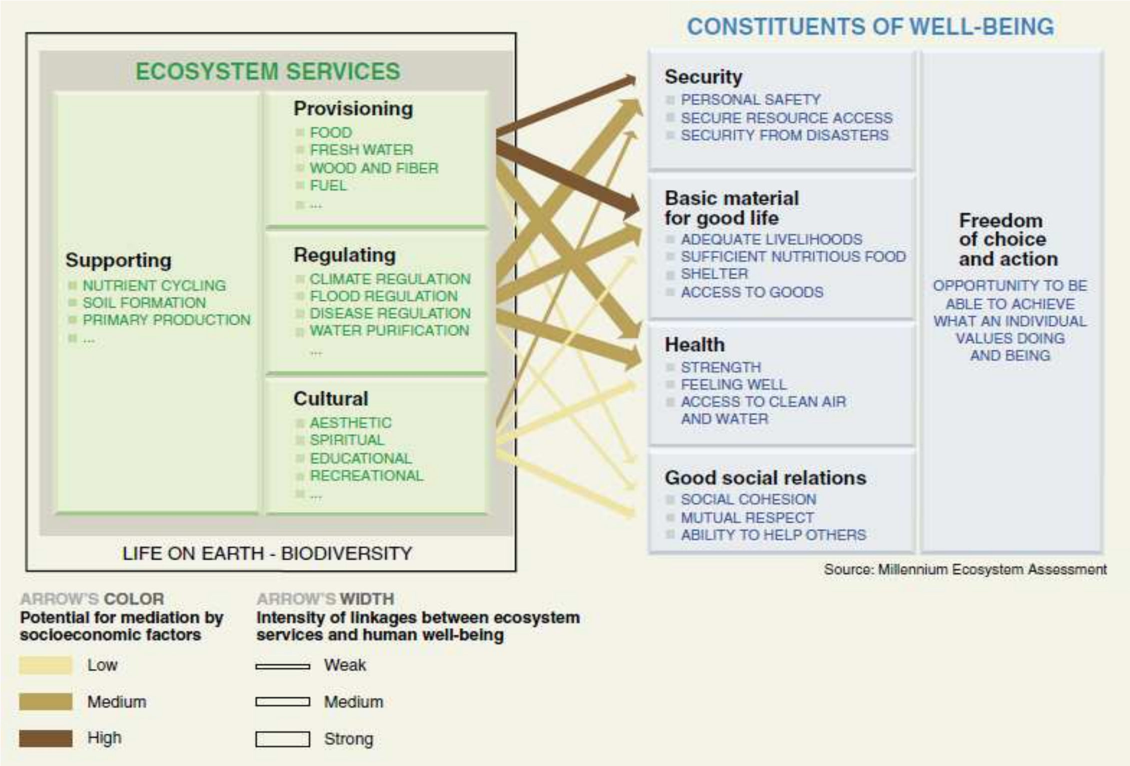

Figure 3.2: Millennium ecosystem assessment diagram depicting the strength of linkages between categories of ecosystem services and components of human wellbeing (Source: MEA, 2005).

Ecosystems provide humans with goods and other services that sustain various aspects of human well-being (Carney 1998; Ellis 1998). As noted in section 3.2.4 above, the MEA (2003) has identified four major categories of ecosystem services that bear directly on human well-being: provisioning, regulating, cultural, and supporting services. Ecosystems directly provide humans with food, fibre and other products which contribute significantly to human well-being, through both direct and indirect pathways (Koziell, 1998; Chambers, 1997; Davies, 1996).

Ecosystems also sustain human well-being in multiple ways through regulating functions. Through air and fresh water purification, reduction of flood or drought, stabilisation of local and regional climate and through checks and balances that control the range and transmission of certain diseases, including some that are vector-borne (Neffjes, 2000; Scoones, 1998). Without these regulatory functions, the varied populations of human and animal life are inconceivable. Therefore, changes to any ecosystem's function may have consequences for human welfare. For example, the alteration of a regulatory function may affect human food production, health and other components of well-being. In water catchments, for example, clearing of natural vegetation cover impairs the purification of water – a regulatory function – which in turn impairs the quality of water, causing increased waterborne diseases (Naylor *et al*., 2000).

Equally important, ecosystems provide many contributions to human well-being through the cultural services, including totemic species, sacred groves, trees, scenic landscapes, geological formations, and rivers and lakes (Duraiappah, 2002). These attributes and functions of ecosystems influence the aesthetic, recreational, educational, cultural, and spiritual aspects of human experience (Naylor *et al*., 2000). Changes to these ecosystems, through processes of disruption, contamination, depletion, and extinction, may have negative impacts on cultural life and human experience.

Finally, each of the ecosystems provides the supporting services that are essential for sustaining each of the other three ecosystem services. They support them through soil formation, photosynthesis, and nutrient cycling. Thus, the link between this ecosystem services and human well-being occurs indirectly – that is, through other services provided by ecosystems.

3.4. Why is an ecosystem a topic of concern?

The concern about ecosystems stems from the growing recognition of the impacts of human actions on them (Polasky & Segerson, 2009). Over the past five decades, the universe has experienced rapid economic and human population growth (MEA, 2005). The two have increased demand for ecosystem services which has resulted in intensive harvesting of ecosystems services. This tendency has led to declines in many ecosystems worldwide. The MEA (2003) estimates that over the past 50 years, nearly 60 % (15 of 24) of the ecosystems examined have declined, modified, or transformed into other uses. Such a decline in ecosystem services in some areas have sparked a rush of publications on the importance of ecosystem services to human society and the means of preserving them (de Groot *et al*., 2002; Daily, 2000).

Increased economic growth and human population spurred the modification of some ecosystems in favour of the most-demanded services. As a result, many natural and semi-natural areas have been, and are being, modified for curbing the short-run demand pressure. Very few areas have been modified or managed to provide wide-ranging and long-term ecosystem services supply (Kremen *et al*., 2004). Because of this, areas containing ecosystems that provide a wide range of long-term services have been highly affected over the same period (i.e. 50 years). Water catchments provide a good example of such ecosystems; for many years, the target of managing these systems has not been the wide range and long-term services they provide, but for short-term demands and that is water only (Wagener *et al*., 2007). In many of these catchments, reservoirs have been built to meet the immediate demand for water and not for other ecological, hydrological and economic services (Costanza *et al*., 2004).

Such trends have also neglected the fact the relationships between ecosystem services and humans are highly non-linear (Farber *et al*., 2002) and are often interdependent (MEA, 2006). This has often given rise to trade-offs, making their management difficult when attempts to maximise a single ecosystem service are made. Generally, ecosystems have been taken for granted in almost all human development programmes; many of them have been converted into other uses which are thought to be important for human well-being (Meadows, 2004). However, ecosystem services are analogous to other goods and services within the economy, all of which are produced through a combination of inputs and which directly or indirectly generate utility (Bockstael *et al*., 1995). In economic analysis, the production of ecosystem services can be represented by an “ecological production function,” which is conceptually analogous to the standard production function used in economics to describe how inputs are combined to produce intermediate or final outputs (Polasky & Segerson, 2009).

The concern about ecosystems also stems from the fact that there are limited substitutes for ecosystem services, especially among the poor communities, who primarily depend on healthy ecosystems for sustenance of their livelihoods (Gleick, 2000). In this line of thinking, ecosystem services are conceptualised as natural capital that flows parallel to those from physical and human capital (Alisjahbana *et al*., 2004; Ekins *et al*., 2003). Some of these services can be partially replaced by using physical capital; for instance, limited amounts of clean air and water can be obtained by air-conditioning a space or by using water filters (MEA, 2005). In other words, partial substitutability exists for at least some ecosystem services. However, there are limits to substitution possibilities and the scope for substitutions varies by social, economic, and cultural conditions. In fact, the substitution possibilities open to a community depend critically on their economic status. When water catchments, wetlands, forests, and woodlands are converted (for agriculture or urban development), the members of poor local communities are the one who suffer. For them, there are few substitutes or choices as compared with the privileged (Guard & Masaiganah, 1997). For the privileged, there are often substitutes, or they can get the service from somewhere else (Wackernagel & Rees, 1995).

3.5. Water catchments as ecosystems services providers and human well-being

Rivers and streams provide human systems with a wide range of ecosystem services of local and global importance (Cork & Shelton, 2000). Ecosystem services, such as the maintenance of water quality through filtration and purification, delivery of water, buffering of flood flows and soil erosion, maintenance of soil fertility, structure and nutrient cycling, pollination of crops and other vegetation, production of goods like food and fibre and provision of cultural and spiritual resources, and pest control, are pertinent to the sustainability of catchments’ agricultural landscapes and operate at local to sub-catchment scales (Tscharntke *et al.*, 2005). Other ecosystem services provided by vegetation remnants of the water catchments (such as control of the vast majority of potential pests and diseases, provision of genetic resources of intellectual values, climate regulation, and carbon sequestration) have wider global values, as their benefits extend beyond the catchment boundary (Zhang *et al.*, 2007).

In addition to their provisioning, regulating and supporting services, vegetation remnants have direct economic importance (Shiklomanov, 1997). Much of the remnant vegetation in water catchments is grazed, used for income generation through handmade crafts, production of timber, harvesting of bush foods and honey, medicinal products, and cut flowers (Daily, 1997). In terms of social values, native water catchment vegetation provides opportunities for recreation, education and ecotourism, aesthetic value, and in many cultures, spiritual and historical values (also see Table 3.1 for more on water catchments ecosystem services).

Table 3.1: Ecosystem services provided by water catchments.

I	***Provisioning services***	23	Ecosystem stability and resilience
1	Food	***III***	***Cultural services***
2	Fibre	24	Spiritual and religious values
3	Forage	25	Education values (formal and informal)
4	Timber and wood products	26	Knowledge of ecosystems (traditional and formal)
5	Genetic resources	27	Inspiration
6	Natural biochemicals	28	Aesthetic values
7	Fresh water	29	Social relation
II	***Regulation services***	30	Sense of place
8	Air purification	31	Cultural heritage
9	Water purification	32	Natural heritage such as biodiversity
10	Water transportation	33	Recreation and tourism
11	Soil erosion control	34	Existence value
12	Surface water eco-regulation	35	Land value
13	Ground water eco-regulation	***IV***	***Supporting services***
14	Habitat provision	36	Production of atmospheric oxygen
15	Climate regulation	37	Nutrient cycling
16	Carbon sequestration	38	Water cycling
17	Nitrogen fixation	39	Maintenance of biodiversity
18	Maintenance of soil health	40	Reproduction
19	Eco-regulation of human diseases	41	Evolution
20	Biotic pollination	43	Ecosystem dynamic and succession
21	Provision of shade and shelter	44	Primary production
22	Biological pest control	45	Secondary production

Source: Coe (2000).

Besides ecosystem services, water catchments have favourable landscapes and fertile soil for agriculture. Many water catchments have reliable water supplies and favourable climatic conditions that favour the production of a variety of crops, vegetables and fruits (Dooge, 2003). Therefore, in poor rural communities where the majority of people have limited resources to cope with the difficulties of weather conditions, cultivation in water catchments provides a coping mechanism through which communities mitigate crop yield losses (McCarthy *et al*., 2001).

The services provided by water catchments contribute to human social welfare (well-being) in many ways (Boyd & Banzhaf, 2007). The provisioning services from water catchments are strongly linked to the access of water and other basic materials for private and social human well-being (MEA, 2005). Water catchments provide water for consumptive use by households, agriculture and industries. The regulating functions of water catchment affect human private and social well-being in multiple ways. For example, the catchment natural vegetation cover serves as sediment filter beds and also facilitates ground water recharging through percolation (Alyward, 2002). In so doing, it reduces sediment loads and run off, hence sedimentation, erosion and floods downstream. Supporting services are critical for sustaining vital ecosystem functions that deliver many benefits to human beings. For example, degrading wastes into important nutrients and purifying water required by other biodiversities that need to be supported by the catchment (De Groot *et al.*, 2002). Finally, the catchment system functioning and services have significant aesthetic, educational, cultural and spiritual values, and provide invaluable recreational and tourism opportunities, thereby influencing the social relation aspect of social welfare (Lele, 2009).

3.5.1. Water catchment vegetation condition and ecosystem services provisioning

The concept of ecosystem condition is crucial in ecological economic modelling. The concept helps in understanding the interlinkage between ecosystem condition and the services provision continuum (Archibold, 1995). The ecosystem services provision continuum helps in quantification of ecosystem–human interaction effects, which is a major challenge in managing complex ecosystems that involve complex trade-offs. In water catchment, this concept is considered as a gateway to fully understanding the impact of management programmes on the trade-offs involved, and hydrological and private economic benefit flows (Naiman *et al*., 1993)

Water catchment vegetation condition is context-dependent; it depends on the preferred ecosystem services from the catchment (Sivapalan, 2005; Beven, 2000). In this way, therefore, there is no standard definition of catchment vegetation condition. However, broadly speaking, catchment vegetation condition is defined as the capacity of a plant community to provide hydrological and ecological goods and services (Wagener *et al.*, 2007; Dooge, 2003). Ecosystem service providers are comprised of populations of different species, functional groups (guilds), food webs or habitat types that collectively produce ecosystem services (Kremen, 2005). As noted in section 3.2.2, the contribution or functional importance of each component to the provisioning of ecosystem services depends on its abundance in the ecosystem (Balvanera *et al*., 2005).

Vegetation type is crucial in water catchment ecosystem functioning. The capacity of water catchments to provide ecosystem services depends largely on the type of vegetation cover. This is due to the fact that not all services are provided by all vegetation types. For example, open savannah grassland may be ideal for reducing runoff, but is poor in water percolation due to shallow root systems (Lele, 2009). Tree forests, on the other hand, may be ideal for facilitating water percolation and reducing surface evaporation from rivers and streams (Lowrance *et al*., 1995). Apart from the catchment's natural vegetation composition, the existing condition (i.e. density) is also crucial in the catchment ecosystem services provisioning. Different conditions of vegetation produce different levels and quality of water catchment ecosystem services. As Yapp *et al*. (2010) put it, "vegetation condition of the water catchment is crucial in its functioning, quality and quantity of services it provides". According to them, rooting depth for example is crucial in nutrient recycling, carbon capture, water percolation, and evaporation regulation capacity of the catchment.

3.6. Water catchments best management practices: the concept and application

3.6.1. The concept of water catchment best management practices

Best management practice (BMP) covers all aspects of natural resource management – not just the land surface, soils and production-based land use, but also nutrient and energy cycling, geology and minerals, soil biota, ecology, biodiversity, land-based native plants and animals, habitat, water balance and cycling, surface and ground water, riverine ecosystems and associated plants and animals, floodplain management and replenishment (Welsch, 1991). The adoption of BMP addresses the impacts arising from human environmentally unsustainable land use practices.

In the water catchment field, best management practices (BMPs) reflect effective, practical, structural or non-structural methods which prevent or reduce the movement of sediment, nutrients, pesticides and other pollutants from the land to surface or ground water, or which otherwise protect water from potential adverse effects of human activities (Reggiani *et al*., 2000). These practices are proactive, and often voluntary, practical methods or practices developed to achieve goals related to a balance between water quality, silviculture, wildlife and biodiversity, aesthetics or recreation, and the production of crops within natural limitations (Todd, 1995).

The situation encountered in various water catchments is that there may be more than one correct BMP for reducing or controlling potential sources of water pollution. Therefore, care must be taken to select BMPs that are practical and economical, while maintaining the integrity of water catchment functioning (i.e. both water quality and the productivity of the catchment land). Understanding of BMPs and the flexibility in their application offers a good chance of selecting water catchment BMPs which are capable of controlling site-specific potential sources of water pollution, and at the same time providing economic benefits to land holders. As noted in Chapter 1, such a mechanism should produce both private and social benefits. The literature cautions that management practices which prove to be less profitable to the bottom line of land holders or other decision makers (at least in the short term) will engender opposition and are less likely to be implemented (Polasky *et al.*, 2005; Robles-Diaz-de-Leon & Nava-Tudela, 1998). BMPs need to be customised for different enterprise mixes, landscapes and soil types, climates, and human social and economic targets (Polasky & Segerson, 2009).

3.6.2. Fruit tree forests

Fruit tree forests are vegetated systems planted on abandoned agricultural lands, river banks or near other bodies of water. Or, as defined by Robles-Diaz-de-Leon and Nava-Tudela (1998), these kind of forests either exist as naturally vegetated areas, or are established and managed by people to protect agricultural land on steep slopes, aquatic river banks, water catchments, wetlands, shorelines, and terrestrial environments from human disturbance. In water catchments, the fruit trees help to control soil erosion and sediment loads going into streams and rivers resulting from human disturbance in a water catchment (Forest Work Group, 1993). These simple and inexpensive practices have become widely used as a means to divert surface water into undisturbed areas before it gains sufficient speed for large soil removal (Webb, 1994; Welsch, 1991). The natural control mechanisms of an undisturbed tree floor work to stop rapid surface water flow, absorb it, and recapture any removed soil. Techniques, such as building water bars and diversion ditches, are BMPs that control surface water flow and help stabilise disturbed forest floors quickly by conserving exposed soil for future vegetative growth (Neitsch *et al.*, 2002). However, these are short-term solutions and are not effective during severe storms. However, fruit trees present long-term solutions with double effects: catchment protection and economic gains from fruit production (Gregory *et al.*, 1991).

Fruit tree planting is increasingly recommended by ecosystem scientists as the best management practices (BPM) in intensive agricultural landscapes characterised by steep slopes and dominated by poor communities (see Lowrance *et al.*, 1995). The literature demonstrates that fruit tree planting on abandoned lands produces both private and public goods and by so doing, addresses the survival needs of poor farmers in developing countries (Lichtenberg *et al.*, 1991). In developing countries where the majority of people are poor and farmers are adamant about implementing BMPs, the fruit trees species that yield benefits within a short period possible will be the solution to these problems (see Swallow *et al.*, 2009; Hurley, 1990; Todd, 1997).

Presently, fruit trees are more often viewed as human-created systems that serve as buffers between croplands and water ways. They naturally carry out ecosystem activities, such as nutrient cycling, and are capable of reducing the delivery of non-point source pollution to streams and lakes by absorbing excess fertilisers and pesticides from agricultural runoff (FWG, 1993). They also have the capacity to control sediments and sediment-borne pollutants carried in the surface runoff. Fruit tree forests are very effective in filtering fine sediments and promoting deposition of sediment during water infiltration (Kundt & Hall, 1988). These forests are able to take up nitrates, sediment-borne phosphorous, and dissolved phosphorous from shallow groundwater moving towards streams (Lowrance *et al.*, 1995).

Fruit tree forests also affect the physical and chemical environment of the catchment, streams and rivers by providing shade, detritus and woody debris. Shade aids in the maintenance of stable stream temperatures and regulates the amount of light that reaches the stream. Detritus and woody debris help modify channel morphology and enhance food webs and species richness (Lowrance *et al.*, 1995). Other benefits from fruit tree forests include such functions as flood peak attenuation and timber production (Odum, 1978; Gregory *et al*., 1991; Naiman *et al*., 1993).

3.6.3. Application of fruit trees as water catchment externalities internalisation land use practice

With the growing need for more land for agricultural production due to rapid population growth, the increased decline of productive land due to climate change and a non-declining dependence on natural systems, mainly water catchments, among poor communities, the application of fruit tree cultivation to protect water catchments is increasingly recommended in areas characterised by the need of land for livelihood. The approach has received great attention worldwide. For example, in China fruit trees are cultivated to produce more food while reclaiming degraded water catchment lands. Twenty million hectares of farmed water catchment lands have been protected by fruit trees, planted as buffer strips or in abandoned lands left to fallow in the warm temperate region of China. Crop yields in these areas are reported to improve by 8.7 %, compared with non-protected areas. In China, fruit trees are grown in shelter belts intermixed with wheat, soybean and peanuts. The fruit tree species planted in the areas have low to no management and in this way satisfy the farmer’s entire needs (see Webb, 1994).

Another example of the application of fruit trees in protecting agricultural landscapes is observed in the coffee plantations of Latin America (Perfecto *et al*., 1996). In these areas, coffee is traditionally grown under a canopy of cacao (*Theobroma cacao*) tree shade. This provides structural and floristic complexity to the plantation and therefore facilitates high biodiversity. Although shaded coffee plantations have lower per acre production yields than sun-exposed plantations, the management costs and the external costs are dramatically lower in the shaded than in the sun plantations, making the overall gains equal to or greater than those of the sun-exposed plantations. Shaded coffee plantations utilise 17 to 23 % less chemical inputs than sun plantations do, which lowers the production costs significantly (Perfecto *et al*., 1996).

Much like the shaded coffee plantation in South America, in North America *Asimina triloba* (pawpaw) is widely used to protect water catchments. The pawpaw fruit tree is uncommon, but the fruit has become popular among organic fruit lovers in the USA. It is native to the eastern North American temperate regions, ranging from the Gulf of Mexico, north to Michigan, and west to Oklahoma (Peterson, 1991). Pawpaws are found in lowland depressions, forested wetlands, and alongside water systems, and therefore the pawpaw tree is well suited to the demands of a riparian forest system (RFS). The shade provided by larger canopy trees would normally cause difficulties for the establishment of fruit-bearing trees, but the pawpaw, having evolved in this type of ecosystem as an understory tree, thrives in low light situations (Davies, 1994). Apart from ecological qualities, pawpaw fruits are nutritious: its pulp is custard-like, sweet and rich; and it is higher in vegetable fat, protein, carbohydrates, fibre, minerals, vitamin C, and food energy than either peaches or apples (Peterson, 1991). All these qualities make the pawpaw tree an ideal choice for fruit trees buffering water catchments found in the temperate regions.

3.7. Concluding summary

The chapter highlighted the concept of ecosystems and has characterised them. It also highlighted the concept of ecosystem services, their classification and interlinkage with human well-being. It is clear from this review that ecosystems have a strong link with human well-being. The understanding of ecosystems, their services and linkages with human well-being provides a practical flexibility in the modelling and evaluation of ecosystem management mechanisms.

Nonetheless, the chapter highlighted the need for treating ecosystems as a special case. It is clear from this review that despite the strong link between ecosystems and human well-being, the past approaches encouraging conservation of ecosystems concentrated on raising the intrinsic value of the systems and largely ignored their social or human functional value (Bockstael *et al.*, 1995). Solving ecosystems management problems using these approaches has always been very difficult (see Hall & Behl, 2006; Dasgupta & Mäler, 2003). Ecosystems understanding provide a practical and flexible approach to ecosystems protection that integrates intrinsic and economic factors in deriving management policies that eventually help in solving ecosystem management problems (Polasky & Segerson, 2009). As noted by MEA (2005), this is a far-reaching, important step when considering the ecosystem management challenges that occur as a result of deriving policies based on one side only.

The chapter also focused on water catchments as ecosystems providers and on the relationship between water catchment vegetation condition and ecosystem services provision. From this review, it is clear that across a landscape, vegetation can be maintained or restored or modified or removed and or replaced to meet the changing needs of society, thus giving mosaics of vegetation types and ‘condition classes’ that can range from intact native ecosystems to highly modified systems. These various classes will produce different levels and types of ecosystem services and the challenge for natural resource management programmes and land management decisions is to be able to take into account the complex nature of trade-offs between a wide range of ecosystem services. We use vegetation types and their condition classes as a first approximation or surrogate to define and map the underlying ecosystems in terms of their regulating, supporting, provisioning and cultural services. In using vegetation as a surrogate, we believe it is important to describe natural or modified (e.g. agronomic) vegetation classes in terms of structure, which in turn is related to ecosystem functioning (rooting depth, nutrient recycling, carbon capture, water use, etc.). This approach enables the accounting for the effect of changes in vegetation as a result of land use.

Finally, the chapter highlighted the concept of water catchment best management practices (BMPs). It also reviewed in detail fruit tree buffers strips as being the best management practice recommended for agricultural landscape management and its application. The review revealed that economically viable best management practices, like fruit tree buffer strips, are less likely to be rejected in developing countries dominated by poor people who primarily depend on ecosystems for their livelihoods. However, the challenge remains in selecting the appropriate technology and policy to help in minimising the trade-offs between this land use and other competing land uses, which suggests that a more comprehensive approach should be designed for this purpose.

CHAPTER 4

REVIEW OF LITERATURE ON ECOLOGICAL ECONOMIC MODELLING

4.1. Introduction

The purpose of this chapter is three-fold: First, to review literature on the concept of ecological-economic modelling, the system dynamic theory, structures and functioning of systems, and how ecological and economic models can be used to understand ecosystems behaviour and their response to human actions and management decisions. Second, to review literature on how to integrate ecology and economics in understanding ecosystems, the motivations behind integrating ecology and economics in studying ecosystems, and the efforts made so far to achieve this purpose. And third, to review various applications of the approach in studying the impacts of various human actions and management decisions or options on ecosystems services flow and human well-being.

4.2. An overview of integrating ecology and economics

Efforts to integrate ecological and economics sciences in understanding and managing human interactions with nature date back to Faustmann in 1849 who integrated ecological and economic models to resolve optimal forest products harvesting problems (Rapport & Turner, 1977). Modern bio-economic models of fisheries came into use in the 1950s with seminal contributions from Gordon (1954), Scott (1955), and Schaefer (1957). Since then, there have been long-standing interests by both sides in using insights from ecological and economic sciences to understand and manipulate human interaction with ecological systems (Turner *et al.*, 2000). For example, microeconomic tools have been used by ecologists to value the ecological changes occurring as a result of human interaction with ecosystems (Polasky & Segerson, 2009). Similarly, ecological models, particularly the growth models and evolution theory, have been used by economists to solve optimal harvesting of natural resources (Tilman *et al.*, 2005; Vermeij, 2004).

In recent years, the world has experienced a rapid decline in ecosystem services due to increased demand for raw materials required to produce consumer goods (Dasgupta, 2008). To maintain the supply of ecosystem services and minimise the costs of getting them, society had to invest in managing ecosystems. As noted in Chapter 1, section 1, the major challenge has always been in designing mechanisms that will not endanger rejection by both ecosystem managers and policy makers. Therefore, the past decade or so has witnessed strong efforts towards integrating ecology and economic sciences in deriving concrete policies for managing ecosystems which do not engender rejection by ecosystem managers and policy makers at national or international level (Drechsler & Wätzold, 2007, Hall & Behl, 2006; Dasgupta & Mäler, 2003). An example of such an effort is the Millennium Ecosystem Assessment (MEA) which was designed to "assess the consequences of ecosystem change on human well-being and to establish the scientific basis for actions needed to enhance the conservation and sustainable use of ecosystems and their contributions to human well-being" (MEA, 2005). The assessment pointed out several key information/knowledge gaps, including the need for better understanding of the interactions between ecosystems and people, and their impacts on ecosystem services supply.

Another example of such efforts is the panel convened by the US National Academy of Sciences (NAS) in 2002 (see Polasky & Segerson, 2009). The panel was composed primarily of economists and ecologists to design methods for assessing the ecological and economic impacts of aquatic and related terrestrial ecosystems management policies. The panel's report, among other things, highlighted the importance of integrating ecology and economics in understanding the impact of management decisions on ecosystem services and social well-being of people interacting with it. It concludes that the ability to capture the impacts of a management option on ecosystem services supply varies significantly across the two disciplines, for at least two reasons. First, the link between ecosystem structure and functions and the resulting provision of ecosystem services is better understood in one discipline than in the other. Second, in practice, some impacts are easier to estimate in one discipline than in the other. These observations make it clear that the quantification of the impacts is more challenging in contexts where there are multiple, interlinked elements that are affected by a particular action or policy (Sundberg & Söderqvist, 2004). In these contexts, therefore, a holistic understanding is important for management decision-making purposes. Integrating the knowledge from the two disciplines can serve this purpose.

Following the establishment of the NAS panel, the US Environmental Protection Agency's Science Advisory Board in 2003 formulated a committee comprised of experts in economics and ecology, engineering, law, philosophy, political science, and psychology (Daily *et al*., 2009). Unlike the NAS panel, this committee was specifically charged with the task of addressing ecological-economic integration needs and opportunities. In its final report to the U.S. Environmental Protection Agency Advisory Board, the committee outlined the importance and the potential of integrating the two disciplines. Specifically, the report highlighted the point that, structurally, the two disciplines have much in common. Both analyse and predict the behaviour of complex, interrelated ecosystems in which the behaviour of individual agents, flows of energy and matter are central, and the dynamics are governed by the allocation of scarce resources among competing agents (Polasky & Segerson, 2009).

Other efforts have gone beyond evaluating the current methods and identifying potential areas where integration can work. For example, in 2006 Stanford University, in collaboration with the Nature Conservancy (NC) and the World Wildlife Fund (WWF), launched a project named the Natural Capital Project (Daily *et al*., 2009). The project had a task of "mainstreaming" ecological-economic models into everyday decisions. The major thrust of the project was to develop an integrated dynamic landscape model capable of predicting how various decisions will affect the joint provision of ecosystem services, species conservation and social welfare.

4.2.1. Motivations of integrating ecology and economics

Interests in integrating ecology and economics stem in large part from four major reasons: First, from the growing concern prompted by the increasing recognition of the scale of the impact of human actions on ecological systems and the services they provide (see Daily *et al*., 2007). These impacts include not only traditional air and water pollution (such as sulphur dioxide emissions, ground water level, ozone, and eutrophication), but also loss of water catchments and wetlands, and reductions in biodiversity (Pegram & Gorgens, 2001; Daily, 1997). The need to understand and address these problems has led to calls for more ecosystem problem investigations that integrate ecology and economics as part of efforts to combat the effects of human actions on ecological processes that are necessary to support the continued flow of ecosystem services (MEA, 2005).

The second reason arises in increased awareness created by publications of the 21st century in the importance of ecosystem services to human welfare and the threat they are facing. For example, the publication of the book "Nature's Services: Societal Dependence on Natural Ecosystems" (Daily, 1997) and an article on "The Value of Global Ecosystem Services" (Costanza *et al*., 1997), both published in the late 1990s, did much to raise the profile of ecosystem services. A further boost was given by the Millennium Ecosystem Assessment (2005) which focused on the link between ecosystems and human well-being. To date, both ecologists and economists see the role of ecosystem services on a more equal footing with other commercial goods and services and hence embrace it as a means of justifying ecosystem protection, not just for its own sake, but also for its contributions to human welfare (Polasky *et al*., 2005; Bockstael *et al*., 1995). Ecosystems provide a range of goods and services of provisioning, regulating, supporting and cultural importance (MEA, 2005). However, most of them have been severely affected by human activities directly through land clearing and harvesting of resources. The MEA (2003) ascertained that 60 % (15 of 24) of the ecosystem services examined had been degraded over the preceding 50 years. Conservation or maintenance of these ecosystems has ecological and economic dimensions (Wätzold, 2006). In this context, deriving management strategies, policies and practices for these ecosystems requires bringing together ecological knowledge and economic analysis (Drechsler & Wätzold, 2007; Shogren & Tschirhart, 2005; Shogren *et al*., 2003).

The third reason arises from the recognition that there is little extant knowledge or understanding about an ecosystem's structure, functioning and response to interaction with other systems it co-exists with. Ecosystems are extremely complex systems whose functions and processes are not easily characterised (Bockstael *et al*., 1995). Particular troublesome issues on attaining sustainable management of such complex systems involve:

a) Unclear descriptions of factors conditioning the response of ecosystems to natural and human stresses. However, there are some levels of understanding that ecosystems structures change through normal succession and evolution, that processes are altered as the structures occur and change, that processes have various temporal and spatial scales, and that catastrophic changes can occur without much evident alteration of structures and processes (Jogo & Hassan, 2010; Costanza *et al.*, 1996; Farber & Bradley, 1996). However, beyond this abstract knowledge, little is known about ecosystem responses to external stresses and actions so as to be confident that we can predict the full range of impacts of human actions on ecosystems. There is a considerable uncertainty regarding the relative importance of various measures of system stocks and flows in quantifying the impacts of human actions on ecosystems and their response, which need further integration of the two disciplines (Polasky & Segerson, 2009; Bockstael *et al.*, 1995).

b) Unclear understanding of the long-term impacts of ecosystem management decisions and practices on ecosystem functioning and human well-being (Costanza *et al.*, 1993). As noted by Pezzey and Toman, (2002) and later reiterated by Daily *et al.* (2009), there is considerable uncertainty surrounding the long-term impacts of human decisions on natural systems, and vice versa. A stream of literature ascertains that because of this, many policies for managing complex ecosystems are crafted with little attention being paid to their multi-scale impacts on ecosystem services flow and human well-being because of meagre understanding of the wider impacts of the policies (Costanza *et al.*, 2004; Turner, 2002; Voinov *et al.*, 1999; Bockstael *et al.*, 1995). The ultimate effect of this has been rejection of many of the practices by land managers and policy makers because they could not meet their economic expectations or expected ecological economic outcomes. As Polasky *et al.*, (2005) put it, "ecosystem management mechanisms or plans that prove to be less profitable to bottom line land owners and policy makers in the long-run will engender more opposition and are less likely to be implemented". Integrating ecological and economic disciplines has been proven to enable the construction of models that simulate the long-term impacts of different human-designed management mechanism, and resolve the dilemma concerning the likely impacts on ecological and social wellbeing (Eppink *et al.*, 2004; Chopra & Adhikari, 2004; Costanza & Gottlieb, 1998).

Finally, from the need to resolve the shortcomings in ecosystems management policy making that arises from ethical differences between ecological and economic sciences (Polasky & Segerson, 2009). The primary source of these differences is twofold: (a) differences in views on the sources or nature of value and (b) differences in views on the social choice rule that should be used to rank management outcomes (Drechsler & Wätzold, 2007), which are crucial in ecosystem management decision making. Economists define value in terms of trade-offs that individuals are willing to make, while ecologists recognise an intrinsic value of nature that is not defined in terms of trade-offs (Paulsen, 2007). Economists are also more concerned about human well-being, while ecologists are more concerned about conserving natural systems (Dasgupta & Mäler, 2003; Farber & Bradley, 1996). The flip side of this is that scientists from both sides have been neglecting important facts from each discipline. A stream of literature ascertains that economists have been taking the pragmatist's view, disregarding ecological elements which they do not understand or cannot measure, no matter how important, while ecologists on the other hand have been taking the purist's view, taking into account only the biological aspects and disregarding the role of biological–human interaction on human welfare (Shogren *et al*., 2003; Turner *et al*., 2003; Schuijt, 2003).

What is clear from these differences is that although both ecologists and economists use models to study ecosystem problems and derive management policies, each discipline perceives the problem in its own way and comes up with its own most appropriate solution (Hall & Behl, 2006*)*. This has resulted in a body of research work on ecosystem problems completed by both sciences that overlooks the fundamental problems associated with interactions of the ecosystems with people (Paulsen, 2007; Wätzold *et al*., 2006; Bockstael *et al*., 1995). As noted in Chapter 3, section 3.3, ecosystems co-exist with human systems and have strong direct and indirect linkages. From this point, it is not at all clear how one discipline can come up with concrete policy advice when it does not take into account the fact that ecosystems and humans co-exist. This implies that both economic and ecological models are less than useful in terms of leading to the right policies when they stand alone in designing policies for managing ecosystems. To hurdle the problems created by the existing ethical differences, integrated ecological-economic modelling has proven to bridge the gap between the two disciplines, as it incorporates the ecological and economic models (knowledge) to analyse the interaction between ecosystems and humans and subsequently derive management policies (Polasky & Segerson, 2009; Farber *et al*., 2006; Cox, 2005; Turner *et al*., 2000).

4.3. The concept of integrated ecological-economic modelling

Integrated ecological-economic modelling is a modelling system based on system dynamic theory developed by Forrester in the 1950s to understand the dynamic behaviour of complex ecological systems and their response to interaction with other systems (Farber *et al*., 2006; Cox, 2005; Costanza & Ruth, 1998). The approach integrates the ecological and economic models to derive concrete management policies and predict their future impacts on ecosystems structure, functioning and services flow (Susanna & Chen, 2002). It employs the ecological knowledge about the ecosystems' structure, functioning and response to interaction with other interconnected systems to study the behavioural pattern of the systems over time and quantify the impacts of the interaction (Farber *et al*., 2006). The approach employs the economic knowledge to give economic value to the impacts and interpret the economic implications of the systems' response to interaction with other systems (Polasky & Segerson, 2009).

Apart from employing models from the two disciplines to quantify the response of ecological systems to interaction with other systems, the approach exploits the advantage of being able to link different elements that build the system into a single model (Eppink *et al*., 2004; Costanza *et al*., 2002; Gambiza *et al*., 2000). Systems are composed of elements which are tightly interwoven into one system with direct interactions and feedbacks between them (Costanza & Ruth, 2001; Low *et al*., 2001; Costanza & Gottlieb, 1998). To study and quantify the behavioural response of complex systems upon interaction with other systems over time, the model employs stocks and flows (Richmond *et al*., 2010; Morecroft, 2007). These features give the model the ability to predict the future state (or response) of the systems under a given management or treatment option (Nelson *et al*., 2009; Iwasa *et al*., 2007; Antle & Stoorvogel, 2006; Nalle, 2004; Hart, 2003).

For natural systems, the model takes into account the impacts of the interaction between the systems and human component on the ecological services flow and socio-economic benefits (Tilman *et al*., 2005). It is also used to account for the impacts of different human-designed ecological (or natural) systems management policies on ecosystem services supply and social well-being (Polasky *et al*., 2005; Costanza & Gottlieb, 1998). To take into account the links between the natural system and the socio-economic system, the two systems are usually integrated as modules of the models (Costanza & Gottlieb, 1998; Costanza *et al*., 1993). Different equations are used to describe the dynamics of stocks in the system, together with equations specifying relationships between flows (e.g. human consumption of ecosystems services such as abstraction of water) and other elements of the system. The totality of the equations constitutes the structure of the model that simulates the functioning process of a system (Jogo & Hassan, 2010). It is on these premises that the integrated ecological-economic modelling is referred to as the holistic approach (Meadows, 2004).

4.3.1. The system dynamic theory

Natural systems are complex, made up of series of interconnected elements that depend on each other such that a change in one element subsequently impacts on the functioning and response of other elements in the system (Dunne, 2005; Meadows, 2004). In many cases, these systems have taken people by surprise by the way they respond to various interactions (Costanza *et al*., 2011; Nelson *et al*., 2009). As pointed out by Ackoff (1979), systems complexity not only leads to surprising outcomes, but also to dynamic outcomes that make it difficult to predict the future trends of the system's behaviour. To manage such systems, we need to understand the way they work with, or respond to, various interactions over time (Egoh *et al*., 2008; Randers, 1980; Meadows *et al*., 1972). The system dynamic theory provides ecological and economic scientists with important insights essential for understanding complex ecological systems, hence allowing them to derive concrete management policies (Cox, 2005).

The theory not only aims at understanding how complex natural (ecological) systems respond to interaction with other systems, but also redesigning the socio and economic systems so that they co-exist and sustain each other in a sustainable manner (Arrow, 2000). More specifically, it aims at answering questions like why are systems so dynamically complex? What changes would make them less prone to sudden and catastrophic decline? In addition, how will such changes affect the flow of benefits among beneficiaries? (Crépin, 2002; Sophie, 2002; Mass & Senge, 1975). The theory combines the methods and the philosophy needed to analyse the behaviour of systems in not only management, but also in environmental change, politics, economic behaviour, medicine, engineering, and other fields (Meadows *et al*., 2002). It provides a common foundation that can be applied wherever and whenever we want to understand and influence the way systems behave over time (Rwashana & Williams, 2008).

4.3.1.1. Definition of system

The term system has been defined differently by different disciplines. For example in biological science, a system is a set of organs interconnected to perform a certain function (e.g. the digestive system) (Fisher *et al*., 2011). In engineering science, a system is a set of components linked together to perform a certain function (e.g. a car's fuel system) (Bossel, 2007). In the natural world, a system is a collection of different natural elements linked together to produce natural goods or services (Costanza *et al*., 2002). Richmond (2004), describing a natural system, pointed out that "a natural system is not just collection of things (or elements), but it is a collection of elements that are self organized such that exhibit adaptive, dynamic, goal-seeking, self-preserving, and sometimes self-regeneration behaviour".

Elements that make a system are either tangible (physical) or intangible and a single system can have both (Fisher *et al*., 2011). Normally, intangible elements are chemical and in a system they play the role of connecting or holding the system together (Fisher, 2007). For example in a tree system, there are specialised cells that process and relay information throughout the plant, vessels carrying fluids up and down, and chloroplasts that link the root and the rest of the tree system. The information processed by specialised cells is intangible, but it plays a crucial role in connecting the elements that make the tree. Similarly in water catchments, there are elements which are not tangible, but play a great role in the functioning of the system. Describing water catchment system structure, Santhi *et al*., (2006) identified micro-flora and micro-fauna as intangible elements of a system, but they play a great role in purifying water by degrading BODs and CODs in water.

On the other hand, tangible elements of the system are physical ones that one can see and feel them by touching (Sherwood, 2002). For example in a water catchment system, tangible elements includes land, and streams flowing on it towards a single outlet (constituting the hydrology), natural vegetation (natural plants constitute the ecology), and human beings (constituting the social element) (Santhi *et al*., 2006). These elements are interconnected and self-organised in such a way that they collect water from precipitation and slowly release it through streams which eventually join into a river (a defined pattern) to an outlet downstream (also see Sivapalan, 2005). Destroying the natural vegetation canopy, therefore, reduces the capacity of the system to hold water from precipitation and slowly release it downstream. This not only affects the micro- and macro-flora and fauna living in the catchment, but also the water flow pattern, its quantity and quality, and other biodiversity downstream (Arnold & Williams, 1995).

What is evident from all the definitions and the rest of the descriptions of the systems above is that a system must consist of four major things; *elements*, *interconnections*, *self-organisation* and a *function or purpose* (Richmond, 2004; Meadows, 2008), which implies that a system is a whole thing with inter-depending elements linked together such that adding or taking away one element can destroy or weaken it (Sophie, 2002). It is also evident that systems are made up of elements that either tangible or intangible and that are coherently organised in a way that achieves something (Richmond *et al*., 2010).

4.3.1.2. Structure and dynamism of ecosystems

As noted in section 4.3.1.1 above, natural (or ecological) systems are comprised of interconnected elements, which co-exist with other systems. The response to interaction with other elements or interconnected systems, which is dynamic, depends on the structure and level of interconnection (or intricacy) between the elements making the system. As Morecroft (2007) puts it, “what determine the system response to interaction is the raw number of elements and the level of intricacy which bound the system together”. According to him, the number of elements and intricacy determine the time delays, the pace of the processes of stock accumulation and decline, the non-linearity (such as hump-shaped) relationships between element interactions, and number of feedback loops. In other words, the dynamism of natural systems stems from the number of elements and connections that bind together the elements of the systems, such that when a change happens in one element of the system, sooner or later it will have implications on others, and vice versa (Richmond *et al*., 2010; Foschani *et al*., 2000).

Systems' functioning and response to various actions around them not only depend on number of elements and the level of intricacy, but also on internal or external factors that affect the level of elements' stock (Hart, 2003). A system stock is just what it sounds and is not necessarily a physical one (Fitz *et al*., 1996). It can be a store, a quantity, or an accumulation of material such as population, biomass, nutrients, and water in a ground or reservoir, or one's self confidence, or reserve of good will toward others, or supply of hope that the world can be better (Costanza *et al*., 1993). Systems differ in the number of stocks, depending on how complex the system is; simple systems have one stock, while complex ones tend to have more than one stock (Meadows, 2004).

The pattern and rate at which systems change over time are determined by variations in levels of stocks over time (Margolis & Naevdal, 2008). Stock levels change over time through the actions of flow and these can be anything such as filling and draining, births and deaths, growth and decay, deposits and withdrawals (Morecroft, 2007). Stocks change depending on the action(s) the system is subjected to and these actions either add to or reduce the stock level (Meadows, 2004; Costanza *et al*., 2002). Changes in stock levels are caused by factors from within the system, such as self-structuring (or producing new structures), or from interaction with other systems. For example, human interaction with ecosystems is either direct through consumption or indirect through use of the ecosystems for production of consumer goods (Polasky & Segerson, 2009). Changes in stocks set the pace of dynamisms and the momentum of systems' change. Different systems have different paces of dynamisms; some change faster and others slower, with high and low momentum, respectively (Meadows, 2004). The momentum of system change determines the functioning, magnitude of the outcomes, and stability of a system (Richmond, 2004).

Understanding the rate of stock changes is crucial in understanding the response of systems to various interactions over time. Individuals and institutions make ecosystems management decisions that affect the levels of stocks by either raising, or lowering, or keeping them within acceptable ranges (Polasky *et al*., 2005). As Morecroft (2007) puts it, "basically different ecosystem management policies and practices influence ecosystems stock flow by adding up to the ebbs and flows, successes and problems of all sorts to the systems". Based on this fact, system thinkers see the world as a collection of stocks along with the mechanisms for regulating the levels of the stocks by manipulating flows (Jogo & Hassan, 2010; Canadell & Raupach, 2008; Costanza *et al*., 2002).

4.3.2. How the system runs itself: the feedback loops

As noted in section 4.3.1.1 above, systems are organised in such a way that they perform a certain function or have a defined pattern. For a system to be able to perform a certain function or have defined pattern, its elements must be interconnected and coordinated. In systems, interconnections are either direct (physical) or through chemical reactions (Meadows, 2004). Connections play a crucial role of holding together the elements and governing various processes and responses in a system (Laszlo, 1996). On the other hand, a system's behavioural pattern is coordinated. In natural systems, this is evident with the way these systems behave over time. For example, when stocks grow by leaps and bounds, decline swiftly, or are held within a certain range, it gives a clear message that there is a control mechanism at work (Forrester, 1990). In other words, if you see a system behaviour that persists over time, there is a mechanism which creates that consistent behaviour. The consistent behavioural pattern over a long period of time is the indicator of the existence of feedback loops (Jogo & Hassan, 2010; Richmond *et al*., 2010; Farber *et al*., 2006).

A feedback loop is a closed chain of causal connections from a stock, going through a set of decisions, rules, physical laws, or actions that are dependent on the level of stock, and back again through a flow caused by change in a system's stocks level (Richmond *et al*., 2010). Changes in stock level affect the flow into or out of that same stock, and in so doing create a flow of stocks from one point to another (Meadows, 2004). As noted by Senge *et al*, (2008), some feedback loops are quite simple and direct, but others are complex and elegant. However, whether simple or elegant, feedback loops play a massage-relaying role in a system (Morecroft, 2007). For example, in a water catchment the quantity and quality of water flowing downstream has a direct feedback loop that relays a message on what is happening in the catchment that affects the surface flow, hence the level of ground water (the stock), which determines the amount and quality of water draining downstream over time (Nobre *et al*., 2009). Feedback loops, therefore, are crucial in complex systems management decision making. They send messages or signals of the situations that influence the responses of other elements, which are important for adjustment or regulation decision making.

4.3.2.1. Types of feedback loops

Dynamic system scientists categorise the feedback loops into two groups, based on the information links they provide in a complex system (Homer & Hirsch, 2006; Meadows, 2004; McDonnell *et al*., 2004). The first group includes the stabilising (balancing) feedback loops: in dynamic systems stocks are not fixed, but sometimes they stay within an acceptable range and this is brought about by stabilising feedback loops (Morecroft, 2007; Gunderson & Holling, 2002; Woodwell, 1998). Stabilising loops are equilibrating structures in the systems and are both sources of stability and resistance to change (Newman *et al*., 2003). Although they bring or maintain system stability, these loops work as stimulants that only stimulate the system to continue functioning in a normal way for some time, without refilling the stocks (Richmond *et al*., 2010). Therefore, these loops normally leave the system with stock deficiency than it was before after the disturbance has ceased.

The second group includes reinforcing (or runaway) feedback loops which are commonly found in natural systems with the ability to regenerate out of themselves or collapse overtime (Meadows, 2004). Reinforcing loops are self-enhancing, leading to exponential growth or collapse of the systems' stocks overtime (Richmond *et al*., 2010). They relay messages for the system to generate more input to system stocks. The process and magnitude of regeneration depend on the level of stock that is present at a given time (Morecroft, 2007). The more the stock, the more inputs are available for regeneration, and vice versa (Rwashana & Williams, 2008).

Systems complexity is also determined by the number of feedback loops the system possesses at a time (Costanza *et al*., 2002). Based on this, systems are therefore classified as simple or complex systems (Homer, 1993). For example in natural systems with the ability to regenerate themselves, if natural growth and natural death are the only forces governing the natural system (which is very rarely the case in real natural systems), then the system is said to be simple, and vice versa (Richmond, 2004).

In water catchments, these loops can be observed between natural vegetation, human and economic elements (or components). The density of natural vegetation has both a reinforcing loop, causing it to grow through its natural growth rate, and a balancing loop, causing it to die off through its natural mortality rate and mortality caused by human actions (see Figure 3.1) (Meadows, 2004). In this simple case, the density will depend on which force is stronger than the other; if the natural growth is stronger than the natural mortality human actions, the density will be high, and vice versa.

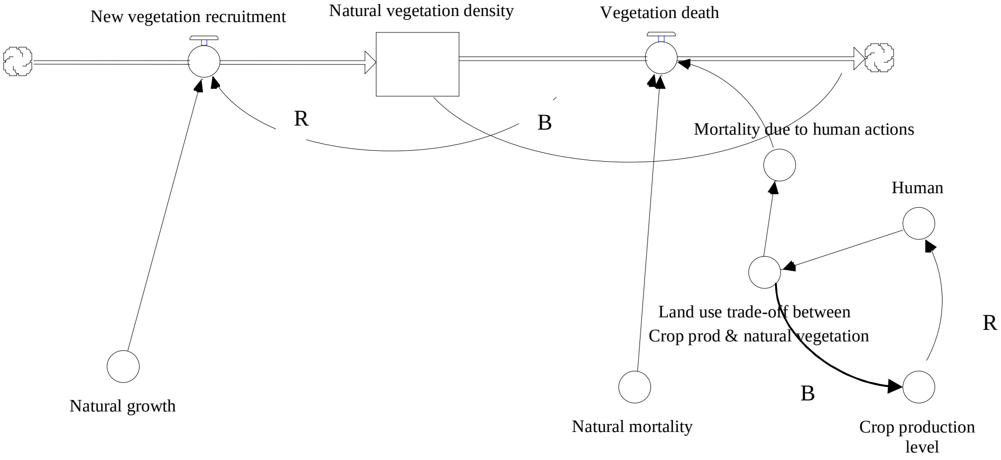

Figure 4.1: Natural vegetation density governed by reinforcing and balancing loops of new recruitment, deaths, land use trade-offs and crop production level (adopted from: Meadows, 2004).

The presence of human interference adds to the mortality rate, resulting in greater death of natural vegetation. Human needs for land to grow crops induce land use trade-offs, which eventually alter the habitat of natural vegetation, thus causing human-induced mortality to natural vegetation (Jogo & Hassan, 2010; Güneralp & Barlas, 2003). This is triggered by a reinforcing loop originating from crop production; when the volume of crop output goes down, a message is sent to land owners (human element) that the land is declining in productivity (Robles-Diaz-de-Leon & Nava-Tudela, 1998), and in turn land owners respond by clearing more natural vegetation for the purpose of maintaining the level of output (see Figure 3.1). New available land increases production, and when this happens, a message is sent to the producers and they reduce clearing the natural vegetation. Intensive clearing of natural vegetation for farmland reduces the level of natural vegetation stock, which in turn affects the regeneration (or recruitment) of natural vegetation (see figure 3.1). As less new plants are regenerated, fewer roots are being formed to hold the soil together and facilitate water percolation, and this results in more soil erosion during rain and shorter water flow towards downstream after rain (Mango *et al.*, 2011).

The susceptibility of system stock level to various human manipulations (alterations) as described in this section (i.e. 4.3.1.2) and the existence of feedback loops which govern the system response to these alterations were included in this study as system response characteristics to test the impacts of different human manipulations on hydrological, private economic and social benefit flows from water catchment systems.

4.4. Application of integrated ecological economic modelling

The application of integrated ecological-economics models in evaluating the impacts of ecosystem management approaches on ecosystem functioning, services supply and human well-being has grown significantly in recent years. The approach has been widely used in marine and fresh water fisheries (see Nobre *et al.*, 2009; Güneralp & Barlas, 2003; Grosso, 1998), coastal ecosystems (Nobre & Ferreira, 2009), wetlands (Jogo & Hassan, 2010; Chopra & Adhikari, 2004; Eppink *et al.*, 2004), forests and woodlands (Portela & Rademacher, 2001; Gambiza *et al.*, 2000) and water catchments (Costanza *et al.*, 2002; Robles-Diaz-de-Leon & Nava-Tudela, 1998).

4.4.1. In fresh water and marine fishery resources management

Nobre *et al.* (2009) developed an ecological-economic model that attempts to understand the sustainable management of mariculture in the China Sea. Their model consisted of three components: (i) the ecological component for accounting for the impacts of system elements interactions, biogeochemistry and the growth of aquatic resources; (ii) the economic component for accounting for the impacts of economic drivers on production decision on sustainability of aquaculture; and (iii) the decision component for accounting for the impacts of the desired production in the next production cycle on the sustainability of aquaculture. The model was then used to simulate and test different management scenarios. The study simulated three scenarios: change in price growth rate; change in per capita income growth rate; and change in maximum cultivated area. The study revealed that the area available for aquaculture production was a limiting factor in both the short-run and the long-run, even though demand for aquaculture products is increasing, implying that reducing the maximum cultivation area as one of the conservation measures will result in the reduction of the net profit to farmers. The study also found that compensating farmers through output price for the reduced maximum cultivation area led to an increase the net profit. Finally, the study revealed that increase in price and per capita income both increase farmers' net profits and demand for area. The study concluded that ecological-economic models are strong in predicting the impacts of management policies on ecological and economic benefits flows. The study also recommended that, although the model provides strong insights on how best to manage mariculture ecosystem, further developments are needed to include as many simulation scenarios as possible to identify concrete management options.

Güneralp and Barlas (2003), working on a shallow freshwater lake ecosystem which was under high nutrient loads and hence eutrophic with macrophyte dominance, also applied the approach to simulate the impacts of potential externalities internalisation policies on ecosystem services flow and social well-being. The goal of the study was to find a balance between the ecosystem and economic activities of the communities living around the lake. The model consisted of three modules: (i) the lake ecosystem module, which further consisted of four sub-modules; hydrology, nutrients, chloro-zooplankton-macrophyte, and fish and crayfish to account for impacts of policies on the lake ecosystem balance and functioning; (ii) the economic activities module to account for the impacts of policies on economic activities (i.e. fishing, agriculture, and industry) and the lake ecosystem; and (iii) the social structure module to account for the impact of policies on the social well-being of the community living around the lake. The study simulated the impacts of introducing healthy crayfish to overcome the fungal disease prevailing in the lake; constructing a dam to regulate the fluctuation of the level of the lake which had created a problem of rapid growth algae during the dry season due to the sun reaching the bottom of the lake; improving tomato productivity per acre (i.e. 30 %

increase in tomato yield per acre); and clearing macrophytes from the bottom of the lake. The study revealed that the dam construction and clearing macrophytes would significantly reduce the threat of a shift to algal dominance in the near future. It also revealed that the introduction of health crayfish would stabilise the fish population. However, it was found that these results would be achieved at the expense of social well-being. On the other hand, the improved agricultural techniques were observed to lead to better social conditions as they increased yield per hectare, and hence the income accrued to farmers. However, this could not solve the problem of the decline in the welfare of the inhabitants, and this was found to be caused by an unsustainable population increase. The study concluded that ecological-economic models can serve as a laboratory to study the different features of the eutrophication problem in shallow freshwater lakes and to analyse the impact of different policy alternatives.

Grosso (1998) constructed an integrated ecological-economic model for mangrove systems in coastal Brazil, focusing on the trade-offs between forestry and fishery production. The main thrust of the study was to study the relationship between the two activities and find a better way that could help to manage the mangrove ecosystem in order to maximise its economic benefits, and at the same time preserve ecosystem services. She developed a model consisting of two major models, i.e. the biological and optimisation models. The biological model consisted of five modules: (i) the fishery module for accounting for the fish population dynamics in the ecosystem, (ii) the fishing revenue module for accounting for the revenue accrued from fishing activity, (iii) the ecosystem module for accounting for the effect of factors that determine the development of mangroves ecosystem, (iv) the forestry module for accounting for the dynamics of forest tree population, and (v) the human activities module for accounting for the effect of ecosystem use decision. The output of the biological model was used in the optimisation model to find shadow prices for the resources. Forest growth rates turned out to be the most important variable, since fishery production in this area is directly dependent on the mangrove forest. The study concluded that an integrated ecological-economic model is useful in generating information for optimising the use of complex ecosystems with multiple benefits, like mangrove forests.

4.4.2. In forests, woodlands and landscape management

Polasky *et al* (2005) employed the approach to analyse the consequences of alternative land-use patterns on the persistence of various species and on market-oriented economic returns. They developed an ecological-economic model that used the habitat preferences, habitat area requirements, and dispersal ability for each species to predict the probability of persistence of that species, given a land-use pattern. The model also used characteristics of the land units and locations to predict the value of commodity production, given a land-use pattern. The model was used to search for efficient land-use patterns in which the conservation outcome could be improved without lowering the value of commodity production, the results of which were then compared by reserve-site selection (commonly known as ecological models). Three alternative land uses, i.e. managed forestry, agriculture, and biological reserves (protected areas) were used to analyse the consequences of alternative land-use patterns on the persistence of various species and on market-oriented economic returns. Their model consisted of two modules: (i) the biological module for predicting the persistence of a large suite of species, given a land-use pattern, and (ii) the economic module for predicting the present value of commodity production for a given land-use pattern. The study simulated four scenarios as follows; the minimum amount of area needed for breeding, the half saturating carrying capacity (*k*), the power of growth (*g*), and changing the number of breeding pairs. Based on the Willamette Basin in Oregon (USA), the study found that a large fraction of conservation objectives can be achieved at little cost to the economic bottom line with thoughtful land-use planning. The study also found that the degree of conflict between conservation and economic returns becomes much lower by using a joint biological and economic modelling approach than by using a reserve-site selection (or ecological models) approach, which assumes that species survive only inside reserves and that economic activity occurs only outside reserves. The study then concluded that an integrated ecological-economic model is very strong when it comes to capturing multi-scale impacts of management options, rather than on site models.

Van Beukering *et al.* (2003) also constructed an ecological-economic model and subsequently employed it to predict the consequences of alternative management options (i.e. deforestation versus conservation and selective use) on ecosystem functioning, ecosystem services supply and the distribution of economic benefits among the main stakeholders and regions involved in conserving the Leuser National Park in Sumatra Indonesia. The model consisted of four modules: (i) the deforestation drivers module to depicts effects of basic social, demographic and economic processes on deforestation; (ii) the land use module to deal with transformation rates of land between the two competing uses; (iii) the ecosystem services module to depict the impact of transformation on the four major ecosystem services (i.e. climate regulation, erosion control, nutrient cycling, and species diversity); and (iv) the species diversity module to capture the effect of trading the land between the two uses on species diversity. Ecosystem services considered in the model included water supply, fisheries, flood prevention, agriculture and plantation, hydroelectricity, timber and non-timber products, tourisms, biodiversity, fire prevention, and carbon sequestration. The study revealed that conservation of the national park spreads the benefits equally among all stakeholders and therefore prevents potential social conflicts, while the deforestation widened the income gap between the rich and the poor. The study concluded that the ecological-economic method had proven to be a strong and useful tool in the analysis of complex systems with multiple beneficiaries.

Costanza *et al.* (2002) employed the method to understand the way regional landscapes operate, evolve and change with human interaction in the Patuxent basin in Maryland, USA. Their model was comprised of six modules: (i) the hydrological module for taking into account a variety of hydrologic functions controlled by physical and biotic processes, (ii) the nutrient module for tracking the effect of nutrients (phosphorous and nitrogen) on natural plant growth, (iii) the plant module for tracking the plant biomass (i.e. macrophytes in aquatic environment, trees in forests, crops on agricultural land, and grasses and shrubs on grass land), (iv) the human module for accounting for the effect of human interaction with the ecosystem, particularly individual agronomic practices, (v) the spatial module for combining the dynamics of the unit model calculated at each time step for each cell in the landscape, and (vi) the economic land use conversion module for calculating the probabilities of land conversion from forest or agriculture to different densities of residential use. The range of 18 scenarios included (1) historical land-use in 1650, 1850, 1950, 1972, 1990, and 1997; (2) a build-out scenario based on fully developing all the land zoned for development; (3) four future development patterns based on an empirical economic land-use conversion model; (4) agricultural best management practices that lower use of chemicals such as through fertiliser application; (5) four replacement scenarios of land-use change to analyse the relative contributions of agriculture and urban land uses; and (6) two clustering scenarios with significantly more and less clustered residential development. The authors found that the integrated ecological economic model is a strong tool for understanding the response of the complex landscape under complex development. The study also revealed that spatial information is crucial in understanding the special impacts of landscape development decisions. The study concluded that for understanding complex special landscapes, there is a need to include as much special information as possible in modelling.

Portela and Rademacher (2001) also employed the model to investigate the consequences of trading forest land between farming and ranching uses in the Brazilian Amazon forests. They developed an integrated ecological-economic model with three modules: (i) the deforestation drivers module for depicting the effect of social economic divers on forestry clearing; (ii) the ecosystem services module for quantifying the impacts of land use change on forest ecosystem cervices; and (iii) the ecosystem valuation module for calculating the economic value of changes in forest ecosystem services. The key ecosystem services considered in the model were: hydrological regulation, nutrient cycling, carbon sequestration, and species diversity. The losses in the value of ecosystem services between farming and rangeland management were compared to the forest reference value, which was based on a global average value of forest ecosystems, to find the net welfare impact of land use practices. The study revealed that there are significant losses in the value of ecosystems under farming and rangeland management regimes, compared with the forest reference value. The study concluded that the model had proven to be effective in comparing ecological and economic impacts of different ecosystem management practices.

Another example is that of Gambiza *et al*. (2000) who applied the approach to examine the ecological and economic impacts of changing stock rates, tree removals, fire regimes and woodland structures for the Miombo woodland ecosystem in Zimbabwe. They developed an ecological-economic model with five interactive modules: (i) the rainfall module for depicting the effect of annual rainfall on vegetation cover growth; (ii) the grass production module for depicting grass production; (iii) the fuel load module for capturing fuel production; (iv) the fire occurrence module for capturing the probability of bush fires occurring; and (v) the tree dynamics module for capturing the variation of tree population in the forestry. The model assumed that tree population varies with natural mortality and commercial harvesting for timber. The economic impacts of alternative woodland management options were explored by comparing the net present values occurring to the state authority that manages the forest and community using the forest. Upon calibration, the study marked the ecological response upon manipulation of the level of grazing. The impacts on economic performance were found to be at a minimum and the net present value (NPVs) for forestry commission in particular remained relatively constant under different management options.

4.4.3. In wetland management

The application of ecological-economic modelling to model the behavioural response of ecosystems for different management options has also gained prominence in wetland ecosystems. Most recently, Jogo and Hassan (2010) developed an ecological-economic model based on the system dynamics framework and applied it to simulate the impacts of alternative management policy regimes on wetland functioning and economic well-being in Limpopo wetlands in South Africa. Their model consisted of five modules: (i) the hydrological module to account for effects of alternative management regimes on ground water level; (ii) the crop production module to account for effects of the alternative management regimes on the economics of crop production in the area; (iii) the land use change module to account for the effects of the alternative management regimes simulated on land use trade-offs in the area; (iv) the natural wetland vegetation module to account for the effects of the alternative management policy regimes on natural wetland vegetation; and (v) the economic well-being module to account for the impact of the management regimes on social well-being of the community living in the catchment. The authors found that wetland services (crop production and natural resource harvesting) are inter-linked with trade-offs involved through their competition for labour, land and water resources. They also found that although they significantly achieve the conservation goals, pure conservation strategies impose significant losses on communities living around, and depending on, the wetland for their livelihood. Finally, they found that diversifying livelihoods out of agriculture simultaneously improves economic well-being and enhances wetland conservation. The study concluded that policies that support livelihood diversification into off-farm livelihood opportunities for rural poor are critical for sustainable wetland management.

Chopra and Adhikari (2004) developed an ecological-economic model and subsequently applied it to simulate the effects of alternative managements on ecological health and incomes derived from a wetland ecosystem in Northern India. Their model was comprised of four modules: (i) the water module for monitoring the state of the wetland; (ii) the biomass module for examining factors impacting on biomass and changes in it; (iii) the birds module for monitoring the factors impacting on bird inflow and outflow and their impact on tourism arrival; and (iv) the net income module for summing up the impact of changes in each of the preceding modules on income from tourism and resources extraction. Upstream agricultural activities were assumed to cause pressures that affect stock of water and biodiversity (biomass and birds), which in turn determine the ecological health and hence the amenity value of wetland. The number of tourist visits to the wetland was considered to be a function of the ecological health of the wetland. The sensitivity of tourist visits to the wetland ecological health indices were derived through simulation scenarios with respect to future pressures on wetland. The study found that the tourist visits to the catchment were sensitive to the conservation efforts; they increased with higher values of ecological health indices, indicating thereby that conservation management options increase the attractiveness of the park above a certain level and hence the income. They concluded that direct and indirect income obtained from the wetland is positively related to the ecological health of the wetland, demonstrating a positive incentive to conserve the wetland. The study also demonstrated that the model can be used to identify management policies which create incentive for conservation of natural ecosystems.

Eppink *et al.* (2004) also developed an ecological-economic model to evaluate the impact of urban growth and agriculture on wetland biodiversity. The model was comprised of four modules: (i) the land accounting module for accounting for the impact of conversion of land to urban and agriculture over time; (ii) biodiversity changes module for accounting for the impacts of land use change on biodiversity; (iii) the land use decision module for describing the process that leads to decisions on urban expansions over time; and (iv) the social evaluation module for accounting for the impact of scenarios on social welfare. The model was used to simulate the impacts of different population, agricultural and urban growth scenarios on wetland biodiversity and social well-being. The study revealed that land use affects species numbers of both plants and animals, and furthermore has an impact on species composition. The study concluded that although the model was applied to a small landscape, it proved to be effective in improving our understanding on how economic development affects biodiversity through various channels.

4.4.4. In water catchments

There has been limited application of ecological-economic modelling in evaluating the hydrological, private economic and social benefits flow of upstream land use externalities internalisation options. Apparently, one study by Robles-Diaz-de-León and Nava-Tudela (1998) attempted to develop a dynamic ecological-economic model and subsequently apply it to evaluate the possible economical gains from applying *Asimina triloba* (pawpaw), a native North American fruit, in eternalising land use externalities in water catchments. The interest in this fruit stems from a deeper environmental problem arising from increased pollution in the Chesapeake Bay Water catchment. Different actions had been taken in order to control and restore its environment and among such actions were the building and maintenance of riparian forest buffer strips. However, farmers had been resistant to implementing these approaches because land would have to be taken out of production, thus incurring an economic loss. The authors applied the model to investigate the likely economic gains accruing from applying pawpaw as riparian buffer strips. Their model comprised three modules: (i) the reproduction module to account for the life cycle of the pawpaw; (ii) the fruit productivity module to account for factors influencing fruit productivity and harvesting of pawpaw; and (iii) the profit flow module to account for the economic gains and costs of having pawpaw buffers strips. Three biological scenarios and four economic scenarios were tested in the model, and the study revealed that the approach enhances farmers' private economic benefits, if associated with input tax cuts and subsidies. The study concluded that to encourage land users, there is a need to reduce input taxes and subsidise farmers practising the cultivation of fruit tree buffer strips.

4.5. Concluding summary

This chapter started by highlighting the motivations behind integrating ecology and economics in studying ecosystems. The lack of scientific understanding of the processes involved in producing ecosystems services and the continuing disagreement between economic and ecological scientists on the sources of values of ecosystems services have been identified as the some of the key factors that motivated the integration of the two disciplines for understanding recent ecosystem management problems. Equally important, the recognition of the important role that ecosystems play in providing goods and services that contribute to human well-being and the impacts human actions have on ecosystems functioning have also motivated the integration of the two disciplines.

The experiences we elucidate from the review show that what appear to be the deep-rooted ethical and theoretical differences between the two disciplines with regard to a more general goal of ecosystem management decision making can be reconciled, if we understand fully the specific nature of human interactions with ecosystems and how these interactions induce subsequent reactions as they unfold in the long term. It should be noted that although there are differences in the dynamics of ecological and economic systems in the long-time horizon, both disciplines make the best use of the integrated model to simulate future trends (Shogren & Tschirhart, 2005; Shogren *et al*., 2003). Nevertheless, both ecologists and economists are interested in understanding the long-term implications of human actions on ecosystems (Bockstael *et al*., 1995). Therefore, integrating ecology and economic models appears to be the solution through which we can achieve this goal.

In addition to these, the chapter reviewed the efforts carried out so far to integrate the two disciplines. It is clear from the literature that many efforts have been put forward at international level and regional level to integrate the two disciplines. At international level, a good example is set by the Millennium Ecosystem Assessment (MEA) Report which suggested that the current ecosystem problems need multidisciplinary and multi-scale approaches to assess and craft policies to combat them. Similarly, a good example of a regional level effort is set by the USA and WWF which have differently brought scientists together from ecology and economics for finding solutions to ecosystem management problems.

After surveying the motivations and efforts to bring together ecological and economic knowledge for understanding and deriving concrete policies for managing ecosystem services, the chapter proceeded with highlighting the concept of ecological-economic modelling and the theory behind it. It is clear from the review that the approach is system modelling, based on system dynamics theory. It employs the theory to provide insights on the interactions and responses to interactions with human and other natural systems of complex ecological systems. It uses the theory to provide insights of ecological system responses to the interactions and the impacts of the responses to human well-being. The chapter proceeded by highlighting the concept of dynamic systems by bringing the insight system structure and functioning.

Finally, the chapter reviewed the literature on applications of the approach in studying the impacts of various human actions, management decisions and practices on ecosystem services flow and human well-being. From the review, it is clear that while there is a wider application of the approach in fresh water and marine fishery, forests and wetlands, there has been limited application of the approach in evaluating the impacts of upstream water catchment land use externalities internalisation mechanisms on ecological, hydrological, private and social economic benefits flow. Many studies have focused on the evaluation of the effects of land use on nutrient concentration. This indicates how important this study is in bringing forward insights on the interactions involved and the long-term impacts of the practices. It also shows the need to invest in research towards this direction.

CHAPTER 5

THE CONCEPTUAL FRAMEWORK AND THE EMPIRICAL ECOLOGICAL ECONOMIC MODEL

5.1. Introduction

This chapter presents an empirical model developed to evaluate the likely trade-offs to be involved and their impacts on hydrological and economic benefits flow when fruit tree buffer strips are opted for as the upstream land use externalities internalisation mechanism in water catchments, and the results of the analysis. The chapter begins by presenting a generalised conceptual framework, highlighting the main elements of the water catchment system that are then transformed into an empirical model. The second section presents the empirical model showing the linkages between the ecological and economic systems, and assumptions behind their specifications. The third section presents the types of data and their sources, the parameters estimated and their values, and concludes by presenting the model test and validation results. Section four of the chapter presents the results of the analysis. A concluding summary of the chapter is presented at the end of the chapter.

5.2. The conceptual framework

As stated earlier, the primary objective of the fruit tree input subsidy and taxation management regimes is to induce internalisation of land use externalities, which is expected to result in sediment load reduction in the streams and rivers draining the catchment for the benefit of downstream ecosystem services users. As noted in Chapter 4, section 4.3.1, and according to Jogo and Hassan (2010) and Costanza *et al*. (2002), extremely complex systems are made up of a set of elements linked together (or self-organised) such that they exhibit adaptive, dynamic, goal-seeking, self-preserving, and sometimes evolutionary behaviour. To understand the long-term impact of fruit tree intervention and identify the policies that will support the intervention in being sustainable, it is deemed important to begin with identifying the main elements of the system under investigation. Therefore, following Nobre, Musango and Ferreira (2009), the catchment is modelled as consisting of four major interacting components: (i) the human component which abstracts ecosystems services, invests capital and labour to produce outputs (crops and fruits), and makes land use decisions, (ii) the land use component, which determines the land use mix following choices made in the human component, (iii) the hydrological component, which determines the hydrological system's response to various land use mixes and the human abstraction of ecosystem services, and (iv) the economic component, which determines private economic incentives.

The four components interact as follows: households decide on the best way to allocate their production resources (land size, seeds, seedlings, capital, labour, etc.) between crop and fruit production in the human component at time t. The impact of such land use choices determine the vegetation/canopy covering the catchment in the land use component at time t+Δt, which in turn affects the catchment's sediment supply as reflected in the quality of water flowing downstream in the hydrological component. The crops and fruits output is eventually harvested and utilised by the human component, quantified in economic value as net revenue accrued from land use decisions, in the economic component. The net income accrued from crop and fruit sends a signal to the human component through a feedback loop, which determines household land use choices in the next decision making cycle. It follows that in this model, the balance between crop production, fruit production and natural vegetation cover influences the hydrological system by altering the density/stocks of the different vegetation covers important in filtering sediment run-off, which feeds back to the human component through water quality.

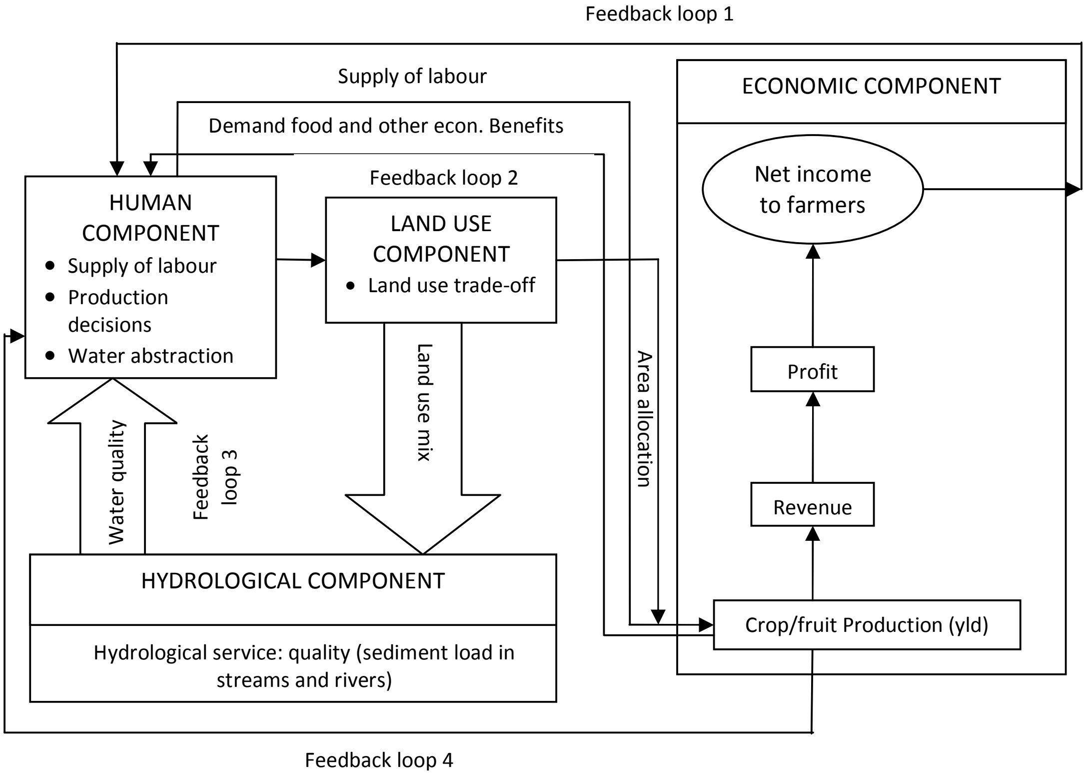

Figure 5.1: Modified analytical framework showing the interlinkage between components of the system [Adapted from Nobre *et al*., 2009].

5.3. The empirical model

To understand the scientific basis of how the water catchment system functions and the behavioural feedback from the interaction with humans, the conceptual framework presented in Figure 5.1 above was translated into an empirical model, made up of five primary modules and two sub-modules, following the approach detailed in Meadows (2004). The primary modules were hydrological, land use, crop production, fruit production, and economic, which were further sub-divided into private and social welfare sub-modules. In the empirical model, the modules and sub-modules were linked to capture the impacts of the management approach (i.e. the fruit tree buffer strips) and different management policies and economic scenarios on ecological, hydrological, private economic and social benefits, as shown in schematic diagram below (Figure 5.2).

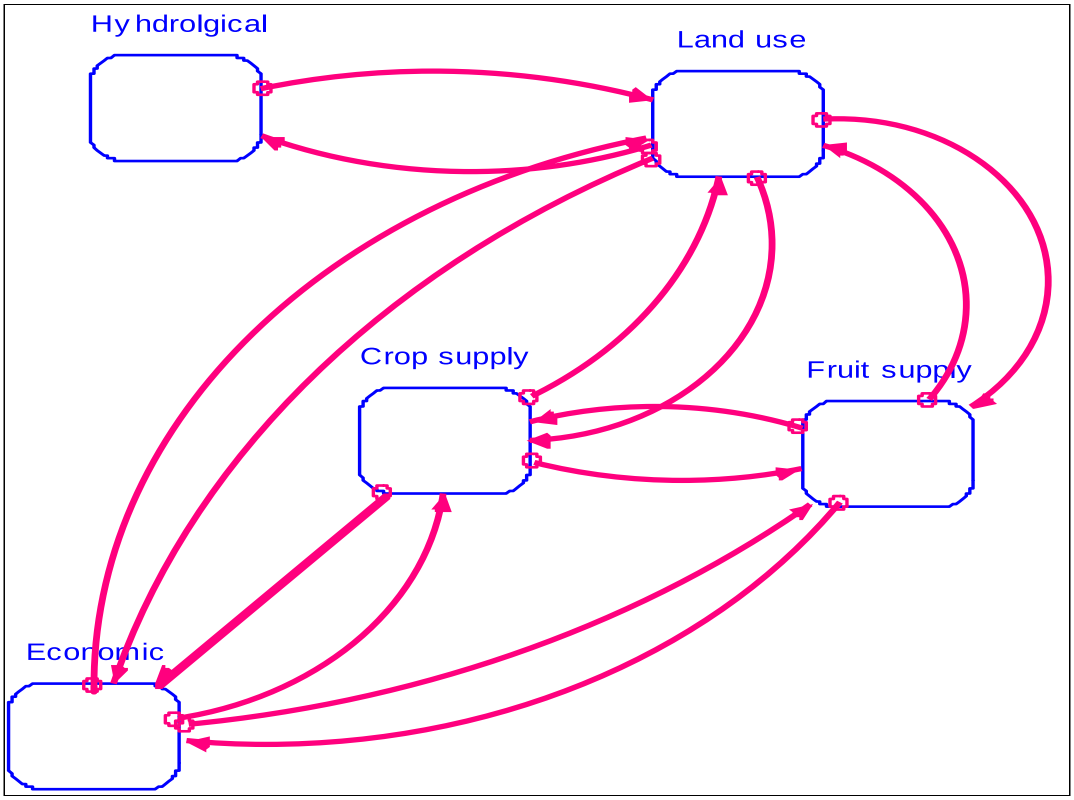

Figure 5.2: A schematic representation of the model, showing the structure with five separate modules

Although internalising externalities by using fruit tree buffer strips results in a number of direct hydrological and economic benefits; water quality, fruit, and crop production were the outcomes used to study the impacts of the approach on ecological, hydrological, private economic and social benefits. The same outcomes were also used to identify the appropriate policy and economic scenarios that will help to persuade upstream farmers to invest in the approach.

5.3.1. Hydrological module

The hydrological module was designed to capture the effect of land use dynamics on hydrological services quality. The module was set up, based on the scientific fact that in water catchments, the hydrological processes are primary drivers of the catchment ecosystem's functioning and service provisioning (Zhang *et al*., 2008; Santhi *et al*., 2006; Bracmort *et al*., 2006). Water flowing in the streams and rivers draining the catchment, and evaporating to the atmosphere through evaporation and evapotranspiration, comes from rain (see Figure 5.2). As precipitation falls on the catchment system, some amount of the water is intercepted and held in the vegetation canopy and the other amount falls to the soil surface (Neitsch *et al*., 2002). Some amount of water on the soil surface infiltrates into the soil profile, while the other flows overland as runoff (Bullock & Acreman, 2003). Runoff moves relatively quickly towards stream and rivers, and contributes to short-term stream response (Pulido-Calvo *et al*., 2012). Infiltrated water is held in the soil as stock, some amounts of which later evapotranspire through the vegetation (or plants) cover leaves, and the other amount slowly makes its way to the surface water system (streams and rivers) via underground paths (Gastélum *et al*., 2009).

Although there are several impacts of land use dynamics operating in water catchment ecosystems, as can be seen in Figure 5.2, this study limited itself to the impacts on the quality of surface water. Specifically, the study focused on the impacts of upstream land use externalities internalisation on water quality. This is attributable to the limited data available on other impacts and the point that the quality of water flowing in the streams and rivers originating from the catchment (see Chapter 2, section 2.5.2) is the main concern of practitioners on the ground (i.e. CARE, WWF, DAWASCO, and MORUWASA) and policy makers (the Government of the United Republic of Tanzania).

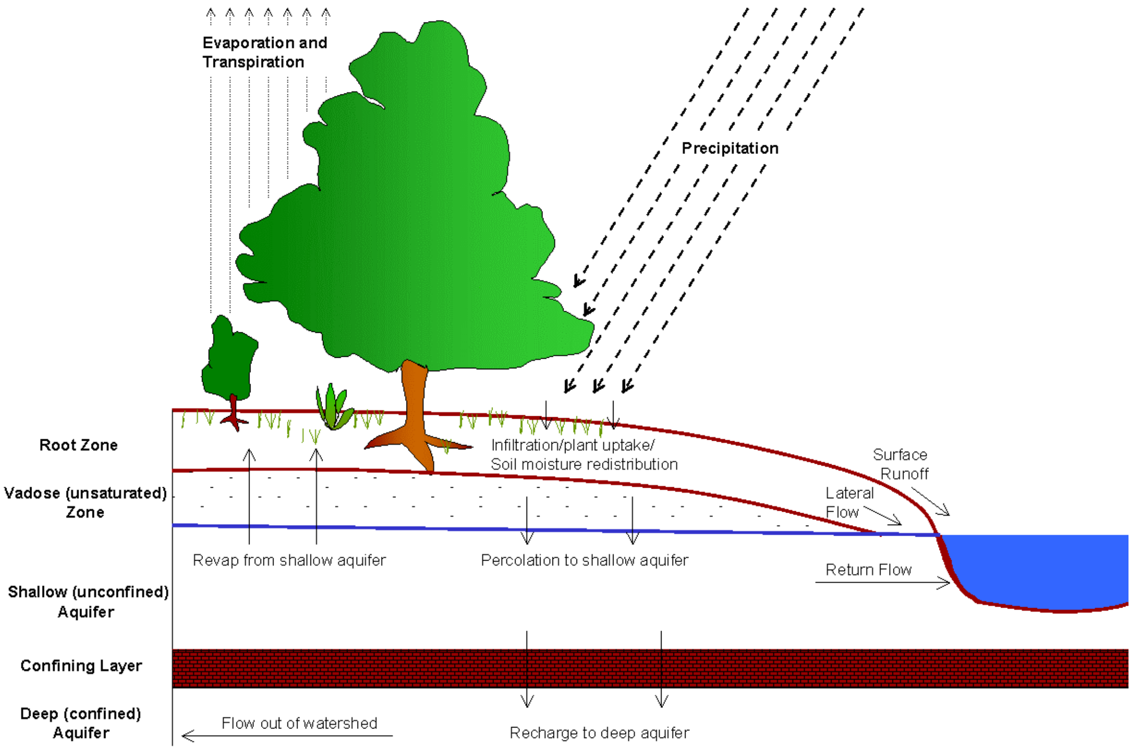

Figure 5.3. Schematic representation of stock and flow in a water catchment system (Adopted from: Neitsch *et al*., 2002).

As noted in Chapter 3, section 3.5.1, water quality depends on the condition of catchment vegetation cover. Intensive and extensive conversion of natural vegetation cover (a very important component for water percolation, runoff reduction and sediment filtering) into other uses, such as crop production, disturbs the aforementioned hydrological processes, leading to soil erosion and excessive runoff during the rainy season, hence flooding downstream, low flow volumes during dry seasons, and too much sediments settling in rivers and streams flowing downstream (Neitsch *et al*., 2002). This module was, therefore, set up to account for water sediment load balance, based on the assumption that it depends on the type of land use, area (A) covered by that land use and sediment filtering capacity (measured as discharge rate (SD)) of a given land use type, as suggested by Johnes (1996). The water sediment load was selected for this modelling because it is an attribute of water quality which is the key target of catchment management (Yanda & Munishi, 2007). Therefore, the total sediment load (measured as tones/m^3) is given by the following equation:

$$\text{Total turbidity (tones/m}^3\text{)} = \sum A_t^i * SD_t^i \qquad (5.1)$$

Where: A_t^i refers to the area of catchment occupied by land use type *i* at time *t*, and SD_t^i refers to the sediment discharge rate of canopy/filter bed *i* at time *t*.

The sediment filtering capacity which was measured through sediment discharge rate (SD) was assumed to be a function of run-off (RO) measured as water flow volume per second (m^3/sec), as suggested by Santhi *et al*. (2001).

$$SD_t^i = \delta_0 + \delta_1 RO_t^i \qquad (5.2)$$

Where: δ_0 and δ_1 = are the parameters estimated econometrically from time series data, and RO_t^i = catchment average run-off through canopy *i* at time *t*.

The run-off was assumed to depend on canopy density (or biomass) of a given land use (or land cover), precipitation and topographical features (particularly altitude-indexed by elevation above sea level) of a given land use as suggested by Neitsch *et al*. (2002).

$$RO_t^i = \omega_0 + \omega_1 DENS_t^i + \omega_2 P_t + \omega_3 Alt_i \qquad (5.3)$$

Where: w_0, w_1, w_2 and w_3 = are parameters estimated econometrically from time series data, $DENS_t^i$ = density (biomass) of canopy *i* at time *t*, P_t = precipitation at time *t*, and Alt_i = altitude where canopy *i* is located.

5.3.1.1. Calculation of natural vegetation density (biomass)

To capture the effect of land use dynamics on hydrological ecosystem services, the study employed the ecological models of natural vegetation variation with variation in area covered by the natural vegetation. Although there are many natural plants in the catchment, as pointed out in Chapter 2, section 2.4, only three major natural vegetation types, named here by their common names (woodland, bushland and grassland), were taken into account, based on their distribution in the catchment and data availability. These vegetation types grow in areas which are also good for agricultural production; therefore their habitats are vulnerable to conversion into farmlands. To calculate the biomass of given natural vegetation at a given time period, the Gordon (1954) logistic growth model was employed. Total biomass of given natural vegetation cover in the catchment was calculated by the following equation:

$$B^i_{t+1} = g_i(1 - B^i_t / K^i_t)B^i_t + B^i_t \tag{5.4}$$

Where: B^i_{t+1}=Biomass of natural vegetation canopy *i* at time *t*+1, B^i_t=Biomass of natural vegetation canopy *i* at time *t*, g_i=Actual growth rate of natural vegetation canopy *i*, K^i_t=Environmental carrying capacity for natural vegetation canopy *i* at time *t*.

The catchment's natural vegetation maximum carrying capacities were set to 142.24, 504.67 and 927.68 tons per hectare per annum for grassland, bushland and woodland, respectively (Doggart *et al*., 2004; Lovett & Pócs, 1993).

To capture the effect of variation in the area covered by natural vegetation on growth of natural vegetation cover, we specified the intrinsic growth rate (r_t) as a function of the area under a given natural vegetation cover i at a given time period (t). From the ecological point of view, it is argued that natural vegetation growth is affected by the space available, which implies that space is bound to affect natural vegetation productivity, hence biomass or density (Lowrance *et al*., 1995). The intrinsic growth rate of biomass is linked to changes in area for natural vegetation in a linear form. This relationship links the hydrological module with land use, crop and fruit production modules through land use trade-offs. Therefore, the intrinsic growth rate was specified and calculated as follows:

$$r^i_t = \beta_0 + \beta_1 ANV^i_t \tag{5.5}$$

Where: $r_{i.t}$=intrinsic growth rate of natural vegetation canopy *i* at time *t*, β_0 and β_1 are parameters estimated econometrically from time series data, ANV^i_t=Area covered by natural vegetation *i* at time *t*.

From the ecological point of view, it is also true that the actual growth rate of natural vegetation decreases as biomass increases due to competition for limited resources such as light, water, nutrients and space (Robles-Diaz-de-León & Nava-Tudela, 1998). However, is also true that when natural vegetation is removed from the catchment by cultivation through conversion of natural vegetation for crop production and other land uses, the actual growth rate will increase (Peterson, 1991). To capture the effect of the limitation caused by competition for resources as biomass stock grows, the intrinsic growth rate (r_t) is adjusted by the growth rate multiplier to get the actual growth rate $(g_{t,i})$.

$$g_{t,i} = r_{t,i} * \upsilon_i \tag{5.6}$$

To calculate the growth multiplier $(\upsilon_{t,i})$ for natural vegetation i at each time period, we assumed that it ranges between $0 < \upsilon < 1$, implying that the growth multiplier is equal to 1 or 100 % when biomass stock is close to zero and the rate decreases to zero when biomass stock is in full growth and is reaching carrying capacity (also see Archibold, 1995). Generally, the growth multiplier is negatively related to the ratio of biomass stock each time period to the carrying capacity which is set at maximum biomass per hectare (Alcon, 1981). Based on the work by Hellden (2008) and Jogo and Hassan (2010), we modelled it as a graphical relationship, as follows:

$$\upsilon_i = \text{Graph}(B_t / \text{Initial} B_t) : 0 < \upsilon_i < 1 \tag{5.7}$$

5.3.1.2. Estimation of fruit tree density

Fruit tree density or biomass was included in the model because it is the best management practice that provides both private and public goods and services (refer to section 5.2), and at the same time competes with crop and natural vegetation for land space. The study assumed that fruit trees play a sediment filtering role, which differs from the sediment filtering roles performed by other land covers, as suggested by Gregory *et al*., (1991). To capture the effect of the dynamics in biomass or density of fruit trees canopy cover (Fru.DENS) due to land use trade-offs, the study employed agronomic models for determining plant population in man-made fields at given period of time. The total biomass of fruit trees per hectare was calculated by the following equation:

$$\text{TFDENS}_t^i = \text{AF}_t^i / \text{Tr}_{spa}^i * \text{Row}_{spa}^i \tag{5.8}$$

Where: TFDENS_t^i = fruit tree *i* canopy density at time *t*, AF_t^i =area covered by fruit tree *i* at time *t*, Tr_{spa}^i = fruit tree *i* plant spacing which is the space between one fruit tree and another, Row_t^i = fruit tree *i* row spacing which is the space between one row of fruit trees and another.

5.3.1.3. Estimation of crop plant density (tones/ha)

Crop density or biomass was also accounted for. Although crop production is considered to be not favourable for hydrological services supply in water catchments, it has some levels of sediment filtering capacity that differ from other land canopy covers. To capture the effect of the dynamics in biomass or density of crop canopy cover $(\mathrm{Crop.DENS})$ due to land use trade-offs, the study employed agronomic models for determining plant population in crop fields at given time period. The total biomass of crop plants per hectare was calculated by the following equation:

$$\mathrm{CDENS}_t^i = \mathrm{AC}_t^i / \mathrm{C}_{spa}^i * \mathrm{Row}_{spa}^i \qquad (5.9)$$

Where: CDENS_t^i=Crop *i* canopy density at time *t*, AC_t^i=area covered by crop *i* at time *t*, C_t^i=crop *i* plant spacing which is the space between one crop plant and another, Row_t^i=crop *i* row spacing which is the space between one row of crop plants and another.

5.3.2. Land use module

This module was designed to account for the dynamics in the areas covered by crops, fruit trees and natural vegetation. Following Kirsch e*t al*. (2002), the study assumed that crops, fruit trees and natural vegetation canopy covers play sediment-filtering roles that differ from one another. Following Kalin and Hantush (2003), the study assumed that inter-temporal changes in areas covered by these canopy types are driven by changes in (i) the price of crop inputs and outputs, which provide farmers with incentives (or disincentives) to convert other canopy types to crop production; (ii) the price of fruit tree inputs and outputs, which provide farmers with incentives (or disincentives) to plant fruit trees on land they had previously left to fallow, (iii) annual precipitation, which has been observed to attract new farmers into the catchment to cultivate crops on subdivided land leased from existing farmers; (iv) fruit tree input subsidies which have been designed to provide farmers with incentives to plant fruit trees on fallow land, (v) altitude, which has been observed to influence farmer decisions to convert land from other uses into crop production, and (vi) changes in population, which indirectly drive land conversion by increasing the demand for food. To account for the effects of these factors on the size of land allocated to different land uses, we followed Kirsch *et al*.

(2003) and fitted some historical annual time series data to the regressions specified by equations below:

$$\begin{aligned} AF_t^i = {} & \alpha_0 + \alpha_1 P_{mango.t} + \alpha_2 P_{orange.t} + \alpha_3 P_{paddy.t} + \alpha_4 P_{banana.t} + \alpha_5 P_{Xmango.t} + \alpha_6 P_{Xorange.t} + \\ & + \alpha_7 P_{Xpaddy.t} + \alpha_8 P_{Xbanana.t} + \alpha_9 P_{mBDGt} + \alpha_{10} P_t + \alpha_{11} SUB_{f.t} + \alpha_{12} ALT_t^i + \alpha_{13} HH_{size.t}^i + \\ & + \alpha_{14} off.inc_t^i + \alpha_{15} Pop_t \end{aligned} \tag{5.10}$$

On the other hand, the regression equation for area converted to crop production in period t was given by:

$$\begin{aligned} AC_t^i = {} & \theta_0 + \theta_1 P_{paddy.t} + \theta_2 P_{banana.t} + \theta_3 P_{mango.t} + \theta_4 P_{orange.t} + \theta_5 P_{Xpaddy.t} + \theta_6 P_{Xbanana.t} + \\ & \theta_7 P_{Xmango.t} + \theta_8 P_{Xorange.t}^i + \theta_9 P_t + \theta_{10} P_{mt} + \theta_{11} P_t + \theta_{12} SUB_{f.t} + \theta_{13} ALT_t^i + \\ & \theta_{14} HH_{size.t}^i + \theta_{15} off.inc_t^i + \theta_{16} Pop_t \end{aligned} \tag{5.11}$$

Where: α_0, α_1 to α_{15} and θ_0, θ_1 to θ_{16} = are parameters estimated econometrically, AF_t^i = area covered by tree fruit *i* at time *t*, AC_t^i =area covered by crop *i* at time *t*, $P_{mango.t}$= market price of mango fruits at time *t*, $P_{orange.t}$= market price of orange fruits at time *t*, $P_{paddy.t}$ =Market price of paddy at time *t*, $P_{banana.t}$ =Market price of first banana at time *t*, $P_{Xpaddy.t}$=Price of production inputs for paddy at time *t*, $P_{Xbanana.t}$ =Price of inputs for production of banana at time *t*, $P_{Xmango.t}$ = market price of inputs for production of mango at time *t*, $P_{Xorange.t}$ = market price of inputs for production of orange at time *t*, P_t =precipitation at time *t*, $SB_{f.t}^i$ =compensation for planting tree fruit at time *t*, external income, ALT_t^i =altitude from sea level of canopy *i* at time *t*, $HH_{size.t}^i$ =household *i* size at time *t*, $off.inc_t^i$ =household *i* off-farm income at time *t* and Pop_t =Catchment population size at time *t*.

P_{xft}^i =Price of production inputs for tree fruit *i* at time *t*, P_{ft}^i =Market price of tree fruit *i* at time *t*, P_{mt}^i =Market price of basic domestic good *i* at time *t*, W_t =Labour wage at time *t*.

Following Santhi *et al*., (2003) the areas calculated from equations 5.10 and 5.11 were then fed into equation 5.12 to calculate the area that remained covered by natural vegetation.

And the area remained covered or converted to natural vegetation in period t was given by:

$$ANV_t^i = TCA - AF_t^i - AC_t^i \tag{5.12}$$

Where: ANV_t^i =area covered by natural vegetation *i* at time *t*, TCA=total catchment area, AF_t^i =area covered by tree fruit *i* at time *t*, and AC_t^i =area covered by crop *i* at time *t*.

The total catchment area covered by natural vegetation was set to be 20490.3 ha, based on the 2006 and 2010 Uluguru water catchments' natural vegetation cover inventories (URT, 2010; 2006).

5.3.3. Crop production module

This module accounts for household crop supply, where crops play both a hydrological role (through their canopy covers) and an economic role (Vache *et al.*, 2002). Although many crops are grown, only two (paddy and banana) were considered in the model. The choice of paddy and banana was based on the scale of production and availability of data (see Table 2.4). Following Jogo (2009), a reduced form of the household crop supply function, derived from an agricultural household model, was estimated. One fixed input (land area allocated to crop *i*), two variable inputs (seeds and labour), soil fertility which was considered to be affected by sediment load produced by given type of canopy cover, and a series of prices were used in the specification. The land area allocated to crop *i* was estimated from equation 5.11, the soil fertility was estimated from equation 5.14, the quantity of seed employed in production was obtained from a household survey, while the amount of labour employed in production was estimated from equation 5.15. Total area used for crop production in the entire catchment was then computed as the aggregate of individual household areas allocated to crop production (Equation 5.15), which was then used to calculate total household crop supply (Equation 5.16).

$$\begin{aligned} HHCS_t^i = {} & \Psi_0 + \Psi_1 A_{ct}^i + \Psi_2 SF_t^i + \Psi_3 SUB_{ft}^i + \Psi_4 P_{mct}^i + \Psi_5 P_{xct}^i + \Psi_6 P_{mango.t} + \Psi_7 P_{orange.t} + \\ & \Psi_8 P_{Xmango.t} + \Psi_9 P_{Xorange.t} + \Psi_{10} P_{mBDGt}^i + \Psi_{11} W_t \end{aligned} \tag{5.13}$$

Where $HHCS_t^i$ =Household crop *i* supply at time *t*, Ψ_0, Ψ_1 and Ψ_{13} = are parameters estimated econometrically, A_{ct}^i =Area under crop *i* at time *t*, SF_t^i = Fertility of soil under crop *i* at time *t*, SUB_{ft}^i =Tree fruit *i* production input subsidy at time *t*, P_{mct}^i =Market price of crop *i* at time *t*, $P_{mango.t}$ = market price of mango fruits at time *t*, $P_{orange.t}$ = market price of orange fruits at time *t*, $P_{Xmango.t}$ = market price of inputs for production of mango at time *t*, $P_{Xorange.t}$ = market price of inputs for production of orange at time *t*, $P_{mBDG.t}^i$ =Market price of basic domestic good *i* at time *t*, W_t =Labour wage at time *t*.

Soil productivity

Household crop supply is affected by soil productivity which was assumed to be affected by canopy type sediment production (Spruil et al., 2000). Therefore, soli fertility was used as a proxy of soil productivity linking crop production module with sediment load and was estimated as follows:

$$SF_t^i = \varsigma_0 + \varsigma_1 SD_t^i \tag{5.14}$$

Where SF_t^i = Fertility of soil under canopy *i* at time *t*, SD_t^i =Sediment discharge rate of canopy/filter bed *i* at time *t*, ς_0 and ς_1 =Are parameters estimated econometrically.

To produce and supply crops, households use labour. Household labour use was assumed to be influenced by a similar set of factors as in crop production. Therefore, to depict the effect of these factors on household labour use per year or production season, we fitted a multiple regression model on cross-sectional data collected from household survey, as follows:

$$\begin{aligned} LC_t^i = {} & g_0 + g_1 A_{ct}^i + g_2 P_{ct}^i + g_3 SUB_{ft}^i + g_4 W_t + g_5 P_{mango.t} + g_6 P_{orange.t} + g_7 P_{xct}^i + \\ & g_8 P_{Xmango.t} + g_9 P_{Xorange.t} \end{aligned} \tag{5.15}$$

Where LC_t^i =Household labour used for production of crop *i* at time *t*, A_{ct}^i =Area under crop *i* at time *t*, P_{ct}^i =Price of crop *i* at time *t*, SUB_{ft}^i =Tree fruit *i* production input subsidy at time *t*, W_t =Labour wage at time *t*, $P_{mango.t}$ = market price of mango fruits at time *t*, $P_{orange.t}$ = market price of orange fruits at time *t*, $P_{Xmango.t}$ = market price of inputs for production of mango at time *t*, $P_{Xorange.t}$ = market price of inputs for production of orange at time *t*,

The second step was to compute the total area converted to crop production and total crop production from the catchment per annum. From equation 5.11, we aggregated the area under crop and then used this to calculate household crop production. Based on reduced form of household crop supply derived from an agricultural household model as suggested by Jogo and Hassan (2010), the household crop production was aggregated across all households in the catchment.

Total area cultivated crop (ha)

$$TAC_t^i = \sum_{k=1}^{H} A_{ct}^i \qquad (5.16)$$

Where TAC_t^i =Total area cultivated crops at time *t*, A_{ct}^i =Area cultivated crop *i* at time *t*.

The total household crop supply measured in tones was aggregated as follows:

$$THCS_t^i = HHCS_t^i * TAC_t^i \qquad (5.17)$$

The total labour use in crop i production measured in hours was aggregated as follows:

This module is linked to the land use and hydrological modules through the size of land under a given crop production due to the fact that it affects canopy type and plant population density, which in turn influences the sediment balance.

5.3.4. Fruit production module

This module accounts for household fruit supply, where fruit trees play both a hydrological role (through their canopy covers) and an economic role (Robles-Diaz-de-León & Alfredo Nava-Tudela, 1998). As stated earlier, the fruit tree input subsidy scheme is designed to incentivise upstream land holders to plant fruit trees on land experiencing declining agricultural production, instead of leaving it fallow, which implies trade-offs between the canopy cover provided by fruit trees against those provided by crops and natural vegetation. The study thus included this module to account for the economic impacts of the trade-offs involved. Although there are many kinds of fruits cultivated in the catchment, only two (orange and mango) were considered in the model. The choice of these two fruits was based on the scale of production and data availability (Table 2.4). Following Jogo (2009), a reduced form of the household fruit supply function (Equation 5.17), derived from an agricultural household model, was estimated. One fixed input (land area allocated to fruit *i*), two variable inputs (seedlings and labour), and a series of prices were used in the specification. The land area households allocated to fruit tree *i* was estimated from Equation 10 of the land use module, the quantity of seedlings employed in production was obtained from the primary survey, and the amount of labour employed in production was estimated from Equation 18. Total area allocated to fruit production in the entire catchment was then computed as the aggregate of individual household areas (Equation 19), which was then used to calculate total household fruit supply (Equation 20).

$$\begin{aligned}\mathrm{HHFS}_t^i &= \rho_0 + \rho_1 \mathrm{NF}^i_{\mathrm{trees/acre,t}} + \rho_2 \mathrm{AF}_t^i + \rho_3 \mathrm{SF}_t^i + \rho_4 \mathrm{P}^i_{\mathrm{ft}} + \rho_5 \mathrm{P}_{\mathrm{paddy.t}} + \rho_6 \mathrm{P}_{\mathrm{banana.t}} + \rho_7 \mathrm{P}^i_{\mathrm{xft}} + \\ &\rho_8 \mathrm{P}_{\mathrm{Xpaddy.t}} + \rho_9 \mathrm{P}_{\mathrm{xbanana.t}} + \rho_{10} \mathrm{P}^i_{\mathrm{mBDG.t}} + \rho_{11} \mathrm{SUB}^i_{\mathrm{ft}} + \rho_{12} \mathrm{W}_t\end{aligned} \tag{5.18}$$

Where HHFS_t^i =Household fruit *i* supply at time *t*, ρ_0, ρ_2 to ρ_{11} =are parameters estimated econometrically, $\mathrm{NF}^i_{\mathrm{trees/acre,t}}$ =Number of tree fruits for fruit *i* per acre at time *t*, AF_t^i =Area under fruit *i* at time *t*, SF_t^i = Fertility of soil under fruit *i* at time *t*, $\mathrm{P}^i_{\mathrm{ft}}$ =Market price of tree fruit *i* at time *t*, $\mathrm{P}_{\mathrm{paddy.t}}$ =Market price of paddy at time *t*, $\mathrm{P}_{\mathrm{banana.t}}$ =Market price of first banana at time *t*, $\mathrm{P}^i_{\mathrm{xft}}$ =Price of production inputs for tree fruit *i* at time *t*, $\mathrm{P}_{\mathrm{Xpaddy.t}}$=Price of production inputs for paddy at time *t*, $\mathrm{P}_{\mathrm{Xbanana.t}}$=Price of inputs for production of banana at time *t*, $\mathrm{P}^i_{\mathrm{mt}}$ =Market price of basic domestic good *i* at time *t*, $\mathrm{SUB}^i_{\mathrm{ft}}$ =Tree fruit *i* production input subsidy/compensation at time *t*, W_t =Labour wage at time *t*.

To produce and supply fruit, households use labour. Household labour use was assumed to be influenced by a similar set of factors as in fruit production. Therefore, to depict the effect of these factors on household labour use per year or production season, we fitted a multiple regression model on cross-sectional data collected from household survey as follows:

$$\begin{aligned}LF_t^i = {} & m_0 + m_1 A_{ft}^i + m_2 P_{ft}^i + m_3 P_{paddy.t} + m_4 P_{banana.t} + m_5 P_{xft}^i + m_6 P_{Xpaddy.t} + \\ & m_7 P_{Xbanana.t} + m_8 SUB_{ft}^i + m_9 W_t\end{aligned} \tag{5.19}$$

Where LF_t^i =Household labour used for production of fruit *i* at time *t*, m_0, m_1 to m_9 =are parameters estimated econometrically, A_{ft}^i =Area under fruit *i* at time *t*, P_{ft}^i =Price of fruit *i* at time *t*, P_{ft}^i =Market price of tree fruit *i* at time *t*, $P_{paddy.t}$ =Market price of paddy at time *t*, $P_{banana.t}$ =Market price of first banana at time *t*, P_{xft}^i =Price of production inputs for tree fruit *i* at time *t*, $P_{Xpaddy.t}$ =Price of production inputs for paddy at time *t*, $P_{Xbanana.t}$ =Price of inputs for production of banana at time *t*, SUB_{ft}^i =Tree fruit *i* production input subsidy at time *t*, W_t =Labour wage at time *t*.

Similarly to crop production module, the second step in this module was to compute the total area converted to fruit tree production and total fruits production from the catchment per annum. From Equation 5.10, we aggregated the area under fruit tree cultivation and then used it to calculate household crop production. Based on reduced form of household fruit supply derived from an agricultural household model as suggested by Jogo and Hassan (2010), the household total fruit production was aggregated across all households in the catchment.

Area covered by fruits (ha)

$$TAF_t^i = \sum_{k=1}^{H} AF_t^i \tag{5.20}$$

Where TAF_t^i =Total area cultivated tree fruit at time *t*, AF_t^i =Area cultivated fruit *i* at time *t*.

Total household fruit supply (tons)

$$THHFS_t^i = HHFS_t^i * TAF_i^i \tag{5.21}$$

Where $THHFS_t^i$ =Total household fruit *i* supply at time *t*, $HHFS_t^i$ =Household total tree fruit *i* supply at time *t*.

This module is linked to the land use and hydrological modules through the size of land under a given fruit production due to the fact that it affects canopy type and plant population density, which in turn influences the sediment balance.

5.3.5. Economic module

This module was designed to account for the welfare of the catchment upstream and downstream communities, which according to Van Liew and Garbrecht (2003), is determined by demand for food, fruits and income among others. Trading-off land between the three major uses (i.e. crop and fruit production, and natural vegetation) affects the flow of economic benefits among the human population living in the catchment. The distribution of benefits among the beneficiaries is a major concern in water catchment conservation programmes. This is derived from the fact that it directly affects the sustainability of management activity. Many management programmes tend to overlook the distribution of economic benefits among the community living in the catchment (Currie, 2003; Redford & Richter, 1999).

To account for the effects of encouraging farmers to plant fruit trees on the land left to fallow as a way of internalising their externalities in water catchments, we included this module. The module was divided into two sub-modules: one that accounted for net revenue from fruit and crop production, following Robles-Diaz-de-León and Nava-Tudela (1998), and the other that accounted for social welfare, following Jogo and Hassan (2010).

5.3.5.1. The net revenue from fruit and crop production

The net revenue from crop production was computed as specified in Equation 5.21, fed by household labour used in crop production and total household crop supply computed from Equations 5.14 and 5.16, respectively. Similarly, the net revenue from fruit production was computed as specified in Equation 5.22, fed by household labour used in fruit production and total household fruit supply computed from Equations 5.18 and 5.20, respectively. The present values of net revenues from crop and fruit production were computed at a 5 % discount rate adopted from the Central Bank of Tanzania, as specified in Equation 5.23.

Net revenue from crop production (Tsh)

$$NR_{ct}^{i} = P_{ct}^{i}\sum_{q=1}^{Q} THHCS_{t}^{i} - \left(\sum (Q_{seed,ct}^{i} * P_{seed,ct}^{i}) + (LC_{t}^{i} * W_{ct}^{i})\right) \qquad (5.22)$$

Where $\mathrm{NR}^{\mathrm{i}}_{\mathrm{ct}}$ =Net revenue accrued from crop *i* production at time *t*, $\mathrm{P}^{\mathrm{i}}_{\mathrm{ct}}$ =Market price of crop *i* at time *t*, $\mathrm{THHCS}^{\mathrm{i}}_{\mathrm{t}}$ =Total household crop *i* supply at time *t*, $Q^{i}_{seed,ct}$ =Total quantity of seed input used for production of crop *i* at time *t*, $\mathrm{P}^{\mathrm{i}}_{\mathrm{seed,ct}}$ =Price of seed used to produce crop *i* at time *t*, LC^{i}_{t} =Household labour used to produce crop *i* in time *t*, $\mathrm{W}^{\mathrm{i}}_{\mathrm{ct}}$ =Wage paid to produce crop *i* in time *t*.

Net revenue from fruit production (Tsh)

$$\mathrm{NR}^{\mathrm{i}}_{\mathrm{ft}} = \mathrm{P}^{\mathrm{i}}_{\mathrm{ft}} \sum_{\mathrm{q=1}}^{\mathrm{Q}} \mathrm{THHFS}^{\mathrm{i}}_{\mathrm{t}} - \left(\sum (\mathrm{Q}^{\mathrm{i}}_{\mathrm{seedling,\,ft}} * \mathrm{P}^{\mathrm{i}}_{\mathrm{seedling,\,ft}}) + (\mathrm{LF}^{\mathrm{i}}_{\mathrm{t}} * \mathrm{W}^{\mathrm{i}}_{\mathrm{ft}}) \right) \qquad (23)$$

Where $\mathrm{NR}^{\mathrm{i}}_{\mathrm{ft}}$ =Net revenue accrued from fruit *i* production at time *t*, $\mathrm{P}^{\mathrm{i}}_{\mathrm{ft}}$ =Market price of fruit *i* at time *t*, $\mathrm{THHFS}^{\mathrm{i}}_{\mathrm{t}}$ =Total household fruit *i* supply at time *t*, $Q^{i}_{seedlings,\,ft}$ =Total quantity of seedlings input used for production of fruit *i* at time *t*, $\mathrm{P}^{\mathrm{i}}_{\mathrm{seedlings,ft}}$ =Price of seedlings used to produce fruit *i* at time *t*, LF^{i}_{t} =Household labour used to produce fruit *i* in time *t*, $\mathrm{W}^{\mathrm{i}}_{\mathrm{ft}}$ =Wage paid to produce fruit *i* at time *t*.

The income flow to farmers from fruit and crop production:

$$\mathrm{PNR}^{\mathrm{i}}_{\mathrm{t}} = \frac{\mathrm{TNR}^{\mathrm{i}}_{\mathrm{t}}}{(1+\mathrm{r})^{t}} \qquad (5.24)$$

Where PNR^{i}_{t} = the present value of net revenue accrued from tree fruits and crop production at time *t*, TNR^{i}_{t} = the total net revenue accrued from crop and fruit *i* at time t; r =the discount rate; and t=simulation period.

5.3.5.2. Social welfare sub-module

Following Jogo and Hassan (2010), the welfare of the communities benefiting from the catchment ecosystem services was defined as the quotient of total income accrued at time *t* and the population size at time *t*. W began by noting that apart from income obtained from crop and fruit production, the community living in the upstream of the catchment also obtains income from other sources. Following the CARE and WWF (2010) livelihood assessment, two other sources of income were considered: income from off-farm activities and the subsidy paid to farmers as fruit tree input subsidies. For the communities living downstream we considered the cost served in cleaning water for domestic use as the major benefit from good land use practices upstream. It follows that total income was computed as the sum of net revenue from crop production, net revenue from fruit production, income from off-farm activities, income from subsidy paid as fruit tree input subsidies and income from saved cost in treating water for domestic use downstream, as specified in equation bellow:

$$\mathrm{NI}_t = \sum \mathrm{NR}_{c.t} + \sum \mathrm{NR}_{f.t} + \sum \mathrm{OI}_t + \sum \mathrm{SUB}_t + \sum \text{Water treatement cost served}_t \qquad (5.25)$$

Where: NI_t = total net income, $\mathrm{NR}_{c.t}$ =net revenue from crop production, $\mathrm{NR}_{f.t}$ =net revenue from fruit production, OI_t =income from off-farm activities, SUB_t = subside received at time *t*.

Income from off-farm activities

Income from off-farm activities (Equation 5.25) was calculated as the product of household labour used for off-farm activities (estimated from Equation 5.27) and the number of households engaged in off-farm activities (estimated from Equation 5.27).

$$\mathrm{OI}_t = \frac{\mathrm{NHO}_t * \mathrm{W}_t * \mathrm{L}_{o.t}}{(1+r)^t} \qquad (5.26)$$

Where OI_t =off farm income at time t, $\mathrm{L}_{o.t}$ =labour used for off-farm income at time *t*, and w_t = wage rate at time *t*.

Household labour used in off-farm work (hours/hh/year):

$$\mathrm{L}_{o.t} = \mu_0 + \mu_1 \mathrm{SUB}_t + \mu_2 \mathrm{W}_t + \mu_3 \mathrm{P}_{c.t} + \mu_4 \mathrm{P}_{f.t} + \mu_5 \mathrm{P}_{x.c} + \mu_6 \mathrm{P}_{x.f} + \mu_7 \mathrm{P}_{m.t} \qquad (5.27)$$

Where: $\mathrm{L}_{o.t}$ =labour used for off-farm income at time *t*, SUB_t =subsidy at time *t*, P_c= price of the main crop, P_f=price of fruit, P_m=price of basic market goods, P_{xc}=price of inputs for crop production, P_{xf}=price of inputs for fruit production, and w_t = wage rate at time *t*.

Number of households (NHO) engaged in off-farm work

$$\mathrm{NHO}_t = \phi_0 + \phi_1 \mathrm{GDP}_{k.t} \qquad (5.28)$$

Income from fruit tree planting subsidy

Following Robles-Diaz-de-León and Nava-Tudela (1998), income from fruit tree planting subsidy (Equation 5.29) was computed as a product of the subsidy rate estimate (Equation 5.30), subsidy amount and number of household engaged in fruit tree planting (Equation 5.31).

$$\mathrm{SUB}_t = \frac{\vartheta * \mathrm{SUB}_t * \mathrm{NHF}_t}{(1+r)^t} \qquad (5.29)$$

Where SUB_t =subside at time *t*; r =discount rate, and t= simulation period, SUB_t =subsidy at time *t*.

Compensation (or subside) rate:

$$\vartheta = \mathrm{r}_0 + \mathrm{r}_1 \mathrm{CPI}_t \qquad (5.30)$$

Where: r_0 and r_1 = are parameters estimated econometrically, CPI_t = consumer price index.

Number of HH engaged in fruit production

$$\mathrm{NHF}_t = \delta_0 + \delta_1 \mathrm{P}_f^i + \delta_2 \mathrm{LF}_t^i + \delta_3 \mathrm{SUB}_f^i \qquad (5.31)$$

Where: ϑ=subsidy rate, δ_0, δ_2 and δ_3 = are parameters estimated econometrically, NHF_t^i =number of households engaged in producing fruit *i* at time *t* and SUB_t =subsidy at time *t*.

Income accrued from sediment load reduction

Income from cost served in treating water for domestic use as result of fruit production was computed as a product of quantities of reduced sediments load estimated by equation 5.1 and the cost of cleaning 1m^3 of water as specifies in the equation bellow:

$$\text{Water cleaning total cost served}_t = (\mathrm{SD}_t - \mathrm{SD}_{t+1}) * \mathrm{P}_{H_2O.t} \qquad (5.32)$$

Where: SD_t = the level of sediment load at initial time t, SD_{t+1} = the level of sediment load at time t+1, and $\mathrm{P}_{\mathrm{H_2O.t}}$ = the price of cleaning a unit of water (TZS/m^3).

Catchment population size

The catchment population size was computed as the sum of the catchment upstream and downstream populations as specified in the following equation:

$$\mathrm{Pop}_{\mathrm{catchment.t}} = \mathrm{Pop}_{\mathrm{u.t+1}} + \mathrm{Pop}_{\mathrm{D.t+1}} \tag{5.33}$$

Total upstream population size

To account for upstream population size at time t+1, we used an exponential population growth function as applied by Woodwell (1998) which assumed that it varies over time with natural growth (Equation 5.34), in-migration and emigration (Equations 5.35 and 5.36, respectively). Following Arabi *et al.*, (2006), we assumed that in-migration and emigration rates vary over time and are influenced by the availability of off-farm opportunities created by economic growth (GDP per capita) and rainfall variability in the catchment surroundings and the catchment itself, as specified in Equations 5.37 and 5.38, respectively. Other factors, such as family planning policies, health services, and death rate which can also influence human population dynamics, were not considered because of difficulties in obtaining data at the catchment level.

Population (number of people)

$$\mathrm{Pop}_{\mathrm{u.t+1}} = \mathrm{Pop}_{\mathrm{u.t}}(1 - \mathrm{g}_{\mathrm{u}}) + (\mathrm{IM}_{\mathrm{u.t}} - \mathrm{EM}_{\mathrm{u.t}}) \tag{5.34}$$

Where: $\mathrm{Pop}_{\mathrm{u.t}}$ =Upstream community population size at time *t*, g_{u} =Upstream population growth rate, $\mathrm{IM}_{\mathrm{u.t}}$ =Upstream in-migration at time *t* and $\mathrm{EM}_{\mathrm{u.t}}$ =Upstream emigration at time *t*.

Number of in-migrants at time t (no. of people):

$$\mathrm{IM}_{\mathrm{u.t}} = \eta_{\mathrm{u.t}} * \mathrm{Pop}_{\mathrm{u.t}} \tag{5.35}$$

Where $\eta_{\mathrm{u.t}}$ =Upstream in-migration rate at time *t*.

Number of emigrants at time *t* (no. of people):

$$\mathrm{EM}_{\mathrm{u.t}} = e_{\mathrm{u.t}} * \mathrm{Pop}_{\mathrm{u.t}} \tag{5.36}$$

Where: $e_{u.t}$ =Upstream emigration rate at time *t*.

In-migration and emigration rates:

$$\eta_{u.t} = f_0 + f_1 GDP_{k.t} + f_2 P_{o.t} \tag{5.37}$$

$$e_{u.t} = d_0 + d_1 GDP_{k.t} + d_2 P_t \tag{5.38}$$

Where: GDP_{kt} = gross domestic product per capita at time *t*, P_t =precipitation in the catchment at time *t*, $P_{0.t}$ =precipitations in areas surrounding the catchment at time *t*, d_0 and f_0 = are constants in the emigration and in-migration rate equations, d_1 and f_1= are coefficients for GDP per capita effect on emigration and in-migration rate equations, and d_2 and f_2 = are coefficients for precipitation effect on emigration and in-migration rate equations.

Downstream population size

To account for downstream population size at time t+1, we also used an exponential population growth function as applied by Woodwell (1998) which assumed that it varies over time with natural growth (Equation 5.39), in-migration and emigration (Equations 5.40 and 5.41, respectively). Again following Arabi *et al.*, (2006), we assumed that in-migration and emigration rates vary over time and are influenced by the availability of off-farm opportunities created by economic growth (GDP per capita), prices of basic domestic goods downstream inside and outside the catchment area, price of house rent inside and outside the catchment area and wage inside and outside the catchment area, as specified in Equations 5.42 and 5.43, respectively. Similarly to upstream, other factors, such as family planning policies, health services, and death rate which can also influence human population dynamics, were not considered because of difficulties in obtaining data at the catchment level.

Downstream population growth

$$Pop_{D.t+1} = Pop_{D.t}(1 - g_D) + (IM_{D.t} - EM_{D.t}) \tag{5.39}$$

Where: $Pop_{D.t}$ =Downstream community population size at time *t*, g_D =Downstream population growth rate, $IM_{D.t}$ =Downstream in-migration at time *t* and $EM_{D.t}$ =Downstream emigration at time *t*.

Number of in migrants downstream at time t

$$IM_{D.t} = \Phi_{D.t} * Pop_{D.t} \tag{5.40}$$

Where $\Phi_{D.t}$ =Downstream in-migration rate at time *t*.

Number of emigrant downstream at time t

$$EM_{D.t} = \Omega_{D.t} * Pop_{D.t} \tag{5.41}$$

Where: $\Omega_{D.t}$ =Downstream emigration rate at time *t*.

In migration and emigration rates

$$\Phi_{D.t} = z_0 + z_1 GDP_{k..t} + z_2 P_{BGDin.t} + z_3 P_{HRin.t} + z_4 W_{Din.t} \tag{5.42}$$

$$\Omega_{D.t} = n_0 + n_1 GDP_{k.t} + n_2 P_{BGEout.t} + n_3 P_{HREout.t} + z_4 W_{Dout.t} \tag{5.43}$$

Where: $GDP_{k.t}$ = gross domestic product per capita at time *t*, $P_{BGDin.t}$ =price of basic domestic goods inside the catchment area at time t, $P_{BGDout.t}$ =price of basic domestic goods outside the catchment area at time t, $P_{HREin.t}$ = price of house rent inside the catchment area at time t, $P_{HREout.t}$ = price of house rent outside the catchment area at time t, $W_{Din.t}$ =wage rate downstream inside the catchment area, $W_{Dout.t}$ =wage rate downstream outside the catchment area, z_0 to z_4 and n_0 to n_4 = are parameters estimated econometrically.

Finally, the economic well-being or social welfare was computed as the net income per capita which is by this study used as a measure (proxy) for social welfare. It was computed by dividing the total income from all sources by total population specified as follows:

$$SW_t = NI_{catchment.\,t}/Pop_{catchment.\,t} \tag{5.44}$$

Where: SW_t stands for social welfare measured as income per capita.

5.3.6. Labour market equilibrium

To ensure that the labour market equilibrium is attained in every simulation, we included equations for balancing the labour force supplied by the upstream community. We began by noting that the community living in the upstream areas supply labour for off-farm activities, fruit and crop production, and accordingly the study assumed the total labour supply in the catchment vary with wage rate and population dynamics. Variation due to population was considered to be due to a proportion of working children (8-14 years) and adults (19-65 years) in the population (NBS, 2002), while variation due to wage rate was considered to be due to variation in GDP per capita. Labour supply was then specified and estimated by Equation 5.45. The proportions (λ_1 and λ_2) were computed from the population data obtained from the 2010 census report (NBS, 2010). On the other hand, the total labour demand in the catchment was the aggregated off-activities labour supply and fruit and crop production labour supply calculated by the equation specified in Equation 5.47 of Appendix A. Labour market balance was then specified and included in the model by Equation 5.48, as used by Jogo and Hassan (2010).

Total labour supply:

$$LS_t = (\lambda_1 L_1 + \lambda_2 L_2) * Pop_t * W_t \tag{5.45}$$

Where: LS_t=labour supply at time *t*, λ_1= proportion of working adults (16-65) in the population, λ_2=proportion of children (8-15) in the population, L_1=labour supplied per adult per year (hours/year), and L_2= labour supplied per adult per year (hours/per year).

Wage rate at time t

$$W_t = q_0 + q_1 GDP_{k.t} \tag{5.46}$$

Where q_0 and q_1=are parameters estimated econometrically.

Total labour in used in livelihood activities (hours/year):

$$LD_t = L_{o.t} * NHO_t + LF_t^i * NH_{fp.t} + LC_t^i * NH_{cp} \tag{5.47}$$

Where: LD_t= labour demand at time t, $L_{o.t}$=household labour used for off-farm activities at time *t*, NHO_t= number of household involved in off-farm activities at time t, LF_t^i = household labour used for fruit production at time t, $NH_{fp.t}$=number of upstream households involved in fruit production at time t, LC_t^i =household labour used for crop production at time t, and $NH_{cp.t}$=number of household involved in crop production at time t.

Labour market equilibrium:

$$LS_t = LD_t \tag{5.48}$$

This module is linked to hydrological, land use, crop and fruit production modules through population density in the sense that a growing population increases demand for food and other utilities, which in turn affects the size of land allocated to crop production that eventually affects other canopy covers, apart from crops. It is also linked to crop and fruit production modules through net incomes from fruit and crop production in the sense that total income used to calculate net income per capital is a summation of these net incomes.

5.3.7. Catchment commodities market equilibrium

To ensure that the catchment commodities market equilibrium is attained in every simulation, we included equations for balancing commodities demand and supply. We began by noting that the community living in the upstream supply crops and fruits (i.e. paddy, banana, mango and oranges). These crops are sold to the communities living upstream and downstream of the catchment. The quantity of these commodities demanded is functions of their own prices, GDP per capita of upstream and downstream communities, and population of the communities living upstream and downstream as specified in the following equation:

$$\begin{aligned} QC_i^D &= \psi_0 + \psi_1 A_{ci} + \psi_2 SUB + \psi_3 HH_{size} + \psi_4 P_m + \psi_5 P_{zci} + \psi_6 P_{Fi} + \psi_7 P_{ZFi} + \psi_8 W_o) \\ QF_i^D &= \omega_0 + \omega_1 A_{Fi} + \omega_2 SUB + \omega_3 HH_{size} + \omega_4 P_m + \omega_5 P_{zci} + \omega_6 P_{Fi} + \omega_7 P_{ZFi} + \omega_8 W_o) \end{aligned} \tag{5.49}$$

Where

Catchment commodities Market equilibrium

$$QS_t = QD_t \tag{5.50}$$

This module is linked to hydrological, land use, crop and fruit production modules through population density in the sense that a growing population increases demand for food, water and other utilities, which in turn affects the size of land allocated to crop production that eventually affects other canopy covers, apart from crops. It is linked to crop and fruit production modules through crop and fruit production, supply of labour for crop and fruit production. It is also linked to crop and fruits production through net incomes from fruit and crop production in the sense that quantity of crops supplied is determined by demand and the total income used to calculate net income per capital are a summation of net incomes from production fruits and crops.

5.3.8. Type of data and sources

Data on labour, crop and fruit supply were collected through household survey. Data on the current land mosaic and location were collected through field survey. On the other hand, farm plot altitudes, sizes and distribution in the catchment were collected using GIS systems. Finally, secondary data on runoff, rainfall pattern, GDP and many others were collected through reviewing reports and records in various institutes responsible for collecting and handling those data (see Table 5.1).

Table 5.1: Types and sources of data used to estimate parameters

S/N	**Module**	**Type of data used**	**Sources**
1	Hydrological		
		1. Secondary data	
		Historical data on	
		Run-off	Wami/Ruvu water board Morogoro office
		Precipitation (mainly rainfall)	Tanzania metrological agency (TMA) Morogoro office
		Natural vegetation biomass	EAMCEF, MoA, MoW, and MNT
		Area covered by natural vegetation	EAMCEF, MoA, MoW, and MNT
		Area covered by crops	EAMCEF, MoA, MoW, and MNT
		Area covered by fruit trees	EAMCEF, MoA, MoW, and MNT
		Conservation subsidies	CARE and WWF
		Point data on	
		Altitude	Field survey
		Environmental carrying capacities	TAFORI and EAMCEF
		Crop plants spacing	Sokoine University of Agriculture; Crop Science Department
		Fruit tree spacing	Sokoine University of Agriculture; Crop Science Department
2	Land use		
		Secondary data	
		Total catchment area	EAMCEF, MoA, MoW, and MNT
		Area covered by natural	EAMCEF, MoA, MoW, and

S/N	**Module**	**Type of data used**	**Sources**
		vegetation	MNT
		Primary data	
		Crops input and output market prices	Household survey
		Basic domestic goods and their prices	Household survey
		Household sizes	Household survey
		Household off-farm incomes	Household survey
		Household area converted to crop and fruit production	Household survey
		Altitude for each land use type	Household survey
S/N	Module	Type of data used	Sources
3	Crop production		
		Secondary data	
		Historical data on wage rates	BOT
		Primary data	
		Crops input and output market prices	Household survey
		Basic domestic goods and their prices	Household survey
		Household sizes	Household survey
		Household labour use	Household survey
		Household off-farm incomes	Household survey
		Household area converted to crop and fruit production	Household survey
4	Fruit production		
		Secondary data	
		Historical data on wage rates	BOT
		Primary data	
		Crops input and output market prices	Household survey
		Basic domestic goods and their prices	Household survey
		Household sizes	Household survey
		Household labour use	Household survey
		Household off-farm incomes	Household survey
		Household area converted to crop and fruit production	Household survey
S/N	Module	Type of data used	Sources
5	Economic module		
		Secondary data	
		Historical data on	
		In-migration and emigration	WEO
		GDP per capita	BOT
		Number of household engaged in	WEO

S/N	Module	Type of data used	Sources
		off-farm activities	
		Consumer price indices	BOT
		Point data on	
		Population size	NBS
		Proportions of children (4-14) and adults (15-65) years	NBS
		Discount rate	BOT
		Secondary data	
		Crops input and output market prices	Household survey
		Basic domestic goods and their prices Household sizes	Household survey Household survey
		Household labour use	Household survey
		Household off-farm incomes	Household survey
		Household area converted to crop and fruit production	Household survey

5.4. Concluding summary

In this chapter the conceptual framework on which the study based its analysis has been presented. The chapter, through the framework, has depicted the linkage between the elements (or components) making up the Uluguru water catchment system. It clearly showed how a change in one element affects the rest of the system in functioning and its services flow. The framework also showed how the changes induce land use trade-off between competing uses (i.e. natural vegetation, fruit tree and crop production) and the feedbacks involved.

The chapter has also presented the empirical model in detail, showing how various elements of the systems are transformed into modules, which were implemented in the STELLA software for simulation analysis. The chapter showed how the modules were linked to each other to capture the effect of change in one element (or component) of system on the rest of the elements.

The chapter concluded by presenting the parameters estimated; it began with highlighting the type of data used to estimate the parameters, how they were collected and how the parameters were estimated. Finally it presented the labels, symbols, the parameters and their sources.

CHAPTER 6

MODEL PARAMTER ESTIMATION

6.1. Introduction

The chapter presents the theoretical and empirical models used to estimate parameters used to in ecological economic model presented in chapter 5. Specifically the chapter presents the models for examining the determinants of upstream land holders land and labour allocation, crop and fruits supply and demand, and population migration. Furthermore, the chapter present and discuss the results of the model estimates. The chapter begins by presenting the model for analysing the determinants of land and labour allocation between different economic activities, crop and fruit supply and demand decision. The following section (section three) present specification of the reduced household model. Section four present data and data collection method for the model estimation. Section five presents the reduced household model estimation procedure. Section six present specifications of regression models for estimation of other parameters used in the model. Results and discussion are presented in section seven, and section eight present the conclusion of the chapter.

6.2. Determinants of household land, labour, crops and fruits supply and demand

The primary objective of the study is to evaluate the role of market based policy instruments on inducing land use externalities internalisation. To achieve this the study considered upstream landholders households as decision making units. The households decide on allocation of land and labour to various economic activities, production/supply of crops and fruits, and consumption. Therefore, the study based its estimation of parameters for land and labour allocation, production/supply of crops and fruits, and demand for the products on agricultural household model.

6.2.1. The analytical framework

The study based the analysis of the Uluguruth water catchment upstream landholders land and labour allocation, production and supply produce on agricultural household modelling approach as applied by Singh *et al*, (1986); Chen *et al*, (2006); Dayal (2006); Adekola (2006); and recently by Jogo and Hassan (2010). Upstream land holders households in the catchment are both producer and consumer of crops they produce, and sell excess to the market. Therefore, a household approach is the most appropriate approach for analysing Uluguru catchment upstream household's decision on allocating their land and labour to different uses, consuming and supplying crop and fruit products.

The neoclassical model of a farm household (agricultural household model) described by Singh et al, (1986) has been the main analytical approach used for analysing the resources allocation, production and consumption decision made by a rural household. The approach is based on the assumption that rural households in subsistence economies are both producers and consumers. The household can separate production and consumption decisions by first maximising profit from production and use the profit from production to maximise utility from consumption. The major difference between the farm household model and the pure consumption model is that in the later the household budget is exogenously fixed whereas in the former is influenced by production decisions that contribute to income through farm profits.

The model assumes that a household maximises its utility which is dependent on the consumption of agricultural products (in our case crops and fruits $(C_i \& F_i)$); marketed basic domestic commodities (X_{mi}), and leisure time (L_z). Household utility is assumed to vary with different household characteristics (Ω) including family size, age of a household member, and education, which can influence household consumption preferences. For simplicity marketed domestic good X_m is assumed to be purchased from the market. Thus, our Uluguru water catchment upstream household utility maximization problem is defined as:

$$\text{MaxU} = U(C_i, F_i, X_{mi}, L_z, \Omega) \qquad (6.1)$$

The household also depend on crop and fruit production for its livelihood. The production technology of crop (C_i) and fruit (F_i) is a function of household labour allocated to agricultural production $(L_{ci} \& L_{Fi})$, an area allocated to crop and fruit *i* production $(A_{ci} \& A_{Fi})$ a vector of household assets endowments such as land and farm implements (plough and hoe) (ω) influencing the production; a composite of inputs capturing all the inputs used in crops and fruits production which are purchased from the market such as seeds $(Z_{ci}$ & $Z_{Fi})$, and the production technology parameter (α).

$$C_i = C_i(\alpha L_{ci}, A_{ci}, Z_{ci}, \omega) \qquad (6.2)$$

$$F_i = F_i(\alpha, L_{fi}, A_{Fi}, Z_{Fi}, \omega) \qquad (6.3)$$

The upstream household can purchase additional agricultural crops and fruits $(C_i^p$ & $F_i^P)$ from the market to meet any consumption requirements, which are not supplied by its own production. In addition, the upstream household can sell the surplus crops or fruits $(C_i^s$ & $F_i^s)$ in the market and hence faces a crop and or fruit balance.

$$C_i = C_i + (C_i^p - C_i^s) \qquad (6.4)$$

$$F_i = F_i + (F_i^p - F_i^s) \qquad (6.5)$$

Upstream household expenditures are constrained by the income from selling the agricultural products, off-farm labour, renting out their land and exogenous income (E). In our case we considered input subsidies through PES arrangements as the only exogenous income to catchment upstream land holders. The household can spend its income on purchasing agricultural crops and fruits, marketed basic domestic goods and agricultural inputs used for crop and fruit production. It was assumed that all market prices are exogenous, and expenditure cannot exceed the total income. Therefore, a household budget constraint is given by:

$$P_{ci}C_i^s + P_{fi}F_i^s + L_oW_o + R_iA_i + SUB \geq P_{ci}C_i^p + P_{fi}F_i^P + P_{zi}Z_i + X_{mi} \qquad (6.6)$$

Where: $P_{ci}; P_{ft}, P_{zi}, W_o$ and SUB refer to market prices of the crops and fruit products, crop and fruit inputs, exogenous off-farm wage rates and fruit production subside. L_o refers to the labour time spent on off-farm wage work.

Upstream households have limited labour time available (L_T) and divide this time between crop and fruit production, off-farm activities, and leisure. Therefore, household labour time is given by:

$$L_T = LC_i + LF_i + L_o + L_z \qquad (6.7)$$

Upstream households also have limited land resource available (A_T) and they have to allocate this land to crop and fruit production, and natural vegetation growth. Thus, land resource constrain is given by:

$$A_T = A_{Ci} + A_{Fi} + A_{NVi} \qquad (6.8)$$

The decision problem for an upstream household is to maximise the utility function (6.1) subject to production, budget, labour time and land constraints specified in 6.2; 6.3; 6.6; 6.7 and 6.8.

$$\begin{aligned}\ell = {} & U(C_i^c, F_i^c, X_{mi}, L_z, \Omega) - \lambda_1(C_i - C_i(\alpha, L_{ci}, A_{ci}, Z_{ci}, \omega)) - \lambda_2(F_i \\ & - F_i(\alpha, L_{fi}, A_{Fi}, Z_{Fi}, \omega)) - \lambda_3(P_{ci}C_i^P + P_{fi}F_i^P + P_{zci}Z_{ci} + P_{ZFi}Z_{Fi} + RA_{ci} + RA_{Fi} \\ & + P_{mi}X_{mi} - P_{ci}C_i^s - P_{fi}F_i^s - L_oW_o - SUB) \\ & - \lambda_4(L_{ci} + L_{Fi} + L_o + L_z - L_T) - \lambda_5(A_{Ci} + A_{Fi} + A_{NVi} - A_T)\end{aligned} \tag{6.9}$$

There are 17 decision variables to solve in the model, which are: $C_i^c; F_i^c; X_m; C_i, F_i; C_i^P; F_i^P; Z_{ci}; Z_{Fi}; A_{ci}; A_{Fi}\ C_i^S; F_i^S; L_{ci}; L_{Fi}; L_o; \lambda_1; \lambda_2; \lambda_3; \lambda_4, \lambda_5$. Therefore, one needs 19 equations to solve these 20 endogenous variables.

From the first order conditions with respect to these decisions variables, a system of 19 reduced forms of equations is derived. The system of equations, 1.1 to 1.19 in Appendix 1, gives the complete set of 19 equations needed to solve the 20 endogenous variables. All endogenous variables will be reduced form of functions of the set of exogenous variables in the model, which are: $P_{ci}; P_{ft}, P_{zi}, W_o, SUB, \Omega, \alpha$ and ω.

First order conditions A1.1, A1.2, and A1.3 show how an upstream household allocate its labour among the productive activities and leisure. The three conditions show that the optimum labour allocation is such that the marginal value of labour across the productive activities is equalised. By rearranging the first order conditions A1.8 and A1.11 to $\partial U / \partial C_i^c = \lambda_1$ and $\partial U / \partial F_i^c = \lambda_2$ respectively and then substitute the λ's in the first order conditions A1.1, and A1.2. The two conditions also show that, at the optimum, the household allocates its labour across the productive activities that the marginal utility of labour in each of the activities is equal and is also equal to the marginal utility of leisure (λ_4) (which represents the shadow wage or opportunity cost of household labour time). This shadow wage is internal to each household and depends on the full set of exogenous variables.

First order condition A1.3 can be rearranged to $\lambda_3 W_o = \lambda_4$. This condition shows that the decision on the participation in off-farm work is influenced by: off-farm wage rates (W_o); marginal utility of income (λ_3), and the marginal utility of leisure (λ_4). The marginal utility of leisure can be equal to or higher than the off-farm wage rate. If it is equal, the household participates in off-farm work. If it is higher than the wage rate, the household will not supply labour to off-farm work.

First order conditions A1.10 and A1.13 relate to purchasable crop and frit products and give us the familiar consumer theory results that the marginal rate of substitution between two goods purchased in positive quantities is equal to the ratio of their relative prices. In addition, these first order conditions also show that an upstream household can improve its welfare by purchasing additional products from the market. However, in making the decision to purchase products from the market the household compares the costs of purchasing (the price) and the marginal utility gained from consuming purchased products (the welfare benefit). This is the fundamental micro-economic theory of consumer behaviour, which states that "a consumer equates the marginal utility to the price in purchasing goods from the market".

Selling of products (crops and fruits) produced from the catchment reduces upstream household's welfare. The first order conditions A1.9 and A1.12 show that the marginal rate of substitution between two goods is equal to the ratio of their relative prices. These first order conditions also show that in making the decision to sell a product in the market the household equates the marginal utility of income (λ_4) derived from selling the product to the marginal utility forgone by choosing not to consume the product (welfare loss to the household). At the optimum, the marginal utility of income across the products is equalised at (λ_4). The first order conditions for selling and purchasing decisions also show that upstream households that sell and purchase products will normally face a market price.

Conditions A1.15 and A1.16 recover the production functions for crop and fruit products, which are functions of production parameters; labour; land, inputs and household endowment. First order conditions A1.17, A1.18 and A1.19 recover the full budget, time and land constraints respectively.

Rural households allocate their labour, capital and other resources between competing livelihood activities that include crop and livestock production, off-farm activities, harvesting of wetland resources and leisure. Households decide on the allocation of resources between these activities which maximises their utility given their resource endowment; prices; the efforts required (production technology); and household characteristics.

6.3. The reduced household model specification

From the solution of the first order optimality conditions presented in section 5.4.1.1 above, a set of reduced form equations can be derived showing the endogenous variables as functions of all the exogenous variables. As done in other similar studies, these equations form the basis for empirical estimation (Jogo and Hassan, 2010; Fisher *et al*., 2005; Chen *et al*., 2006). As shown earlier, the household model comprises of 20 endogenous variables and therefore we have 19 reduced form equations. However, it is not necessary to estimate the full system of equations (Sadoulet and De Janvry, 1995).

Given that our primary interest is to examine the factors that influence household labour use in each of the livelihood activities (crop and fruit production, and off-farm work) and the supply of crop and fruit products, we focus our empirical analysis on the following endogenous variables: household labour time used in each of the productive activities (L_{ci}, L_{Fi}, L_o); the quantity of crop (QC_i^s) and fruit (QF_i^s) supplied; area allocated to crop (AC_i) and fruit (AF_i). The reduced form functions for crop (QC_i^s) and fruit (QF_i^s) will give rise to household supply functions for crop and fruit products and are specified as:

$$\begin{aligned} QC_i^s &= C_i^s(A_{ci}, SUB, HH_{size}, P_m, P_{zci}, P_{Fi}, P_{ZFi}, W_o, \varepsilon_{ci}) \\ QF_i^s &= F_i^s(A_{Fi}, SUB, HH_{size}, P_m, P_{zci}, P_{Fi}, P_{ZFi}, W_o, \varepsilon_{Fi}) \end{aligned} \qquad (6.10)$$

Where ε_{ci} and ε_{Fi} are error terms, and HH_{size} is household size.

The reduction form equation for household labour time used in each of the livelihood activities is given by:

$$\begin{aligned} L_i &= L(L_T, A_{ci}, SUB, W_o, P_{ci}, P_{Fi}, P_{zci}, P_{ZFi}, \mu_{ci}) \\ L_o &= L(L_T, SUB, W_o, P_{Fi}, P_{ci} P_{zci}, P_{ZFi}, \mu_{Fi}) \end{aligned} \qquad (6.11)$$

Where L_i represent labour time spent in crop and or fruit production, μ_{ci} and μ_{Fi} are error terms.

The reduction form equation for household land resource allocation to various crops is given by:

$$\begin{aligned} AC_i &= A(P_{ci}, P_{Fi}, P_{zci}, P_{ZFi}, P_{mi}, SUB, HH_{size}, W_o, \eta_{ci}) \\ AF_i &= A(P_{Fit}, P_{ci}, P_{zci}, P_{ZFi}, P_{mi}, SUB, HH_{size}, W_o, \eta_{Fi}) \end{aligned} \tag{6.12}$$

Where η_{ci} and η_{Fi} are error terms.

And the reduction form equation for household demand for additional crops and fruits to maximise their utility is given by:

$$\begin{aligned} QC_i^D &= C_i^D(A_{ci}, SUB, HH_{size}, P_m, P_{zci}, P_{Fi}, P_{ZFi}, W_o, \upsilon_{ci}) \\ QF_i^D &= F_i^D(A_{Fi}, SUB, HH_{size}, P_m, P_{zci}, P_{Fi}, P_{ZFi}, W_o, \upsilon_{Fi}) \end{aligned} \tag{6.13}$$

Where υ_{ci} and υ_{Fi} are error terms.

6.4. Data collection for the reduced household model estimation

A combination of participatory rural appraisals (focus group discussions and key informant interviews) and formal methods (household surveys) were used. The former was used to gain a baseline understanding on the main livelihood activities, the type of land use and household decision makers. The information was then used as guide for the design of the subsequent household survey. Two complimentary face-to-face household surveys, using structured household questionnaires, were carried out in the study area in November, 2011. In both surveys a purposive random sampling was used to select households for interviews. The purposive selection of households from the population was based on type of land use (producing crop or fruit), location of the area, altitude of the area, and closeness to the water hotspot. The first survey was done was conducted in December, 2011; and the second in January, 2012. A total of 140 households were interviewed in the two phases using a structured questionnaire administered by trained enumerators in *Swahili* language. The household questionnaire collected data on: household demographics; land uses; description of crop production activities (area under cultivation, production levels, input use including labour, prices of inputs and output); and sources of income.

6.4.1 Reduced household model variables and expected direction of relationships

The dependent variables in this study's empirical model are the amount of labour time used in each of the productive activities; quantities of crop and fruit products supplied, and sizes of land allocated to crop and fruit production. The selection of explanatory variables for the empirical model was based on the analytical framework developed section 5.2.1.2. The explanatory variables in the labour use, crop and fruit products supply, and land allocation equations include: exogenous variables, such as household characteristics; product and inputs prices; household exogenous income and off-farm wage rates.

The selection of explanatory variables pertaining to household demographic and endowment characteristics is informed by theoretical and empirical literature and data availability. Various studies have shown that household demographic characteristic such as gender, the size of the household, the age of the head of the household and a household's education level influences rural household labour supply decisions for different livelihood activities, including natural resource activities (Jolliffe, 2004; Matshe and Young, 2004). A household's size is used as a proxy for household labour time endowment (L_T). It is expected that a household's size is positively related to the labour that is allocated to crop production, and off-farm work, because of the demand for food and availability of surplus labour. Because of this, it is expected that household size will have negative relation with land allocated to fruit and positive relation land allocated to crop. Accordingly, it is expected that a household's size should be positively related to crop supply, and negatively related to fruit supply also due to demand for food and the availability of labour to use in the production of crops.

Matshe and Young (2004) showed that gender influences labour allocation decisions of rural households because of their time commitment to activities within the household, females are less likely to participate in off-farm activities than males. In most subsistence farming communities in Africa women tend to do much of the agricultural work and interact with the environment more often than their male counterparts. Therefore, one can expect female-headed households to allocate more time to crop production and less time to off-farm work. Similarly, tree fruits production in Africa is seen as male job; therefore, one can expect to see lees time is allocated to fruit production in female headed household than in male headed household. Because of these, one can expect female-headed households to supply more crop than fruit products than their male headed counterparts.

It can expected that the head of the household's age is positively related to labour used in crop and fruit production, but negatively related to labour time allocated to off-farm work. It is also expected older household heads to have positive relation with land allocated to fruit and crop production. This is based on the expectation that older heads have more experience in farming than younger ones. Their experience creates inertia and results in them being interested in their traditional sources of livelihood (i.e. farming). Also, their position in the social network which gives them better access to natural resources such as land for cropping, hence they will have more land to allocate to the two productions. Accordingly, it is expected that the age of a household head has a positive effect on crop and fruit products supply.

Many empirical studies have shown that education increases potential employment opportunities in off-farm work, but negatively affects the labour time allocated to farm work (Fisher *et al*., 2005; Chen *et al*., 2006). Therefore, it is hypothesised that the education level of the head of the household is negatively related to labour allocated to crop production, but positively related to time allocated off-farm. Such a decreased interest on crop production will increase land left for fruit tree planting. Because of this, it is expected that the education level of a household's head to be negatively related to supply of crop products, and positively related to supply of fruits.

A household's exogenous income is another explanatory variable in the labour; crop and fruit supply equations, and land allocation with fruit production subsidy in a form of PES arrangement representing the main source of external income. According to Chen *et al*. (2006) a household's exogenous income targeted to encourage best practices decreases labour time allocated to destructive land use practices and it may induce higher time allocated to best practices or consumption of leisure. However, this depend on the management of the funds (i.e. follow up of the use). Following this, it is expected that a household's exogenous income to be negatively related to labour time used in off-farm work and crop production, and positively related to labour time allocated to fruit production.

With regards to the impact of exogenous income on grain supply, Holden *et al.* (2004) found that better access to non-farm income (exogenous or off-farm work income) reduces incentives to do farming, which leads to lower agricultural production; therefore, households become net buyers of food. The impact of exogenous income on fruit supply could be positive or negative depending on the management of funds. We expect a household's exogenous income to be positively related to labour time used in fruit production. Such a positive relation is also expected from land allocated to fruit production; this is because households will reduce dependence on land as their main source of income.

One expects that the price of crop and fruit products to be positively related to labour used in producing the products, the supply of the product, and the area allocated to production of the products. Both prices of crop and fruit products are expected to negatively impact on labour used in off-farm work.

An increase in the price of crop inputs reduces returns to crop production and is therefore expected to result in the shifting of household labour resources away from crop production towards fruit production and off-farm work. Such a shift in labour will induce increase in area allocated to fruit production and decrease in area allocated to crop production. As a result, the supply of fruits products is expected to increase and that of crops reduced. The price of basic domestic market goods is expected to be positively related to labour time used in the crop and fruit production, as well as off-farm work, since an increase in the price of market goods reduces household real income, inducing the household to forego leisure. Similarly such a shift in labour will increase areas allocated to crop and fruit production. Accordingly, the supply of crop and fruit products is expected to be positively related to the price of market goods.

The off-farm wage rate is expected to be positively related to labour used in off-farm work but negatively related to labour used in crop and fruit production. Therefore, a negative relationship between off-farm wage rates and supply of crop and fruit products is expected. Accordingly, the areas allocated to production of crop and fruit is expected to be negatively related to off-farm wage rates.

Many studies have shown that wealth status influences labour allocation decisions of rural households. Although wealthier households are more likely to participate in off-farm work than the poor, but the effects of wealth on intensification of agricultural production could also be possible since wealthier households can afford factors of production than poor (Matshe and Young, 2004). Thus, the relationship between wealth status and labour use and the supply of crop and fruit products could be positive or negative. Similarly the areas allocated to production of crops and fruits could also be positive or negative. The relationship between a household's wealth status and the supply of crops and fruit is expected to be positive as wealthier households are expected to have more farm assets and access to inputs to enhance farm productivity. However, one may expect wealthier households to allocate less of their time to crop and fruit production given that they can hire labour and also can use machinery for some of the activities which are done manually by poor households.

In developing the wealth index, we followed the approach of Campbell *et al*. (2002) and Démurger and Fournier (2006) in developing a composite wealth index computed as a linear combination of household assets using a principal component analysis (PCA)[2]. The key household asset variables used for constructing the wealth index are based on household assets identified by Tinguery (2006) through participatory wealth ranking conducted in the study area. In constructing the household wealth index, physical assets were first categorised into three main variables: farm assets (hoe, shovel, plough etc.); domestic assets (radio, television, telephone etc.); and transport equipment (bicycle, motorcycle etc.). A PCA was then done using 5 variables namely: housing type; farm assets; domestic assets; transport equipment; and land area. The index was computed by multiplying the standardised value of each of the 5 variables by the first factorial coordinate of the variable in the PCA and then summed across all 5 variables. A wealth index computed in this way is much more encompassing and better reflects the wealth status of a household than the use of a single proxy variable, as done in most studies.

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[2] This technique involves combining several original variables into few derived variables or principal components (factors). In this case the single derived variable is wealth index.

6.5. Reduced household model econometric estimation procedures

Reduced form models 5.60, 5.61, 5.62 and 5.63 constitute the system of equations, which were estimated econometrically. As the error terms across the equations in the system are potentially correlated due to the fact that the same explanatory variables and unobserved characteristics may influence the different equations, estimating the individual equations using ordinary least-squares yields biased and inconsistent estimates as it ignores error correlations across equations (Woodridge, 2002). Seemingly unrelated regression (SUR) models proposed by Zellner (1962) are the most appropriate econometric techniques to account for the cross equation correlations. The merit of the SUR model is that it allows the estimation of the system of equations simultaneously, thereby controlling correlation across the error terms (residuals) in the different equations. This yields unbiased and efficient estimates (Bartels and Fiebig, 1991).

This study employed the SUR procedure as suggested by Jogo and Hassan (2010) to jointly estimate models 5.60, 5.61, 5.62 and 5.63 as a system. It should be noted that if the regressors in each equation are the same as is in this study's case, then the parameters of each independent variable obtained by a SUR model are identical to those obtained through equation-by-equation ordinary least-squares estimation (Greene, 2003). However, it is important to know that even when this is the case, there is still a good reason to estimate the equations jointly using a SUR model (Woodridge, 2002). One reason for this is that one may be interested in testing joint hypotheses involving parameters in different equations. The Breusch-Pagan test was employed to test the null hypothesis that the error terms of the equations in the system are independent. The results of the test showed that $\chi^2 = 45.38; p < 0.001$ and therefore the null hypothesis of independence of errors across the equations is rejected and hence the use of the SUR model to jointly estimate the equations is justified.

6.6. Other paramters estimation

As noted section 5.4.1 the model involved a number of paramters, other paramters were not from upstream land holders decision making but from scientifically measured data which have been generated for a period of time (i.e. time series data). Others were from household survey. Parameters from these data were estimated using Ordinary Least Square regression (OLS) models spefified as follows:

The hydrological module paramters:

Sediment load downstream is a results of catchment cannopy cover which serves as filter bed for runoff from rain. Each cannopy cover has its capacity to filter sediments in runing water; therefore, the rate at wich sediment are allowed to flow downstrean $(\mathrm{SD_i})$ is a function of runoff $(\mathrm{RO_i})$. The relation btween sediment dioscharge and runoff is such that as runoff increases sediment discharge increases. The econometric model to estimate the parameter relating sediment discharge rate and runoff was specified as follows and estimated using OLS from time sries data:

$$\mathrm{SD_i} = \mathrm{SD}(\mathrm{RO_i}, \varepsilon_{\mathrm{SDi}}) \qquad (6.14)$$

Where $\varepsilon_{\mathrm{SDi}}$ error term.

Each vegetation cannopy cover has its capacity to reduce runoff, hence different sediment discharge rate; therefore, runoff is a function of cannopy cover. The capacity depends on the type and density (DENS) of the cannopy cover. The velocity of runoff depends on the amount of rain drop (storm) (PRES) and slope of the area; the more the rain and the steeper the area the higher the runoff. The slope is determiend by the altitude (ALT) of the area (the higher the altitude the steeper the slope). Therefore, runoff is a function of cannoy cover density, stom and altitude of the area where the cannopy cover is. Thus the econometric model to estimate the parameter relating runoff, the denity of cannopy cover, rain drop (storm), and altitude was specified as follows and estimated using OLS:

$$\mathrm{RO_i} = \mathrm{RO}(\mathrm{DENS_i}, \mathrm{PRES}, \mathrm{ALT_i}, \mu_{\mathrm{RO}}) \qquad (6.15)$$

Where $\varepsilon_{\mathrm{SDi}}$ is an error term.

Fruit tree planting subsidy rate paramters

The study assumed subsidy rate as a function of consumer price index. It therefore vary with with variation in consukmer price index and the relationship is positive, meaning that as consumer price index increases subsidy rate also increase. Using times series data on consumer price index obtained from the central bak of Tanzania subsidy rate paramters were estmenated using an econometric model specified as follows:

$$\vartheta = \vartheta(\mathrm{CPI}, \varepsilon_{\vartheta}) \qquad (6.16)$$

Where ε_{ϑ} is an error term.

To account for the total subsidy dibused to upstream land holders, the study assumed that the number of upstream land holdeders household which engage in producing fruits is function of market price of fruit, labour time needed for producing fruits, and subsidy given a year back. The number of households enganging in fruits production were expected to be poaitively related to to these determinants. Using the crossectional data gathered from household survey, the paramters for this relationship were estimated econometrically using the model specified as follows:

$$NHF = NHF(P_f, L_f, SUB_f, \varepsilon_{NHF}) \qquad (6.17)$$

Population dynamic paramters

The catchment is a home of upstream and downstream inhabotats and this population exert pressure on catchment ecosystem services i.e. they directly and indirectly benefits from the catchment ecosystem services and produce externalities which affect some of the beneficiaries, hence affecting the social welfare. The study assumed that upstream population varies over time with growth (g), in-migration (IM) and emigration (EM). Population growth rate was adopted from the national beaureau of statistics, but in-migration and emigration rates $(\eta_U \,\&\, e_U)$ were estimated from time series data using econometric models. The study assumed that in-migration and emigration rates are functions of gross domestic product per capita (GDP_{KU}) and precipitation of the area $(PRES_{in/out})$. Therefore, the in-migration and emigration rates for both upstream population were estmated using the model specified as follows:

$$\eta_U = \eta_U(GDP_{KU}, PRES_{in}, \varepsilon_{\eta U}) \qquad (6.18)$$

$$e_U = \eta_U(GDP_{KU}, PRES_{out}, \varepsilon_{eU}) \qquad (6.19)$$

In the downstream the study assumed that population varies over time with growth, in migration and emigration. Simlarly to upstream population, downstream gopulation growth rate was aslos adopted from the national beaureau of statistics, but in-migration and emigration rates were estimated from time series data using econometric models. The study assumed that in-migration and emigration rates are functions of gross domestic product per capita (GDP_K), prices of basic domestic products (P_m), house rent prices $(HRent)$, and labour wage rate (W_D). Therefore, the in-migration and emigration rates for both upstream population were estmated using the model specified as follows:

$$\eta_D = \eta_D(GDP_{KU}, P_{MD}, HRent_D, W_D, \varepsilon_{\eta D}) \qquad (6.20)$$

$$e_D = \eta_D(GDP_{KU}, P_{MD}, HRent_D, W_D, \varepsilon_{eD}) \qquad (6.21)$$

6.7. Model results and discussion

6.7.1. Summary statistics of variables used in the econometric analysis

Reduced household model variables

Table 6.2 presents descriptive statistics of the variables used in the reduced household model econometric analysis. The table shows the average household labour time used in different livelihood activities[3]. The figure for labour time allocated to off-farm work is relatively small than that spends on other economic activities with more labour time being spent on rice production followed by banana production. Household spent much of their labour on rice presumably because the crop is used as food crop in area while banana, mango and orange are considered as cash crops. These results compares well with Lopa et al, (2012).

The low time allocated to off-farm works is presumably to due to low levels of education and skills reduce the productivity and returns from off-farm work, which reflect the opportunity cost of farm labour time. The results show that the average level of years spent in schooling is seven which is primary education. Therefore, households rationally allocate more time to farm work than off-farm work. This finding is consistent with that of Laszlo (2008) that on average rural households particularly those with lower levels of education allocate more labour time to farm activities than to off-farm activities despite the fact that the returns to labour time are lower in farm activities than in off-farm work. This can also be attributed to the overriding importance of farm activities in enhancing food security among rural households in developing countries.

Table 6.2: descriptive statistics of variables used in the reduced household model econometric analysis

Variable	**Mean**
Independent variables	
Labour used in rice production(hours/household/year)	701.93(318.233)
Labour used in banana production(hours/household/year)	535.56(379.073)

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[3] Labour hours worked per year were calculated from respondent estimates of how many hours are worked per week and the number of weeks worked per year for each activity.

Labour used in orange production(hours/household/year)	241.24(145.446)
Labour used in mango production(hours/household/year)	255.90(138.369)
Labour used in off-farm works (hours/household/year)	145.80(96.231)
Area allocated to rice production (acres)	3.5 (0.161)
Area allocated to banana production(acres)	5.73(0.257)
Area allocated to orange production(acres)	1.04(0.210)
Area allocated to mango production(acres)	1.5(0.110)
Household rice supply (Kg/household/year)	236.78(41.915)
Household banana supply (baskets/household/year)	2006.42(152.137)
Household mango supply (pieces/household/year)	8308.57(3186.8)
Household orange supply (pieces/household/year)	7366.07(1370.8)
Explanatory variables	
Household size (number of people/household)	4.5 (2.5)
Age of household head (years)	55.5 (13.6)
Education level of household head (years in schooling)	7.5(3.2)
Household exogenous income (fruit production subsidy) (TZS/month)	100,000(100.56)
Price of marketed goods (TZS/piece)	2300 (612.034)
Market price of inputs for rice production (TZS/kg)	954.29(39.682)
Market price of inputs for banana production(TZS/seedling)	262.5(20.352)
Market price of inputs for mango production(TZS/seedling)	154.64(17.076)
Market price of inputs for orange production(TZS/seedling)	211.07(19.836)
Market price of rice (TZS/kg)	1674.64(353.65)
Market price of banana (TZS/basket)	4035.71(360.89)
Market price of mango(TZS/piece)	50.5 (5.741)
Market price of orange(TZS/piece)	30.5(4.923)
Wage rate (TZS/hour)	1463.58(443.69)
Wealth index[4]	

Table 6.2 also shows that households allocate more of their land to banana followed by rice production that fruit production. On average household allocate about 5.7 and 3.5acres to banana and rice production compared to1.04 and 1.5 for orange and mango production. Again this can also be attributed to the overriding importance of farm production in enhancing food security among rural households in developing countries. From crop production household derive two benefits; food to feed their families and income from selling the excess. Results in table 6.2 also show that household supply more banana that rice. This can be attributed to the fact that banana crop is grown for commercial purposes while rice is for food supply.

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[4] Wealth index is not reported as it is an index ranging from -5.2 to 5.2 with a mean of 0.

Table 6.2 also shows that the average age of household heads is 55.5 years; household size is 4.5 persons per household and education levels is 7.5 which is primary education. This education level is quite low for a person to have the necessary skills to tape the existing off-farm opportunities. Table 6.2 also show that upstream landholders face higher input prices than output prices, which implies that the two can be targeted in inducing internalization of land use externalities..

Other parameters econometric model variables

Table 6.3 shows that natural vegetation cover has the highest capacity of reducing runoff with grass cover being the best of all (0.0079628m^3/second) followed by bush land and woodland. On the other hand mango and orange fields are better covers than banana canopy cover in reducing runoff. Paddy provides a much better canopy cover than banana and fruits but only when the crop is standing in the field.

Table 6.3 also show that banana is grown in the highest altitude (740m above sea level) where grass land and bush land are found (730 and 710 respectively). This implies that production of this crop encroaches much of these natural vegetation covers. On the other hand paddy is grown at 501m above sea level where woodland (503a.s.l) is dominating; this implies that much of woodland is cleared for paddy production. Mango fruits are grown in higher altitude than orange i.e. 691 and 482m a.s.l respectively. This implies that the choice of the two fruits did take into account the altitude; that is mango fruits can be used to solve the problems caused by banana production while orange fruits can be used to solve the problems caused by paddy production.

Table 6.3: descriptive statistics of variables used in the sediment discharge rate and runoff econometric analysis models

Variable name	**Mean values**						
	Woodland	**Bush land**	**Grassland**	**Mango filed**	**Orange filed**	**Banana filed**	**Paddy filed**
Runoff at canopy cover *i*(m^3/second)	0.0126077 (0.0055655)	0.079627 (0.0351499)	0.0079628 (0.003515)	0.1459828 (0.0644416)	0.1393472 (0.0615124)	0.2521521 (0.1113081)	0.1092539 (0.0702999)
Canopy *i* density (tones)/number of plants/acre	3,092,325 (614,919.9)	1,682,211 (354,191)	474,148.5 (282,858.4)	47.549 (4.429)	73.4615 (10.4741)	50.64 (5.23)	630,090.7 (359,807.2)
Rain fall inside the catchment (measured and specified as precipitation) (mm)	1365.824 (1011.791)						
Slope (measured and specified as altitude) (masl)	503.903 (221.475)	710.926 (276.615)	730.076 (295.984)	691.279 (167.15)	482.575 (173.126)	740.066 (285.084)	501.903 (220.405)

Table 6.4 shows that GDP per capita in downstream is relatively higher than in the upstream but other living costs are higher. For example on average the price of basic domestic good is higher in downstream than in upstream i.e. Tsh.3567.64 compared to Tsh. 2300; house rent upstream is Tsh. 22480 compared to 153421 downstream. This implies that people will prefer to stay in upstream than downstream. Table 5.4 also show that wage rate is relatively higher in the downstream than upstream i.e. Tsh. 3867 per hour compared to 1463per hour. However, this is not enough to convince people to move from upstream to downstream because the majority lack necessary skills to tape the job opportunities available downstream.

Table 6.4: descriptive statistics of variables used in the in-migration and emigration rate econometric analysis models

Independent variable	**Upstream**	**Downstream**
Gross domestic product per capita (TZS)	273965.1 (178223.3)	425367.5 (231762.1)
Rainfall outside the catchment (mm)	1365.824 (1011.791)	1136.365 (841.81)
Price of basic goods downstream (TZS)		3567.64(564.3)
House rent price inside/outside downstream (TZS)	22480.32(204.42)	153421.6(36569.3)
Wage rate inside/outside downstream (TZS)/hour		3867.4(246.6)

6.7.2. Empirical econometric estimation results

Tables 6.5 and 6.6 present results of the SUR model for factors determining labour and land allocation decisions, while tables 6.7 and 6.8 present results for factors determining crops and fruits supply and demand. The results in table 6.5 indicate that household size is positively related to the amount of labour time used in banana and paddy production, off-farm work and negatively related to fruit production. This result can be attributed to the fact that larger families have surplus labour to allocate to these livelihood activities. However, the allocation of labour is sensitive to time needed to realise returns; the negative relation with fruit production is an indication of this sensitivity as fruits need not less than three to four years before realising the returns. The positive relationship between household size and labour allocated to off-farm work is consistent with income diversification strategies for risk smoothing. As the household size increases the household diversifies its income base and diverts part of its labour force into off-farm activities to generate more income in order to meet the increased consumption demands (Jogo and Hassan, 2010).

The results in table 6.6 show that household size is positively related to land allocated to crop production and negatively related to fruit production. This could be attributed to the fact that household developing focuses more on short term solutions than longer term. Meeting household food demand is their major objective and is done in short term. This is due to the fact that production in developing countries is seasonal depending rainfall. These results are in line with that of Hougue and Hella (2013) who found that large households in developing countries positively influence resource allocation to economic activities which higher promises of assuring immediate food supply for the household. The larger the size of the household the more the demand for food, hence more area will be allocated to crop production.

Results in table 6.7 show a positive relationship between household size and the supply of crops and negative relationship with the supply of fruits. This can be explained by amount of labour and land resources allocated to crop production compared to fruit production. Similarly results in table 6.8 show a positive relationship between demand for crops and negative relationship with demand for fruits. Again this can be attributed to the fact that larger the household the higher the demand for food crops.

As expected, the education level of the head of the household has a positive effect on labour time allocated to off-farm work and fruit production, and a negative effect on labour used in crop production. The significant positive effect of education on labour time spend in off-farm work can be explained by the fact that education increases one's potential productivity in off-farm work (because an educated person is more knowledgeable of employment opportunities and more adaptable in a range of off-farm tasks) and therefore increases the opportunity for lucrative off-farm work. Households with educated heads spend less time crop production, because the opportunity cost of spending their time in that economic avenue (in terms of off-farm income foregone) is very high. The positive relation with fruit production even though is not significant can be explained by the fact that an educated household head prefer to spent their leisure time on economic activities which are not time demanding; crop production is more time demanding than fruit production. Hence, the more educated the household is the more time will be allocate to fruit production than crop production.

Also education level of the household head is negatively related to land allocated to crop production and positively related to land allocated to fruit production. This can be explained by the fact that a household with an educated household head tend to allocate its land in productions that are not involving and protect land from invasion. Therefore, fruit production becomes the choice as it provides three benefits; it is less involving, provide income from selling fruits and protect land from invasion.

While education has a negative effect on labour allocated in crop production, it has a positive effect on crop and fruit supply. Households with more educated heads are more efficient in grain production. This could be because education enhances opportunities for off-farm work and therefore leads to less labour allocated to on farm work but the resultant increased income from off-farm activities provides the necessary financial resources required to purchase agricultural inputs, which has a positive effect on crop and fruits supply. These results conform to that of Narain *et al*. (2008) who also found a positive relationship between the household head education level and the quantity of crop and fruits supply. Accordingly, household head education is positively related to demand for crops and fruits.

Fruit production subsidy has a significant negative impact on labour used in crop production and off-farm work, and a significant positive impact on labour used in fruit production. Subsidising fruit production increase reduces production costs of fruits; hence fruit production become more profitable than crops and off-farm works. Since fruit production is more profitable households shift their labour time to fruit production. Fruit production subsidy also has a significant negative relation with areas allocated to crop production and a significant positive relation with areas allocated to fruit production. Again this is attributed to the fact that fruit production becomes less costly than crop production, therefore, households shift their production resources to fruit production. In line with the negative relationship between labour and land allocated to crop production, fruit production subsidy is significant negatively related to crop supply. Again this can be attributed to the fact that household will produce more products from a cheaper production line than from a costly one and be able to sell more of the product from a cheaper production line. These findings are similar to that of Sanga and Mungatana (2016), who find that subsidising an agricultural production tend to induce resource allocation from an expensive production line to subsidised cheaper production, which eventually it affect supply of the products.

While fruit production has a negative effect on labour and area allocated to crop production, it has a positive and significant effect on crop demand and a negative but not significant effect on fruit demand. A household which receive more of the subsidy produces more fruits than crops. This household will have a net deficit of crops; therefore will need to buy crops to meet that deficit.

The results show that the price of crops and fruits inputs is positively related to labour allocated to off-farm work. A possible explanation for this result is that increased agricultural input prices increase input costs and reduce returns to production to which households respond by using less labour and shift some of their labour resources towards off-farm work. The results also show the expected negative cross-price effects on labour and land allocation to banana, paddy, orange and mango production, which imply that the livelihood activities compete for labour and land resources. This is also confirmed by the negative cross-price effects of supply of crops and fruit products. With regards to own price effects on supply, the results show a positive supply response of a crop or fruit and a negative to a competing crop or fruit, which is consistent with the microeconomics foundations of an upward sloping supply curve. Negative cross price effect is also observed in crops and fruits demand and with regards to own price effects on demand, the results show a negative demand response of a crop or fruit and a positive to a competing crop or fruit, which is consistent with the microeconomics foundations of a downward sloping demand curve. The insignificance of prices could imply that markets for the products are too thin such that labour allocation and supply decisions are influenced more by subsistence considerations.

Table 6.5: Regression results on labour use in off-farm works, crop and fruit production

Independent variable	Labour used in crop production		Labour used in fruit production		Labour used in off farm works
	Banana crop	Paddy crop	Orange production	Mango production	
Household size	0.248**(2.09)	0.0482***(3.01)	-0.013(0.65)	-0.032(0.58)	0.043*(1.98)
Age of household head	0.353*(1.89)	0.0043*(1.88)	0.034**(2.06)	0.068*(1.62)	-0.354*(1.58)
Education level of household head	-0.023*(1.61)	-0.0173*(1.94)	0.166(1.06)	0.0245(1.03)	0.868**(2.43)
Household exogenous income (fruit production subsidy)	-0.224**(2.23)	-0.153**(2.11)	3.468***(3.02)	2.323**(2.12)	-0.068*(1.56)
Area allocated to rice production	0.112*(1.86)	4.924*(1.71)	-0.146**(2.01	0.242*(1.67)	-0.148*(1.94)
Area allocated to banana production	1.340*(1.65)	0.123(1.23)	-0.168*(1.64)	-0.231*(1.79)	-0.361**(2.21)
Area allocated to orange production	-0.243*(1.56)	-0.114**(2.04)	0.368**(2.13)	0.023(1.44)	0.0243(0.78)
Area allocated to mango production	-0.108**(2.34)	-0.213*(1.81)	0.132(1.11)	0.143**(2.31)	0.0442(1.34)
Price of marketed goods	1.484*(1.89)	0.115*(1.62)	-0.059*(1.54)	-0.092*(1.98)	0.242*(1.68)
Market price of inputs for rice production	0.126(1.36)	-0.965**(2.34)	0.013(1.41)	0.065(1.22)	0.142*(1.87)
Market price of inputs for banana production	-0.996**(2.01)	0.003(0.68)	0.189*(1.99)	0.228*(1.63)	0.341**(2.35)
Market price of inputs for mango production	0.845*(1.76)	0.361*(1.84)	0.146(1.34)	-0.342**(2.48)	0.154*(1.52)
Market price of inputs for orange production	0.144*(1.52)	0.018*(1.63)	-0.256**(2.45)	0.477(0.44)	0.013*(1.69)
Market price of rice	-0.117*(1.58)	1.358**(2.30)	-0.164*(1.62)	-0.481*(1.91)	-0.142*(1.59)
Market price of banana	2.354***(3.02)	-0.389**(2.04)	-0.351**(2.40)	-0.283**(2.05)	-0.562**(2.34)
Market price of mango	-0.043*(1.56)	-0.014*(1.86)	-0.004(1.34)	1.649**(2.43)	-0.004(1.32)

Market price of orange	-0.061*(1.55)	-0.024*(1.69)	2.341**(2.22)	-0.234(1.20)	-0.063(0.98)
Wage rate	-0.782*(1.64)	-0.481*(1.51)	-3.123***(3.12)	-2.043**(2.38)	4.234***(3.1)
Wealth index	-0.465*(1.76)	-0.264*(1.82)	0.068(0.88)	0.024(1.26)	-2.468**(2.13)
Constant	2865.885*(1.54)	204.765(0.11)	151.796(0.26)	122.243(1.43)	4.462*(1.84)
Breusch-Pangan test for independence of residuals (χ^2)	49.06				

Absolute value of z-statistics in parenthesis denotes that ***significance at 1%, ** significance at 5% and * significance at 10% level of significance.

Table 6.6: Regression results on area allocated to crop and fruit production

Independent variable	Area allocated to crop production		Area allocate to fruit production	
	Banana crop	Paddy crop	Orange production	Mango production
Household size	0.0347**(2.29)	0.0482***(3.33)	-0.0013(0.65)	-0.0032(0.58)
Age of household head	0.0464*(1.79)	0.0043*(1.58)	0.0034**(2.16)	0.0068***(3.42)
Education level of household head	-0.0023*(1.50)	-0.0173(0.94)	0.0156*(1.86)	0.0245**(2.03)
Household exogenous income (fruit production subsidy)	-0.0234**(2.43)	-0.0142**(2.01)	0.0468***(3.02)	0.0323**(2.12)
Price of marketed goods	0.294**(2.03)	0.323*(1.65)	0.207(1.20)	0.419(1.42)
Market price of inputs for rice production	1.311*(1.79)	-4.569**(1.73)	0.919*(1.50)	0.511*(1.73)
Market price of inputs for banana production	-4.131***(3.21)	2.251*(1.65)	5.814**(2.10)	3.438**(2.41)
Market price of inputs for mango production	0.0106***(2.46)	0.00992(1.03)	0.0007(0.02)	-0.0051(0.09)
Market price of inputs for orange production	0.0039(1.04)	0.0058**(2.06)	-0.001*(1.68)	0.0017(0.38)
Market price of rice	-0.0018(0.10)	0.00283**(2.2)	-0.0019*(1.65)	0.0017***(2.45)
Market price of banana	0.0118*(1.89)	-0.0194(0.89)	-0.0038**(2.08)	-0.0012*(1.71)

Market price of mango	-0.0127*(1.53)	-0.0171***(2.78)	-0.0015(0.27)	0.0027**(2.23)
Market price of orange	-0.0167*(1.56)	-01248*(1.68)	0.01834**(2.47)	0.0016(0.11)
Wage rate	-0.0456**(2.16)	-0.0549*(1.75)	0.03712**(2.56)	0.0632*(1.81)
Wealth index	-0.0357*(1.62)	-0.0125**(2.12)	0.0243*(1.71)	0.0478(0.89)
Constant	-2.218(0.94)	0.145(1.30)	2.669*(1.78)	5.674**(2.20)
Breusch-Pangan test for independence of residuals (χ^2)	45.38			

Absolute value of z-statistics in parenthesis denotes that ***significance at 1%, ** significance at 5% and * significance at 10% level of significance.

Table 6.7: Regression results on crop and fruit supply

Independent variable	Crop supply		Fruit supply	
	Banana crop	Paddy crop	Orange fruits	Mango fruits
Household size	4.123**(2.31)	6.421***(3.23)	-0.982*(1.52)	-0.413*(1.54)
Age of household head	0.698(0.88)	0.126(1.34)	0.198*(1.68)	0.098*(1.78)
Education level of household head	0.456*(1.85)	0.301*(1.65)	0.089*(1.51)	0.032*(1.57)
Household exogenous income (fruit production subsidy)	-9.235***(3.40)	-4.876**(2.32)	18.864***(3.24)	12.568***(3.45)
Price of marketed goods	1.449*(1.89)	0.058**(2.10)	28.256*(1.54)	11.169*(1.98)
Market price of inputs for rice production	0.463(1.01)	-0.158*(1.87)	7.675*(1.95)	3.169*(1.82)
Market price of inputs for banana production	-0.112**(2.14)	0.066*(1.66)	6.696*(1.64)	1.113*(1.81)
Market price of inputs for mango production	1.104**(2.09)	0.415**(2.20)	6.391*(1.93)	-46.178**(2.03)
Market price of inputs for orange production	2.043*(1.55)	1.541*(1.62)	20.865**(2.12)	8.013*(1.53)
Market price of rice	-0.388*(1.65)	1.213**(2.69)	-2.089*(1.60)	-2.905*(1.58)

Market price of banana	1.266**(2.06)	-0.901*(1.90)	-3.392**(2.08)	-2.266**(2.04)
Market price of mango	-2.651*(1.81)	-0.664**(2.05)	-0.057(0.89)	16.164**(2.16)
Market price of orange	-1.372*(1.72)	-1.240*(1.76)	53.906**(2.23)	-10.3*(1.58)
Area allocated to crop or fruit *i* production	140.340*(1.65)	1.924*(1.71)	14.525*(1.55)	40.935**(2.40)
Wage rate	-0.038(1.02)	-0.029(1.22)	-1.816*(1.88)	-1.668*(1.64)
Wealth index	-2.867*(1.62)	0.984*(1.50)	0.456**(2.4)	0.232*(1.60)
Constant	1669.8097*(1.54)	461.021(0.77)	-38270.33*(1.59)	-10402.05*(1.66)
Breusch-Pangan test for independence of residuals (χ^2)	48.34			

Table 6.8: Regression results on crop and fruit demand

Independent variable	Demand for crops		Demand for fruits	
	Banana crop	Paddy crop	Orange fruits	Mango fruits
Household size	3.523**(2.01)	4.021**(2.03)	-0.561*(1.61)	-0.434*(1.59)
Age of household head	0.468(0.53)	0.171(1.04)	0.164(1.08)	0.084(0.78)
Education level of household head	0.346(1.05)	0.431(1.05)	0.065(0.51)	0.042*(1.07)
Household exogenous income (fruit production subsidy)	0.246*(1.60)	3.461**(2.02)	-0.824(1.24)	-0.536(1.45)
Price of marketed goods	-0.643*(1.89)	-0.243**(2.30)	-0.056*(1.74)	-0.069*(1.68)
Market price of inputs for rice production	1.831*(1.61)	-3.188*(1.67)	0.655*(1.55)	0.769*(1.62)
Market price of inputs for banana production	-4.582**(2.04)	1.966*(1.56)	0.196*(1.54)	0.125*(1.61)
Market price of inputs for mango production	2.164*(1.59)	1.334*(1.60)	0.091(0.93)	-6.528**(2.13)

Market price of inputs for orange production	1.643*(1.70)	0.981*(1.52)	-4.421**(2.02)	0.813(1.23)
Market price of rice	0.928*(1.60)	-1.406**(2.09)	2.169*(1.70)	1.613*(1.68)
Market price of banana	-4.376**(2.31)	0.501(1.90)	1.344**(2.08)	0.386**(2.44)
Market price of mango	0.651*(1.62)	1.543**(2.15)	0.907(1.09)	1.984**(2.06)
Market price of orange	1.461*(1.52)	1.333*(1.68)	-3.832**(2.03)	1.342*(1.68)
Area allocated to crop/fruit *i* production	-1.238**(2.01)	-3.531**(2.11)	0.976*(1.72)	0.625*(1.70)
Wage rate	0.928*(1.62)	0.635*(1.76)	0.016(1.08)	0.068(1.04)
Wealth index	0.837(1.02)	0.674(1.10)	0.236(1.40)	0.032(1.0)
Constant	658.137*(1.84)	83.136*(1.67)	870.36(1.09)	142.305(1.16)
Breusch-Pangan test for independence of residuals (χ^2)	44.86			

Off-farm wage rates were found to be negatively related to labour input in crops and fruits production, but positively related to labour supply to off-farm work. As labour returns to crops and fruits production are quite low, higher off-farm wage rate increases the opportunity cost of labour used in crops and fruits production and this results in labour resources being shifted away from these activities towards off-farm work. However, the effect of wage rate on land allocation is negative on crop and positive on fruit production. This is attributed to the fact that fruit production is less labour intensive than crop production, hence less labour opportunity cost than crop. Accordingly, the supply of crop and fruit products significantly decreases with increase in wage rate. Off-farm wage rate is also found to positive related with demand for crops and fruits. This attributed to the fact that a shift in labour from crop and fruit production results to deficit of these products to household; therefore, households will increase purchase of these products from the market to meet their deficit. The positive relationship between off-farm wage rates and labour used in off-farm work conforms with the upward sloping labour supply curve, which shows that as the wage rate increases leisure becomes relatively more expensive (the opportunity cost of leisure increases) causing households to substitute away from leisure to more work.

Household wealth status has a significant negative effect on labour and area allocated to crop production, hence the supply of these crops. This implies that poor households spend more time crop production than wealthier households. The results also indicate that wealthier household allocates more of their land on fruit production than poor household. This could be attributed to the fact that unlike the wealthier households, poor households have limited access to assets and other sources of income that can buffer them against negative income and food shortfalls. This result supports findings by studies that show that poorer households are more reliant on agricultural production than wealthier households.

This study's results also indicate that a household's wealth status has a positive effect on labour time allocated to off-farm work. Asset-wealthier households put less labour input into food production and spend more time with off-farm work due to their low marginal productivity of farm labour in crop production compared to off-farm work. These result are similar to that of Matshe and Young (2004) and Fafchamps and

Quisumbing (1998) who also found that wealthier households spend less time working off-farm.

Although households who are better-off allocate less time to crop production than their poorer counterparts, they supply more crop presumably due to their better access to productive assets which enhance agricultural productivity.

6.7.3. Emperical econometric results for other parameters estimated econometrically

Determinants of sediment discharge rate, runoff and natural vegetation intrinsic growth rate

As noted in chapter 5 canopy type and density plays a crucial role on determining the quality of water flowing downstream, hence the social welfare. Sediment discharged into streams and rivers draining the catchment are externalities to downstream water users. Dirty water lead to higher cleaning costs downstream, which may outweigh the benefits accrued to upstream land holders. In catchments with upstream downstream relations normally the upstream land users do not take into account externalities in the decisions. Estimating marginal costs of land use externalities is very important in policy making as it helps policy makers to reinforce upstream land holders to take into account the cost of the externalities they cause downstream.

Table 6.9 present results for the determinants of sediment discharge rate and runoff estimated econometrically from time series data. The results show that the sediment discharge rate is significantly positively related to runoff. The results also show that runoff is significantly positively related to precipitation intensity and slope/gradient of the area where the canopy is located, and significantly negatively related to canopy density. These results implies that the intense the precipitation and the steeper the slope/gradient the higher the runoff, hence the higher the sediment discharge rate. Also the result implies that the denser the canopy cover the lower the runoff, hence the lower the sediment discharge rate.

Table 6.9: Factors influencing sediment discharge rate and runoff

Independent variable	Woodland	Bush land	Grassland	Mango filed	Orange filed	Banana filed	Paddy filed
Runoff at canopy cover *i*	0.3653*(1.56)	0.453**(2.10)	0.645(0.89)	0.472**(2.13)	0.432*(1.52)	0.356*(1.67)	0.542**(2.32)
Constant	0.2758(1.04)	0.2637*(1.56)	0.0365**(2.11)	0.411(1.09)	0.327*(1.98)	0.652(1.32)	0.972*(1.670
Breusch-Pangan test for independence of residuals (χ^2)	49.86						
Runoff model							
Canopy *i* density	-0.02489*(1.52)	-0.0486**(2.39)	-6.421e-3*(1.65)	-0.0567*(1.67)	-3.86e-2*(1.76)	-0.484***(3.0)	-0.2758**(2.0)
Rain fall (measured and specified as precipitation)	1.43e-8**(2.34)	4.35e-8*(1.50)	1.13e-8*(1.70)	2.43e-6**(2.4)	6.32e-6*(1.63)	2.62e-5*(1.81)	6.24e-7*(1.56)
Slope (measured and specified as altitude)	2.57e-5(0.98)	0.112e-4*(1,56)	8.41e-7(1.34)	4.47e-5(1.23)	2.14e-4**(2.34)	0.0075*(1.65)	2.43e-6*(1.78)
Constant	8.55e-6*(1.65)	0.206e-4(1.20)	9.75e-6(0.98)	0.213e-4*(1.89)	1.21e-5(0.13)	0.00134(0.36)	3.21e-6*(1.76)
Breusch-Pangan test for independence of residuals (χ^2)	46.78						

While canopy cover density plays a crucial role in quality of water flowing downstream, natural canopy covers growth depend on intrinsic growth rate which is determined by area. Results in table 6.10 show that natural canopy cover intrinsic growth rate is significantly positive related to area covered. This can be attributed from the fact that plants compete for light, space, nutrients and water; therefore, area covered determine the space available for the plants to grow. These results conform to results by Nestch et al, (2002) who found that space has a positive relation with intrinsic growth of natural plants; therefore, the larger the space the higher the intrinsic growth rate.

Table 6.10: Factors influencing natural vegetation intrinsic growth rate

Independent variable	Woodland	Bush land	Grassland
Area covered by natural vegetation *i*	3.07e -8**(2.34)	1.71e-7*)1.67)	-8.48e-7***(3.12)
Constant	8.02229e-2 *(1.54)	-3.53e-7(0.89)	0.4548*(1.65)
Breusch-Pangan test for independence of residuals (χ^2)	47.01		

Determinants of number of households engaging in off-farm and fruit production

To household living in the catchment engaging in the off-farm works and fruit production is optional. So the number of household engaging in these economic activities is determined by different factors. Results in table 6.11 show that off-farm age rate and gross domestic per capita plays are significantly positive related to the number of household engaged in off-farm work. This implies that higher off-farm wage rate increases the opportunity cost of labour; therefore, more household will engage in off-farm activities than farm activities. The GDP per capita on the other hand increases the household ability to acquire the necessary skills to tape off-farm opportunities; therefore, the higher the GDP per capita the more the household engaging in off-farm activities.

Table 6.11: Factors determining the number of households engaging in off-farm works

Independent variable	**Coefficient**
Off farm wage rate	0.043*(1.78)
Gross domestic products per capita	0.096**(2.30)
Constant	33.256(1.42)

With regards to the household engagement in fruit production, table 6.12 shows that fruits market prices and subsidy provided are positive and significantly related to number of households engaging in fruit production, and labour needed in fruit production negatively related. This can be attributed to the fact that own price increases the opportunity cost of labour and profit margin, so households will engage more in the production with higher return to inputs. Fruit production subsidy will lower cost of production and increase profit margin, hence increase returns to factors of production. Labour need in fruit production reduces the labour time available for other economic activities increasing the opportunity cost of labour time. Labour intensive economic activity tend to receive less attention by many household and may be rejected (TEEB, 2010).

Table 6.12: Factors determining the number of households engaging in fruit production

Independent variable	**Orange**	**Mango**
Market price of fruits	1.345*(1.62)	0.892**(2.3)
Labour time needed per day to work in fruit filed	-0.453**(2.45)	-0.633***(3.2)
Subsidy provided for fruit production	2.568*(1.85)	0.908*(1.56)
Constant	14.874(1.22)	22.867(1.38)

Determinants of subsidy provision rate

Fruit production subsidy is determined by consumer price index because it is mint to help upstream fruit producers in lowering the costs of production. Table 5.13 show that subsidy is positively related to consumer price index, implying as it goes up the subsidy also goes up to cover the additional production costs.

Table 6.13: Factors determining subsidy rate

Independent variable	**Coefficient**
Consumer price index	4.386*(1.60)
Constant	12.349(1.40)

Determinants of population migration rates

Upstream and downstream population sizes vary with natural growth and migrations (i.e. in-migration and emigration). Migrations are determined by rates at which people are migrating from one location to another which are also determined by various factors. Results in table 6.13 shows that upstream population migration rates are positively related to precipitation inside and outside the catchment, price of basic domestic goods and GDP per capita. Accordingly, downstream population migration rates are positively related to price of basic goods, house rent, and wage rate inside and outside. This can be attributed to the fact that household are sensitive to the living costs and opportunities. Therefore, they tend to move from one area to anther depending on living condition and opportunities.

Table 6.14: Determinants of population migration rates

Independent variable	Upstream		Downstream	
	In-migration	**Emigration**	**In-migration**	**Emigration**
Gross domestic product per capita	2.91e-9*(1.83)	1.02e-8**(2.22)	3.45e-4*(1.56)	2.34e-5*(1.78)
Rainfall inside/outside the catchment (measured as precipitation)	2..94e-8**(2.30)	1.02e-9(1.23)		
Price of basic goods downstream			4.32e-2(0.98)	2.34e-2*(1.60)
House rent price inside/outside downstream			6.19e-3(0.98)	1.98e-2*(1.56)
Wage rate inside/outside downstream			0.145***(3.40)	0.231**(2.10)
Constant	-4.88e-5(0.89)	-0.101e-3(1.09)	0.0245*(1.51)	0.0104(0.67)
Breusch-Pangan test for independence of residuals (χ^2)	46.32			

6.7.4. Adopted parameters

Other parameters were adopted from literature; table 6.14 indicate the biomass and carrying capacity for woodland, bush land and grassland natural vegetations in tones per hectare.

Table 6.15: Parameter values adopted from literature

Natural vegetation density (biomass) equation (tones/ha)	Symbol	Woodland	Bush land	Grassland	
Grass biomass at time t	B_{ti}	3092324.74	1682211.2	474148.54	URT(2011)
Carrying capacity	K_{ti}	9276974.22	5046633.6	1422445.63	URT(2011)

After estimating all the parameters, the model was specified and solved in STELA, an icon-based simulation software designed for simulating dynamics of ecological-economic systems (Costanza & Gottlieb, 1998).

6.8. Concluding summary

This chapter analysed the factors that influence household labour and land allocation for crops and fruits production, and off-farm work. It also analysed factors influencing crops and fruits supply and demand decisions by rural households. Reduced form labour and land allocation, crops and fruits supply and demand equations derived from an agricultural household model were estimated jointly using a SUR approach to analyse the determinants of household labour allocation and product supply decisions.

The results presented in this chapter indicated that large families allocate much of their land to crop production than fruit production. The positive and significant effect of household size on land allocate to crop production shows that it is critical to achieve land use externalities internalization bottlenecks by introducing fruit production only. It require additional interventions which will ensure food security to the household in short run, and in the long run introduce family planning.

Our results showed that education is positively related to labour time allocated to off-farm activities, which implies that investment in education and skills development of the upstream population is important for the population to reduce dependence on the catchment resources. The positive effect of fruit production subsidy income on fruit production and its negative effect on crop production show that the policy measure (which reduce production cost of best practices) can improve land use externalities internalization in water catchment with upstream and downstream set of beneficiaries with upstream affecting downstream beneficiaries.

The responsiveness of crop and fruit production to its own price and the negative cross price effects shows that government intervention in agricultural markets can have significant impacts on land use externalities internalization. Government regulations, which artificially suppress producer prices and increase input prices for bad land use practices, can create a disincentive for farmers to produce. Therefore, the government, in close partnership with the private sector, should strongly support and strengthen reforms in the input and output markets to ensure that input and output prices provide incentives for farmers to invest in best land use practices.

The finding that poor upstream households spend more time on farm activities and supply more of farm products has one major implication: that is there is need to induce the necessary skills which will enable upstream households to tape opportunities that come with development so as reduce dependence on natural resources.

CHAPTER 7

RESULTS FROM ANALYSIS OF THE IMPACTS OF FRUIT TREES ON HYDROLOGICAL, ECOLOGICAL AND ECONOMIC BENEFITS FLOW

7.1. Introduction

This chapter presents the simulation results of the analysis of the likely trade-offs to be involved and their impact on the flow of hydrological and economic benefits when fruit tree buffer strips are opted for in internalising upstream land use externalities in water catchments, together with the test of the hypotheses which motivated this study. The chapter begins by presenting results of the model test and validation. The following section presents how simulation scenarios were developed or derived, followed by simulation results and discussion. The chapter ends with a concluding summary.

7.2. Model testing and validation results

The model was specified and solved in STELLA software, which is well situated for simulating the dynamics of ecological-economic systems (Costanza & Gottlieb, 1998). In dynamic modelling, model validation is done to establish structural conformity of the model with respect to the modelling purpose and to establish confidence in the simulation results. As noted by Richmond (2004), confidence in model simulation results is high only if the model has robust predictive ability in reproducing historical trends. The validation tests always put more emphasis on patterns of prediction of key variables rather than on point predictions, because of the long-term orientation of these models (Fisher, 2010; Morecroft, 2009). Because of the limited availability of observed time series data for most of the variables used in the model, the validation exercise was done for two variables for which past trend data was available. The period used for validation was 1990 to 2010, using data on land that had remained covered by natural vegetation obtained from Yanda and Munishi (2007), and total sediment load in the Uluguru catchment streams and rivers obtained from DAWASCO. After validation, the model was subsequently used to conduct policy simulations for a 30-year period (between 2011 and 2041), following Robles-Diaz-de-León and Alfredo Nava-Tudela (1998). Chopra and Adhikari (2004) also note that “when the problem at hand is such that the impacts of exogenous change is on a slowly changing ecological system, to be able to obtain appropriate and realistic results, a significantly long-run simulation model is advised"

Figures 7.1 and 7.2 compare the observed versus model predicted values for these variables. The area that remained covered by natural vegetation has been decreasing (Figure 7.2), while sediment load shows an increasing trend over time (Figure 7.2). Although the model-predicted values are not exactly equal to the observed values in both cases, the model does well in predicting the observed pattern of these two variables. The correlation between model-predicted and observed values is more than 0.84 in both cases, suggesting that the model can be used with confidence.

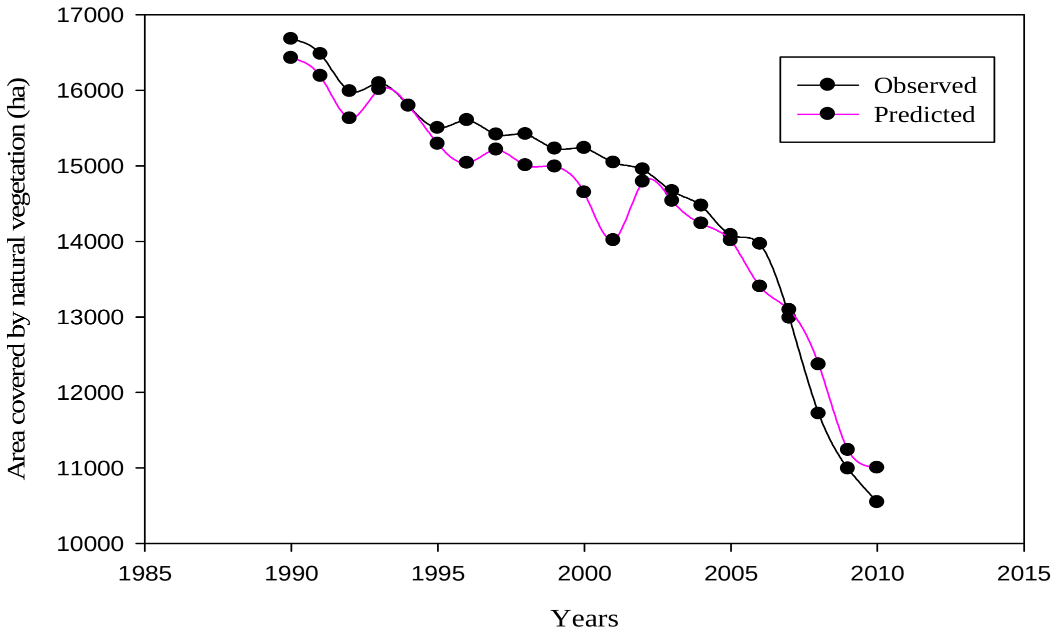

Figure 7.1: Comparison of model predicted and observed catchment area that remained covered by natural vegetation (1990 – 2010)

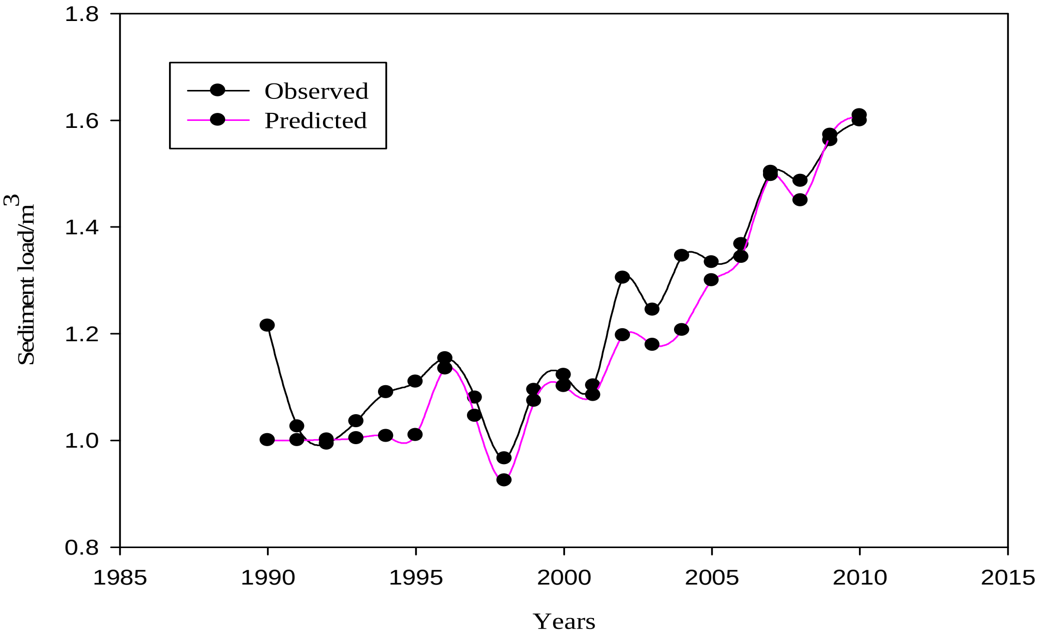

Figure 7.2: Comparison of model predicted and observed (actual) sediment load in uluguru catchment streams and rivers (1990 – 2010).

From these validation results, it is clear that it would be possible to establish a much stronger case if more numerical time series data were available for more variables in the model. However, the lack of past trend data on most variables severely restricted our validation options and collecting new dynamic data necessitates long time periods. That said, it should be kept in mind that the main purpose of this model is to capture broad dynamic behaviour patterns of the real system, and not to provide point predictions. Once the model was validated, it was subsequently used to conduct policy simulations for a 30-year period (between 2011 and 2041).

7.3. Development of simulation scenarios

Water catchments management in Tanzania is governed by the National Water Policy (2002), the National Water Sector Development Strategy (2006), the Water Resources Management Act No. 11 (2009) and the Water Supply and Sanitation Act No. 12 (2009). There are five management levels for water resources: the national, basin, catchment, district and community levels. At national level, the Ministry of Water is the sole manager of water in the country. The key responsibilities include the development and review of policies and registrations, and the coordination of all activities for water resources management, such as planning, capacity building, data collection and dissemination, monitoring, and evaluation (URT, 2002). At basin level, water resources are managed by nine Basin Water Offices (BWO) (Table 7.1). The role of the BWO is to ensure data collection and processing, to prepare water utilisation plans, to collect water use fees and charges, and to resolve conflicts at basin level (URT, 2011b). In addition, the pollution control and quality standards are administered by the BWOs. Below these, there are two levels of management, namely the Catchment Water Committees and the Sub-Catchment Water Committees (UTR, 2010). The function of these committees is to support the role of BWO, to implement the catchment plans, and to solve water-related conflicts at the catchment level.

Table 7.1: Basin, size and year of establishment of the basin water office

S/N	Name of basin	Size (km^2)	Office established (year)
1	Pangani	53 600	1991
2	Rufiji	183 791	1993
3	Lake Victoria	115 400	2000
4	Wami – Ruvu	66 820	2002
5	Lake Nyasa	131 652	2002
6	Lake Rukwa	80 000	2003
7	Internal drainage	153 800	2003
8	Lake Tanganyika	151 000	2004
9	Ruvuma and southern coast	52 000	2004

Source: Ministry of Water and irrigation, http://www.maji.go.tz/basins/nine.php

At district level, there are district councils with the role of formulation and enforcement of bylaws, promoting efficient use of water resources, and preparing district plans regarding water issues. At the community level, there are Water Users Associations (WUA) responsible for local-level management of allocated water resources, mediation of disputes among water users and between groups within their area of jurisdiction, and participation in the preparation of conditions and terms of water rights. However, their establishment is yet fully operationalised and only a few WUAs have been established in some of the basins (Mehari *et al*., 2007).

Despite the well-organised water catchment use and management, catchments have continued to deteriorate at an alarming rate throughout the country. Such a deterioration rate has been attributed to the lack of a proper mechanism to collect revenue for financing the management. The nine Water Basin Offices depend on government funding to execute their daily activities; something that has been very difficult to accomplish for all the management activities. This situation necessitated that other means of raising funds to finance management of the catchments be found. Equally important, as mentioned in Chapter 1, section 1, there has been a growing debate on the advantage of exploiting the potential of upstream land users and downstream water catchment ecosystem services users in managing the catchment. It is argued that this potential has not been fully exploited. Based on fruit trees, this study investigated this by simulating six scenarios that are likely to occur as government policy options, as well as changes that are likely to come about as a result of global climatic change. The scenarios involved were tax-based policy options (taxing crop output and inputs; tax cuts on inputs to fruit production; and tax cuts on basic domestic goods), economic growth-based scenarios (improving economic growth), market-based scenarios (compensating upstream land users-a PES scheme) and a climate-change-based scenario (decrease in rainfall in the areas surrounding the catchment).

The tax- and market-based scenarios were selected/chosen based on the possible government policies to be taken as a means of raising funds to finance the management of catchments, given the current financing problems. The economic growth scenario was included in this study, based on the facts in the literature and the trend of the country's economic growth. The economy of Tanzania is growing at 7 % per year and the literature suggests that this can go in two directions: first, it may lead to intensification of catchment resources use, and second, it may lead to reduction in dependence on catchment resources (Jogo & Hassan, 2010; Polasky *et al*., 2005). The climate change scenario was included, based on the fact that climate is changing and the catchment is not an exception to this, and the study collected trend data on rainfall to establish the trend of rainfall in the areas surrounding the catchment. The trends showed that the rainfall is decreasing, which is an indication that this may force people to migrate from the surrounding areas into the catchment. Finally, consultations were held with government official from the ministry responsible for managing water catchments and ecosystem services users, both upstream and downstream, to certain the validity of the scenarios used in the analysis.

7.4. Simulation results and discussion

To perform the simulations, we first ran a baseline scenario which was used as the benchmark against which other simulation scenarios were compared. The purpose of the baseline scenario is to reproduce (or replicate), to the extent possible, the current situation that is obtained in the catchment. Our simulation scenarios were performed by changing values of exogenous variables, composed of policy and economic scenarios, which were subsequently compared with the baseline. As noted above, the policy and economic scenarios considered for simulations were selected on the basis of possible government policy interventions and economic changes. Nine scenarios, namely (1) taxing crop outputs and inputs; (2) Changes in crop and fruits output prices, (3) changes in crop and fruits input prices, (4) changes in wage rate inside and outside the catchment, (5) tax cuts on inputs to fruit production; (6) tax cuts on basic domestic goods; (7) improving economic growth; and (8) compensating upstream land users, (9) decreases in rainfall, were simulated.

The simulations evaluated how a change in the policy or economic scenarios would affect the following outcomes in the catchment land use: total area (ha) converted to crop production per year, total area (ha) converted to fruit tree cultivation per year, total area (ha) converted to natural vegetation to regenerate per year, net profit (TZS[5]) from crop production per hectare per year, net profit (TZS) from fruit production per hectare per year, sediment load in the streams draining the catchment area and rivers (tons per m^3 per year), reduced cost for producing a m^3 of water for domestic use (TZS), and net income per capita (TZS) per year. The areas converted to crops, fruits and natural vegetation will be used to understand land use trade-offs that are likely to occur when a fruit tree buffer strip is used to internalise land use externalities and the mentioned policies are used in the water catchments. Profits accrued from crop and fruit production will be used as indicators of the impacts of the management approach and the supporting policies on private economic benefits to farmers in the upstream. Sediment load in the streams and rivers, hence the reduced costs of producing a m^3 of water for domestic use will be used as an indicator of the impact of the management approach and the supporting policies on hydrological benefits accrued to downstream water users. Finally, the net income per capita per year will be used as an indicator of the impacts of

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[5] TZS refer to Tanzania shillings.

the management approach and supporting policies on social welfare to both upstream and downstream beneficiaries.

Simulations were then run for a period of 15 years (between 2014 and 2029), following Robles-Diaz-de-León and Alfredo Nava-Tudela (1998). Chopra and Adhikari (2004) also note that "when the problem at hand is such that the impacts of exogenous change is on a slowly changing ecological system, to be able to obtain appropriate and realistic results, a significantly long-run simulation model is advised". Therefore, 15 years was considered in the study to be long enough to obtain realistic results from the model. Values obtained at the end of the simulation period were then compared with the baseline scenario (also see Jogo & Hassan, 2010; Nobre *et al.*, 2009; Eppink *et al.*, 2004; Costanza *et al.*, 2002). The specific policy scenarios evaluated and results of the simulation experiments are presented in Table 6.2.

Scenario 1: Taxing crop outputs and inputs

Simulation results in Table 7.2, block 1A (i), columns 1, 2 and 3 indicate that a 5 % output tax on banana production will reduce the total area converted to crop production by 27.76 % per annum, increase the total area converted to fruit tree production and natural vegetation by 6.86 % and 46.34 % per annum respectively. The results also indicate that the same level of tax on paddy output will reduce the total area converted to crop production by 9.68 % per annum, and increase the total area converted to fruit production and natural vegetation by 3.61 % and 2.24 % per annum respectively (Table 7.2, block 1A(ii), columns 1, 2 and 3). A similar effect is observed when inputs to banana and paddy are taxed; the results in Table 6.2, block 1B(i), columns 1, 2 and 3 indicate that a 10 % output tax on banana production will reduce the total area converted to crop production by 14.15 % per annum, and increase the total area converted to fruit production and natural vegetation by 41.34 % and 10.38 % per annum, respectively. The results also indicate that the same level of tax on paddy output will reduce the total area converted to crop production by 2.36 % per annum, and increase the total area converted to fruit tree production and natural vegetation by 31.53 % and 3.48% per annum, respectively (Table 7.2, block 1B(ii), columns 1, 2 and 3).

Taxing crop outputs and inputs will reduce the net profit from crop production, hence supply of crops: the results in Table 7.2, block 1A(i & ii), column 4A and 4B indicate that by imposing a 5 % tax on banana output, the net profits from banana and paddy production will decrease by 26.48 % and 68.35 % per annum, respectively, compared with 11.26 % per annum and 70.64 % per annum when the same level of tax is imposed on paddy output (Table 7.2, block B: i & ii, columns 4A & 4B). A similar effect is observed when inputs to crop production are taxed; a 10 % tax on inputs to banana production will decrease the net profit from banana by 81.87 % and increase the net profit from paddy by 23.94%, while the same level of tax when applied to paddy inputs will decrease the net profit from paddy by 46.63 % and increase the net profit from banana by 122.87 %. Again, a strong effect is observed when banana output and inputs are taxed, rather than those for paddy.

The simulation results in Table 7.2, block 1A (i & ii), columns 5a and 5b indicate that taxing crop outputs and inputs will favour fruit production by increasing the net profit from fruit production; a 5 % tax on banana output will increase net profit from orange and mango by 4.31 % and 4.63 % per annum, compared with 0.18 % and 0.48 % per annum, respectively, when the same level of tax is applied to paddy output. Results also indicate that a 10 % tax on inputs to banana production will increase net profit from orange and mango by 2.48 % and 9.69 % per annum, respectively, compared with 0.32 % and 0.84 % per annum, respectively, when the same level of input tax is applied to paddy inputs (Table 7.2, block 1B: i & ii, columns 5a & 5b). Again cuch tax on banana inputs will reduce demand for banana and paddy by 3.04% and 1.57%, and increase demand for fruits by 1.08% and 2.17% respectively. Similar level tax on paddy will reduce demand for banana by 6.13% and paddy by 10.07%, and increase demand for orange by 0.62% and 0.14% respectively. This can also be attributed to the fact that taxing crop output lead to an increase in price which in turn affect negatively demand for the crops. These results conform with the theory of demand which is negatively related to price.

Such tax on banana output will reduce demand for banana and paddy by 4.34% and 2.08%, and increase demand for fruits by 1.21% and 2.33% respectively (Table 7.2., block 1A, column 6a and 6b). Similar level tax on paddy will reduce demand for banana by 1.03% and paddy by 2.34, and increase demand for orange by 0.18% and 0.38%

respectively Table 7.2., block 1A, column 7a and 7b). This can be attributed to the fact that taxing crop output lead to an increase in price which in turn affect negatively demand for the crops. These results conform with the theory of demand which is negatively related to price.

Nevertheless, simulation results indicate that the policy will induce a reduction of sediment load in the streams and rivers draining that catchment, which eventually reduce the cost of producing 1m^3 of water for domestic use downstream. Results in Table 7.2, block A (i & ii) column 8 and 9 indicate that a 5 % output tax on banana production reduce sediment load by 61 % per annum, compared with 1.32 % per annum when the same level of output tax is applied to paddy outputs. Such reduction in sediment load results into reduction in the cost of producing 1m^3 of water for domestic use of about 18% and 3.66% per annum respectively when the two crops outputs are taxed. Results also indicate that a 10 % input tax imposed on banana reduces sediment load by 16.67 % per annum, compared with 3.42 % per annum when paddy inputs are taxed (Table 7.2, block B (i & ii) column 8). Similarly, such reduction in sediment load results into reduction in the cost of producing 1m^3 of water for domestic use of about 4.67% and 0.66% per annum respectively when the two crops outputs are taxed. These results also suggest that the induced resource shift to fruit production and natural vegetation increase space for more fruit trees to be planted and natural vegetation to grow. Such increase in the number of new plants increases plant population (or density), which is a key factor for sediment load reduction (see Chapter 5, section 5.3.1 and Johns, 1996).

Finally, the simulation results indicate that that the policy will result in the gain and loss of social welfare. Results in Table 7.2, block 1A: i & ii, column 10 indicate that imposing a 5 % output tax on banana outputs increases the social welfare measured as net income per capita by 4.41 % and reduces it by 0.57 % per annum when the same level of tax is applied to paddy. A completely reduction in welfare is observed when a 10 % input tax is imposed on banana and paddy inputs; the net income per capita is reduced by 0.11 % and 1.01 % per annum, respectively. These results suggest that taxing crop inputs and outputs results in a reallocation of resources that leads to loss in income to the level that the profit generated from fruit production is not enough to outweigh the loss. However, in banana the outcome is different when 5% tax is raised, the reallocation of resources results into reduction in sediment load which its value outweigh the loss in income from the reduced crop production and this is contrary to when 10% is raised, the loss in income due to reduced crop production is higher than the income served from sediment load reduction. This shows the differences in the roles played by the two crops as sources of income and food supply, and taxes on resources allocation. These results show clearly that banana is grown in the catchment for income generation (i.e. cash crop), while paddy is grown for food.

These results suggest that the policy will induce resource reallocation from crop production to fruit production and natural vegetation. The results also indicate that such reallocation of resources will reduce the net profits from crop production and increase profit from fruit production. At the same time, simulation results indicate that the policy will improve the quality of water by reducing sediment load in the streams and rivers draining the catchment, hence reducing the cost of producing a unit of water for domestic use downstream. With regard to the social welfare, simulation results indicate that the policy will result in gain and loss in social welfare. In both cases, a strong effect is observed when outputs and inputs to banana are taxed, rather than when the same tax level is applied to paddy. These results are consistent with H_1: “taxing crop outputs and inputs induces reallocation of resources across land uses that differently affect the flow of hydrological and economic benefits”.

These results derive from the fact that taxing inputs to crop production and outputs increases agricultural production costs and reduces a return to agricultural production, therefore reducing the rate of conversion of natural vegetation to cultivated land. As can be noted from the results, a much higher area is converted from crop production to fruit tree production and natural vegetation, with a strong effect being observed when banana is taxed rather than paddy. Doing this increases the area under fruit and natural vegetation, which in turn increases fruit tree and natural vegetation density. The increased fruit tree and natural vegetation density improves water percolation and therefore reduces surface run-off and sediment load in the streams and rivers draining the catchment (see Johnes, 1996). This however, is achieved at a gain and loss in social welfare, measured in net income per capita. The gain in social welfare when5% tax is applied to banana output is attributable to the fact that the reduced banana production reduces income from banana but the loss is outweighed by the gain from reduced sediment load which reduce the cost of producing portable water for domestic use downstream and income from fruit production. The loss in social welfare when 5% is applied to paddy output and 10% to banana and paddy output is attributable to the fact that a reduced area for crop production reduces the supply of crops from the catchment, which in turn reduces income from crop production which outweighs the gain from reduced sediment load and income from fruit production. The income generated from sediment load reduction and fruit production may not be enough to offset the loss incurred from reduced crop production.

The observed differences in the impacts when the tax is applied to inputs and outputs of the two crops clearly indicate the differences in the importance of the two crops to the community living in the catchment. Furthermore, the direction of change of profit flow suggests that the two crops do not substitute for income generation when outputs are taxed, but do substitute when inputs are taxed. The results suggest that banana plays a great role as a cash crop, while paddy is a food crop. Therefore, farmers are willing to give up more of the cash crop than the food crop. These results demonstrate the importance of understanding the important distinctions and carefully weighing the potential net impacts of the policy. They also make clear the trade-offs that need to be managed when using policy for securing upstream land use externalities, without compromising human economic well-being in the long-run.

Simulation scenario 2: Changes in catchment crops outputs and inputs market prices

2A: Increase in crops output market prices

Simulation results in Table 7.2, block 2A(i), columns 1, 2 and 3 indicate that a 10 % increase in banana output price will increase the total area converted to crop production by 22.45% per annum, and reduce the total area converted to fruit tree production and natural vegetation by 30.08% and 44.26 % per annum, respectively. The results also indicate that the same level of price rise in paddy output will increase the total area converted to crop production by 13.23 % per annum, and reduce the total area converted to fruit tree production and natural vegetation by 14.65 % and 38.46 % per annum, respectively (Table 7.2, block 2A(ii), columns 1, 2 and 3). The rise in crop outputs prices will increase the net profit from crop production: the results in Table 7.2, block

2A(i and ii), column 4A and 4B indicate that a 10 % rise in banana output price will increase the net profits from banana and paddy production by 24.36 % and 42.52 % per annum respectively, and 13.56 % and 28.36 % per annum when the same level of paddy output price rise. On the other end of the spectrum, such rise in price of banana and paddy outputs will negatively affect fruit production by reducing the net profit from fruit production. Simulation results in Table 7.2, block 2A(i and ii), columns 5a and 5b indicate that a 10 % rise in banana output price will reduce the net profit from orange and mango by 10.46 % and 6.43 % per annum respectively, and 3.24 % and 1.34 % per annum respectively, when paddy output price rise.

Such rise in own price of crop output will affect negatively the demand for that crop and favour the other; a 10% increase on banana price will reduce demand for banana and paddy by 12.02 % (Table 7.2., block 2A, column 6a and 6b) and increase demand for paddy by 0.88% and orange and mango fruits by 0.66% and 0.43% respectively (Table 7.2., block 2A, column 7a and 7b). Similar level price rise in paddy output will increase demand for banana by 8.06% and reduce demand for paddy by 4.36%, and increase demand for orange by 0.84% and 0.34% respectively (Table 7.2., block 2A, column 7a and 7b). Again this can be attributed to the fact that an increase in crop own price affect negatively demand for the crops. These results conform with the theory of demand which is negatively related to price.

Nevertheless, simulation results indicate that such rise in crops output prices will induce an increase of sediment load in the streams and rivers draining the catchment, which eventually increase the cost of producing water for domestic use downstream. Results in Table 7.2, block 2A(i and ii) column 6 and 7 indicate that a 10 % increase in banana and paddy output prices will increase sediment load by 76.84 % and 46.23% per annum. Such increase in sediment load results into an increase in the cost of producing 1m^3 of water for domestic use downstream by 24.67% and 11.76% per annum respectively. Furthermore, the simulation results indicate that that such rise in prices of the two crops will result in the gain in social welfare of the beneficiaries. Results in Table 7.2, block 2A(i and ii), column 10 indicate that the social welfare measured as net income per capita will increase by 2.32 % and 1.23 % per annum when the prices of banana and paddy rises respectively.

These results suggest that the policy will induce resource reallocation from fruit production and natural vegetation to crop production. Such reallocation of resources will reduce the net profits from fruit production and increase profit from crop production. Doing so will deteriorate the quality of water by increasing sediment load in the streams and rivers draining the catchment, hence increasing the cost of producing a unit of portable water for domestic use downstream. However, such shifts in resource allocation will positive affect the social welfare by increasing it significantly. In both cases, strong effects are observed when price for banana outputs rises than paddy output price rises. These results are consistent with $H_{\#}$: “increase in crop outputs prices induces reallocation of resources across land uses that differently affect the flow of hydrological and economic benefits”.

These results derive from the fact that rise in crop output prices increases net return from agricultural production, which send a signal to household that agriculture production is profitable. Such a signal increases the rate of conversion of natural vegetation to cultivated land. As can be noted from the results, a much higher area of natural vegetation cover is converted to crop production, with a strong effect being observed when banana output price rise than paddy. Doing this increases the area under crop production. The increased cultivated land negatively affects the capacity of land to percolate surface water resulting to increased surface run-off, hence sediment load in the streams and rivers draining the catchment (see Johnes, 1996). This effect however, does not lead to loss in social welfare; the net gain in social welfare is positive in both crops (i.e. banana and paddy). The observed gain in social welfare is attributable to the fact that the net income from crop production outweighs the loss from reduced fruit production and increased cost of producing portable water for domestic use downstream due to increased sediment load.

The observed differences in the effect of price rise between the two clearly indicate the differences in the importance of the two crops to the community living in the catchment. Furthermore, the direction of change of profit flow suggests that the two crops do not substitute for income generation. The results suggest that banana plays a great role as a cash crop, while paddy is a food crop. Therefore, farmers respond more to price change in a cash crop than a food crop. These results demonstrate the importance of understanding the distinctions of the two major crops in the catchment and carefully weighing the potential net impacts of policies that target output prices. They also make clear the trade-offs that need to be managed when using policies for securing upstream land use externalities, to avoid compromising the economic well-being of the communities living in the catchment in the long-run.

2B: Increases in crops input prices

Simulation results in Table 7.2, block 2B(i), columns 1, 2 and 3 indicate that a 10 % increase in banana input price will reduce the total area converted to crop production by 27.34% per annum, and increase the total area converted to fruit tree production and natural vegetation by 5.89% and 58.34 % per annum respectively. The results also indicate that the same level of price rise in paddy input will decrease the total area converted to crop production by 12.36 % per annum, and increase the total area converted to fruit tree production and natural vegetation by 2.82 % and 8.67 % per annum, respectively (Table 7.2, block 2B (ii), columns 1, 2 and 3). The rise in crop input prices will reduce the net profit from crop production: the results in Table 7.2, block 2B(i and ii), column 4A and 4B indicate that a 10 % rise in banana input price, will reduce the net profits from banana and paddy production by 58.34 % and 29.34 % per annum, respectively, compared with 36.32 % and 86.46 % per annum when the same level of paddy input price rise. On the other end of the spectrum, such rise in price of banana and paddy inputs will positively affect fruit production by increasing the net profit from fruit production. Simulation results in Table 7.2, block 2B(i & ii), columns 5a and 5b indicate that a 10 % rise in banana input price will increase the net profit from orange and mango by 2.42 % and 3.65 %, and 1.41 % and 0.89 % per annum, respectively, when paddy input price rise.

Such rise in input price will affect negatively the demand for crops and favour the demand for fruits; a 10% increase on banana input price will reduce demand for banana by 9.04 % and increase demand for paddy by o0.34 (Table 7.2., block 2B, column 6a and 6b), increase demand for orange and mango fruits by 0.22% and 3.65% respectively (Table 7.2., block 2B, column 7a and 7b). Similar price rise in paddy input price will increase demand for banana by 6.02% and reduce demand for paddy by 0.46%, and increase demand for orange by 0.31% and 0.89% respectively (Table 7.2., block 2B, column 7a and 7b). Again this can be attributed to the fact that an increase in crop output price increases costs of production, hence price of the crop which affect negatively demand for the crops. These results conform with the theory of demand which is negatively related to price.

Nevertheless, simulation results indicate that such rise in input prices will induce a decrease of sediment load in the streams and rivers draining the catchment, which eventually reduces the cost of producing water for domestic use downstream. Results in Table 7.2, block 2B(i & ii) column 6 and 7 indicate that a 10 % increase in banana and paddy output prices will reduce sediment load by 2.12 % and 0.98 % per annum. Such decrease in sediment load will result into decrease in the cost of producing $1m^3$ of water for domestic use downstream by 1.24% and 0.31% per annum respectively. However, such rise in the two crops input prices affect negatively the social welfare; the simulation results in Table 7.2, block 2B(i & ii), column 10 indicate that the net income per capita will decrease by 2.46 % and 3.44 % per annum when the prices of banana and paddy production inputs rises respectively.

These results suggest that the crop production input price rise will induce resource reallocation from crop production to fruit production and natural vegetation. The results also indicate that such reallocation of resources will reduce the net profits from crop production and increase profit from fruit production. At the same time, simulation results indicate that the crop production input price rise will improve the quality of water by reducing sediment load in the streams and rivers draining the catchment, hence reducing the cost of producing a unit of portable water for domestic use downstream. With regard to the social welfare, simulation results indicate that the crop production inputs price rise will negatively affect social welfare. In both cases, strong effects are observed when price for banana production inputs price rises than when that of paddy rises. These results are consistent with $H_{\#}$: “increase in crop production input prices induces reallocation of resources across land uses that differently affect the flow of hydrological and economic benefits”.

These results derive from the fact that rise in crop production input prices decreases the net return from agricultural production, which send a signal to household that agriculture production is not profitable. Such a signal results to a reduced rate of conversion of natural vegetation to cultivated land. As can be noted from the results, a much higher area of cultivated land is left to fallow, with a strong effect being observed when banana production input price rises than that of paddy. Doing this increases the area under natural vegetation cover. Such increased area under natural vegetation cover increases the capacity of land to percolate surface water resulting to reduced surface run-off, hence sediment load in the streams and rivers draining the catchment (see Johnes, 1996). The reduced sediment load reduces the cost of producing a unit of portable water for domestic use downstream. These effects however, do not lead to net gain in social welfare. The observed loss in social welfare is attributable to the fact that the net income from increased fruit production and reduced cost of producing portable water for domestic use downstream is not enough to outweigh the loss from reduced crop production.

Simulation scenario 3: Changes in catchment fruits outputs and inputs market prices

3A: Increases in fruits output prices

Simulation results in Table 7.2, block 3A(i), columns 1, 2 and 3 indicate that a 10 % increase in mango output price will reduce the total area converted to crop production by 3.89% per annum, and increase the total area converted to fruit tree production and natural vegetation by 18.41% and 1.06 % per annum respectively. The results also indicate that the same level of price rise in orange output price will decrease the total area converted to crop production by 2.48 % per annum, and increase the total area converted to fruit tree production and natural vegetation by 8.98 % and 0.98 % per annum respectively (Table 7.2, block 3A(ii), columns 1, 2 & 3). Such rise in fruit output prices will reduce the net profit from crop production: the results in Table 7.2, block 3A(i & ii), column 4A and 4B indicate that a 10 % rise in mango output price, will reduce the net profits from banana and paddy production by 0.98 % and 2.42 % per annum, respectively, and 0.64 % and 1.46 % per annum when the same level of orange output price rise. On the other end of the spectrum, such rise in price of mango and orange outputs will positively affect fruit production in by increasing the net profit from fruit production. Simulation results in Table 7.2, block 3A(i & ii), columns 5a and 5b indicate that a 10 % rise in mango and orange output price will increase the net profit from the two crops by 8.21 % and 11.24 % respectively when mango out price rise, and 14.43 % and 6.31 % per annum respectively, when orange output price rise.

Such rise in own price of fruits output will affect negatively the demand for that fruit and favour the other; a 10% increase on mango output price will reduce demand for mango 4.01 % (Table 7.2., block 2A, column 7a) and increase demand for orange by 1.04%(Table 7.2., block 2A, column 7b) and banana and paddy fruits by 1.52 and 1.58% respectively (Table 7.2., block 2A, column 6a and 7b). Similar price rise in orange output will reduce demand for orange by 3.14%, and increase demand for mango by 4.23% (Table 7.2., block 2A, column 7a and 7b). Again this can be attributed to the fact that an increase in crop own price affect negatively demand for the fruits. These results conform with the theory of demand which is negatively related to price.

Nevertheless, simulation results indicate that such rise in fruits output prices will induce a decrease of sediment load in the streams and rivers draining that catchment, which eventually reduces the cost of producing water for domestic use downstream. Results in Table 7.2, block 3A(i & ii) column 6 and 7 indicate that a 10 % increase in mango and orange output prices will reduce sediment load by 16.22 % and 12.56% per annum. Such decrease in sediment load results into a decrease in the cost of producing 1m^3 of water for domestic use downstream by 6.68% and 4.02% per annum respectively. However, such rise in output prices of the two fruits affect positively the social welfare; the simulation results in Table 7.2, block 3A(i & ii), column 10 indicate that the net income per capita will increase by 3.33 % and 1.64 % per annum when the prices of mango and orange rise respectively.

These results suggest that such a rise in fruits output prices will induce resource reallocation from crop production to fruit production and natural vegetation. Much effect of this price rise is on area allocated to fruit production than natural vegetation. The results also indicate that such reallocation of resources will reduce the net profits from crop production and increase profit from fruit production. At the same time, simulation results indicate that reallocation of resources from crop production to fruit production and natural vegetation will improve the quality of water by reducing sediment load in the streams and rivers draining the catchment. Such reduction in sediment load reduces the cost of producing a unit of portable water for domestic use downstream. With regard to the social welfare, simulation results indicate that the policy will positively affect social welfare. In both cases, strong effects are observed when price for mango outputs rises than when for orange output. These results are consistent with $H_{\#}$: “increase in fruit output prices induces reallocation of resources across land uses in favour of fruit with higher price and differently affect the flow of hydrological and economic benefits”.

These results derive from the fact that rise in fruits output prices increases the net return from fruit production, which send a signal to household that fruit production is profitable. Such a signal results into an increased conversion of agricultural land to fruit production. Much of the cultivated land is converted to fruit production and less to natural vegetation. This can be attributed to fact that farming is the main source of income to upstream land holders; therefore, leaving their land to fallow gives nothing in return than committing it to fruit production which will assure them of income after some time. As can be noted from the results, a much higher area of agricultural land is converted to fruit production than that left to fallow, with a strong effect being observed when mango output price rise than orange. Doing this increases the area under fruit production which increases the density of fruit tree per area. The increased area under fruit production, hence the density of fruits trees increases the capacity of land to percolate surface water resulting to reduced surface run-off. The reduced surface run-off will reduce sediment loads in the streams and rivers draining the catchment (see Johnes, 1996). These effects will lead to a net gain in social welfare and the gain in social welfare can be attributed to the fact that the net income from increased fruit production and reduced cost of producing portable water for domestic use downstream will outweigh the loss from reduced crop production.

3B: Increases in fruits input prices

Simulation results in Table 7.2, block 3B(i), columns 1, 2 and 3 indicate that a 10 % increase in mango production input price will increase the total area converted to crop production by 12.24% per annum, and decrease the total area converted to fruit tree production and natural vegetation by 24.32% and 2.43 % per annum respectively. The results also indicate that the same level of price rise in orange input will increase the total area converted to crop production by 8.35 % per annum, and decrease the total area converted to fruit production and natural vegetation by 11.46 % and 1.22 % per annum, respectively (Table 7.2, block 3B(ii), columns 1, 2 & 3). Such rise in fruit production input prices will increase the net profit from crop production: the results in Table 6.2, block 3B(i & ii), column 4A and 4B indicate that a 10 % rise in mango production input price, will increase the net profits from banana and paddy production by 21.11 % and 10.21 % per annum when mango production input price rise respectively, and 12.12% and 6.42 % per annum when the same level of orange production input price rise. On the other end of the spectrum, such rise in price of mango and orange inputs will negatively affect fruit production in by decreasing the net profit from fruit production. Simulation results in Table 7.2, block 3B(i & ii), columns 5a and 5b indicate that a 10 % rise in mango and orange production input prices will reduce the net profit from the two fruits by 15.27 % and 10.15 % per annum when mango reduction input price rise, and 8.21 % and 6.87 % per annum respectively when orange production input price rise.

Such rise in own price of fruits output will affect negatively the demand for that fruit and favour the other; a 10% increase on mango intput price will reduce demand for mango 1.35% (Table 7.2., block 2A, column 7a) and increase demand for orange by 5.07%(Table 7.2, block 2A, column 7b) and banana and paddy fruits by 1.01% and 2.21% respectively (Table 7.2., block 2A, column 6a and 7b). Similar price rise in orange input will reduce demand for orange by 4.08%, and increase demand for mango by 2.01% (Table 7.2., block 2A, column 7a and 7b). Again this can be attributed to the fact that an increase in crop output price increases costs of production, hence price of the crop which affect negatively demand for the crops. These results conform with the theory of demand which is negatively related to price.

Nevertheless, simulation results indicate that such rise in fruits production input prices will induce an increase of sediment load in the streams and rivers draining that catchment, which eventually increase the cost of producing water for domestic use downstream. Results in Table 7.2, block 3B(i & ii) column 6 and 7 indicate that a 10 % increase in mango and orange production input prices will increase sediment load by 11.43 % and 6.87 % per annum respectively. Such increase in sediment load results into an increase in the cost of producing 1m^3 of water for domestic use downstream by 3.38 and 2.68% per annum respectively. However, such rise in the two fruits production input prices will not affect the social welfare; the simulation results in Table 7.2, block 3B(i & ii), column 10 indicate that the net income per capita will increase by 2.21 % and 1.01 % per annum when the prices of production inputs for the two fruits rises respectively.

These results suggest that such a rise in fruit production input prices will induce resource reallocation from fruit production and natural vegetation to crop production. The results also indicate that such reallocation of resources will reduce the net profits from fruit production and increase profit from crop production. At the same time, simulation results indicate that such rise in production input prices will negatively affect the quality of water by increasing sediment load in the streams and rivers draining the catchment, hence increasing the cost of producing a unit of portable water for domestic use downstream. With regard to the social welfare, simulation results indicate that the rise in fruits production input prices will not affect the social welfare; the social welfare will increase. In both cases, strong effects will be observed when price for mango fruits production input prices rises than that of orange fruits. These results are consistent with $H_{\#}$: “increase in fruits production input prices induces reallocation of resources across land uses that differently affect the flow of hydrological and economic benefits”.

These results derive from the fact that rise in fruits production inputs decreases the net return from fruit production, which send a signal to household that fruit production is not profitable. Such a signal results to a reduced rate of conversion of agricultural land to fruit production. As can be noted from the results, higher area for fruit production is converted cultivated land, with a strong effect being observed when mango production input price rise than orange fruits. Doing this increases the area under crop production, and such increased area under crop production reduces the capacity of land to percolate surface water resulting to increased surface run-off, hence sediment load in the streams and rivers draining the catchment (see Johnes, 1996). This effect however, does not lead to a loss in social welfare. The observed gain in social welfare is attributable to the fact the increased net income from crop production is enough by far to offset the loss from the reduced net income from increased fruit production and increased cost of producing portable water for domestic use downstream.

Table 7.2: Change in values of selected variables expressed as percentage of baseline values.

Policy and economic scenarios		Total area converted to crop per year (ha)	Total area converted to fruit per year (ha)	Total area covered by natural vegetation (ha/year)	Net profit from crop production (TZS/ha/year)		Net profit from fruit production (TZS/ha/year)		Demand for crop		Demand for fruits		Sediment load (tons/m^3)	Costs of producing portable water/m^3	Net benefits (income per capita TZS/year)
		1	2	3	4a[6]	4b[7]	5a[8]	5b[9]	6a	6b	7a	7b	8	9	10
(1)	Taxing output and inputs														
	A: Taxing crop outputs														
	(i) 5 % on banana output price	-27.76	6.86	46.34	-68.35	-26.48	4.31	4.63	-4.34	-2.08	1.21	2.33	-61	-18	4.41
	(ii) 5 % on paddy output price	-9.68	3.61	2.24	-11.26	-70.64	0.18	0.48	-1.03	-2.34	0.18	0.38	-1.32	-0.66	-0.57
	B: Taxing crop inputs														
	(i) 10 % increase on banana input price	-14.15	41.34	10.38	-23.94	-81.87	2.48	9.69	-3.04	-1.57	1.08	2.19	-16.67	-4.98	-0.11
	(ii) 10 % increase on paddy input price	-2.36	31.53	3.48	-46.63	-122.87	0.32	0.84	-6.13	-10.07	0.62	0.14	-3.42	-2.06	-1.81
(2)	Changes in crops output														

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[6] 4&6a stand for paddy crop
[7] 4&6b stand for banana crop
[8] 5&7a stand for orange fruits
[9] 5&7b stand for mango fruits

	and input market prices														
	A: Increase in crops output market prices														
	(i)10% increase in price of banana	22.45	-30.08	-44.26	42.52	24.36	-10.46	-6.43	-12.02	0.88	0.66	0.43	76.84	24.67	2.32
	(ii)10% increase in price of paddy	13.23	-14.65	-38.46	28.36	13.56	-3.24	-1.34	8.06	-4.36	0.84	0.34	46.23	11.76	1.23
	B: Increase in crops inputs market prices														
	(i)10% increase in banana input price	-27.34	5.89	58.34	-29.34	-58.34	2.42	-1.05	-9.04	0.34	0.22	3.65	-2.12	-1.24	-2.46
	(ii)10% increase in paddy input price	-12.36	2.82	8.67	-36.32	-86.46	1.41	0.68	6.02	-0.46	0.31	0.89	-0.98	-0.31	-3.44
(3)	Changes in fruit output prices														
	A: Increase in fruit output market price														
	(i)10%increase in price of mango	-3.89	18.41	1.06	-2.42	-0.98	11.24	8.21	1.52	1.58	1.04	-4.01	-16.22	-6.68	3.33
	(ii)10% increase in price of orange	-2.48	8.98	0.98	-1.46	-0.64	6.34	14.43	3.06	2.44	-3.14	4.23	-12.56	-4.02	1.64
	B: Increase in fruits inputs market prices														
	(i)10% increase in mango input price	12.24	-24.32	-2.43	11.21	21.11	-15.27	-10.15	1.01	2.21	5.07	-1.35	11.43	3.38	2.21
	(ii)10% increase in orange	8.35	-11.46	-1.22	6.42	12.12	-5.68	-8.21	3.12	-1.12	-4.08	2.01	6.87	2.68	1.01

	input price														
(4)	(i) 10% rise in off-farm wage rate inside the catchment	-20.34	5.12	36.42	-23.35	-58.42	3.26	2.87	-3.45	-8.12	-3.16	-1.47	-56.89	14.34	3.24
	(ii) 10% raise in off-farm wage rate outside the catchment	-12.43	8.24	3.26	-14.12	-34.23	1.62	1.04	-4.32	-4.33	-2.12	0.84	-32.65	9.83	2.13
(5)	5 % tax cut on fruit production inputs	-4.67	13.75	2.78	-4.83	-15.64	0.46	76.14	-2.43	-5.04	2.36	6.04	-13.21	-4.33	3.22
(6)	5 % tax cut on basic domestic goods	-53.23	5.69	44.94	-19.22	-54.48	4.64	2.42	9.02	4.28	3.14	1.32	-49.09	-12.67	4.88
(7)	7 % increase in economic growth (GDP)	-5.38	3.34	1.08	-2.92	-0.64	0.82	0.46	3.42	2.34	1.02	2.06	-4.56	-2.95	1.62
(8)	30 % increase in subside in inputs to fruit tree production (PES)	-2.02	26.62	0.8	-23.82	-12.21	20.4	14.87	-8.82	-4.31	3.04	4.07	-5.24	-3.33	1.49
(9)	10 % decrease in rainfall	36.42	-16.22	-48.36	57.62	28.43	-10.34	-11.86	-7.02	-8.03	-1.24	-1.16	15.16	5.31	1.20

Scenario 4: Changes in wage rate inside and outside the catchment

Simulation results in Table 7.2, block 4(i), columns 1, 2 and 3 indicate that a 10 % increase in wage rate inside the catchment will decrease the total area converted to crop production by 20.34% per annum, and increase the total area converted to fruit tree production and natural vegetation by 5.12% and 36.42 % per annum, respectively. The results also indicate that the same level of rise in wage rate outside the catchment will decrease the total area converted to crop production by 12.43 % per annum, and increase the total area converted to fruit production and natural vegetation by 8.24 % and 3.26 % per annum, respectively (Table 7.2, block 4(ii), columns 1, 2 and 3). Such rise in fruit production input prices will increase the net profit from crop production: the results in Table 7.2, block 3B (i and ii), column 4A and 4B indicate that a 10 % rise in wage rates, will decrease the net profits from banana and paddy production by 58;42 % and 23.35 % per annum when wage rate inside the catchment rise respectively, and 34.23% and 14.12 % per annum when wage rate outside the catchment rise at the same level. Such a rise in wage rate will positively affect fruit production by increasing the net profit from fruit production. Simulation results in Table 7.2, block 4(i & ii), columns 5a and 5b indicate that a 10 % rise in wage rate inside the catchment will increase the net profit from the two fruits by 3.26 % and 2.87 % respectively per annum, and 1.62 % and 1.04 % respectively per annum when wage rate outside the catchment rises.

Such rise in off-farm wage rate will affect negatively labour allocated to production of crops, hence supply of crops. The low supply will lead to increase in price of crops which will affect negatively the demand fro crops. A 10% rise if wage rate inside the catchment will decrease the demand for banana and paddy by 4.32% and 4.33% respectively, and increase demand for orange and mango by 2.12% and 0.84% respectively. On the other hand a 10% rise in wage rate outside the catchment will increase demand for both crops and fruits. This can be attributed to the fact that in the catchment much of labour time is used for agricultural activities, when off-farm wage rate increases it induces labour shift from crop production to off-farm works, hence reduces supply of crops. The reduced supply of crops induces price rise which affect negatively the demand. Contrary to this is an increase in wage rate outside the catchment increases purchasing power of the population, which increase demand for agricultural commodities.

Furthermore, simulation results indicate that such rise in wage rate will induce a decrease of sediment load in the streams and rivers draining that catchment, which eventually decrease the cost of producing water for domestic use downstream. Results in Table 6.2, block 4(i and ii) column 6 and 7 indicate that a 10 % increase in wage rate inside and outside the catchment will decrease sediment load by 56.89 % and 32.65% per annum respectively. Such decrease in sediment load results into a decrease in the cost of producing 1m^3 of water for domestic use downstream by 14.34% and 9.83% per annum respectively. Such rise in the wage rate will positively affect the social welfare; the simulation results in Table 7.2, block 4(i and ii), column 10 indicate that the net income per capita will increase by 3.24 % and 2.13 % per annum when the wage rates inside and outside the catchment rises respectively.

These results suggest that such a rise in wage rate will induce resource reallocation from crop production to fruit production and natural vegetation. The results also indicate that such reallocation of resources will reduce the net profits from crop production and increase profit from fruit production. At the same time, simulation results indicate that such rise in wage rate will positively affect the quality of water by reducing sediment load in the streams and rivers draining the catchment, hence decreasing the cost of producing a unit of portable water for domestic use downstream. With regard to the social welfare, simulation results indicate that the rise in wage rates will not affect the social welfare; the social welfare will increase instead of decreasing. In both cases, strong effects are observed when wage rate inside the catchment rises than outside the catchment.

These results derive from the fact that rise in wage rate inside the catchment increases production costs to productions that are labour intensive, which send a signal to household that such production is not profitable. Such a signal results to reallocation of resources to more profitable productions. As can be noted from the results, much more area from crop production is converted to fruit production and natural vegetation, with a strong effect being observed when wage rate inside the catchment rises than outside. Also the results show that much is the converted area is left to fallow than to fruit production. This is attributed to the fact that rise in wage rate not only affect crop production but also fruit production. However, the effect to fruit production is not that higher compared to crop production, indicating that fruit production is less labour intensive than crop production. An increased area left to fallow increases the capacity of land to percolate surface water resulting to reduced surface run-off, hence sediment load in the streams and rivers draining the catchment (Johnes, 1996). This effect substantially reduce sediment load in the streams and rivers draining the catchment, hence the costs of producing water downstream. Such a reduction in cost of producing water for domestic use downstream leads to a significant gain in social welfare.

Scenario 5: Tax cut on inputs to fruit production

With regard to this policy, the simulation results in Table 7.2, block 5 indicate that a 5 % tax cut on inputs to fruit production will decrease the total area converted to crop production and natural vegetation by 4.67 % per annum (column 1) and increase the total area converted to fruit production and natural vegetation by 13.75 % and 2.78 % per annum, respectively (columns 2 and 3). The results in Table 7.2, block 5 column 4a and 4b also indicate that the policy will decrease the net profit from paddy and banana production by 4.83 % and 15.64 % per annum (column 4a and 4b) and increase the net profit from orange and mango production by 0.46 % and 76.14 % per annum, respectively (columns 5a and 5b). At the same time, the simulation results indicate that the policy will improve water quality and social welfare; the results in Table 7.2, block 5 column 6, 7 and 8 show that under this policy, sediment load will be reduced by 13.21 % per annum which will reduce the cost of producing potable water for domestic use downstream by 6.33% and increase the net income per capita of the communities living in the catchment by 3.22% per annum.

Simulation results from tax cuts on inputs to fruit production indicate that the policy will achieve conservation objectives. This conclusion is drawn from the fact that the policy will induce reallocation of resources from crop to fruit production. With respect to the effect of reallocation of resources due to tax cuts on inputs to fruit production on hydrological, private economic benefits, and social welfare, the simulation results indicate that the policy will compromise the private economic benefits accruing from crop production and favour benefits from fruit production. At the same time, the simulation results indicate that the policy will improve water quality, hence reduce costs of producing portable water for domestic use, and social welfare, which is consistent with H_2: “tax cuts on inputs to fruit production achieve internalisation of land use externalities in water catchments without compromising social welfare”.

These results derive from the fact that tax cuts on inputs to fruit production lower the fruit production costs and increase the net return to fruit production, which encourages farmers to increase the rate of conversion of the area for cultivated crops and natural vegetation to fruit production. The increased area converted to fruit production and the lowered costs of production increase the net profit accruing from fruit production. Equally important, the increased area for fruit production and natural vegetation cover reduce sediment load produce which in turn reduces the cost of producing portable water for domestic use downstream that in total with profit from fruit production are by far large enough to offset the loss from reduced crop supply due to decreased area converted to crop production, hence the social welfare for the communities living in the catchment increases significantly. These results demonstrate the potential of tax cuts on inputs in supporting the best management practices (BMPs) in achieving water catchment conservation goals. These results also indicate that this policy has a double dividend effect, as it simultaneously improves water quality and social welfare.

Scenario 6: Tax cuts on basic domestic goods

The simulation results in Table 7.2, block 6 columns 1, 2 and 3 indicate that by imposing a 5 % tax cut on domestic goods, the total area converted to crop production is reduced by 53.23 % per annum and the total area converted to fruit production and natural vegetation is increased by 5.69 % and 44.94 % per annum, respectively. The results also indicate that the policy will reduce the net profit from crop production and increase the net profit from fruit production. Results in Table 7.2, block 6 columns 4a, 4b, 5a and 5b indicate that a 5 % tax cut on domestic goods will decrease profit from paddy and banana by 54.48 % and 19.22 % per annum, and increase the net profit from orange and mango by 4.64 % and 2.42 % per annum, respectively. Finally, the results indicate that the policy will be effective in improving water quality. Simulation results in Table 7.2, block 6 columns 6, 7 and 8 shows that the policy will result in a reduction of sediments load and costs of producing portable a m^3 of water for domestic use, and increase social welfare by 49.09 %, 14.67% and 4.88% per annum, respectively.

As with tax cuts on inputs to fruit production, tax cuts on domestic goods that go into the catchment indicates that the policy will achieve conservation objectives without compromising the social welfare. The results indicate that the policy will induce reallocation of land from crop to fruit production and natural vegetation, with much of it being left for natural vegetation to grow in. The results also indicate that policy will reduce the net profit accruing from crop production. On the other hand, the results indicate that the policy will increase the net profit from fruit production. At the same time, the results indicate that the policy will improve water quality, and hence reduce the cost of producing a m^3 of portable water for domestic use downstream.

The observed policy outcomes derive from the fact that the policy will lower the cost of living and raise the purchasing power of farmers' disposable income in the catchment, hence decreasing pressure on natural resources (particularly land), which is consistent with H_3: tax cuts on basic domestic goods lower the cost of living and increase the purchasing power, and hence reduce dependence on natural resources. Doing so will induce a reallocation of resources (particularly land) from crop to fruit production and natural vegetation, much of it being left for natural vegetation to grow in, suggesting that land resource allocation in the catchment is cash demand-driven. Therefore, when a need for cash is reduced due to availability of cheaper domestic goods, pressure on land is reduced and much of it is left to fallow. These results are also consistent with the predictions of literature (see for example Swallow *et al*., 2009), which ascertain that poor communities in developing countries depend primarily on natural resources for their livelihoods. Therefore, when the purchasing power of their income increases, the need for income decreases, hence the pressure on natural systems decreases. However, this will only reduce the land allocated to crop production to a level that remaining cultivated land is produces enough to meet their food needs and surplus for the needed income to buy manufactured domestic goods and other services. Such a decrease in cultivated land and increase in an area left to fallow allow growth of natural vegetation which reduces run-off and enhance percolation both of which reduce sediment load, hence cost of producing a m3 of portable water for domestic use downstream. These results demonstrate the potential of the policy in achieving internalisation of land use externalities in water catchments.

Scenario 7: Improving economic growth

With respect to this policy, the simulation results in Table 7.2, block 7 indicate that a 7 % growth in GDP per capita will decrease the total area converted to crop production by 5.38 % per annum, and increase the total areas converted to fruit production and natural vegetation by 3.34 % and 1.08 % per annum, respectively. The results also show that such decrease and increase in areas converted to crop and fruit production will induce a decrease in the net profit from paddy and banana production by 0.64 % and 2.92 % per annum and an increase in the net profit from orange and mango production by 0.82 % and 0.46 % per annum, respectively (columns 4a, 4b, 5a and 5b). Finally, columns 6, 7 and 8 show that the policy will reduce sediment load by 4.56 % per annum which will reduce the cost of producing a m^3 of portable water for downstream use by 0.95%, and increase the net income per capita by 1.62 % per annum, respectively.

The area converted to crop production decreases considerably, the areas converted to fruit production and natural vegetation increase, net income from crop production decreases while the net income from fruit production increases, sediment loads in streams draining the catchment and rivers decrease resulting to a decline in cost of producing portable water for domestic use downstream, and social welfare increases with improving economic growth by increasing GDP per capita. These results derive from the fact that economic growth creates new economic opportunities that reduce dependence on agriculture and natural systems for livelihood. They also derive from the fact the new economic opportunities created induce emigration of people from the catchment. This leads to a reduction in population living in the catchment, which in turn reduces the conversion of land to crop production as demand for food is reduced.

Improved economic growth also increases income from off-farm employment opportunities, which increases the number of people available to engage in off-farm activities. To protect their land and have enough time to engage in off-farm activities, people moving into off-farm activities convert their land into uses that need less labour and management time, such as fruit tree production, which is consistent with H_3. The results indicate that much of the land is converted to fruit production and a very small proportion is left to fallow. As with the aforementioned policies, the increased total area converted to fruit production and natural vegetation growth increases the density of both fruit and natural vegetation, which in turn improves the percolation capacity of the catchment, hence reducing surface run-off. Doing so reduces soil erosion and hence sediment loads in the streams and rivers draining the catchment. Such reduction in sediment load result into reduction of cost of producing portable water for domestic use downstream. The observed positive net income per capita results from the fact that the fruit production, income from off-farm activities and the served cost for producing portable water for domestic use downstream in total offset the loss resulting from the reduced area for crop production. As with tax cuts on inputs to fruit production, this policy has a double dividend effect, as it simultaneously improves water quality and social welfare.

These results demonstrate the potential of indirect economic incentives measures, such as improving off-farm employment, for securing upstream land use externalities internalisation in water catchments. However, as demonstrated by Ferraro and Kramer (1997) and more recently by Jogo and Hassan (2010), such measures do not automatically lead to sustainable management; in some cases the availability of alternative income sources may lead to intensification of resource use. For alternative income to spur the conservation of water catchments, it is important to emphasise the overall economic development in the area needed to increase availability of off-farm employment opportunities outside the catchments.

Scenario 8: Compensating upstream land users

With regard to the compensation paid to farmers through payment for ecosystem services (PES) schemes for supplying good quality water by implementing fruit tree buffer strips, simulation results in Table 7.2, block 8 indicate that a 30 % increase in price in the current compensation level will induce a decrease in the total area converted to crop production by 2.02 % per annum, and an increase in the total area converted to fruit production and natural vegetation by 26.62% and 0.8 % per annum, respectively (columns 1, 2 and 3). The results also indicate that it will reduce the net profit from crop production by 23.82 % and 12.11 % per annum and increase the net profit from orange and mango production by 20.4 % and 14.87% per annum, respectively (columns 4a, 4b, 5a and 5b). At the same time, the results show that the policy will decrease sediment load by 5.24 %, which in turn result into a decrease in cost of producing $1m^3$ of portable water downstream by 1.33%, and increase the net income per capita by 1.49 % per annum, respectively (columns 6, 7 and 8).

As with tax cuts on inputs to fruit production and basic domestic goods that go into the catchment, intervention through conservation incentives paid to farmers for implementing fruit tree buffer strips in the catchment encourages farmers to reduce the total area converted to crop and increase the total area converted to fruit production and natural vegetation. The results indicate that the policy encourages farmers to convert much of their land to fruit production, rather than natural vegetation. Such reallocation of resources, however, results in a substantial reduction in the net profit accruing from crop production. This is attributed to the fact that the reallocation of resources from crop production to fruit production reduces resources available for crop production, and hence the supply of crops from the catchment. Reduced supply of crops reduces the net profit from crop production. However, despite the considerable loss in the net income from crop supply, the net income per capita increases substantially. This derives from the fact that an increase in the total area converted to fruit production increases the net profit from fruit production. An increased fruit density reduces run-off and increase percolation capacity which together they improve the quality of water flowing downstream; hence the cost producing a unit of portable water downstream is reduced. Therefore, the income from fruit production and the income from served costs of producing portable water downstream together are far enough to offset the loss in income from crop production. However, the policy achieves conservation goals at a lower level compared with taxing inputs to banana production and outputs, and tax cuts on inputs to fruit production and basic domestic goods that go into the catchment.

Scenario 9: Rainfall decrease in the catchment surrounding areas

Although climate change predictions for precipitation are less consistent, most simulations for East African countries indicate that in the next 100 years, rainfall will decline by 10 to 20 % of the 1950–2000 average rainfalls (Agrawal *et al.*, 2003). The study took the lower value for the purpose of being within the range of the predictions. Simulation results indicate that natural vegetation cover and total area under fruit trees will decline by 48.36 % and 16.22 %, respectively, and crop land will increase by 36.42 % (Table 7.2, block 9, columns 3, 2 and 1, respectively). Such a decrease in land covered by natural vegetation and fruit trees will deteriorate the quality of water flowing downstream by increasing sediment loads by 15.16 %, which will increase the cost of producing a m^3 of portable water for downstream domestic use by 4.2 (Table 7.2, block 9 column 6 and 7). However, such a change will not affect the welfare of the communities living in the catchment; their welfare measured as income per capita will increase by 1.20 % and this can be attributed to the fact that land converted to crop will increase and hence so will income from crop production (i.e. 57.62 % and 28.43 % from paddy and banana production, respectively) (Table 7.2, block 9 columns 4a and 4b respectively). This is attributed to the fact that in developing countries, the majorities of the populations are poor, with low capacities to adapt to climate change. Therefore, in extreme climatic conditions, water catchments will be the areas in which to seek refuge (Sanga *et al.*, 2013). Many people will migrate into the catchments searching for water, agricultural land and pasture. Such in-migration will increase the population in the catchment, which will increase demand for land for settlement and crop production, which will alter fruit tree and natural vegetation density and affect their filtering capacity, hence increasing sediment load downstream.

7.5. Concluding summary

The chapter presented the testing and validation of results. The results indicate that, structurally, the model conforms with the purpose of the study. The testing, which involved comparing the predicted and observed variables, shows that the model has robust predictive ability in reproducing historical trends, which is consistent with the purpose of integrated ecological-economic modelling.

The simulation results clearly indicate that economic and ecological systems are intricately interlinked, with important feedbacks effects such that a change in one system impacts on the other. At the same time, the results have proven that water catchment systems are interlinked with human systems, such that changes in human systems influence the functioning of water catchment system, and a change in water catchments impacts on human systems through provisioning of ecosystem services.

The results of the simulation for fruit tree buffer strips supporting policies indicate that crop production, fruit tree production, natural vegetation, hydrological services (particularly water) quality, and social welfare are interlinked, with subtle trade-offs being involved through their competition for resources (particularly labour and land). The simulation results show that some policy interventions, such as taxing inputs on crop production and on outputs, may secure land use externalities internalisation by using fruit tree buffer strips and improve ecosystem services (particularly water quality) from water catchments by reducing sediment loads in the streams and rivers draining the catchment, but at the expense of social welfare. At the same time, simulation results show that other policies, such as tax cuts on inputs to fruit production and compensation for upstream land users, may secure land use externalities internalisation by using fruit tree buffer strips without compromising social welfare. In other words, these policies have double dividend impacts, i.e. reducing sediment load in the streams and rivers draining the catchments hence costs of producing water for domestic use downstream and improving social welfare.

Simulation also indicates that the existing demand for crops is enough to absorb the taxes. Also the demand for fruits is strong enough to encourage fruit production; therefore, if fruit production will be supported by other policies can help in internalizing externalities.

The simulation results also show that increasing off-farm employment opportunities has double dividend impacts, because it simultaneously achieves internalisation of land use externalities by inducing a reallocation of resources from crop production to fruit production and natural vegetation, which eventually reduces sediment load in streams and rivers draining the catchment, hence cost of producing water for domestic use downstream and improves social welfare.

CHAPTER 8

SUMMARY, CONCLUSIONS AND POLICY IMPLICATIONS OF THE RESULTS, AND AREAS FOR FURTHER RESEARCH

8.1. Introduction

The purpose of this chapter is two-fold. First, the chapter present a brief summary of the key findings and policy implications. Second, the chapter highlights the study limitations and suggests possible areas for further research.

8.2. Summary of the key findings and policy implications

The purpose of this study was to evaluate the likely trade-offs to be involved and their impacts on the flow of hydrological and economic benefits when economically viable land use practice is opted for in internalising upstream land use externalities in water catchments, and to test the hypotheses proposed in this study. To achieve this objective, the study developed an integrated ecological-economic model based on a systems dynamics framework which was subsequently applied to simulate the likely impacts of different supporting potential policies and economic scenarios on hydrological services (particularly water quality), private economic benefits, and social welfare measured as net income per capita. Also to achieve the objective, the study considered the implementation of fruit tree buffer strips as an economically viable land use practice. Five scenarios were simulated, i.e. (1) taxing crop outputs and inputs; (2) tax cuts on inputs to fruit production; (3) tax cuts on basic domestic goods; (4) improving economic growth; and (5) compensating upstream land users. The results of the study are useful for designing credible policies to secure upstream land use externalities internalisation in water catchments and thereby enhance the sustainable management of the catchments.

Simulation results showed that taxing inputs to crop production and outputs achieves internalisation of land use externalities considerably, but at the expense of social welfare. As noted in Chapter 7, section 7.3, the policy will induce reallocation of resources from crop production to fruit production and natural resources to a point where the net profit accruing from fruit production is not enough to offset the income loss from reduced crop production caused by reallocation resources. The policy implication from this result is that it reduces the social welfare. Therefore, the government should not focus on this approach alone, but should also integrate it with other policies, such as providing education which will enable upstream land holders to acquire the necessary skills to tap other economic opportunities. This stem from the fact that upstream land holders compare the opportunity cost of their labour across economic activities before committing it; economic activities with high opportunity cost of labour are turned down. They also compare the marginal cost of production across production activities, and production activities with lower marginal costs are favoured.

Simulation results further suggest that tax cuts on inputs and subsidies (or compensation) for fruit production will achieve conservation objectives without compromising social welfare. Tax cuts on inputs and increasing compensation to fruit production will reduce agricultural production costs and increase the net income from fruit production, compared to crop production. This will encourage farmers to convert much of their land to fruit production, which has the potential to improve water percolation and hence reduce surface run-off. The main policy implications that can be drawn from these results are: first, reducing the cost of agricultural production costs can serve the purpose of internalising harm done in the water catchment in a very smooth way. However, subsidies are too costly for poor countries where resources are limited and those that are available have many important demands made on them.

With regard to tax cuts on domestic goods that go into the catchment, simulation results suggest that the policy will achieve conservation objectives at the expense of social welfare. The results suggest that the policy will influence farmers to reallocate much of their land from crop to natural vegetation, rather than to fruit production, hence lowering profits from both crop and fruit production (particularly profits from orange production). The net effect of this policy is a substantial reduction in social welfare. These results imply that the government and other conservation agents on the ground need to understand the likely trade-offs and their impacts on ecosystem integrity and the long-term economic impacts.

Finally, simulation results suggest that increasing off-farm activities has a double dividend effect because it simultaneously enhances internalisation of land use externalities and improves social welfare in water catchments. Improving economic growth increases opportunities for diversifying livelihoods out of agriculture, which in turn reduces dependence on natural systems and encourages land owners to invest in land uses that need less labour. The major policy implication that can be drawn from these results is that government and other development agents should focus more on improving rural infrastructure, market chains and education, all of which will open the rural economy and increase opportunities among rural communities.

Generally, these results clearly show the importance of understanding the distinctions between, and carefully weighing the potential impacts of, the different supporting policies to be opted for on the net benefit flow of the best management practice. The results also demonstrate the likely trade-offs for each supporting policy that need to be managed for the policy to achieve internalisation of land use externalities in water catchments.

8.3. Limitations of the study and areas for further research

Although the dynamic simulation model we developed has generated useful results and policy insights for securing internalisation of land use externalities in water catchments, the model has a number of limitations, which could be the basis for further research. The main practical challenges arose from the lack of available data needed to estimate various parameters and an insufficient understanding of the linkages and feedback mechanisms the modelled system. Among the more important practical challenges that need improvement for the model to become more informative and thus be able to provide insight to more complex systems include:

- Adding a module to account for ground water dynamics which is the key measure of the canopy cover percolation effect and determinant of hydrological services flow.
- Adding a module which account for the impact of fruit tree production on soil fertility upstream and downstream
- Having capacity to include as many crops and management technologies so as to identify the appropriate conservation technologies with maximum hydrological benefits and minimum economic impacts.

- Including the effects of climate change, which the literature has proven to comprise one of the major ecosystem management challenges, as it accelerates conversion of natural vegetation in water catchments, particularly in developing countries where poverty limits the capacity of the majority of people to cope with extreme climatic conditions.
- Including an institutional aspect, particularly regarding the mechanisms for ensuring that upstream and downstream participants are linked in a mutually exclusive market, such as the payment for ecosystem services (PES) so as to minimise the burden to the governments.

As some of the components of the water catchment system were not included in the model due to unavailability of data and insufficient understanding of the linkages and feedback involved, there is room for the model to be extended by including other important elements. On the other hand, because of the importance that water catchments can play in overcoming challenges of climate variability on agriculture, it is important to identify local catchment management practices and include them in the model. The simulation scenarios will then include local alternatives rather than macro-policies. This will enable the determination of management practices that rural people are familiar with and can easily adapt in order to enhance the management of the catchment and their social welfare.

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List of Appendices

Appendix 1: first order conditions for the household optimisation model

$$\partial\ell/\partial L_{ci} = \lambda_1 \, \partial C_i/\partial L_{ci} - \lambda_4 = 0 \qquad \textbf{(1.1)}$$

$$\partial\ell/\partial L_{Fi} = \lambda_2 \, \partial F_i/\partial L_{Fi} - \lambda_4 = 0 \qquad \textbf{(1.2)}$$

$$\partial\ell/\partial L_o = \lambda_3 W_o - \lambda_4 = 0 \qquad \textbf{(1.3)}$$

$$\partial\ell/\partial Z_{ci} = \lambda_1 \, \partial C_i/\partial Z_{ci} - \lambda_3 P_{zci} = 0 \qquad \textbf{(1.4)}$$

$$\partial\ell/\partial Z_{Fi} = \lambda_2 \, \partial F_i/\partial Z_{Fi} - \lambda_3 P_{ZFi} = 0 \qquad \textbf{(1.5)}$$

$$\partial\ell/\partial A_{ci} = \lambda_1 \, \partial C_i/\partial A_{ci} - \lambda_3 R_{Aci} = 0 \qquad \textbf{(1.6)}$$

$$\partial\ell/\partial A_{Fi} = \lambda_2 \, \partial F_i/\partial A_{Fi} - \lambda_3 R_{AFi} = 0 \qquad \textbf{(1.7)}$$

$$\partial\ell/\partial C_i = \partial U/\partial C_i^c \; \partial C_i^c/\partial C_i - \lambda_1 = 0 \qquad \textbf{(1.8)}$$

$$\partial\ell/\partial C_i^S = \partial U/\partial C_i^c \; \partial C_i^c/\partial C_i^s - \lambda_4 P_{ci} = 0 \qquad \textbf{(1.9)}$$

$$\partial\ell/\partial X_{ci}^p = \partial U/\partial C_i^c \; \partial C_i^c/\partial C_i^p - \lambda_4 P_{ci} = 0 \qquad \textbf{(1.10)}$$

$$\partial\ell/\partial F_i = \partial U/\partial F_i^c \; \partial F_i^c/\partial F_i - \lambda_2 = 0 \qquad \textbf{(1.11)}$$

$$\partial\ell/\partial F_i^S = \partial U/\partial F_i^c \; \partial F_i^c/\partial F_i^s - \lambda_4 P_{Fi} = 0 \qquad \textbf{(1.12)}$$

$$\partial\ell/\partial F_i^p = \partial U/\partial F_i^c \; \partial F_i^c/\partial F_i^p - \lambda_4 P_{Fi} = 0 \qquad \textbf{(1.13)}$$

$$\partial\ell/\partial X_{mi} = \partial U/\partial X_{mi} - \lambda_3 P_{mi} = 0 \qquad \textbf{(1.14)}$$

$$\partial\ell/\partial\lambda_1 = C_i(\alpha, L_{ci}, Z_{ci}, \omega) - C_i = 0 \qquad \textbf{(1.15)}$$

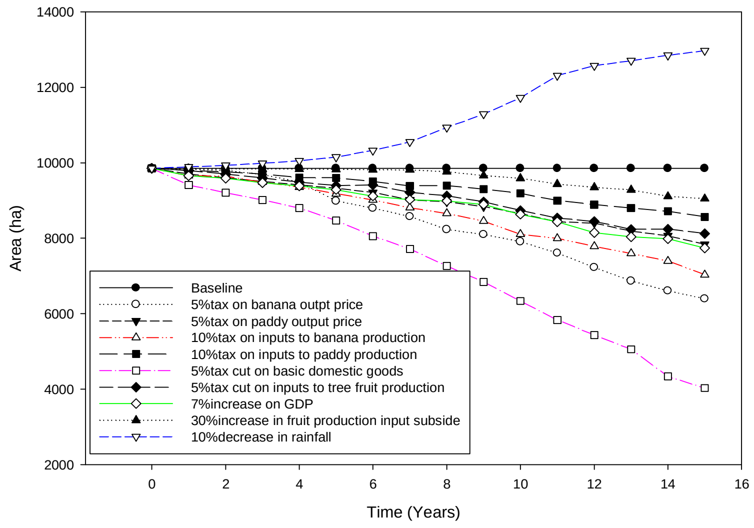
$$\partial\ell/\partial\lambda_2 = F_i(\theta, L_{Fi}, Z_{Fi}, \omega) - F_i = 0 \qquad \textbf{(1.16)}$$

$$\partial\ell/\partial\lambda_3 = P_{ci}^s + P_{Fi}^s + L_o W_o + SUB - P_{ci}^p - P_{Fi}^p - P_{ci} Z_{ci} - P_{Fi} Z_{Fi} - P_m X_m = 0 \qquad \textbf{(1.17)}$$

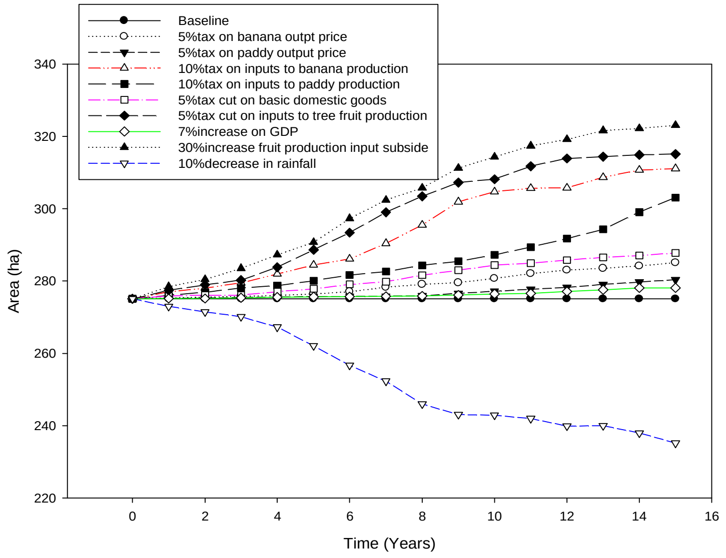
$$\partial\ell/\partial\lambda_4 = L_T - L_{ci} - L_{Fi} - L_o - L_z \qquad \textbf{(1.18)}$$

$$\partial\ell/\partial\lambda_5 = A_T - A_{ci} - A_{Fi} - A_{NV} \qquad \textbf{(1.19)}$$

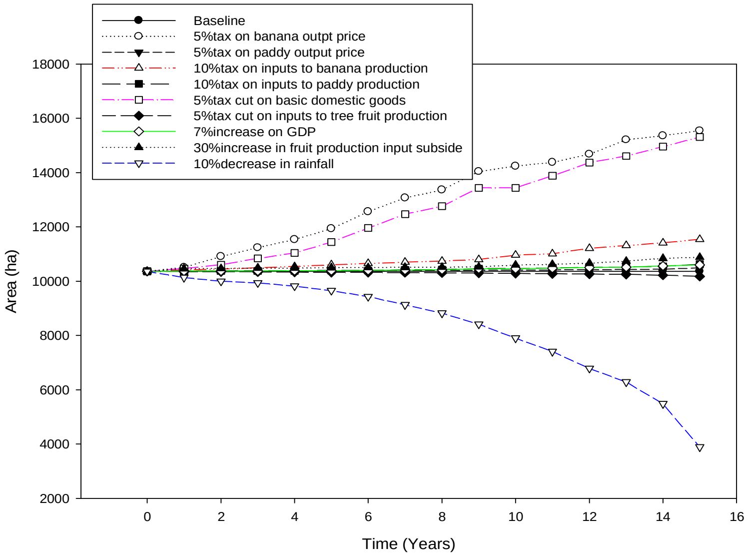
Appendix 2: Trends of canopy cover change, flow of benefits and quality of water under different simulations



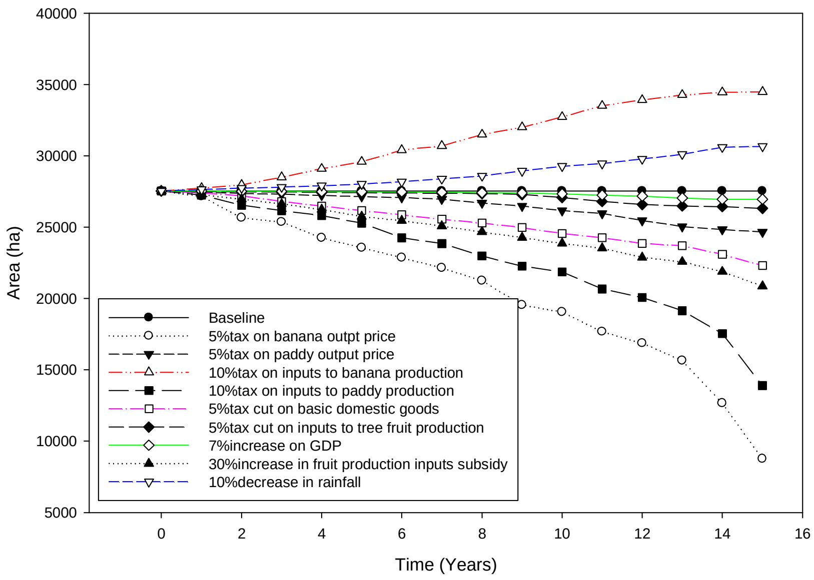
(A) Total area converted to crop production over time



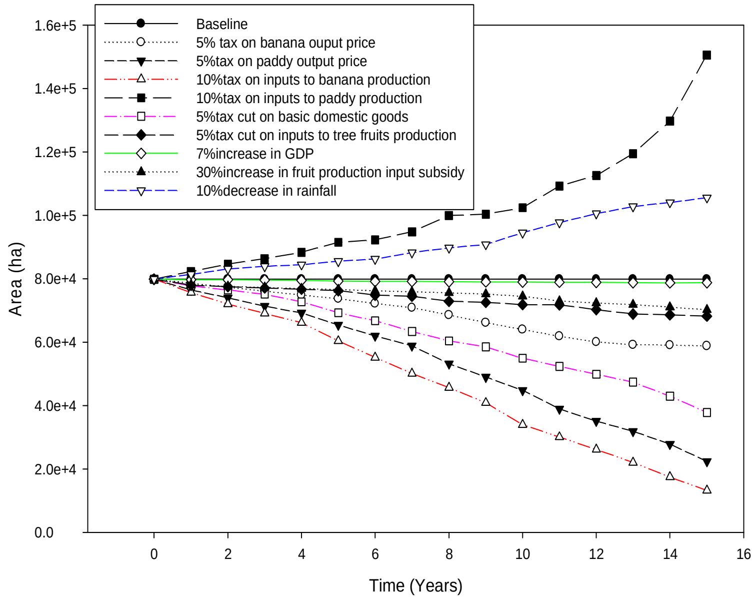
(B) Total areas converted to fruit production over time



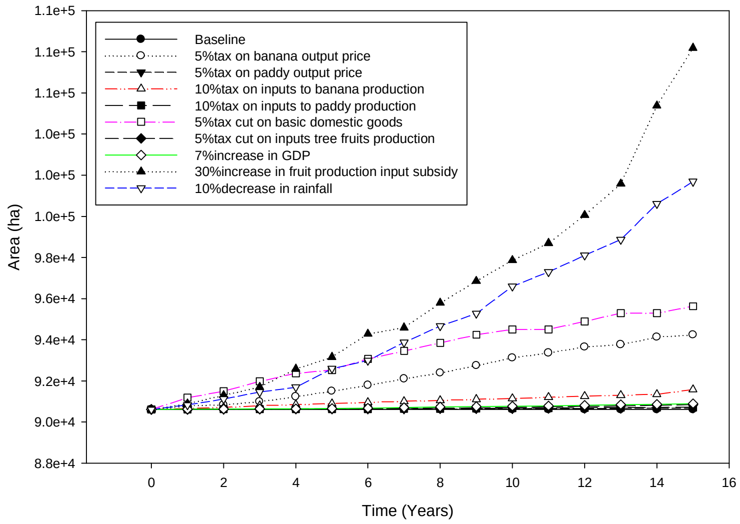
(C) Total area left for natural vegetation



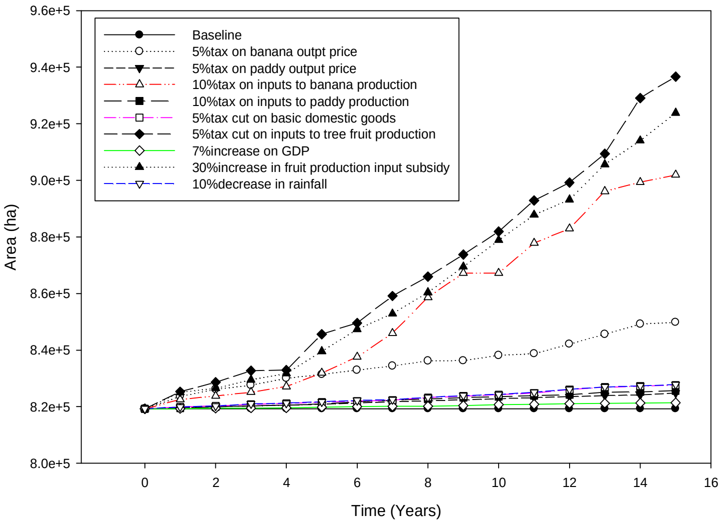
(D) Net revenue from paddy production over time



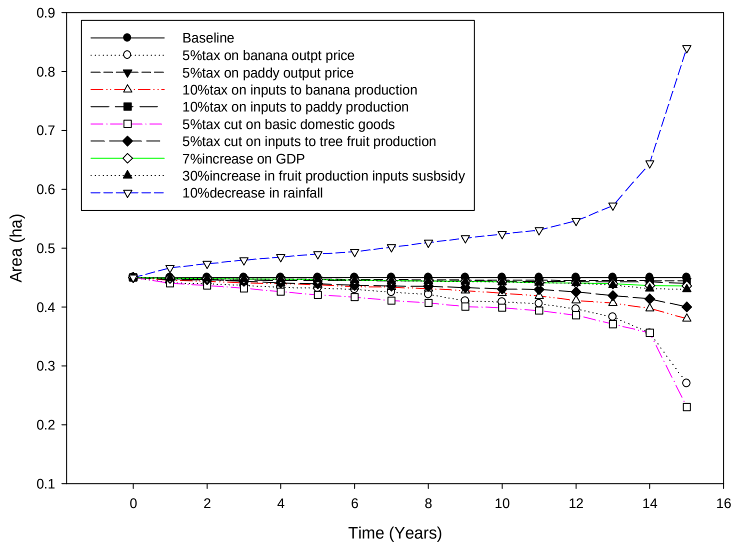
(E) Net revenue from banana production over time



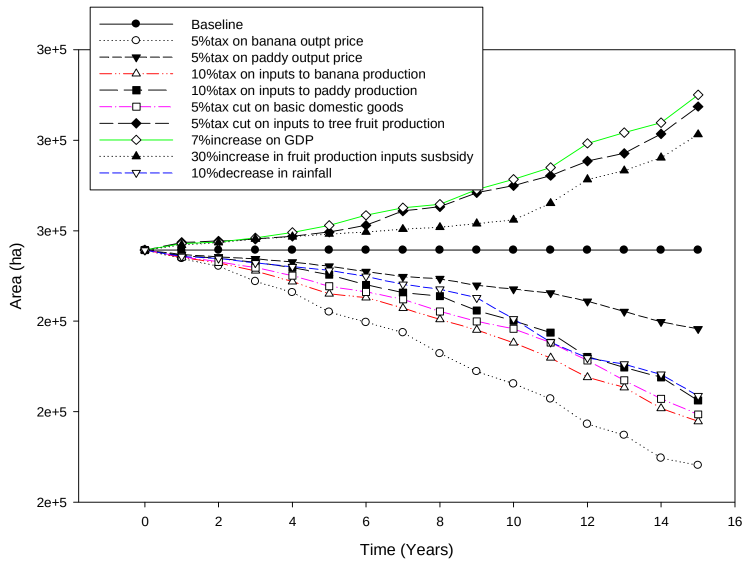
(F) Net revenue from orange production over time



(G) Net revenue from mango production over time



(H) Sediment load in water flowing downstream over time



(I) Social well-being of upstream community over time