PLANNING OF SYSTEM INNOVATIONS IN WATERSHEDS:

SPATIAL MAPPING OF ENVIRONMENTAL AND HYDROLOGICAL DETERMINANTS IN THE PANGANI AND UPPER EWASO NG'IRO NORTH RIVER BASINS, AFRICA

Jeniffer Kinoti Mutiga

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DISSERTATION

to obtain
the degree of doctor at the University of Twente,
on the authority of the Rector Magnificus,
prof.dr. H. Brinksma,
on account of the decision of the graduation committee,
to be publicly defended
on Wednesday 15 June 2011 at 14:45 hrs

by

Jeniffer Kinoti Mutiga

born 25 December 1969,

in Meru, Kenya.

This thesis is approved by

Prof. Dr. Z. Su, promotor
Dr. Tsehaie Woldai, assistant promotor

Dedication

To the very under-privileged but zealous woman, may this piece of work inspire and empower you to achieve your dreams in life!! May it form the basis for your strength, courage and endurance today and always.

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Abstract

In Sub-Saharan Africa (SSA), about 95% of agriculture is mainly rain-fed, which means that the majority of the population depends on rain-fed agriculture for their survival. In many countries of SSA growth of the agricultural sector has been reported to be low in the past decade, despite the fact that this sector is recognized as a priority area in an effort to reduce poverty. This low growth is a result of poor farming practices as well as the effects of climate variability.

Although the situation appears to be desperate, all is not lost as adoption of rainwater harvesting (RWH) technologies might serve as a remedy, since they have shown promising potential for upgrading rain-fed agriculture. However, most of the existing technologies in these areas have low performance rates, resulting in relatively low adoption rates. It is against this background that this research study was conducted with the aim to contribute to the already existing knowledge base, which is paramount in formulating sustainable water and land resource management strategies for water scarce river basins in SSA. Enhancing water productivity may lead to improved food security and contributes to the on-going global dialogue on water for food and environment with the aim to meet the already stipulated millennium development goals (MDGs).

To achieve this goal, the study applied a rapid GIS-based analytical tool to assess the suitability of various water system innovations (WSIs), such as rainwater harvesting technologies capable of improving agricultural productivity in these dry areas of SSA. Remote sensing technology was used to extract most of the data (from different multi-sensor missions) required for the various decision support tools (DSTs) applied during this study and this was complemented with existing rich indigeneous knowledge.

In order to promote the uptake of these innovative water management technologies on a larger scale, particularly amongst smallhold farmers, a spatial multi-criteria evaluation process (SMCE) was applied, a decision support tool to identify suitable areas for implementing appropriate RWH technologies in two basins: the Upper Ewaso Ng'iro North in Kenya and the Pangani River Basin in Tanzania. A weighted linear combination procedure, which allowed for full tradeoffs amongst various factors influencing suitability for RWH was applied in the data rich Ewaso Ng'iro Basin. The results obtained were then transferred to the data scarce Makanya catchment located in the upstream of the Pangani Basin in Tanzania. Suitability maps depicting suitable areas for RWH were produced, with attributes serving as indicators for targeted RWH interventions. The information generated can be used to raise awareness and to guide policy decisions on the contribution of RWH in meeting the MDGs.

However, while recognizing the benefits that can be harnessed from RWH (increasing yields through improved water productivity, improving rural livelihoods) it was critical to investigate the impacts that would accrue, if RWH technologies were adopted at a large scale by many smallhold farmers in the area. This was accomplished by applying a soil and water assessment tool (SWAT), a hydrological model to assess and compare the impacts of land cover/use changes emanating from upscaling RWH technologies on the hydrology. This assessment was evaluated for the year 2003 and for the alternative (upscaling of RWH technologies) scenario (2015).

Hydrological responses were estimated using historical land cover/use scenarios obtained from multi-temporal historical satellite imageries of 1987, 1995 and 2003. The results obtained showed an increase in total surface runoff during this period, with decreasing forest, bush and grass cover in the area. However, adoption of RWH as a water management strategy at a large scale reduced the overall surface runoff and at the same time, increased base flow with almost similar magnitude, thus compensating for the reduced runoff. It was further revealed that upscaling of suitable RWH technologies already in use in the area resulted in an increase in actual evapotranpiration (*ET*), showing how water is being used productively to improve yields.

The study concludes that the most feasible and cost effective way to confront the water scarcity challenge and deal with water related problems effectively in these dry areas of SSA is to promote and encourage the adoption of water management innovations such as RWH, which have been proven to have great potential for making more water available to help improve food production and hence improve the rural livelihoods. This can be made possible by providing farmers with incentives such as credit facilities and markets for their products. Capacity building through agricultural extension services on technology choice based on the land characteristics can further enhance adoption rates.

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CHAPTER 1
General Introduction

1. Introduction

Globally about 14% of the land surface is covered by agricultural land, which is primarily rain-fed (Rijsberman and Molden, 2001). Furthermore, agriculture is the world's biggest user of both land and water resources and accounts for over 85% of water withdrawal in Africa (Rosegrant and Perez, 1995). In Sub-Saharan Africa (SSA), about 95% of agriculture is mainly rain-fed, which means that the majority of the population depends on rainfall and agricultural productivity for their survival (FAO, 2002). Research has shown that about 41% of agricultural land is located in the semi-arid regions of SSA, of which a mere 2% is irrigated. This implies that, for the foreseeable future, rain-fed agriculture will remain the dominant source of food for the increasing population in these regions (FAO, 1990; Parr et al., 1990; Fox and Rockström, 2000). Thus, smallholder system innovations aimed at improving agricultural productivity while conserving water and land resources is vital in the struggle to feed this rapidly growing population.

The immense challenge to increase food production in SSA to keep pace with population growth and diminishing water resources requires extra focus on water productivity for both rain-fed and irrigated agriculture, through integrated soil and water management as well as innovations in water management, such as precision irrigation and rainwater harvesting. Such innovatons can contribute significantly to the upgrading of rain-fed agriculture (Falkenmark and Rockström, 2003).

Reduction in poverty, which is the main objective of the Millennium Development Goals (MDG*s*), will require an increase in productivity in agriculture in order to improve incomes, thus improving the living conditions of the poor and reduce environmental degradation. This could be achieved by improved efficiency of water use in rain-fed agriculture. While improving agricultural productivity is a priority to enable feeding a growing population, water crises are becoming a policy challenge in many countries in SSA (Ngigi et al., 2006).

It has been observed that, water-related problems in rain-fed agriculture in the water scarce areas of SSA are often related to rainfall of high intensity and short duration with large spatial and temporal variability, rather than to a low cumulative amount of rainfall (Rwehumbiza et al., 1999). The high risk of meteorological droughts and intra-seasonal dry spells leads to low crop yields and sometimes total crop failures. The challenge therefore is how to reduce the impacts of such climatic disparities and cushion farmers against their effect on rain-fed agriculture.

Research in several semi-arid tropical regions (Tiffen et al., 1994; Rockström et al., 2001) shows, that dry spells, i.e. short periods of 2 to 4 weeks without rainfall, occur more frequently than droughts. According to Rockström et al. (2001), mitigation of such intra-seasonal and inter-seasonal dry spells is a prerequisite for improving water productivity of rain-fed agriculture in these areas. When managing water for agriculture, especially in areas where water rather than land is the limiting resource, the focus should be on increasing the productivity of water. That is, identify and adopt agricultural and water management practices, which achieve more output per unit of water consumed, thereby easing the strains of water scarcity and reducing the need for additional storage (McCornick et al., 2003).

Improved water use efficiency (crop-per-drop) can be secured in different ways in both rain-fed and irrigated agriculture (Falkenmark and Rockström, 2003). On the one hand, infiltration potential can be improved by soil conservation measures so that, more rainwater can infiltrate into the root zone. This will also reduce the destructive overland flows that tend to cause severe erosion damage in many parts of the tropics. Land degradation in the form of water erosion, affects 60% of the rain-fed cropland in SSA (Chou and Dregne, 1993). On the other hand, evaporation losses between plants can be reduced by increased foliage to protect the plants from dryspell damage to their roots.

The demand for food and fibre in the face of population growth has largely been met through the expansion of agricultural land and increased withdrawal of water. These options are becoming increasingly difficult to sustain in the light of the heightened competition for water from other sectors as well as pressures to meet other demands for ecological and environmental purposes. Current impending water shortages are a fact of life in many parts of the world especially in SSA where the situation is further escalated by population pressures and degradation of the arable land. Improving the productivity of both land and water resources through the adoption of innovative techniques such as rain water harvesting, precision irrigation, and better integrated management practices are now an accepted way forward in meeting the challenge of growing more food with less water. The sustainability of these innovations has been receiving growing attention in recent years, and especially so in Kenya and Tanzania, with more emphasis on participatory identification and adaptation of techniques. Water use innovation in these regions is a prerequisite for upgrading rain-fed production systems. If water flows to crops or livestock can be better secured, then incentives for other system dependent improvements can also increase.

Research has shown that water system innovations (WSIs) are still predominately found as small islands of success within isolated development projects in the dry areas of SSA (Rockström et al., 2004), and the upper Ewaso Ng'iro North Basin in Kenya and the Pangani Basin in Tanzania are no exception. Further, there is very little known about the actual reasons why these innovations or the preconditions, which are needed to enable adoption, are not adopted at a larger scale (Reij, 2001; Rockström et al., 2004). In addition, nothing is known about the consequences for downstream water dependent ecosystems and human societies, if WSIs are successfully adopted at a basin scale. This research study attempted to address these issues within the two case study basins (Upper Ewaso Ng'iro North and Pangani).

There is already a rich knowledge base on promising innovations in water management for rain-fed agriculture in these basins, including a broad spectrum of water harvesting practices, conservation farming systems, and water conservation techniques, all of which aim to improve rainfall productivity and reduce the risk of crop failure due to poor rainfall distribution. This knowledge served as valuable information input into this research.

Thus, this study was conducted with the aim to address some of the concerns about sustainable land and water productivity, by developing a mapping methodology that focuses on sustainable water resource planning and management. This was achieved by applying a simple water balance model in the two case study basins in which both biophysical and socio-economical variables were integrated into a GIS environment to identify suitable areas for WSIs.

1.1 The study areas

The study was conducted in both the Upper Ewaso Ng'iro River Basin in Kenya (Figure 2.1B) and the Pangani River Basin in Tanzania (Figure 2.9A). Various WSIs practised in the two basins were analysed and compared in order to gain more insight in location specific knowledge on water resource management issues.

1.1.1 The Upper Ewaso Ng'iro North Basin

The Ewaso Ng'iro North Basin is the largest of the five major drainage basins making up the Kenyan drainage network, and covers 210,226 km^2, thus representing about 37% of the total area and contributing only about 7% of the total annual river flow discharge, making it a chronically water scarce basin. The Upper Ewaso Ng'iro North Basin constitutes the upper stream section of the drainage area, covering 15,251 km^2, and is situated between the latitudes 0^{0}20'S and 1^{0}01'N, and the longitudes 36^{0}10'E and 38^{0}00'E as defined by the natural topographic divide. The Upper Ewaso Ng'iro North basin drains from the Rift Valley escarpment to the west, the Nyandarua ranges to the north-west, Mt. Kenya to the south, the Nyambene hills in the east, and the Mathews ranges to the north, while the downstream outlet is at Archers Post (Figure 1). This study was conducted in this basin with a notion of replicating the results obtained in other similar areas, not only in Kenya but also within the SSA region in general.

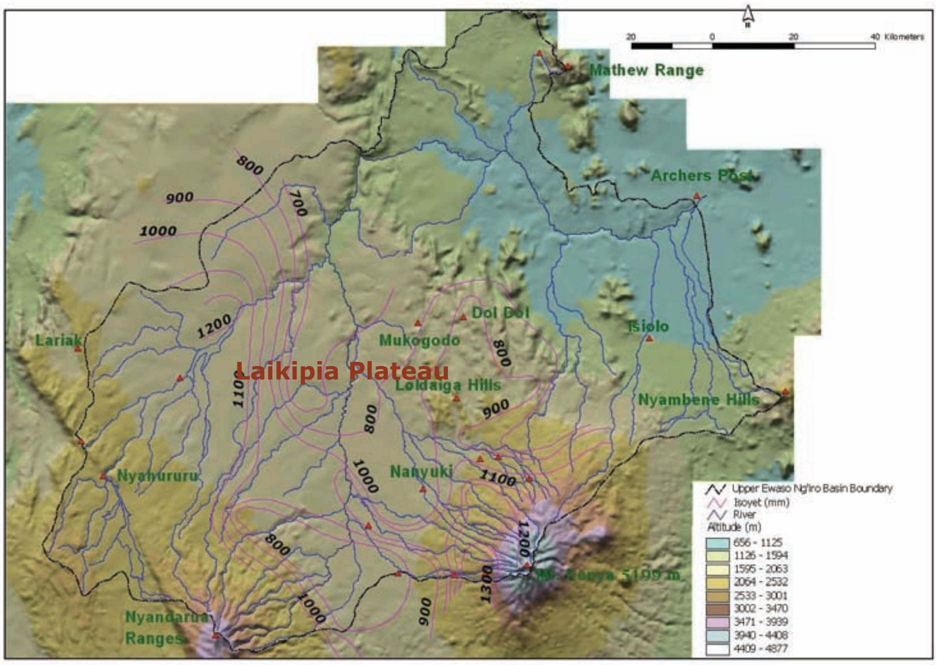

Figure 1: Topographic variation in the Upper Ewaso Ng'iro North Basin in Kenya.

A substantial portion of the basin is covered with unimproved grassland, although the major land use is agriculture (Figure 5.3). Large tracts of land are owned by a relatively small number of commercial farmers with average farm sizes greater than 700 hectares, frequently with access to river water for supplementary irrigation. In the rural areas, rainfed subsistence agriculture and pastoralism form the dominant land uses since few of the rural communities have access to irrigation water.

Although the main Ewaso Ng'iro River originates in the Nyandarua ranges, most of the flow (50%) comes from the tributaries draining the Mt. Kenya sub-basin (Jaetzold and Schidt, 1983; Decurtins, 1992). Whereas the surface runoff from the Ewaso Ng'iro River disappears into the Lorian swamp in Kenya, subsurface flows continue eastwards to recharge rivers inside Somalia and eventually drain into the Indian Ocean. The topography is dominated by Mt. Kenya and the

Nyandarua ranges in the south and the Nyambene hills to the east of the basin (Decurtins, 1992) as shown in Figure 1. Altitude ranges between 862 m above mean sea level (a.s.l.) at Archer's Post to 5,200 m a.s.l. at the Mt. Kenya summit (Jaetzold and Schidt, 1983).

The mountain slopes consist of deeply incised V-shaped valleys where elevation varies from 2,500 to 4,000 m a.s.l.. The gentle undulating Laikipia Plateau with an elevation of 1,700 to 1,800 m a.s.l. occupies most of the central region of the basin (Figure 1). The large elevation differences in the basin give rise to various climatic zones, ranging from humid to arid. The annual rainfall pattern shows spatial and temporal variations from 300 mm in the north eastern areas of the basin to 1500 mm in the Nyandarua ranges with a mean annual rainfall of about 700 mm (Berger, 1989; Decurtins, 1992; Sturm, 2001; Liniger et al., 2005).

1.1.2 The Pangani River Basin

The Pangani River Basin is located in the north-eastern part of Tanzania between the latitudes $3^{o}05'$S and $6^{o}06'$S and the longitudes $36^{o}45'$E and $39^{o}36'$E. The river has its sources at the slopes of Mount Kilimanjaro and Mount Meru. Except for a small part of the catchment, which lies in Kenya, the major part of the basin is located in the Kilimanjaro, Arusha and Tanga regions in Tanzania. The total area of the basin is estimated to be 42,200 km^2 (PBWO, 2006).

The highest rainfall (1,000 – 2,000 mm/year) occurs on the south-eastern slopes of Mount Kilimanjaro and Meru. Southwards, rainfall reduces to 500 – 600 mm/year in the semi-arid areas of the central portion of the basin, where this study was conducted (Western Pare Lowlands - WPLL). This area experiences rains characterized by an unreliable and varying distribution pattern with evapotranspiration rates far exceeding rainfall for most of the year (URT, 2002 & 2004).

The WPLL covers an area of 5,152 km^2 and has a total population of about 9,700 people who are predominantly agro-pastoralists. However, crop production in the area is not feasible without some form of supplementary irrigation, either from runoff harvesting or diversion of river flows (Rockström et al., 2004). The study was however conducted in the Makanya Catchment (located in the upper reaches of WPLL), to facilitate a detailed characterization of both bio-physical and socio-economic determinants for water system innovations in the area. The Makanya Catchment covers an area of about 320 km^2 with a vegetation composition varying from east to west and in relation to altitude (Figure 2.10).

Water in this catchment has been identified as the key factor and a challenging resource for upstream and downstream users, which has changed from being an ample and reliable common pool resource to a scarce and unreliable one. This is mainly due to population growth and land degradation, especially in the upstream area.

For over 50 years, farmers in the Makanya Catchment have been using various water system innovations (WSIs), especially rainwater harvesting technologies (Figure 2.11B). This is because of the low rainfall amounts the watershed receives. However, some of these technologies have not yet been used in certain parts of the catchment and introducing such technologies there could help solve some of the water-related problems currently being experienced in the area. For example, sand dams can slow down the runoff which usually causes soil erosion and floods in downstream areas. Applying an appropriate methodology could facilitate identifying suitable areas to introduce these technologies.

Different types of water system innovations that have been in use in this catchment include runoff diversion, storage reservoirs (locally called ndivas), charco-dams (locally called lambos) and tie-ridges. In the upstream area, which is at an altitude of about 1,800 m a.s.l., farmers mainly use ndivas to divert water from a natural water source (mostly overnight) to distribute it during the day for supplementary irrigation. The number of ndivas in the area has increased due to population growth as well as the increased awareness of their importance in improving yields. Lambos on the other hand, are mainly used in the lowlands as water storage for livestock. The actual extent of the impact of increased withdrawal of water upstream on downstream areas is not known, making it necessary to carry out a comprehensive assessment.

1.2 Problem statement

In many countries of SSA such as Kenya and Tanzania, the growth of the agricultural sector has been reported to be low over the past decade, despite the fact that this sector is recognized as a priority poverty reduction sector. Low availability of soil moisture for crops has been identified as one of the main causes. This is a result of poor management and ineffective utilization of rainwater, especially in the semi-arid areas that cover more than 50% of the country (SWMRG, 2001). Over 70% of the total area covered by both the Upper Ewaso Ngi'iro North Basin in Kenya and the Pangani River Basin in Tanzania is classified as semi-arid. Studies carried out in the dry areas of SSA with similar bio-physical characteristics as Ewaso Ng'iro and Pangani have shown that only a small fraction of rainwater reaches and remains in the root zone long enough to be useful to the crops. Furthermore, it is estimated that in many farming systems in these regions, more than 70% of the rain falling directly on a crop-field is lost through non-productive evaporation or flows into sinks before it can be used by plants. In extreme cases, only 4 - 9 % of rainwater is used for crop transpiration (Rockstrom et al., 1998). Efforts should therefore be made to promote optimal utilization of available rainwater by adopting appropriate water system innovations such as rainwater harvesting (RWH) in order to alleviate water scarcity crises and improve rural livelihood not only in the two basins but in the SSA region in general.

Agriculture is the main economic activity for Kenya and Tanzania, and as such it is seen as the backbone for their economic development in the future. However, the agricultural productivity is generally low (1 ton/ha) which is equivalent to a poverty threshold of US$ 1 per day. This situation is aggravated by a water scarcity situation, which lies below the per capita water security threshold of 1,000 m^3/year. Nevertheless, although the situation appears to be desperate, RWH interventions could serve as a remedy. RWH has shown promising potential in upgrading rain-fed agriculture, since it improves water availability for crop production (Fox and Rockström, 2000).

In Kenya, for example, the government has instigated the Economic Recovery Strategy (Republic of Kenya, 2003), which promotes initiatives facilitating the achievement of the millennium development goals (MDGs). The strategy recognises water as a pivotal element in poverty reduction/alleviation and emphasizes the importance of providing safe drinking water to the rural-resource poor while at the same time ensuring adequate water for other competing demands such as agriculture. However, Kenya as a country does not have sufficient water to drive her economic development. This means that the management of water resources in the face of this scarcity has been very poor and has resulted in chronic water shortages affecting most parts of the country like the Upper Ewaso Ng'iro North Basin, and thus affecting agriculture and tourism (the main drivers of economy) in the basin. With this in mind, an attempt was made to explore various ways to increase the amount of water available for productive use, such as RWH. This could be achieved through formulation of effective and sustainable integrated water resource management strategies at a river basin scale. The outcomes from this study could be applied to other similar areas within SSA in general.

1.3 Research goal

This research envisages contributing to the knowledge base required for developing and formulating sustainable water and land resource management strategies in water scarce river basins (Upper Ewaso Ng'iro North in Kenya and Pangani River in Tanzania) with the aim to enhance water productivity and improve food security within the semi-arid lands of SSA. This might thus also contribute to the on-going global dialogue on water for food and environment to meet the already stipulated MDGs.

1.4 Research objectives

To achieve the above stated goal, the following specific objectives were investigated:

- Determine both bio-physical and socio-economic factors that influence the suitability of various WSIs;
- Identify/ determine and rank potential and suitable sites for WSIs at watershed scale;
- Develop and evaluate a suitable DSS for selecting suitable sites for WSIs;
- Evaluate the impact of land cover/use changes in the upstream part of the basin on downstream water users;
- Recommend suitable water management strategies that would improve water resources in the basin.

In addition to the above formulated objectives, the following questions formed the basis of this research:

- What is the current water situation in the two basins?
- What are the main bio-physical and socio-economic factors that influence the suitability of various WSIs necessary for upgrading rainfed agriculture?
- What is the most efficient methodology for evaluating 'suitable areas' for different WSIs considering that relevant data at appropriate scale are not readily available?
- What are the hydrological and socio-economic consequences of upscaling suitable WSIs in smallholder rainfed agriculture at watershed scale?

1.5 Methodology

In order to answer the above formulated questions, various approaches were employed ranging from simple statistical analysis (comparison of data from different sources) to decision support systems (a spatial multi-criteria evaluation tool for identifying suitable areas for rainwater harvesting), and hydrological modeling (a water evaluation and planning tool for equitable water allocation and a Soil and Water Assessment tool for evaluating the impacts of upscaling rainwater harvesting). To facilitate the effective running of these approaches, both in-situ (climate, discharge, socio-economic) and remote sensed (MSG-2, TRMM, MODIS, LSA SAF, Landsat ETM+) data sets were used. In addition, the collected in-situ data were used to validate the results obtained from both remote sensing applications (rainfall, evapotranspiration, surface albedo, surface temperature estimates) and hydrological models (runoff simulations). Figures 2.9, 5.2 & 8.1 show the location of various meteorological stations, while Figures 6.1 & 8.1 show the location of various discharge stations in the two study areas.

1.6 Justification of the study

Rain-fed agriculture remains the major food provider for the majority of farmers in the foreseeable future in SSA (Fox et al., 2003). The immense challenge of increasing food production in SSA countries in order to keep pace with the ever growing population and diminishing water resources, as in the upper Ewao Ng'iro in Kenya and Panagani in Tanzania, therefore requires focus on water productivity in both rain-fed and irrigated agriculture through integrated soil and water management. Methodological innovations in water management such as precision irrigation and rainwater harvesting need to be identified. Improving water resource management could make a significant contribution to achieving most of the MDGs, particularly those dealing with poverty, hunger and disease (Rockström and Falkenmark, 2003).

Water productivity in rainfed agriculture will need to increase dramatically over the next generation if food demands are to be met (Rockström et al., 2002). However, water resource planning for agriculture has largely neglected rainfed agriculture. Irrigation in SSA countries in general has been tried, but only a limited amount of effort has been directed to up-grading rainfed agriculture through improved water use effectiveness (Rockström et al., 2004).

In order to meet the ever increasing food demands, irrigated agriculture will have to expand. However, this could be in conflict with the increasing demand for water for domestic and industrial purposes, especially in water scarce regions (Tesfaye and Walker, 2004) such as the Upper Ewaso Ng'iro North and Pangani River Basins. In this respect, RWH could play a major role in the sustenance of rural livelihoods by reducing food insecurity. Research on the performance of already existing rainwater harvesting and management systems in Kenya shows that most RWH storage systems such as farm ponds perform poorly due to high water losses (30 – 50%) mainly through seepage and evaporation, especially in systems found on sandy soils where harvested water is lost immediately after the rains (Ngigi et al., 2006). The poor performance of these systems has led to low adoption rates and abandonment of these systems by farmers. This research intended to develop a methodological framework that would facilitate identification of suitable areas for implementation of appropriate innovative systems, geared towards upgrading rainfed agriculture.

1.7 Outline of the thesis

This thesis is presented as nine chapters, each contributing to the knowledge base required to formulate sustainable water and land resources management strategies for water scarce river basins (such as the Upper Ewaso Ng'iro NorthBasin in Kenya and the Pangani River Basin in Tanzania) in SSA. The aim of such strategies is to enhance water productivity and improve food security, particularly in the semi-arid lands of these regions, and thus contribute to the on-going global dialogue on water for food and environment to meet the already stipulated MDGs.

Chapter 1 presents a general introduction to the major challenges faced when dealing with water scarcity, a threat to food security particularly in the dry areas of SSA such as the Upper Ewaso Ng'iro North Basin in Kenya and the Pangani River Basin in Tanzania. The chapter provides an overview of the problem statement, objectives, research questions, and methodological approaches applied.

Chapter 2 gives a comparative overview of the water situation in two case study basins. For detailed analysis and based on data availability, two catchments (Mt. Kenya and Makanya) representing the Upper Ewaso Ng'iro North and the Pangani River basins, respectively, were selected. Various sources of water in the two catchments are explored to determine how the current supply is spatially distributed, in an attempt to identify areas of shortage, causes of shortage, user conflicts and existing strategies aiming to address them. This could then assist in formulating appropriate strategies to adress the various water-related challenges, not only in the study basins but also in similar areas in SSA.

Chapter 3 evaluates the degree of accuracy of some of the freely available products derived from remote sensing data, using in-situ data to ascertain their level of usability and suggest ways of improving them. For this study, LSA SAF products from EUMETcast archives (derived from MSG-2 satellites) were used as an example. The main reason for undertaking this study was because most countries in the SSA region are located in remote areas which are difficult to access and hence a problem for any field based compaigns including data collection. This situation renders these areas data scarce and therefore a major challenge for conducting sound scientific research. Remote sensing forms an alternative source of data for such areas. However, since the information derived from remote sensing applications is indirect, continuous validation of data aquired is necessary to improve their accuracy.

Chapter 4 demonstrates how remote sensing techniques can be used in a case study (remote Makanya catchment) to generate spatio-temporal rainfall data for ungauged river basins especially in SSA regions, which usually have poor ground monitoring stations. The potential of this novel technology, which is not yet fully exploited in these regions, is clearly demonstrated.

Chapter 5 attempts to quantify water use and availability both in space and time by applying remote sensing techniques. Actual evapotranspiration, which is a good indicator of how water is being used, is first evaluted. Using the water balance concept, total water storage (availability) is calculated next. The availability is then linked to existing water harvesting storage facilities to investigate their relationship.

Chapter 6 explores the suitability of rainwater harvesting in the two water scarce basins for bridging dry spells that result from rainfall variability. This was achieved by adopting a spatial multi-criteria evaluation process (SMCE) as a decision support tool. The tool was developed for a data rich river basin and subsequently adopted in a data scarce basin.

Chapter 7 identifies a suitable framework in the form of a decision support system (DSS) for allocating the already recognised scarce water (Chapter 2) equitably to all main economic sectors in the basin. A water evaluation and planning (WEAP) model is adopted for the upper Ewaso Ng'iro Basin in Kenya. Various water management strategies are adopted and simulated (rainwater harvesting, improving irrigation efficiency, changing crops), all aimed at enhancing water productivity in the basin as well as in similar areas within SSA.

Chapter 8 looks at the impacts of agricultural intensification resulting from upscaling of suitable rainwater harvesting technologies (as identified in Chapter 6) on the hydrology of the area. A soil and water assessment tool (SWAT) model is used to evaluate these impacts, ultimately to assist in formulating suitable water management strategies for the basin.

Chapter 9 attempts to consolidate the major findings from all the chapters in order to gain a better understanding of how water productivity can be enhanced in order to improve food security in SSA. In this chapter, conclusions are drawn and recommendations made, which may assist in the formulation of sustainable water resource management strategies not only for the case study areas, but also SSA in general.

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CHAPTER 2

Water use situation in the Mt. Kenya and Makanya Catchments.

Abstract

The status of surface water resources which form the main water supply in both the Mt. Kenya and the Makanya catchments was assessed. The results reveal that water availability varied significantly both in space and time with critical water scarcity being experienced during the dry season. The reason for this is increased water use, mainly for irrigation by farmers supposedly earning higher returns for their investments. The study further revealed that with the population increasing, water scarcity will remain a major challenge unless remedial strategies are put in place. However, integrating rainwater harvesting (RWH) in agricultural and water policies and paying attention to the different needs may greatly improve the situation. The study therefore recommends that existing water users associations (WUAs) be strengthened by empowering the local community managing them, to execute their mandate of regulating water rights for different stakeholders in the basins.

Key words*:* *Water use conflicts, Rainwater Harvesting, Water users associations, Water use efficiency, water resources management.*

This chapter is based on:

Mutiga, J.K., Su, Z. and Woldai, T., (2010). Water use situation in the Mt. Kenya and Makanya Catchments. *(In Preparation).*

2.1 Introduction

Approximately 90% of the population within the arid and semi-arid zones of the world, of which the majority is found in Sub-Saharan Africa (SSA), depends entirely on rain-fed agriculture for their livelihood. Food security in most countries in SSA is threatened by increased water shortages particularly for crop production. Insufficient water availability is partly due to the little amounts of rainfall received to support crops through to maturity and partly due to inefficiency in directing the received rainfall towards crop production processes.

Research has shown that water-related problems in rainfed agriculture within the dry areas of SSA are often related to large spatial and temporal rainfall variability rather than low cumulative volumes of rainfall. The overall result of rainfall unpredictability is a high risk of meteorological droughts and intra-seasonal dry spells (Rockström et al., 2003). Bridging crop water deficits during dry spells through supplementary irrigation can stabilize production by increasing water productivity, if water is applied at the moisture-sensitive stages of plant growth.

Rockström, (2003) observed that the occurrence of dry spells (two in three years) and droughts (two in ten years), lower the chance of realizing good crop yields. However, adopting dryspell mitigation efforts such as rainwater harvesting, rainfed agriculture can be upgraded in these regions by doubling or even tripling the yields, for example by small scale, short-term protective irrigation based on rainwater harvesting, (Rockström and Falkenmark, 2000). This emphasizes the need to improve efficiency of use by capturing as much water as possible for use in crop production activities, especially at smallholder scale.

Since rainfed agriculture remains the major food provider for the majority of farmers in the foreseeable future in SSA (Fox et al., 2003), there is a need to focus on means of improving water productivity through integrated soil and water management. It is clear that water productivity in rainfed agriculture will need to increase dramatically over the next generation if the food demands are to be met (Rockström et al., 2002). However, water resources planning for agriculture has largely neglected rain-fed agriculture. For example, irrigation in SSA has been tried, but only a limited amount of effort has been directed to up-grading rainfed agriculture through improved water use effectiveness (Rockström et al., 2004).

Water has been widely recognised as the most limiting factor in crop production particularly in SSA. Nutrient levels and farm management practices, while also considered important, do not play as significant component as water in the whole cropping process. Currently, the amount of water received either as runoff or as direct rainfall, is not channeled effectively to green water processes resulting in unnecessary loss of water from catchment systems mainly through runoff and evaporation.

It is estimated that in many farming systems, more than 70% of the rain which falls directly on a crop field, is lost as non-productive evaporation or flows into sinks before it can be used by plants. In extreme cases, only 4 - 9 % of rainwater is used for crop transpiration (Rockström et al., 1998). Efforts should therefore be made to promote optimal utilization of available rainwater by adopting appropriate water related innovations in order to alleviate water scarcity and improve livelihoods in generally in the rural communities within SSA such as Kenya and Tanzania where most people live below poverty line. This could be achieved by increasing the capability of the rural poor to manage and sustainably use the available rainwater, in order to effectively deal with climate variability (Hatibu et al, 2006).

2.2 Study Areas

2.2.1 Mt. Kenya Catchment

Mt. Kenya catchment is the water tower of the upper Ewaso Ng'iro North Basin: its slopes, which receive higher rainfall amounts than the surrounding areas, are the origin of most of the perennial rivers which, in the dry season form the only source of surface freshwater in the semi-arid laikipia plateau to the north-west of the mountain, and the arid lowlands of the lower basin (Figure 1 and Table 2.1). Population growth, immigration, and the intensification of irrigated agriculture in its foot zone and along the rivers in the plateau, have dramatically raised water demand in the past decades. The direct impact of this development is the reduced water availability in the rivers due to increased water abstraction. Additionally, land use changes indirectly affect the water cycle by influencing the ratio between surface runoff and groundwater recharge. These two combined have caused the Ewaso Ng'iro and its tributaries to dry up during the dry seasons with increasing frequency. This has led to conflicts between upstream and downstream water users (Liniger et al., 1998a).

Water resources in the Mt. Kenya region are becoming increasingly scarce due to rising water demand for both irrigation and domestic use. Land use and climate change could also be posing additional challenges to water management in the future. Some of the water related problems in the area include water scarcity, high water variability both in space and time and inadequate access during times of low flows. The problems cited are the result of catchment degradation, over-dependency on river water, inefficient irrigation practices and increased human and animal population which in turn have resulted in increased water demand. Such water scarcity scenarios are common particularly during the dry season.

The upper Ewaso Ng'iro North river basin is divided into three main sub-basins, namely: the Ewaso Narok sub-basin, the Ewaso Ngiro-Mt. Kenya sub-basin and the Ewaso Ngiro lower sub-basin (Figure 2.1B). Of these, the Mount Kenya sub-basin however, provides most of the total flow during the long and short rains for the whole basin (Table 2.1).

Table 2.1: Ewaso Ng'iro sub-basins and their flow contribution in percent (%)

	Percent Contribution		
Period	Ewaso Narok sub-basin (5AC8) (3380 km^2)	Ewaso Ng'iro-Mt. Kenya sub-basin (5D5) (4640 km^2)	Ewaso Ngiro-Lowland catchment sub-basin (7180 km^2)
1951 (Wet year)	22	22	56
1952 (Dry year)	18	75	7
1960 (Average rainfall year)	11	67	22
April (Wet month)	11	40	49
September (dry month)	59	41	0
November (Wet month)	23	36	42
February (dry month)	28	69	3
Annual mean	30	46	24

Source: MoWD 1992 and NRM[3], 2000.

The main water resources for the Mt. Kenya sub-basin include rivers, springs, boreholes, and dams/pans. River water is estimated to provive the total population with about 90% of its water demand. Burguret River, one of the perennial rivers in this sub-basin and the main focus of this study, does not fully meet all its water demand, resulting in water scarcity related conflicts especially during the dry season (usually in February and March). As the demand for water increases, the potential for conflict over this resource also increases. River water resources in the area are currently under heavy pressure, due to increasing human and livestock populations as well as rapid horticultural development, which leads to increased water abstractions to meet the ever increasing irrigation water demand. Increased water abstractions in the upper reaches of the Burguret catchment (Figure 2.1D) particularly during the dry season have resulted in a decline in flow in the lower reaches.

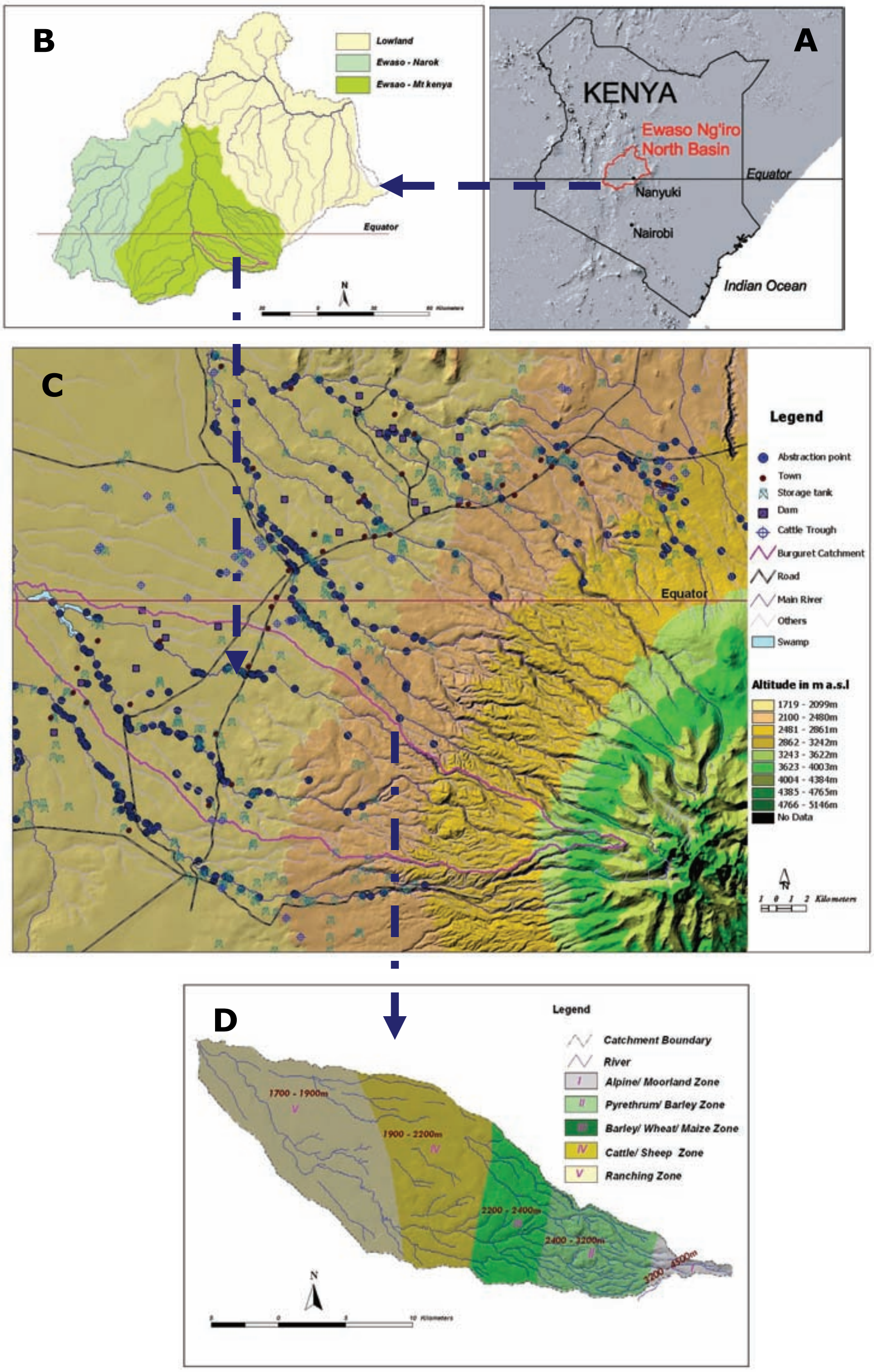

Figure 2.1: The extent of the Burguret Catchment in Mt. Kenya sub-basin context.

The highland areas are thus crucial to the sustainability of downstream flows, particularly during the dry season. It is of paramount importance that suitable water management strategies are put in place to solve the current water scarcity issues. These strategies should pursue efficient and sustainable use of available water as outlined in the new water Act, (2002), which is hinged on:-

- Rain water harvesting technologies,
- Promotion of better irrigation methods for efficient water use,
- Promotion of catchment conservation efforts.

To facilitate analysis Burguret cachtment, which is part of the Mt. Kenya sub-basin, was selected for detailed study of the water situation (Figure 2.1D).

2.2.2 Burguret Catchment

The Burguret catchment covers an area of 310 km^2, constituting about 2% of the total area of the Upper Ewaso Ngiro North Basin. The catchment has two main rivers (Burguret and Rongai) with Burguret River as the major river in the catchment (Figure 2.1D). This river, which originates in Mt. Kenya, (Figure 2.1C) experiences a cool wet climate and flows down to the Laikipia Plateau, which is characterized by a semi-arid type of climate.

The altitude of the catchment ranges from 4,200 m a.s.l in the upper parts of the catchment to 1,800 m a.s.l at the outlet where it joins with Ewaso Ngiro (Figure 2.1C). The slope ranges from 17% to 3% with the steeper slopes occurring on the higher reaches of Mt. Kenya. The upper part of the catchment is consists of natural and plantation forests, while the lower part is inhabited by small-scale farmers and ranchers. Farming in the catchment is mainly rain-fed, small scale and commercial irrigation.

2.2.2.1 Climate

Burguret catchment is characterized by a rapid highland to lowland climatic change. Climatic variations are mainly determined by altitude and aspect, due to its proximity to Mt. Kenya (Figure 2.1C). Its location on the leeward side of Mount Kenya contributes to the lower amounts of rainfall received in comparison with the windward side of the mountain.

The climate of the region is a result of the interactions between atmospheric circulation and topography. Its yearly fluctuations are mainly dominated by the position of the Inter-Tropical Convergence Zone (ITCZ), which is generally the zone on the meteorological equator receiving the highest amount of radiation, causing high-reaching convection. When the rising air cools at higher altitudes due to pressure reduction, its relative humidity rises, and rain clouds form.

Generally, the climate in the area can be characterized as semi-arid in the savannah zone, with between 600 and 750 mm rainfall per year and semi-humid to humid in the forest and moorland zones with about 1,600 mm/year. The rainfall pattern is bimodal, as shown by the two distinct rainy seasons. Potential evaporation is high, reaching between 1,700 – 2,000 mm/year on the semi arid zone, and decreases with increasing altitude (Mutiga et al., 2010). The onset of the rainy season is unreliable, and its duration varies. Sometimes, dry spells occur during rainy season, in addition to high inter-annual rainfall variability, thus limiting crop production.

There are two rainy seasons a year in the catchment. The long rains last from around March to June, and the short rains from September to December. Rainfall varies considerably from year to year in duration and intensity. Average annual precipitation climbs from 600 - 700 mm/year in the savannah to 1,600 mm in the upper forest and lower moorland zone and drops back to 800 mm in the summit region (Sturm, 2002; Gichuki et al., 1998b). Potential evapotranspiration drops from around 1,700 mm/year in the savannah zone to less than 500 mm in the summit region, which means, all areas below the forest zone experience a rainfall-evaporation deficit. The forest and moorland zones are thus the areas sustaining most of the discharge of the rivers during the dry periods (Decurtins, 1992).

2.2.2.2 Soils

The distribution of soil types in the area follows the ecological zonation. The dominant soil types include shallow and poorly developed soils on the mountain slopes, well developed soils on the plateau and gentle slopes and poorly drained soils in the river valleys (Mungai et al., 2004). In the alpine zone only lithosols and regosols are found. These soils are poorly drained, with a thickness of 10 cm (USDA SCS, 1985). In the moorland zone rankers occur next to lithosols and regosols with average thickness of about 25 cm and poor drainage, while the upper forest zone and the bamboo belt, are characterised by moderately well to well drained humic andosols with a thickness of about 80 cm on the slopes, and poorly drained humic gleysols on the valley bottoms. In the lower forest zone, the deep and well drained humic acrisols with about 150 cm are dominant.

In the foot zone, moderately drained ferric luvisols are dominant on the slopes and undulating plateaus, while gleysols are found in the valley bottoms. On average, these soils are about 150 cm deep. Their drainage properties range from imperfectly to moderately drained. In the savannah zone imperfectly to poorly drained Phaeozems and Vertisols which tend to form crusts are dominant, with a thickness of 150 to 180 cm (Decurtins, 1992).

2.2.2.3 Agro-ecological zones

The catchment crosses five ecological zones from the peak to the plateau, with an ecological gradient extending from the Alpine slopes of Mt. Kenya to the semi-arid plains of the laikipia plateau (Figure 2.1D). They are: the afro-alpine zone (above 4,000 m a.s.l.), the moorland zone (3,200 – 4,000 m), the forest zone (2,300 – 3,200 m), the foot zone (2,000 – 2,300 m) and the savannah zone (below 2,000 m). Climatic conditions cause a clear altitudinal zonation of vegetation with land use influenced by orientation.

2.2.2.4 Land cover/use

Land use in the catchment varies from forest reserve on the upper mountain slopes to large and small scale farming on the lower mountain and foot slopes to public and private ranches on the dry lowlands. The most significant change that has taken place in the basin in the past 30 years is the conversion of grazing land, bush land and natural forests into small-scale crop lands (Figure 2.2), resulting in resource use conflicts. These human-induced land use changes are taking place with limited soil and water conservation measures leading to soil and water degradation.

The changes in land cover/use have been most rapid on the lower mountain and foot slopes, where large horticultural enterprises have been established. Commercial horticulture increased at a rate of 9% per year between 1991 to 2002 increasing demand for irrigation water (Schuler, 2004). Diminishing water availability constrains the horticultural farming activities in the area, thus jeopardizing future development of the agricultural sector.

Land use and management affect the partitioning of rainfall into runoff and infiltration and consequently influence the availability of soil water content, surface water and ground water resources. Socio-economic and land use dynamics coupled with inadequate planning and management policies have led to a broad range of problems related to natural resource use such as over-exploitation of the river water resource (Kiteme et al., 1998b). This has affected downstream populations, livestock, economics and ecological systems leading to a wide range of user conflicts in the area. This calls for careful management with negotiations involving all stakeholders, in order to solve conflicts and alleviate the growing water crisis in the area.

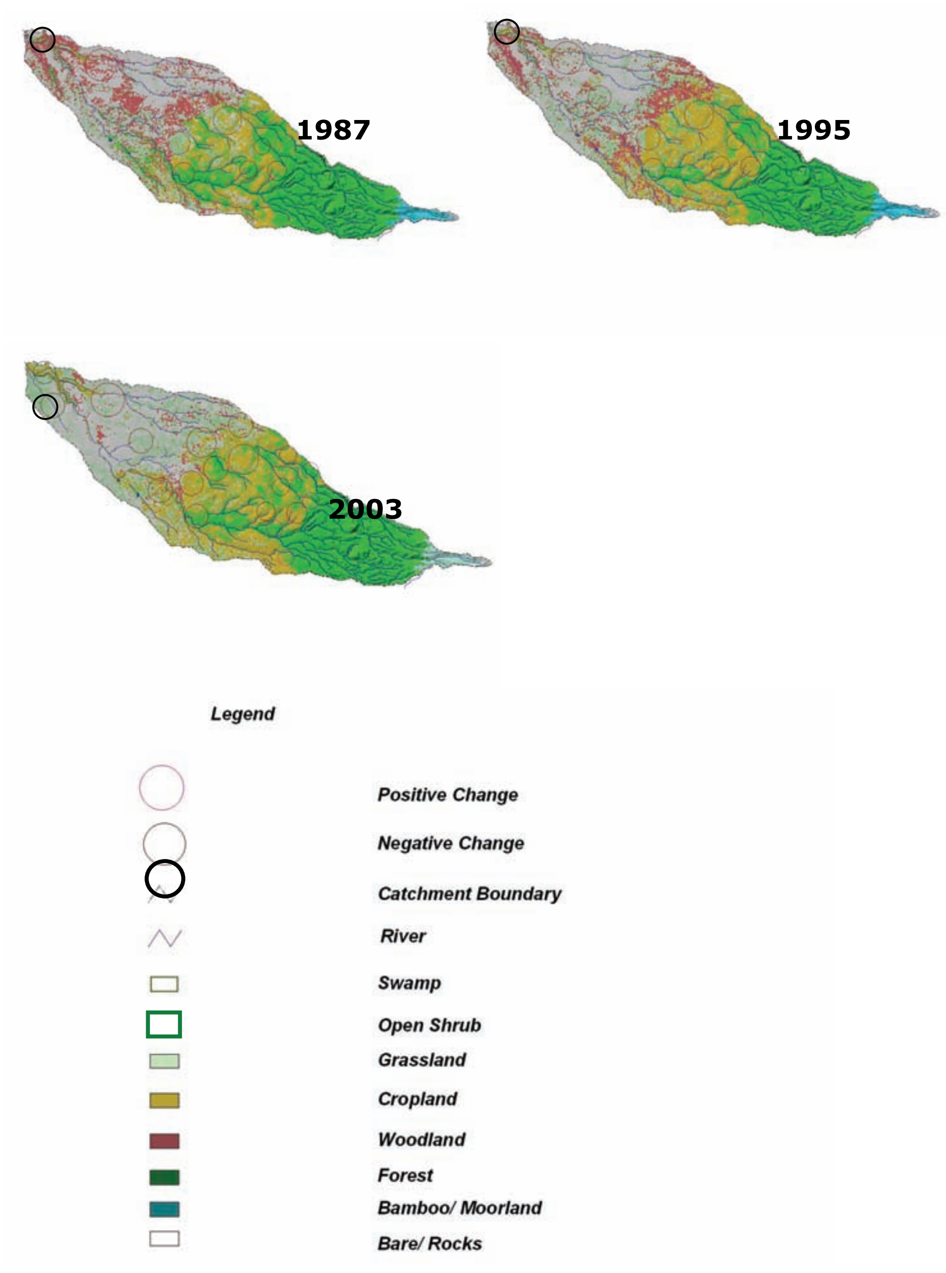

Figure 2.2: Land cover/use types in Burguret Catchment for 1987, 1995 and 2003.

Cultivation has traditionally been intensive in the foot zones, but results indicate that crop land has also been increasing significantly in the lowlands in the past decade. Expansion of agricultural land into the forested and wetland areas on the other hand, had significantly increaced by 2003 (Figure

2.2) mainly due to an increase in population in the catchment. These human activities have resulted in the degradation of natural vegetation, subsequently causing increased runoff generation and hence soil erosion.

Water has been identified as the major limiting factor to crop production in the area, in addition to the lack of appropriate knowledge on dry land farming techniques, resulting in frequent crop failures. Attempts to improve crop production in the area include experimenting with various irrigation methods (regardless of their efficency). This has resulted in an increase in irrigated area (14.9 km^2) causing a drastic increase in irrigation water demand (using about 80% of the total water available).

2.2.2.5 Surface Water Resources

The main source of water in the catchment is river discharges which is usually in excess during the rainy season but becomes limited during the dry season when the demand is the highest (60-80% of the available river water). This scenario is worsened by large scale, capital intensive farming, where large areas are irrigated to grow flowers and vegetables for European markets (Liniger et al., 1998b).

However, Burguret River, which originates from dense forests upstream of the catchment, provides a continuous flow throughout the year. Analysis of existing long term data nevertheless indicates a significant change in the overall annual flow rates over the past few years (Figure 2.3). This is as a result of increasing demand for irrigation within the riparian areas. It was observed that both the dry season (January, February and March) and the wet season (April, November, December), have been experiencing a decline in flow regime (Figures 2.4 & 2.5 respectively).

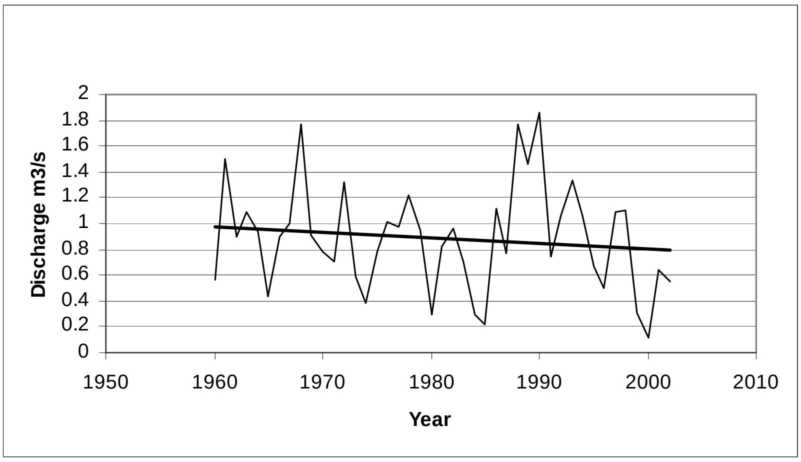

Figure 2.3: Mean annual flow in the Burguret River Catchment

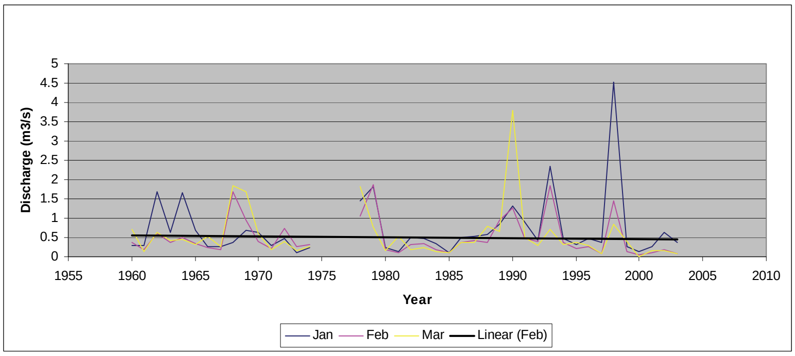

Figure 2.4: Mean monthly flows during the dry season.

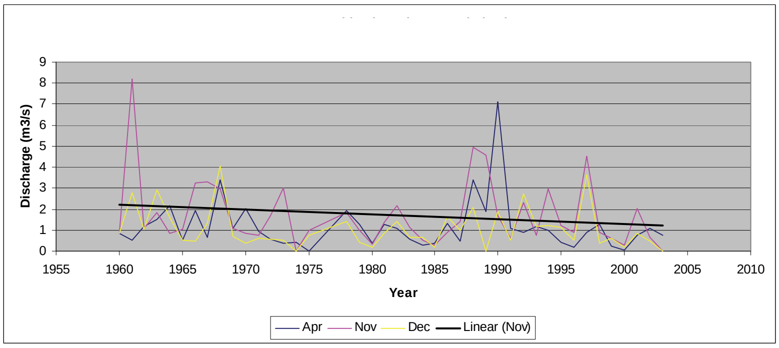

Figure 2.5: Mean monthly flows during the wet season.

Results further show that the degree of abstraction increases downstream in the catchment (Figure 2.6). This is attributed to the existing land use systems in the lowland areas. The upper parts are predominantly forested while the lower parts are smallholder parcels under subsistence cultivation (Figure 2.2).

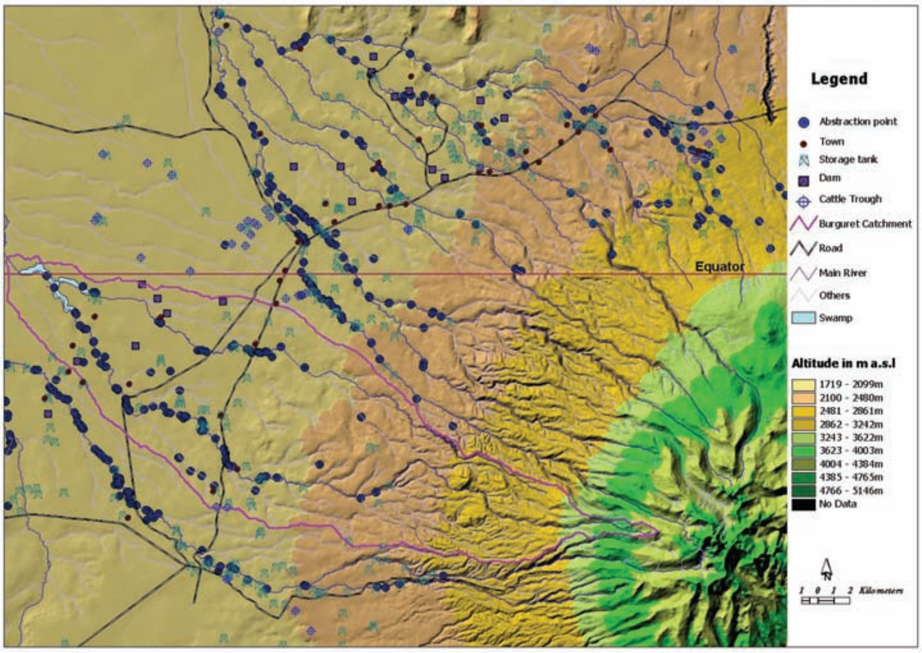

Figure 2.6: Spatial distribution of water abstraction points in the Burguret catchment in Mt. Kenya sub-catchment.

Currently, there are no valid water abstraction permits along the Burguret River, implying that all water users are operating 100% illegally. However, there is a record of permits that have expired but are still in use. This contradicts the Water Act (2002), which states that the use of any equipment extracting river water must be in compliance with a valid water permit specifying the amount of water to be used as well as the purpose and conditions or requirements for water use. The current status makes planning and management of the resource extremely difficult.

2.2.2.6 Water use conflict in the Burguret Catchment

Conflicts in water use in the catchment arise from a combination of factors:

- Insufficient water availability for both domestic use and irrigation, particularly during the dry season;
- Illegal water abstractions leading to scarcity;
- Inefficient use of the scarce water resources (e.g. Furrow irrigation);
- Inadequate enforcement of the water by-laws.

The underlying issue in all these is scarcity, and in order to maximize user benefits, efficient water resource management in the catchment is therefore crucial. In an attempt to address this issue of water scarcity with minimal user conflicts, communities have formed water users associations (WUAs) with the mandates to:

- Create and raise awareness of water situations in the catchment;
- Resolve water use related conflicts in the catchment;
- Regulate water use allocation, especially during the dry season;
- Ensure fair water sharing between upstream and downstream users that would enhance cooperation among different users;
- Promote water saving technologies through incentives for farmers using them (e.g. Drip irrigation, rainwater harvesting);
- Address issues related to the water pollution and catchment degradation;
- Promote other income generating activities (IGAs), creating diversification aimed at reducing over-exploitaion of river water particularly through small scale commercial irrigation.

2.2.2.7 Supplementing river water with RWH

Rainwater Harvesting (RWH), which is now commonly practised, is described as a range of methods for the collecting, storing and conserving of local surface runoff for use in agricultural production (Reij, 1996). Such runoff can either be diverted to the fields directly or be stored for use at a later date. In its broadest sense, RWH can be defined as the collecting of rainwater for productive use. The purpose is to increase the amount of available water in the soil, thereby enabling crops to be grown in areas with insufficient rainfall. RWH technologies have demonstrated improvement in residual moisture retention capacity.

The technologies can be classified either as micro-catchment or as macro-catchment depending on their operational scale: field or catchment/basin, respectively (Figure 2.7). Rainwater harvesting has recognized as a promising way to improve livelihood of many inhabitants of the vast dry regions of the world. It can be viable in areas with annual rainfall of as low as 300 mm/year (Kutch, 1982). The productivity of land and water in such areas may be greatly enhanced by RWH and supplemental irrigation. Even marginal lands with annual rainfall of less than 300 mm/year may be cultivated, if limited additional water is made available in controlled manner (Oweis, et al., 1999).

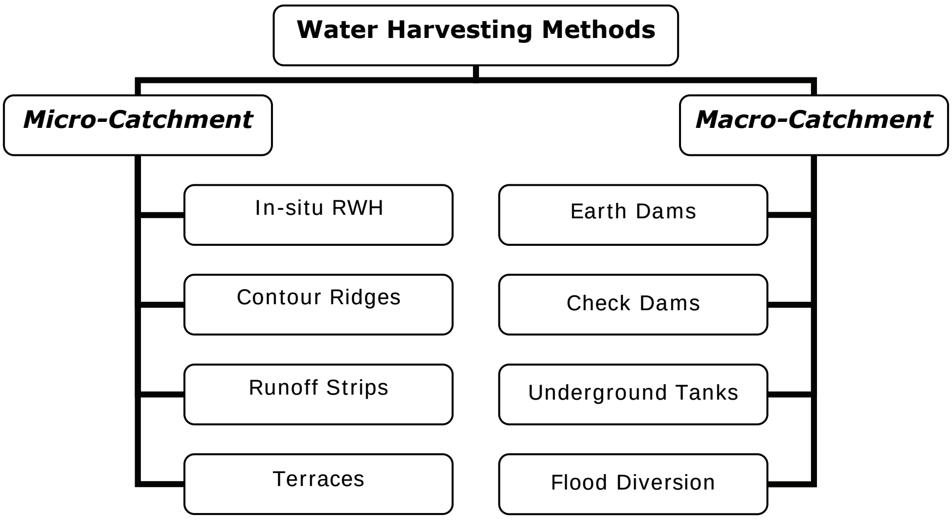

Figure 2.7: Existing RWH technologies practised in the Burgurent Catchment.

Runoff is mainly collected from the ground catchments but also from ephemeral streams (flood water harvesting) and road/footpath drainage. Storage can either be in different structures, such as tanks, reservoirs and water pans to be used mainly in supplemental irrigation systems, or in soil profile like in-situ systems. RWH may be considered a rudimentary form of irrigation (Fentaw et al., 2002). In regions where crops are entirely rain-fed, a reduction of 50% in seasonal rainfall, for example, may result in a total crop failure (Critchley and Siegert, 1991). However, if the available rain can be concentrated on a smaller area, reasonable yields could still be produced.

In areas characterised by variable rainfall, dry spells and frequent droughts appropriate rainwater management form the key to improving the livelihood of a large number of the world's poor, who depend mainly on rain-fed farming systems (Rockström, et al., 2006). Thus reducing vulnerability to water related risks and at the same time improving productivity can greatly reduce hunger and poverty in these areas.

More rainwater is made available to crops, when most needed to enhance crop yield, through storage for later use in either full or supplementary irrigation.

The technologies for tapping this resource have not yet reached the local farmers fully. Nevertheless, there are several RWH methods, which work well in this basin both in-field and external field catchment systems where runoff water is collected from hillsides, cropped areas and roadsides (Figure 2.8). The system used depends on the terrain in the area.

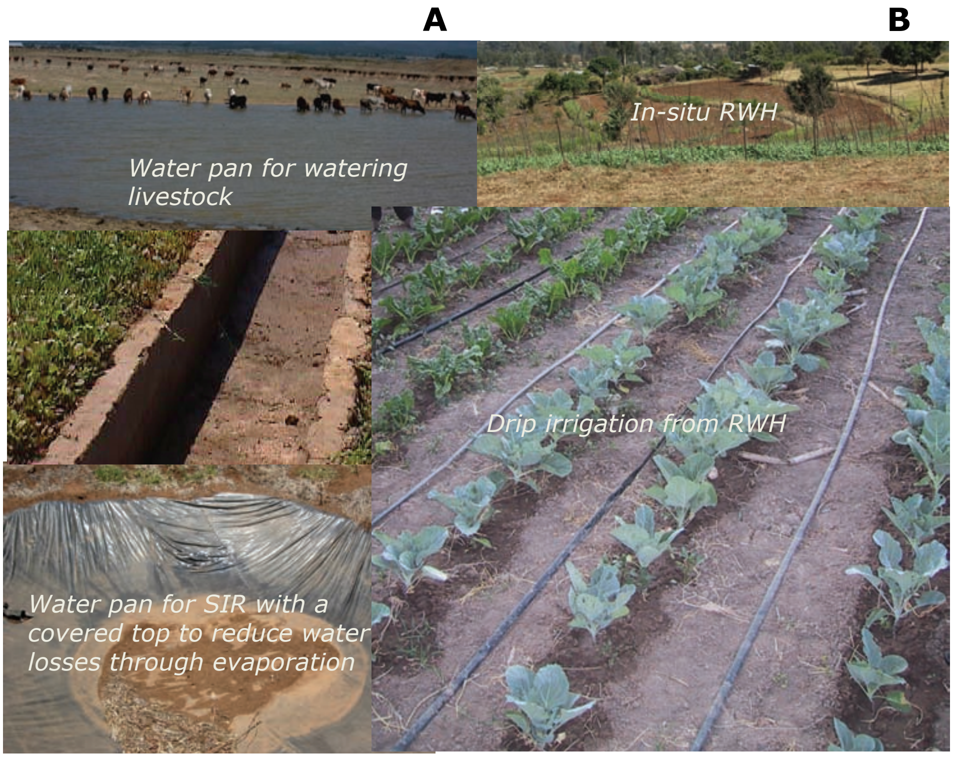

Figure 2.8: Examples of RWH technologies in the Burguret catchment

2.2.3 Makanya Catchment

Makanya Catchment which forms the upper reaches of the Pangani river basin is located in Same District, Kilimanjaro Region in northern Tanzania (Figure 2.9A). The Pare Mountains are located to the south east of Mt. Kilimanjaro, between 600 and 2,424 m a.s.l. The western side of the Pare Mountains has steep slopes, that abruptly join the plains that extends to the Pangani River. The catchment has low, erratic and unreliable rainfall with upstream receiving more rains. Water harvesting for agriculture is common especially during the dry season (November to January), locally known as "*Vuli*". Makanya lies between latitudes 4^{o}15' to 4^{o}21'S south and longitudes 37^{o}48' to 37^{o}53' east and lies in an altitude ranging from 600 to 2,500 m a.s.l (Figure 2.9B). The chatchment which is located in the western pare lowlands (WPLLs), has a semi-arid climate with two agro-ecological zones, the highlands and the lowlands.

2.2.3.1 Climate

Rainfall distribution in Makanya catchment is bimodal, occurring in November – January (short rains, locally called "*Vuli*") and in March – May (long rains, locally called "*Masika*"). Daily rainfall is characterised by high intensity events of short duration. The average annual rainfall ranges from 400 – 1000 mm/year depending on the altitudinal gradient and potential evapotranspiration of over 2,000 mm/year. Rainfall pattern divides the catchment into semi-arid lowland and sub-humid upland. Moving westwards away from the mountains, rainfall decreases while its variability increases. "Vuli" rains are highly unreliable and the seasonal amount exceeded 70% of the time is only 178 mm (Figure 2.10A). On the other hand, rainfall during "Masika" is higher and varies between 140 – 720 mm during the months of March and April (Figure 2.10B).

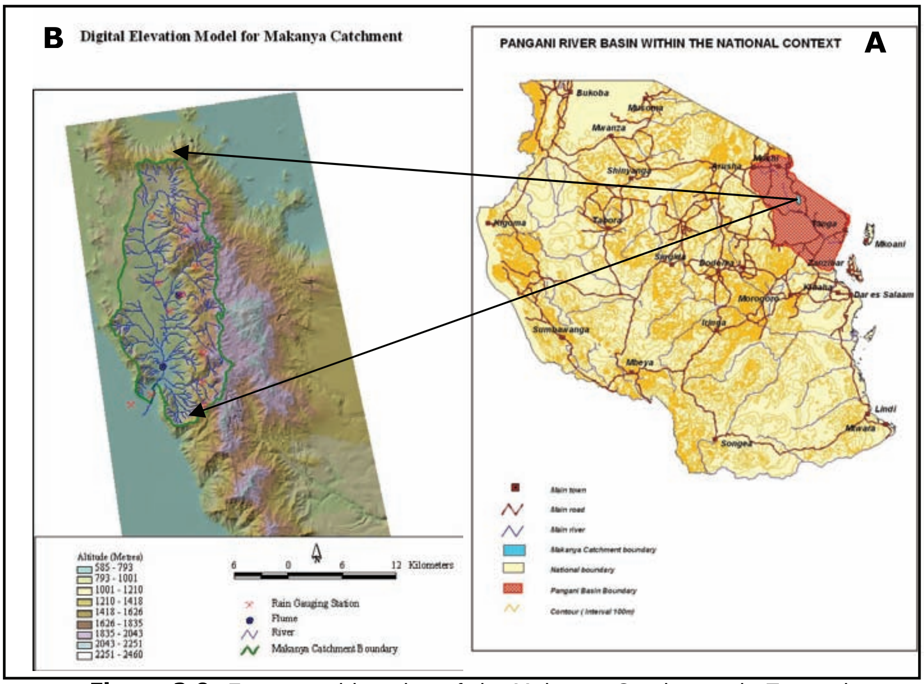

Figure 2.9: Extent and location of the Makanya Catchment in Tanzania.

Potential evaporation during "*Vuli*" varies between 1,120 to 1,610 mm while during "*masika*", it varies between 870 to 1,325 mm. The highlands form the source of numerous springs and streams, which flow down to the lowlands (Figure 2.9B). Most of these streams are perennial with low water yields which are mainly used for domestic and some for supplementary irrigation. However, some of these streams have dried up due to poor catchment management in the upstream areas.

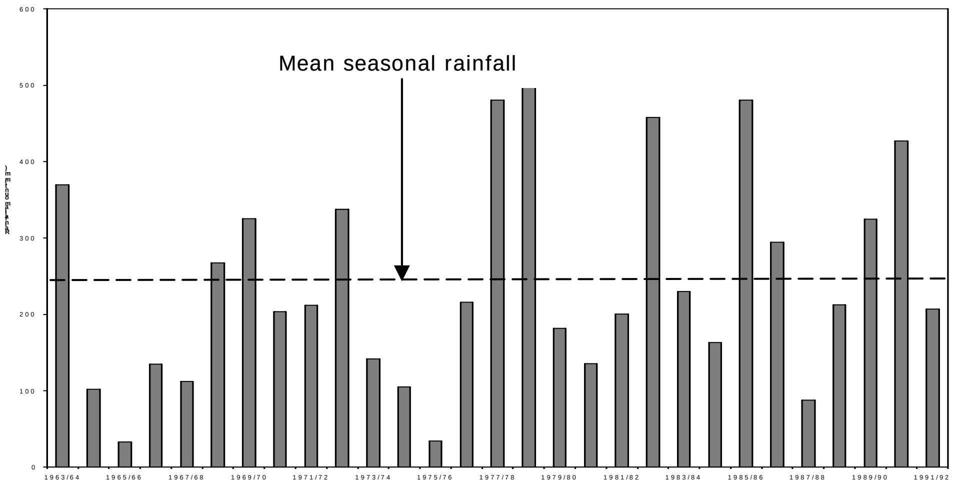

Figure 2.10A: Rainfall variation (1963 – 1992) in Makanya Catchment during the short rain season (*Vuli*). Source: District Meteorological Department, Same, Tanzania.

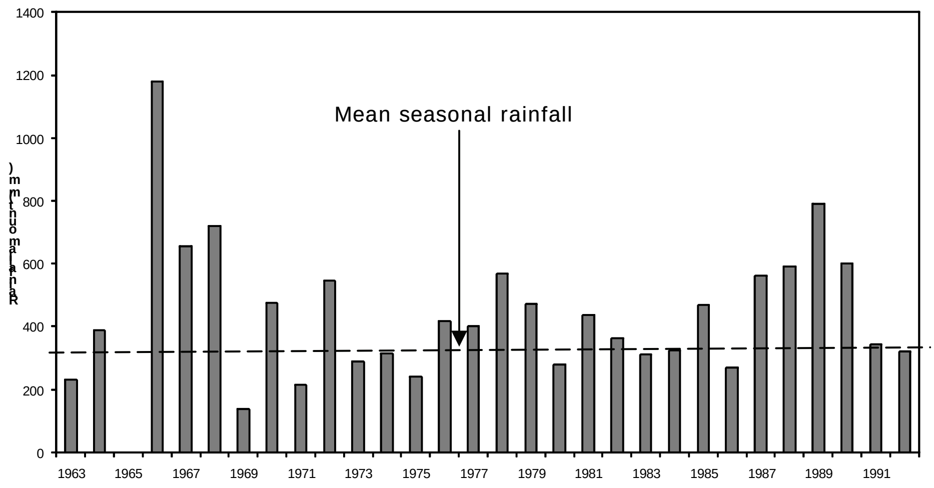

Figure 2.10B: Rainfall variation from (1963 – 1992) in Makanya Catchment for the long rain season (*Masika*). Source: District Meteorological Department, Same, Tanzania.

2.2.3.2 Soils

The soils in the Makanya catchment vary between sandy clay and loam. The highlands and midlands are generally characterised by shallow soils while soils in the lowlands compose of alluvium deposits with high moisture holding capcity. These deposits originate from soil erosion processes in the upstream catchment due to poor agricultural practices with little soil and water conservation measures thus rendering them to be nutrient rich.

2.2.3.3 Agricultural potential

The Makanya catchment has low, erratic and unreliable rainfall. This usually results in very low annual yields (1.5 to 2 tons/ha for maize). People in the catchment experiences water scarcity caused by increased population pressure on meagre water resources in turn resulting in increased land degradation. Water productivity in the area is low and the available water is insufficient for the command area. Effective rainfall is low due to high evaporation rates impacting negatively on crop production.

Generally, the area has an erratic rainfall regime particularly in terms of distribution with high probabilities of the occurrences of both seasonal droughts and intra-seasonal dry-spells. This situation impacts negatively to the performance of agriculture, which is the mainstay of people's livelihoods. However, over time, farmers have developed innovative mechanisms such as rainwater harvesting, to cope with this climate variability. Water has been identified as key and challenging resource between food and nature and also between upstream and downstream users in the catchment. The main cause of water scarcity in the catchment is population increase (increased water use demand) which has triggered rapid changes in land cover/use with the expansion of agriculture, (Figure 2.11). Results indicate that vast stretches of forest land have been cleared for agricultural use (52%) between 1987 and 2001. Even steep areas (45%) previously covered with forests are now being cultivated without terracing or other forms of protection from degradation (Enfors and Gordon, 2007).

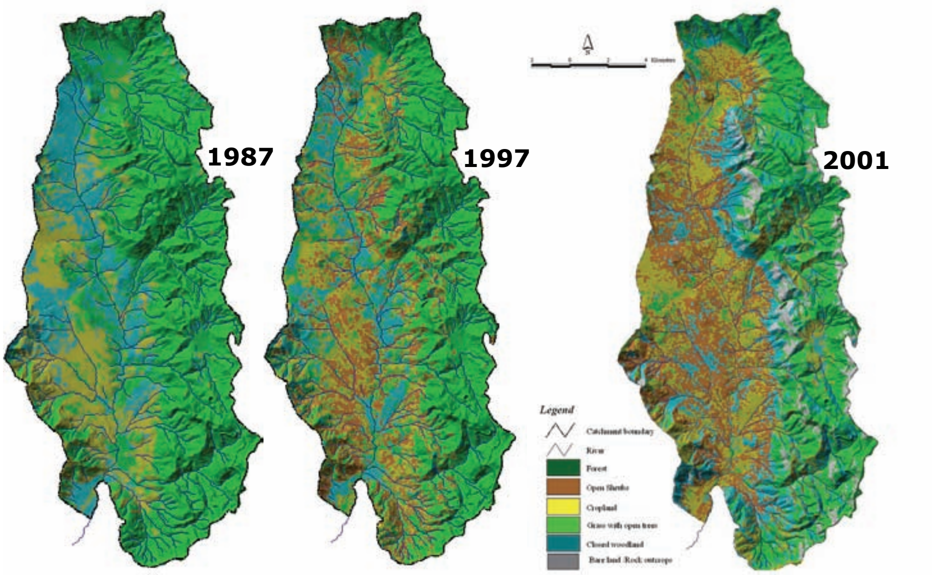

Figure 2.11: Land cover/use changes in the Makanya Catchment for 1987, 1997 and 2001.

Increase in agricultural land upstream has led to more water diversion from their natural pathways to croplands, thereby making less water available for the downstream users. This has led to the shrinkage of irrigated land in the downstream, causing food insecurity in these areas. Soil erosion emanating from the conversion of forests and woodlands to agriculture (Figure 2.11), has caused increased land degradation in the area.

The population in the Makanya catchment is estimated to be about 35,000 and is rapidly increasing with an estimated growth rate of 1.6% per annum (URT, 2004). About 90% of this population relies on rain-fed agriculture for their livelihoods thus exerting increased pressure on both land and water resources. The watershed exhibits a prominent adoption of rainwater harvesting innovations. Farmers in this watershed use different water systems innovations ranging from runoff diversions, storage reservoirs (*ndivas*), earth excavations (*lambos*), tie-ridges and terraces (Rockström et al., 2004). The number of "*ndivas"* has been on the increase due to increasing demand for water from population increase.

2.2.3.4 Supplementing surface water with RWH

Over the past five decades, water resources have shifted from being a reliable common pool resource to a scarce and unreliable in Makanya catchment. This is mainly due to a rapid population growth particularly in the highland areas which receive adequate rainfall amounts as compared to the lowland areas. This has led to reduced water availability especially in the lowland areas as a result of increased agricultural activities in the highlands. For this reason, RWH has been on the increase in the catchment with the aim to improve water productivity and hence yields. However, increased water diversions upstream have led to reduced water available in the downstream of the catchment. Farmers in this catchment use various types of water harvesting systems depending on their geographical locations within the catchment (Figure 2.12A).

For instance, RWH systems used in the upstream of the catchment are more related to soil and water conservation (micro-systems). This is because of hilly and steep slopes with altitudes ranging between 1,200 and 2,000 m a.s.l. For example, ditches are used to retain runoff water, enabling it to infiltrate into the soil, whereas deep tillage facilitate in-situ water capturing and infiltration (Figure 2.12B). Irrigation furrows are widely used in the area to convey water from streams or storage ponds locally called "*ndivas*" to the fields. "*Ndivas*'' have been identified as main water sharing systems between upstream and downstream users particularly during the dry spell. These

storage systems are usually filled with water during the night and distributed to the community members during the day for supplementary irrigation.
In middle slope areas, "*ndiva*", irrigation furrows, deep tillage and diversion canals are common. These are technologies that involve water abstraction, storage, distribution and enhance infiltration in the field. Middle slope areas receive less rainfall than the highlands hence making farmers more dependent on supplementary irrigation. Irrigation furrows are very important for distributing water to the fields, while diversion canals are used for diverting water from streams/rivers and conveying it into ''*ndivas*'' which are usually used as overnight water storage systems for irrigation during the day.

The lowlands, diversion canals, deep tillage and flood harvesting from rangelands are common. These areas receive as little as 400 mm of rainfall annually. Farming here depends mainly on flood water harvested from ephemeral streams and diverted to croplands or grazing areas. Diversion canals are also crucial in the other areas.

2.2.3.5 Water use conflicts

Water use conflicts in the catchment usually occur between upstream (farmers) and downstream (pastoralists) as a result of:

- Inadequate water supply for domestic use, livestock and irrigation particularly during the dry season;
- Depletion of resources particularly by the upstream users, for irrigation purposes during the dry season
- Inefficient use of scarce water available (e.g flood irrigation)
- Inadequate enforcement of water laws by the existing WUAs;
- Lack of water accounting framework to ensure equitable allocation of water

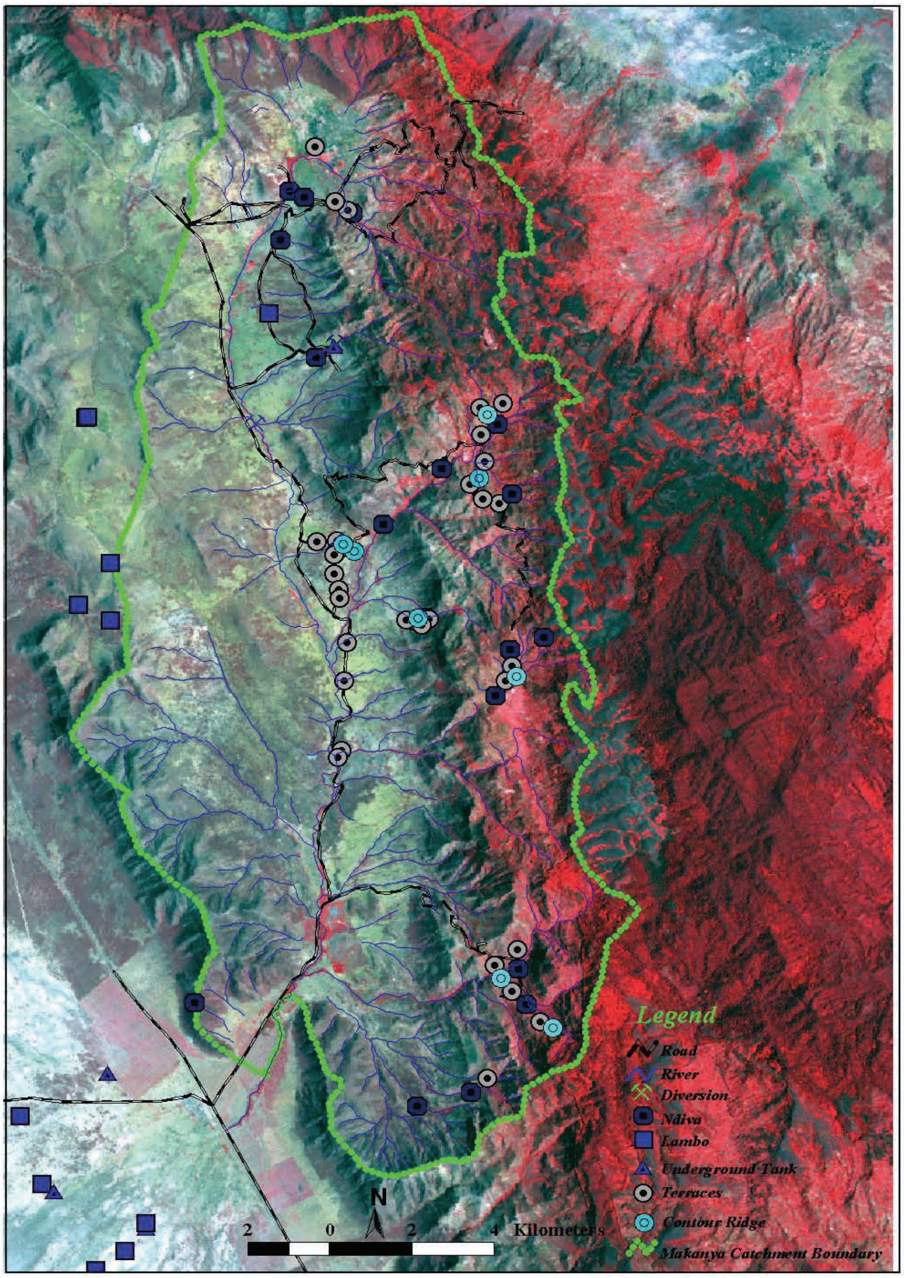

Figure 2.12A: Spatial distribution of existing RWH technologies in the Makanya catchment.

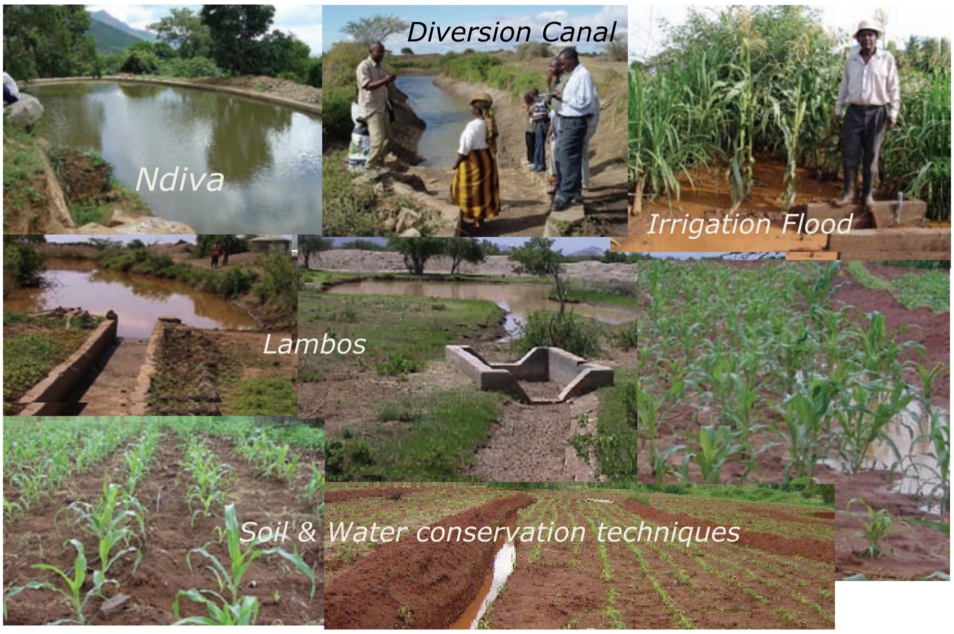

Figure 2.12B: Existing RWH technologies in the Makanya Catchment.

2.3 Conclusion

The results from this study indicate that surface water in the two catchments can only meet user demand during the rainy seasons. Critical shortages occur during the dry season, when a lot of water is mainly used for irrigation purposes. Sustainable use of the available water resource and better management of the natural water flow is therefore essential. Agricultural water management is seen as the key to food security and income generation for the rural poor in these areas. However, sustainable management of the available water resource can only be achieved with greater cooperation of communities and individual farmers. Water user conflicts in the catchments are mainly caused by the perceived unequal water allocation, where downstream farmers complain that upstream farmers use more water than their allocation, leaving very little or sometimes nothing to flow downstream.

The success of improving water management activities depends totally on the willingness and collaboration of the people as well as the political will to enforce the water laws. The study shows that many farmers perceive supplementary irrigation to be a solution to their water-related problems in the catchments and since the areas have a high potential for rainwater harvesting, it is considered possible. If harnessed and complemented with improved water saving technologies and nutrient management, RWH could significantly contribute to the enhancement of the livelihood of the communities in these catchments.

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CHAPTER 3

Validation of Satellite derived surface albedo and temperature for regional estimation of evapotranspiration in data scarce areas of Sub-saharan Africa

This chapter is based on:

Mutiga, J.K., Su, Z. and Woldai, T. and Maathius, B.H.P., (2010). Validation of satellite derived surface albedo and temperature for regional estimation of evapotranspiration in data scare areas of Sub-saharan Africa. Revised for re-submission in *Remote Sens. Lett*.

Abstract

The reflective and emissive characteristics of the earth's surface are mainly characterized by surface albedo and temperature. Albedo, which is highly variable in space and time over the land surface, controls the fraction of solar energy absorbed by the earth's surface significantly affecting its climate. Similarly, land use changes resulting from both natural and human activities can also modify radiative climate forcings on regional scales by changing surface albedo and hence the energy budget of the lower atmosphere. Surface albedo is thus a key variable for characterizing the energy balance in the coupled surface-atmosphere system and constitutes an indispensable input quantity for soil-vegetation-atmosphere transfer models.

On the other hand, land surface temperature (LST) also referred to as skin temperature is a key parameter in land surface processes since it reflects the energy and water exchange processes between land and the atmosphere such as evapotranspiration and desertification processes. Thus, LST, an indicator of land degradation and climate change, can be used for drought detection and impact assessment based on the estimation of indices of vegetation stress, especially those designed to monitor vegetation health and moisture conditions.

Therefore, for adequate representation of land surface processes and their interaction with the atmosphere, it is necessary to estimate accurately land surface albedo and temperature in time and space. In contributing toward this goal, ground based instruments (albedometer and thermal sensors) were set up in the upper Ewaso Ng'iro North basin in Kenya to monitor temporal variability of surface albedo and skin temperatures respectively. Data collected for the two variables from January to mid-February, 2009 at one minute interval was aggregated to daily and hourly averages for albedo and surface temperature respectively and then compared with satellite derived products for the same period. The results show that, there is a strong agreement (R^2 of 0.70 and 0.54; RMSE of 6 K and 0.005) between the remotely sensed and the in-situ measurements for surface temperature and albedo respectively. This shows the great potential that remote sensing technology has in providing valuable and timely information on spatial variations in flux partitioning and thus making it an indispensable means for monitoring vegetation conditions and ecosystem health over large land surfaces particularly in data scarce areas of Sub-saharan Africa.

Keywords: *Land surface albedo, land surface temperature, satellite products, validation, data scarce regions, evapotranspiration.*

3.1 Introduction

The reflective and emissive characteristics of the earth's surface are mainly characterized by surface albedo and temperature. Surface albedo quantifies the fraction of energy reflected by the surface of the earth and therefore significantly affects its climate (Kiehl et al., 1996; Pinty et al., 2000; Liang et al., 2002). As a corollary it then also determines the fraction of energy absorbed by the surface and transformed into heat or latent energy. Land surface albedo therefore is a key variable for characterizing the energy balance in the coupled surface-atmosphere system and constitutes an indispensable input quantity for soil-vegetation-atmosphere transfer models. Land surface temperature (LST) also referred to as skin temperature is a key parameter in the physics of land surface processes because it controls the energy and water exchange processes between land and the atmosphere such as evapotranspiration and desertification processes (Chehbouni, et al., 2001; Su, 2002; Peres and DaCamara, 2004; Kerr et al., 2004).

LST is a good indicator of land degradation and climate change, and may be used for drought detection and impact assessment based on the estimation of indices of vegetation stress, especially designed to monitor vegetation health, soil moisture and thermal conditions (Kogan, 2001). Moreover, most fluxes at the surface-atmosphere interface can only be parameterized through the use of LST. This is because the partitioning of sensible and latent heat fluxes and hence surface radiant temperature response is a function of varying surface soil water content and vegetation cover (Owen et al., 1998). However, land surface temperatures derived from remote sensing are not often used because accurate estimates are difficult to obtain (French et al., 2003). This is as a result of the high land surface heterogeneity, mainly due to vegetation, topography and soil physical properties in addition to uncertainty in instrumental calibration, surface emissivity, and atmospheric effects.

The retrieval of diurnal LST is usually estimated from clear-sky measurements in the thermal infrared window MSG/SEVIRI channels IR10.8 and IR12.0 using the generalized split window algorithm (Sobrino et al., 1994; Sobrino and Romaguera 2004). Usually, LST products are generated every 15 minutes on a pixel by pixel basis with satellite viewing angles below 57.5. On the other hand, surface albedo is generated from three short-wave channels (VIS 0.6µm, NIR 0.8 µm and SWIR 1.6 µm) as well as the visible, near infrared and total short-wave wavelength ranges by first correcting for atmospheric effects on cloud free images using a simplified radiative transfer model (Rahman and Dedieu, 1994).

Although the retrieval of these variables from satellite appears to be very attractive, indirect measurements often bring up the complex mathematical issues associated to the inverse problems (Rodgers, 2000). This is because, the radiance measured is affected by surface parameters, such as temperature and land surface emissivity (LSE) as well as the thermal structure and composition of the atmosphere (Govaerts et al., 2006). Accurate estimation of LST from space data therefore requires a proper characterization of the atmospheric influence (e.g., absorption and emission processes) as well as an adequate knowledge of LSE because natural surfaces do not act as blackbodies. A distinction between the effects of LST and LSE is not possible solely based on observations of the radiance emitted by the land surface.

Although the split window (SW) technique is simple and computationally efficient (Sobrino et al., 1994), it has the disadvantage in that, small uncertainties in LSE may lead to high errors in LST estimation and therefore, its application is constrained to areas where LSE is well known a priori (Gillespie et al., 1998). The benefit of the SW method is based upon the fact that the atmospheric absorption of the surface radiation varies strongly with wavelength, and so, atmospheric effects can be corrected by using data from two different spectral channels. Since the water vapor continuum absorption coefficients in the thermal infrared band are not well known, the coefficients from the split-window algorithm depend strongly on the transmission code used (Grant, 1990).

Adequate representation of land surface processes and their interaction with the atmosphere requires accurate estimation of land surface albedo and temperature at appropriate time and space scales. Remote sensing is the only practical means for generating these two variables on spatio-temporal scales using surface signatures in reflective (optical) and emissive (thermal infrared) bands. Moreover, the multiple acquisitions per day from the geostationary sensors have the advantage of enabling time series data to be acquired with options for studying diurnal daily, monthly, seasonal and annual patterns.

It is therefore of critical importance that the retrieved variables are validated using field measurements with an aim of improving the accuracy of predictive models. This would consequently enhance a good understanding of the processes governing the water and energy cycles across different spatial and temporal scales for a number of different disciplines including food security. For example, effective and sustainable agricultural production requires an advanced monitoring of agricultural processes and practices, which can be provided by means of remote sensing imagery acquired at high spectral, spatial and temporal resolution (Moran et al., 1994).

To contribute towards the validation efforts of the Satellite Application Facility on Land Surface Analysis (LSA SAF) products, we conducted a study to monitore the variation of the two main drivers of land surface processes (Albedo and temperature) in the Upper Ewaso Ng'iro basin in Kenya. The measurements were compared with estimates obtained from existing archives of EUMETSAT LSA SAF products for the same period.

3.2 Material and Methods

During this study, we set up ground based instruments (Albedometers and thermal sensors) to monitor land surface albedo and temperature during the months of January to mid February, 2009. Data was recorded every minute and aggregated to daily averages and quarter of an hour for surface albedo and temperature respectively. The aggregated values were compared with LST and Albedo from LSA SAF products for the same period. The ground measurements were conducted over grassland with open shrubs site, with data generated used for validation of algorithms for quantitative land surface parameter estimation and land surface hydro-meteorological process studies. Nine thermal sensors were fixed within a field site covered by grass (Figure. 3.1).

LSA SAF Network is a set of specialized development and processing centres, serving as EUMETSAT (European organization for the Exploitation of Meteorological Satellites) distributed Applications Ground Segment. The SAF network complements product-oriented activities at the EUMETSAT Central Facility in Darmstadt in Germany. The main purpose of the LSA SAF is to take full advantage of remotely sensed data, particularly those available from EUMETSAT sensors, to measure land surface variables, which will find primary applications in meteorology (http://landsaf.meteo.pt/).

Satellite products validation usually relies on field measurements. However, validating of these products using ground measurements is very challenging due to scale mismatch between ground ''point'' measurements and the image resolutions. Unless the surface is large and perfectly homogeneous or a sufficient number of point measurements are made during the satellite overpass, point measurements may not be sufficient to validate the 3-km SAF products if direct comparison is employed. To minimize the effects of scale issue, a homogeneous grassland cover was selected on which temporal variation of both surface albedo and temperature was monitored for a period of two months.

Figure 3.1: Configuration of albedometer in the field for calibration.

Figure 3.2: Configuration of themal sensors in the field.

3.3 Results and Discussions

Validation of the retrieved surface variables (albedo and LST) from LSA SAF products was based on ground measurements. However, it should be noted that, direct comparison of ground "*point/plot*" measurements with SAF products of 3 km resolution is not feasible over most natural landscapes (Garrigues et al., 2006). Nevertheless, this challenge can be overcome by upscaling point measurements using high-resolution remotely sensed imagery.

However, since high-resolution images for the same period and location are unaffordable particularly for developing countries, use of point measurements is therefore inevitable. To obtain close to reality measurements, a homogeneous land cover type was selected where the monitoring was conducted.

3.3.1 Validation of SAF Albedo

Surface albedo is defined as the ratio of reflected solar radiation and the incoming solar radiation in the entire shortwave (0.3–4.0 mm) band region. The albedo data collected was cleaned to remove any anomalies and then plotted showing the daily behavior (Figure 3.3) and subsequently its hourly variability (Figure 3.4).

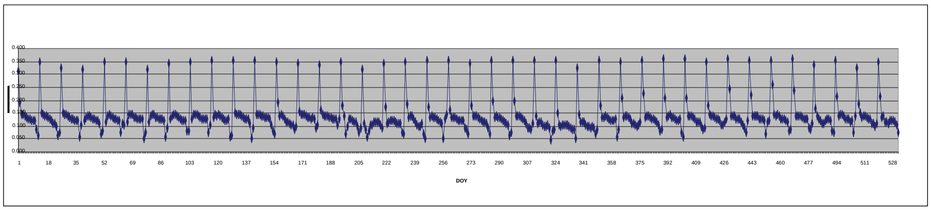

Figure 3.3: Daily variation of in-situ surface albedo during the month of January, 2009.

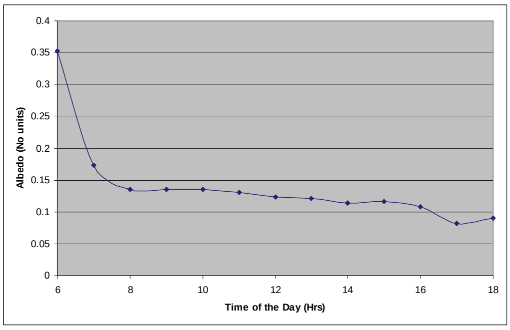

Figure 3.4: Average hourly in-situ surface albedo during the month of January, 2009.

Since the SAF albedo products are only available on daily basis, the in-situ measurements were therefore aggregated to the same scale to enable comparison. SAF albedo estimates were then validated with ground measurements obtained from an albedometer over open shrub vegetation type (Figure 3.2). The Albedo values derived from SAF varied from 0.120 and 0.135 while the in-situ values varied from 0.115 to 0.140. The results indicate that the SAF estimates generally tend to underestimate (75%), (Figure 3.5A). This observation could be attributed to the fact that the region is usually covered by cloud during this part of the year and may have contributed to the lower values obtained in addition to error propagation due to direct aggregation of the ground measurements. In addition, absorption and scattering in the atmosphere cause the albedo, as observed by the satellite to differ from the actual surface albedo as measured on the ground.

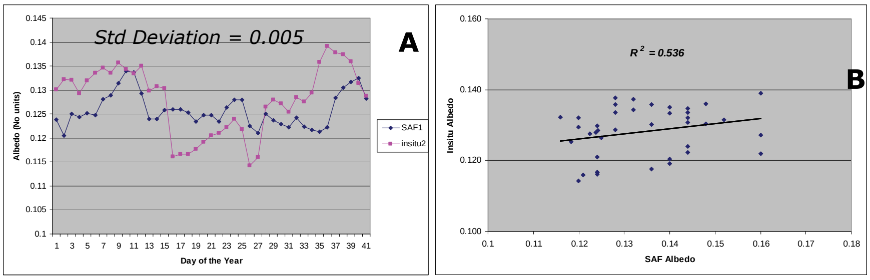

Figure 3.5: Comparison between daily in-situ and SAF surface albedo values during the month of January, 2009.

The retrieved surface albedo estimates were found to be relatively in good agreement with the in-situ measurements (Figure 3.5B) with the difference arising mainly from the land surface heterogeneity and other factors as observed by Liang et al., (2002). The standard deviation and RMSE for the retrieved albedo were relatively low (0.002 and 0.005 respectively).

3.2 Validation of SAF LST

Land surface temperature (LST) is an important surface variable that summarizes the energy dynamics of a surface (Dash et al., 2002a & b) and in order to estimate this variable to an acceptable accuracy, the prevalent methods require a priori emissivity information. It was therefore necessary to validate the LST estimates obtained from SAF products. This was achieved by comparing the corresponding values with measured values in the study area which produced a relatively good correlation (Figure 3.6B).

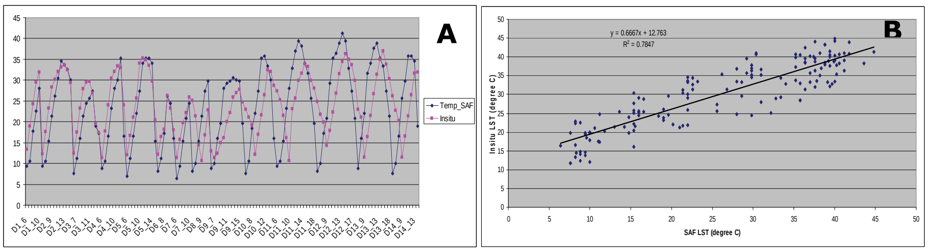

Figure 3.6: Comparison between SAF and In-situ LST Measurements

The results further show that SAF LST tends to over-estimate (Figure 3.6A) when compared to in-situ measurements giving a mean difference of 2.4 K and RMSE of about 6 K closely agreeing with the observations made by Wan et al., (2002) who obtained similar results between MODIS LST derived values and the in-situ measurements over a grassland cover with a uniform soil moisture conditions.

It was further revealed that LST decreased with increasing surface albedo, NDVI and actual evapotranspiration, all indicating a negative correlation, (Figures 3.7, 3.8 & 3.9) but with a strong negative correlation with NDVI (Figure 3.8) which was computed by using the visible channels of MSG for the same period. The slope of LST and NDVI curve can be related to soil moisture content (Goetz, 1997; Goward et al., 2002) while that of LST and surface evapotranspiration can be related to energy availability (which depends on temperature). This is because vegetated areas tend to reduce the surface resistance of evapotranspiration, thereby resulting into low surface temperatures (Boegh et al., 1998). Research has shown that vegetation condition greatly influences and controls LST through partitioning the solar radiation into fluxes of sensible and latent heat (Weng et al., 2004).

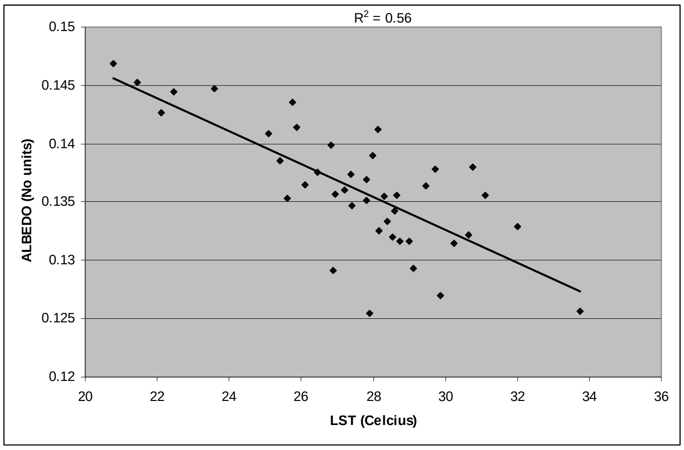

Figure 3.7: Comparison between Albedo and LST.

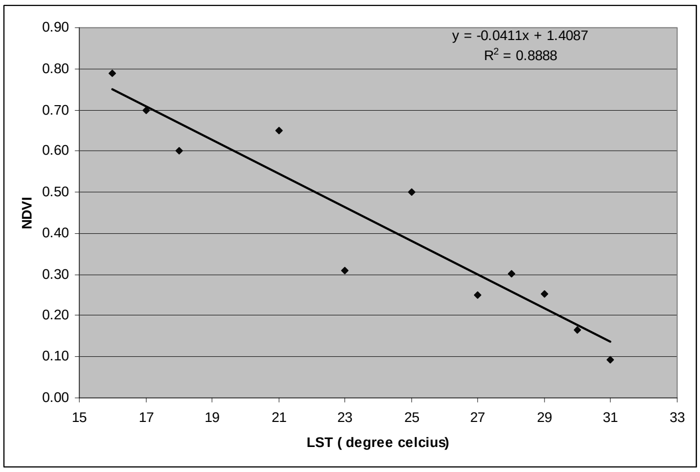

Figure 3.8: Comparison between LST and NDVI.

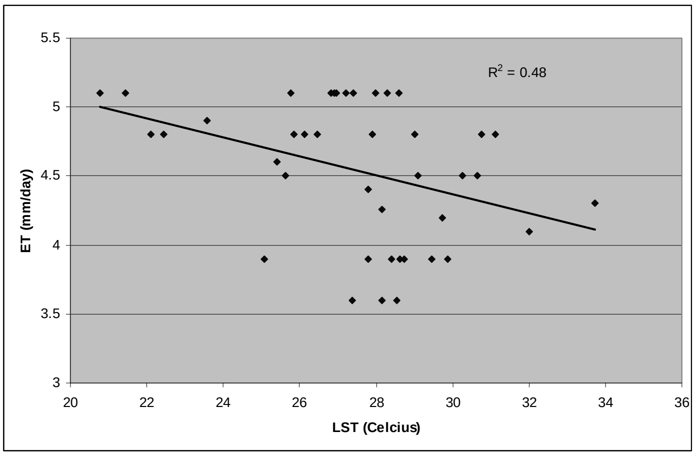

Figure 3.9: Comparison between LST and *ET*.

However, it should be noted that accurate validation of the LST is a difficult task (Figure 3.7) because of non-linear mixing (Moran et al., 1994; Stisen et al., 2007), and variability in surface emissivity makes it even more complex (Stisen et al., 2007). Therefore, validation of the SAF LST in the present study only comprised of statistical comparison with the collected insitu measurements.

Further, it was observed that SAF estimates tend to under-estimate in the morning hours (6.00 to 10.00 HRS) and in the late afternoon (17.00 to 18.00 HRS), while overestimating midday (11.00 to 16.00 HRS) as can be seen in Figure 3.10. This could be attributed to the fact the area is normally covered by cloud during the morning and evening hours. However, during midday, the sky is in most cases clear and hence reduced perturbations. Moreover, this scenario can also be associated with uncertainty in surface emissivity particularly for semi-arid areas (Wan et al., 2002).

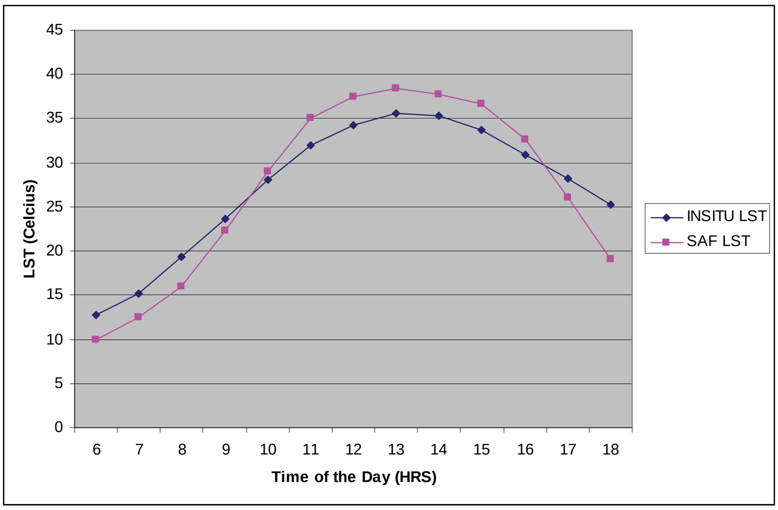

Figure 3.10: Comparison between hourly variations for in-situ LST and SAF LST estimates during the month of January, 2009.

3.4 Conclusion

This paper highlights the validation procedure of two important land surface variables, (albedo and LST), required for the land surface radiation budget processes. The mean standard deviation and RMSE (0.002 and 0.005 respectively) for the SAF albedo were relatively low indicating the level of accuracy at which SAF products are estimated and hence their potential particularly in the data scarce regions of SSA like the upper Ewaso Ng'iro North basin. Similarly, comparison of SAF LST estimates with the corresponding ground measurements produced an RMSE of 6 K which was found to be within acceptable margin given that in most cases, most areas in SSA have serious data scarcity. However, the error between the two estimation approaches may have been caused by the effects of atmospheric water vapor and surface emissivity.

It is worthy to note that, validation of such data from coarser resolution sensors like MSG is a difficult task because of their relatively greater spatial variability as compared to point based meteorological variables (Garrigues et al., 2006). For instance short time (hourly daily, monthly) variability can result from changes in soil wetness (Sun and Pinker, 2004a). This implies that, a global algorithm such as the one used in deriving LSA SAF global products need to be validated frequently with in-situ data from different regions with different climatic and environmental characteristics such as altitude, wind, moisture, etc, in order to minimize systematic errors that could be propagated during the processing period or improve their accuracy. The present study is an attempt to contribute towards this novel objective.

Furthermore, validation of land surface products such as albedo and surface temperature is necessary since their accuracy is critical for sound scientific work for various applications and for their quality improvement in future.

In conclusion, the study recommends that a more comprehensive campaign be conducted so that these variables can be monitored within various dominant land cover types in the region in order to avoid biasness in the results. Emissivity, which also greatly controls land surface processes need to be monitored as well in the main land cover types.

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CHAPTER 4

Estimation of spatial temporal rainfall distribution using remote sensing techniques: A case study of the Makanya Catchment, Tanzania

This chapter is based on:

Mutiga, J.K., Su, Z. and Woldai, T. and Maathius, B.H.P., (2010). Estimation of Spatial Temporal Rainfall Distribution using Remote Sensing Techniques: A Case Study of Makanya Catchment, Tanzanian. *Int. J. Appl. Earth Observ. Geoinform, (12S): S90-S99.*

Abstract

Rainfall–runoff modeling provides a tool to easily simulate the response of a watershed, thus providing an option for sustainable water resources management particularly in dry regions of Sub-Saharan Africa (SSA). Analysis of rainfall-runoff relationships in a catchment forms the basis of hydrological modelling. However, rainfall is a highly dynamic process, constantly changing in form and intensity as it passes over a given area. Traditionally, rainfall is measured using limited rain gauges at ground stations and often, the dynamics are not captured and yet it is the main input variable in any hydrological modeling. Without improved rainfall estimation, flow discharge estimates from rainfall-runoff relationship in both gauged and ungauged catchments particularly in arid and semi-arid regions remain a major challenge.

Application of remote sensing information becomes crucial in the process of estimating rainfall patterns of these areas. The estimation of rainfall in this study was based on the blending of the geostationary MeteoSat Second Generation (MSG), infrared channel with the low-earth orbiting passive Tropical Rainfall Measuring Mission (TRMM), microwave channel satellite data. To combine these two satellite data, a regression function associated with a threshold as an upper cloud temperature limit where rain occurs was determined. In this way, Makanya Catchment rainfall maps (daily, monthly, and seasonal) with 3 km pixel size from 2004 to 2006 were generated by aggregating the 15 minutes rainfall values. Comparison of the results obtained from the blended TRMM-MSG with the available ground gauge data for 2004 and 2005 periods, gave a good correlation of about 80%. In conclusion, the developed TRMM-MSG blending procedure was found to be a reliable and robust way of obtaining spatial temporal rainfall distribution of a given area and particularly so for Arid and Semi Arid Lands (ASALs) such as Makanya with sparse data acquisition networks.

Key words: *MSG, Rainfall estimation, Remote Sensing, TRMM***,** *ungauged Catchments and spatio-temporal variability.*

4.1 Introduction

In order to promote sustainable development and conservation of the environmental flows, estimation of catchment water balance is needed to give an overview of periodic water availability for the purpose of water resources planning and management. Generally, precipitation is the main input for water balance models and as such, its accuracy of the measurement from a network of stations determines to a considerable extent the reliability of water balance computations. Rainfall being amongst the hydrological parameters is the most difficult to measure due to its greatest temporal and spatial variability and discontinuity. With the advent of meteorological satellites however, improved quantification of rainfall at different time scales consistent with the nature and development of clouds can be realized (Levizzani and Amorati, 2002).

The quantification of individual components of the hydrologic cycle, especially at catchment scale is a crucial step in integrated watershed management. Effective integrated water resources management requires timely, accurate and comprehensive meteorological, hydrological and other related information. Determining the spatial and temporal depth of rainfall input to a catchment is necessary for everyday planning and management of the water resources. It is well documented that rainfall on the earth surface varies both in time and space and therefore satellite rainfall data becomes an important additional source.

Historically, the estimation of rainfall has been accomplished by relatively simple instrumentation using rain gauges that sample the rain by capturing a volume over a continuous or fixed time interval. Rain gauges provide a fairly accurate measure of point rates and depths of rainfall. Their major shortcoming however, is that their measurement is only at certain predetermined and limited points and do not provide adequate areal coverage. Although there are a vast number of rain gauges world-wide, they are not sufficient to define rainfall inputs for most needs. The result of this is that rainfall is measured relatively accurately for small areas with a network of rain gauges, but this approach is not practical for large and remote areas of the earth such as the Makanya catchment in the study.

Recognizing these practical limitations of rain gauges therefore, scientists have increasingly turned to remote sensing as a possible means for quantifying the rainfall input to the earth. It should be stressed however, that remote sensing is at present, and will continue to supplement, rather than to replace these traditional methods of rainfall assessment. Although the measurement of rainfall by rain gauges is fraught with some problems, they will continue to provide the data against which rainfall assessments by other means can be adjusted and validated. The main objective of this study was to apply satellite remote sensing for rainfall estimation in terms of occurrence, amount and areal distribution for the Makanya Catchment in Tanzania (Figure 2.9). The uneven distribution of the existing rain gauges in the catchment, and their limited sampling area represents a substantial problem when dealing with effective spatial coverage. As a result, satellite rainfall monitoring becomes an appropriate means to address the key issues of spatial and temporal coverage, which can not be achieved by the existing monitoring system in the area. Specifically, the study tried to evaluate if routine satellite observation of rainfall provides a reliable alternative for spatial and temporal rainfall fields needed for rainfall-runoff modeling.

Satellites obtain information about the distribution and amounts of precipitation both directly and indirectly (Arkin, 1989; Levizzani et al., 2002). Direct observation is by passive sensing of the microwave energy absorbed and scattered by hydrometeors and conversion of these observations into estimates of rainfall rates by accounting for the background radiation from the earth's surface and making assumptions about the size distribution of the hydrometeors. Indirect observation is by sensing infra-red radiation emitted by clouds, converting the radiation flux into cloud-top temperature, making use of empirical correlations of the spatial and temporal coverage of clouds with temperatures below a threshold value and rainfall (Levizzani et al., 2002; Dingman, 2002).

Rainfall estimation using satellite remote sensing methods have been developed for both visible/infrared (VIS/IR) and microwave (MW) instruments for about two decades. The success of the indirect (VIS/IR) and more directly physical (MW) methods has been very variable depending on the type of precipitating system, the timing of observations, and spatial coverage (Levizzani et al., 2002). Geostationary weather satellite visible and infrared images provide rapid temporal update cycle needed to capture the growth and decay of precipitation clouds (Turk et al., 2000). The European Organisation for the Exploitation of Meteorological Satellites (EUMESAT) multi-sensor precipitation estimate (MPE) has been developed in order to derive instantaneous rainfall intensities from MSG and MeteoSat 7. The methodological approach which is based on the blending of brightness temperatures from the geostationary satellites infrared channels with rainfall intensities from the passive TRMM satellites microwave channels was applied for this study.

4.2 Materials

4.2.1 Tropical Rain Measuring Mission (TRMM)

TRMM is designed to provide near-real-time precipitation profiles as well as surface rainfall estimates for operational purposes within the tropical and sub-tropical regions. Two-thirds of the global precipitation falls within the tropical regions between 30^0N to 30^0S (Adler and Negri, 1988; Simpson et al., 1988) where most of the heavily populated developing countries are located. Based on this fact, the monitoring of rainfall in these regions therefore calls for a scientific concern. The Tropical Rainfall Measuring Mission (TRMM) has two unique attributes that make it ideal for observing tropical rainfall systems, and these include its suite of complementary observing instruments (Precipitation Radar), and its orbital characteristics (low altitude, non-sunsynchronous, processing, 35-degree tropical inclination) that enables it to provide sampling in the tropics that is far more frequent, and more spatially comprehensive than that obtained from standard polar orbiting satellites (NAS, 2006).

TRMM is the first satellite earth observation mission to monitor tropical rainfall, since it closely influences the global climate and environmental change. Generally, TRMM is commonly referred to as the "*flying rain gauge*" and is mainly used to obtain improved measurements of tropical precipitation by means of adding information derived from passive microwave and active microwave sensors together with other sensors operating in the visible and infrared portion of the spectrum (NASDA, 2001). TRMM has three main instruments onboard, namely the precipitation radar (PR), the TRMM Microwave Imager (TMI), and the Visible and Infrared Scanners (VIRS) in its rainfall measurement package that is used to obtain tropical and subtropical rainfall measurements, rain profiles, and brightness temperature. TRMM has the only passive microwave instrument (TMI) in an inclined orbit and the only rain radar (PR) in space. In addition, there are two instruments flown on-board TRMM namely, the Clouds and the Earth's Radiant Energy System (CERES) and the Lightning Imaging Sensor (LIS) to measure the radiation budget and global distribution of light respectively (Kummerow et al., 1998; Levizzani et al., 2002). These instruments can function either individually or in combination with one another.

4.3.1.1 Precipitation Radar (PR)

Among the three primary instruments on board TRMM, the most innovative and the first space borne instrument is the Precipitation Radar (PR) designed specifically for rainfall monitoring from space. Thus it provides direct, fine-scale observations of three-dimensional structure of precipitation systems, particularly the vertical and horizontal distribution as well as rainfall intensity measurements over land and ocean. PR has a horizontal resolution at the ground of about five kilometres and a swath width of 247 km with frequency of about three times higher than that of typical ground-based radar (Kummerow et al., 1998).

This high frequency ensures that high resolution three-dimensional maps of rainfall are obtained during the brief time that the satellite is above the local storms. One of its most important features is its ability to provide vertical profiles of the rain and snow from the surface up to a height of about 20 km. The Precipitation Radar is able to detect fairly light rain rates down to about 0.7 mm/hr. However, for intense rain rates, where the attenuation effects can be strong, new methods of data processing have been developed that help to correct for this effect (Iguchi et al., 2000).

4.3.1.2 TRMM Microwave Imager (TMI)

The Tropical Rainfall Measuring Mission's (TRMM) Microwave Imager (TMI) is a multi-channel, dual-polarized, conically scanning passive microwave sensor designed to provide quantitative estimates of rainfall, water vapor, cloud water content and sea surface temperature by carefully measuring the small amounts of microwave energy emitted by the Earth and its atmosphere. TMI is able to quantify the water vapor, the cloud water, and the rainfall intensity in the atmosphere (Kummerow et al., 1998). The TMI 10.7 GHz channel with both vertical and horizontal polarizations is designed to provide a more-linear response for the high rainfall rates common in tropics. Besides providing high resolution rainfall data, TMI can also be used to derive sea surface temperatures (Wentz et al., 2000).

4.3.1.3 The Visible and Infrared Scanner (VIRS)

The Visible and Infrared Scanner (VIRS) is an instrument similar to the TMI and serves an important role of bridging between the high quality but infrequent observations from TMI and PR with the more available data and longer time series data available from the geostationary VIS/IR satellite platforms. VIRS provides indirect measurements on rainfall intensity, distribution and type, storm depth and the height at which the snow melts into rain. The intensity of radiation it senses in five spectral regions (visible to infrared) can be used to determine the brightness temperatures of the source (Kummerow et al., 1998).

If the sky is clear, the temperature will correspond to that of the surface of the Earth, and if there are clouds, the temperature will tend to be closer to those of the cloud tops. Colder temperatures will produce greater rainfall intensities in the shorter wavelength bands while warmer temperatures will produce greater rainfall intensities in the longer wavelength bands. Since colder clouds occur at higher altitudes, the measured temperatures are useful indicators of cloud heights and cloud thickness. The highest clouds can therefore be associated with the presence of rain. The assumption made here is that colder and bright clouds are associated with heavier rainfall while warmer and less bright clouds associated with light or no rain. However, this assumption only holds for convective clouds, stratiform clouds (warm and wet) or cirrus clouds (cold and dry) (Kuligowsky, 2003).

4.3.1.4 The CERES and LIS

The CERES instrument enables the determination of the total radiant energy balance. In addition to latent heating derived from the precipitation, a significantly improved atmospheric energy system can also be obtained from this instrument. The lightning imaging sensor (LIS) on the other hand, besides mapping the global frequency of lightning events, also plays an important role in coupling the occurrence of lightning to the precipitation thus enhancing the overall understanding of lightning as well as precipitation processes (Kummerow et al., 1998).

4.3.2 MeteoSat Second Generation (MSG)

MeteoSat Second Generation (MSG) is a new generation of geostationary satellites developed by European Space Agency (ESA) and European organization for the exploitation of METeorological SATellite (EUMETSAT). MSG is one of the geostationary satellites in the equatorial plane at an altitude of about 36,000 km above the Earth having the same revolution time as the Earth itself and therefore always viewing the same area. Its main payload is the optical imaging radiometer, the Spinning Enhanced Visible and Infrared Imager (SEVIRI) with 12 spectral channels covering from visible to thermal infrared including water vapor, ozone and carbon dioxide channels (Schmetz et al., 2002a) and provides measurements of the earth-disc every 15 minutes at a fixed view angle.

SEVIRI has the capability to observe and characterize clouds with the superior temporal and spatial scales available from a geostationary platform. When combined with near-coincident datasets from microwave imagers aboard low-Earth orbiting satellites, this multispectral combination of observations significantly enhanced the ability of sensing cloud microstructure and precipitation forming processes from space (Levizzani et al., 2000) and subsequently improving rainfall measurements. The spatial resolution of the MSG is 3 km at nadir and the High Resolution Visible (HRV) channel has a sampling distance interval of about 1 km. The repeat cycle of

15 minutes for full-disk imaging provides multi-spectral observations of rapidly changing phenomena such as deep convection.

4.4.3 Methodology

To transform the brightness temperatures into surface rain, TRMM Microwave Imager 2A12 Hydrometeor Profiles, image products at 5 km horizontal resolution either in ascending or descending mode, (Figure 4.4) were downloaded from http://disc.sci.gsfc.nasa.gov/ site from 2004 to 2006. Orbit Viewer software (TSDIS, NASA, 2005), was used to transform the downloaded TRMM data products each day into ASCII format files containing both the geographical location coordinates and the rainfall intensity for each location (Figure 4.4) ready for further processing within a GIS platform.

Using the MSG Data Retriever tool developed by ITC (Retsios et al., 2005; Maathuis et al., 2006), which takes the radiometric and geometric calibration of the images into account, the 10.8 micron and 6.2 micron channel data at 15 minutes interval for the years 2004 - 2006 covering the study area were retrieved and converted to brightness temperature (in Kelvin), (Figure 4.5) and subsequently exported to the ILWIS data format and resampled to UTM at a pixel resolution of 1000 m using the High Resolution Visible (HRV) channel.

In order to obtain the annual temporal variation on daily time scale, the aggregated average daily rainfall totals for the three time period were plotted, (Figures 4.1, 4.2 and 4.3). It was observed that both the years 2004 and 2005 were very dry with rainfall being experienced only during the short rains ("*Vuli*") in 2004 while in 2005, during the long rains ("*Masika*"). However, the year 2006 was a good year with well distributed rainfall throughout the year. For this reason therefore, the year 2006 was used for both the calibration and validation purposes of the MSG data used during this study.

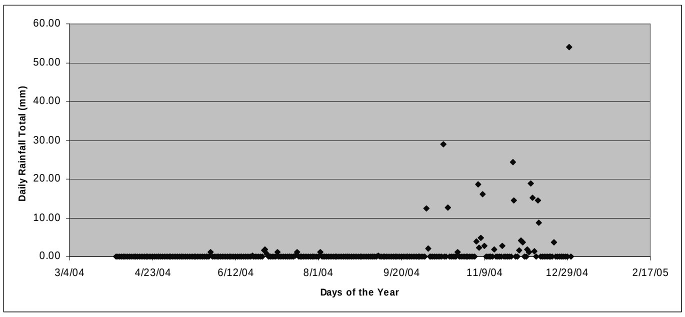

Figure 4.1: Average daily rainfall distribution for the Makanya Catchment in 2004.

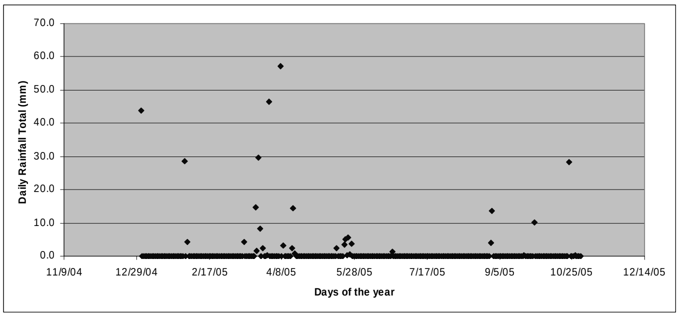

Figure 4.2: Average daily rainfall distribution for the Makanya Catchment in 2005.

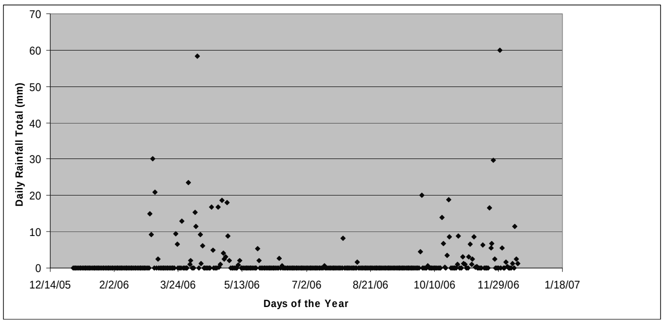

Figure 4.3: Average daily rainfall distribution for the Makanya Catchment in 2006.

Figures 4.4, 4.5, 4.6, 4.7, 4.8, 4.9 and 4.10 attempt to illustrate all the steps followed in the whole process, starting from the data retrieval, (Figures 4.8 and 4.9) through data processing and analysis, (Figures 4.6, 4.7 and 4.8) to producing the final rainfall products, (Figures 4.9 and 4.10). In all cases at different times, it was observed that, only the areas with low temperatures are associated with rainfall, clearly demonstrating the non-linear relationship between temperature and rainfall, (Figure 4.6). However, this relationship can only be considered valid mainly for convective precipitation and is only partially true for frontal or orographic cloud systems (Heinemann, 2003) as it is the case for the Makanya catchment.

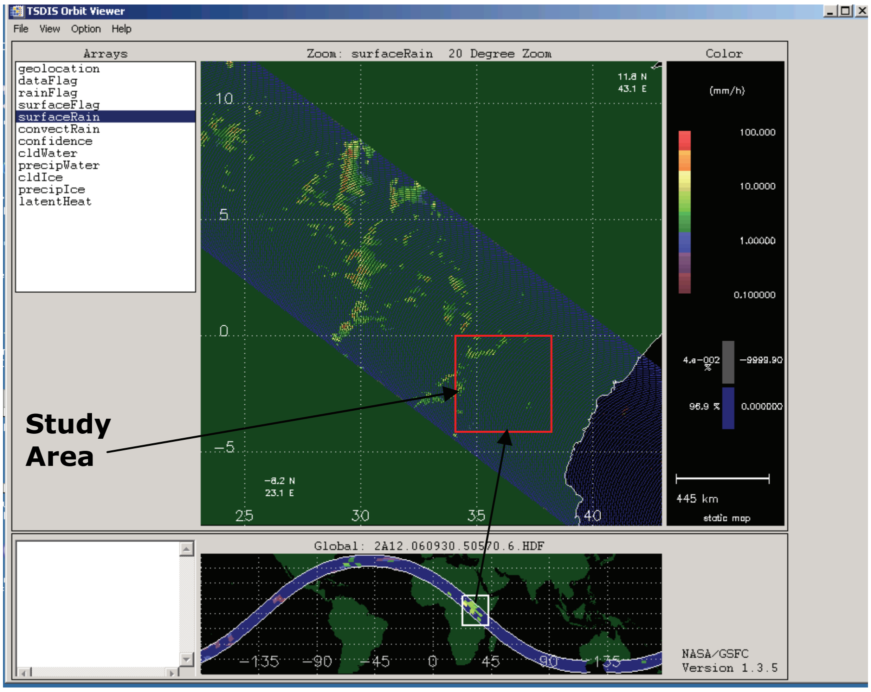

Figure 4.4: Example of a 2A12 TMI profile descending image orbit 50570 covering the study area for the 30th September, 2006, 12:30, UTC Time.

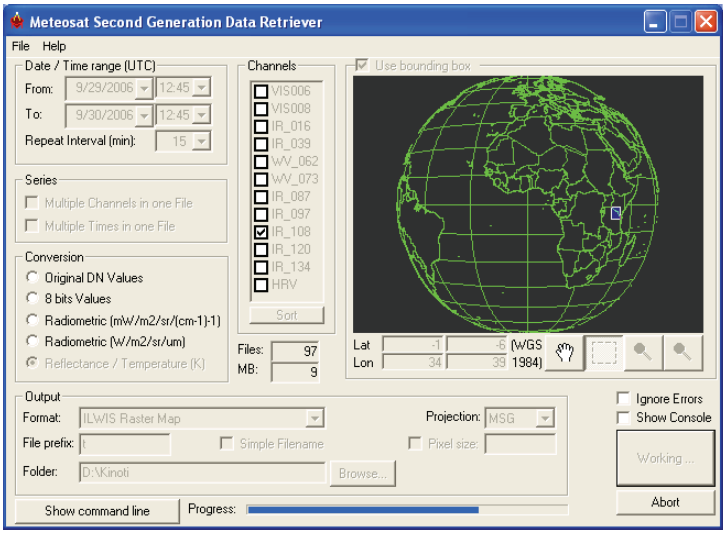

Figure 4.5: MSG data retriever interface showing data extraction process.

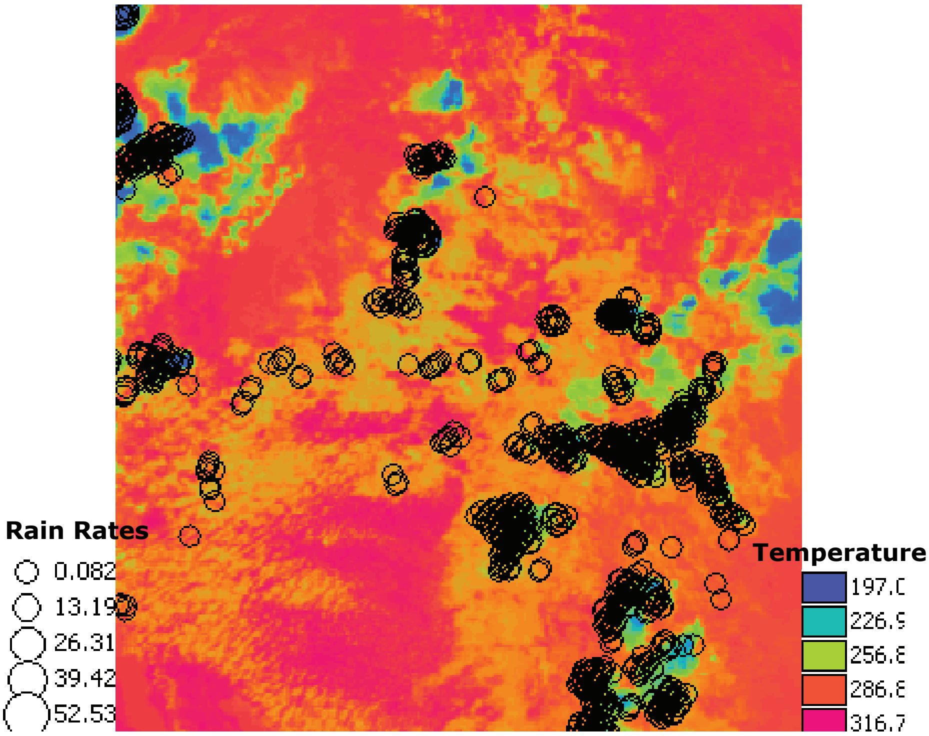

Figure 4.6: Example of a MSG image for the study area for 12:45 UTC Time, 30th September, 2006 overlaid with TRMM rain rates for approximately the same time.

4.3.3.1 MSG and TRMM Relationship

In order to determine the relationship between the cloud top brightness temperatures from MSG and rainfall intensities from TRMM, a correlation coefficient was determined. This is because, correlation coefficient is considered as the first direct validation of the obtained results (Heinemann, 2003). Although a weak overall correlation coefficient (R = -0.42) was obtained, it was found to fall within the acceptable range for tropical regions (Heinemann, 2003) where the study area is located. The main cause of this low correlation could be attributed to the spatial and temporal offset errors emanating from co-llocating TRMM (low earth orbiting passive microwave) with MSG, (Geostationary thermal infrared) satellite observations (Turk et al., 2003) which has an average time difference of about ten minutes within the tropical regions. In order to minimize the effects of these offset errors on rainfall estimation, artificial neural networks (Grecu and Anagnostou, 2001; Hong et al., 2004a)) or temporal averaging techniques of instantaneous rain rates (Ferreira, 2001; Heinemann et al., 2002; Turk et al., 2005) can be applied.

However, for this study, temporal averaging technique which is easy to use and at the same time produces considerably good results was applied to the MSG pixels with equal temperature classes of one degree Kelvin intervals thus giving a temperature range from 100K to 400K. The main reason for incorporating the averaging technique was to account for any collocation problems such as spatial and timing offsets (Maathuis et al., 2006). For this to be implemented, each temperature class interval was assigned average rainfall intensity and the temperature values were then used to determine the new correlation coefficient, which significantly improved from R = -0.42 to R = -0.65. To improve this correlation even further, different regression functions were tested ranging from the first to the fifth order polynomials. The results obtained, revealed that the fifth order polynomial produced the highest correlation results (Figure 4.7) and was thus accepted and adopted for further data processing (Section 4.4.3).

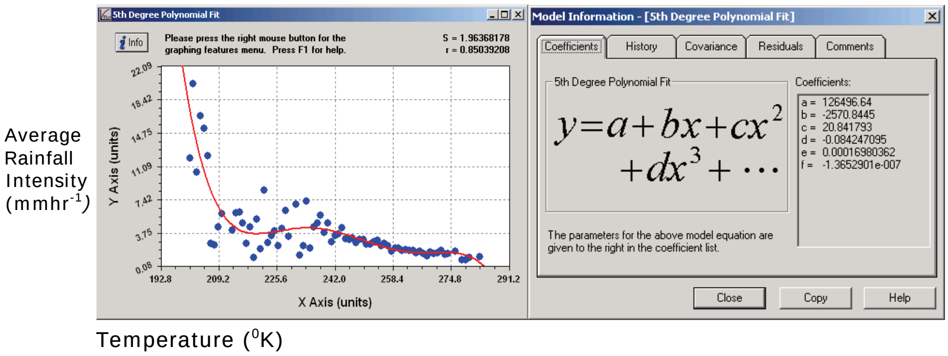

Figure 4.7: Relationship between cloud top temperatures and rainfall intensity.

4.3.2 Precipitating Clouds

To estimate the clouds with high probability of precipitation, brightness temperature difference between the 6.2 µm water vapor channel and 10.8 µm infrared channel was used to detect high and thick clouds that are likely to precipitate (Casanova et al., 2005). Since clouds are formed within the troposphere, maximum water vapor content also occurs at this level.

Empirically, it is well documented that a threshold on brightness temperature difference of less than 11 K between 10.8 µm thermal infrared and 6.2 µm water vapor channels is capable of flagging out the cold clouds that are likely to precipitate (Petty, 2001a; Kidder et al., 2005; Turk et al., 2005). This is because at 6.2 µm, the atmosphere is opaque due to water vapor absorption and low clouds are not sensed at this wavelength hence only the deep clouds penetrate the water vapor to be sensed at both 6.2 µm and 10.8 µm, and when this happens, the brightness temperature difference at these two wavelengths becomes small (Kidder et al., 2005).

Thus channel 6.2 µm acts as an indicator for water vapor content in the upper part of the troposphere but if there is no water vapor, radiation from far below can reach the sensor. Superimposing the precipitating clouds map with rainfall intensity map revealed that areas experiencing high rainfall intensities (high concentration of the rings) were occurred within areas with precipitating clouds (Figure 4.8).

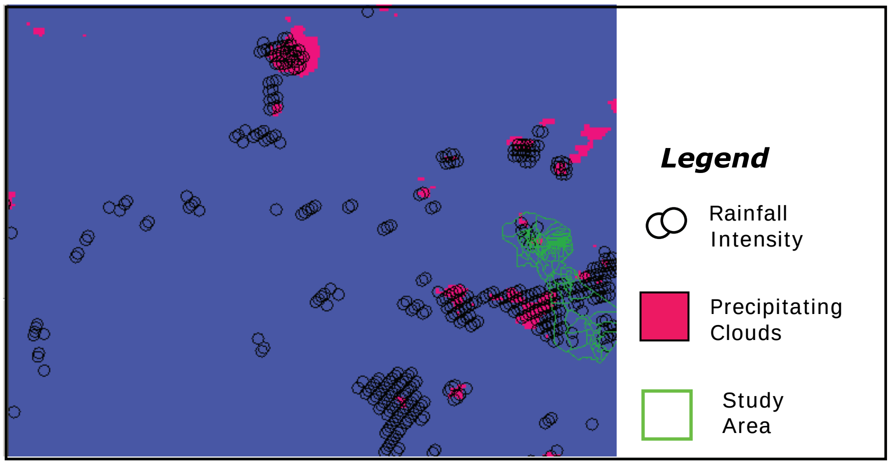

Figure 4.8: Relationship between precipitating clouds (from MSG) and rainfall intensity (from TRMM).

4.3.3 Generating Rainfall from Temperatue

The regression obtained (polynomial function, Figue 4.7) was applied to all 15 minutes MSG temperature images (96) for each day aimed at converting the precipitating clouds to their corresponding rainfall intensities. The results were then aggregated to produce spatial total daily rainfall intensity for the area. During this process, threshold temperature difference for the precipitating clouds was set to less than 11 K, (Section 4.4.2), implying that areas with higher temperature difference than this threshold do not receive any rainfall at all.

4.3.4 Estimating Spatio-temporal Rainfall Distribution

Rainfall measurement is very important for hydrological cycles, flood identification, land and water resources management and for understanding the convective systems (Kamarianakis et al., 2006). Besides, rainfall is one of the most difficult atmospheric parameters to determine because of its highly temporal and spatial variability and discontinuity. However, with the advent of several meteorological satellites, improved identification and quantification of precipitation at different time scales consistent with the nature and development of the cloud rain bands has been realized (Levizzani et al., 2002). Moreover, meteorological satellites expand the coverage and time span that the conventional ground-based rainfall data (Maathuis et al., 2006). For accurate determination of spatio-temporal rainfall distribution, statistical data integration from different satellite sensors (MSG and TRMM) was applied.

For the study, a regression function (5th order polynomial Fit) obtained in section 4.1 was adopted and applied to all 15 minutes MSG images in order to transform the precipitation clouds top temperatures into their corresponding rainfall intensities. This polynomial fit was selected because it produced the highest possible correlation results as compared to the others. Rainfall intensity at every 15 minutes interval was computed by assigning rain rates to regions where temperature difference between channels 10.8 µm and 6.2 µm was below a local average of 11K, (Section 4.4.3) for the active precipitating core (Kidder, et al., 2005) as shown in Equation (4.1).

$$R_{15min} = iff(temp\_108 - temp\_062 < 11, ((a + b*(temp\_108) + c*(temp\_108)^2 + d*(temp\_108)^3 + e*(temp\_108)^4 + f*(temp\_108)^5 * 0.25, ?)) \qquad (4.1)$$

Where a = 126496.64; b = -2570.84; c = 20.84; d = -0.084; e = 0.00016; f = -1.36e-007

temp_108 = MSG Temperature image at Channel 10.8 µm
temp_062 = MSG Temperature image at Channel 6.2 µm

The total daily accumulated rainfall (R_{day}) was computed by summing up all the 15 minutes rainfall intensities ($R_{(1, 2, 3, \ldots n)}$); thus

$$R_{day} = Sum\ (R_{(1, 2, 3, \ldots n)}) \qquad (4.2)$$

Where R_1 *= Rainfall at the first 15 minutes (15)*
R_2 *= Rainfall at the second 15 minutes (30)*
R_3 *= Rainfall at the third 15 minutes (45)*
n *= Rainfall at the 96th 15 minutes (End of the day)*

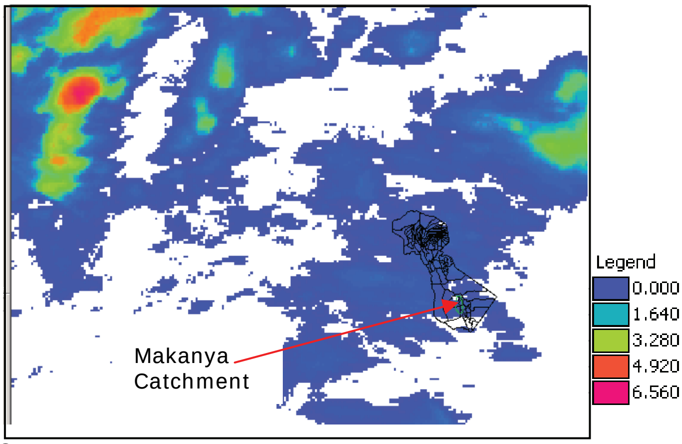

Figure 4.9: Spatial distribution of rainfall intensity (mm) in the Makanya Catchment and its Environs for 12:45 UTC, 30th September, 2006.

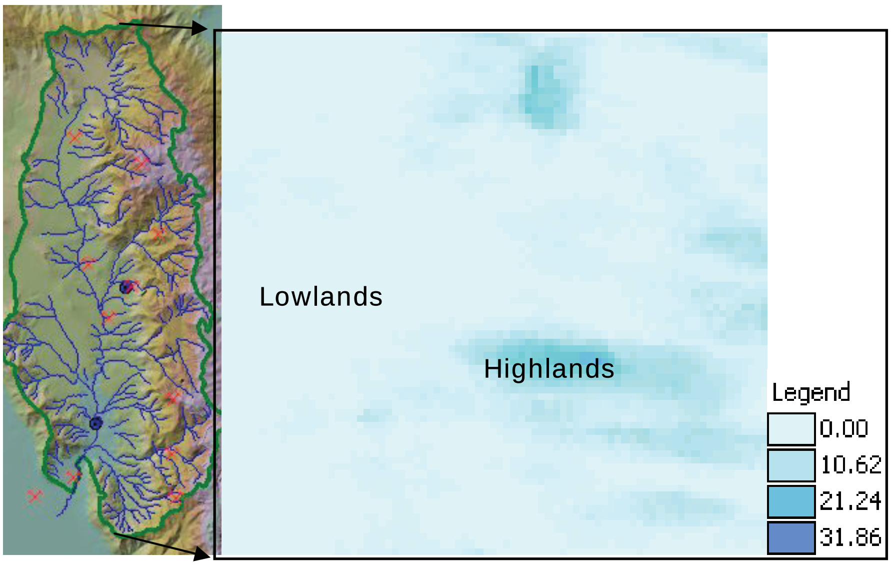

Figure 4.10: Spatial distribution of the accumulated rainfall intensity (mm) in the Makanya Catchment for the 30th September, 2006.

4.4 Results and Discussions

Estimation of the spatio-temporal rainfall distribution in Makanya catchment was achieved through multi- channel and multi-sensor data integration from both MSG and TRMM. The results obtained from this application revealed that rainfall in the catchment is highly variable as one moves from the lowlands to the highlands (Figure 4.10) with the lowlands receiving low rainfall amount (400-500 mm/year) while the highlands receive relatively higher amount (800-900 mm/year) agreeing with the findings of Enfors and Gordon, (2007).

It was further revealed that rainfall was highly variable between and within seasons in any particular year (Figures 4.12 and 4.13).

Comparison of both the gauge data from existing monitoring stations in the study area with their corresponding values estimated from satellite sensors (blended MSG and TRMM) revealed a strong correlation which even improved significantly with widening the time frame window (from daily, monthly, and seasonal), (Figures 4.11, 4.12, and 4.13) respectively. The low correlation values obtained for the daily estimates could be attributed to the fact that the amount of precipitation reaching the ground depend on the structure of the atmospheric layer under the precipitating clouds resulting to sampling errors during the estimation of accumulated rainfall (Ebert and Manton, 1998).

The results obtained also revealed that aggregation of the daily rainfall values to both monthly and seasonal rainfall values, improved the correlations significantly, thus agreeing with the findings of (Turk et al., 2002 and Soman et al., 1995). However, comparison of the obtained results was done for the period (2004 to 2005) due to the availability of rain gauge data from the existing ground based stations taking into consideration the heterogeneity within the catchment. In this case, the catchment was divided into two zones, namely the highlands and the lowlands and for each zone, five ground based rain gauging stations with daily rainfall data were used for this analysis, (Figure 4.10). The results further indicate that combining both brightness temperature from MSG and the rain intensities from TRMM could be used to estimate rainfall for both unguaged and poorly gauged catchments such as the Makanya with relatively high temporal and spatial resolutions, (Figures 4.11, 4.12 and 4.13).

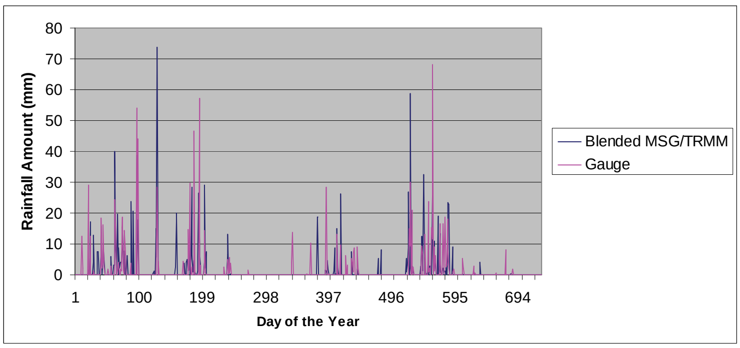

Figure 4.11: Daily rainfall depths (2004 – 2005) in the Makanya Catchment.

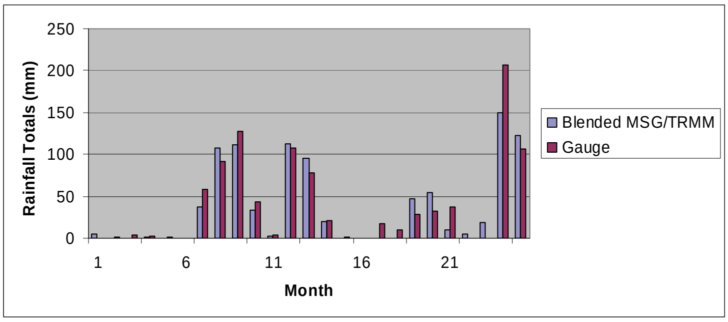

Figure 4.12: Monthly rainfall depths (2004 – 2005) in the Makanya Catchment.

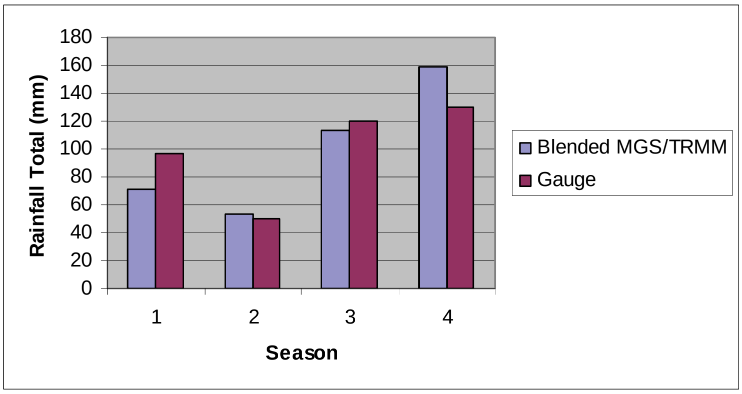

Figure 4.13: Seasonal rainfall depths (2004 – 2005) in the Makanya Catchment.

The results obtained from the analysis show that, the estimated rainfall values from the blended MSG/TRMM are overestimated during the "*Vuli*" season while being underestimated during the "Masika" season. This observation could be attributed to the rainfall distribution patterns in the two seasons in which case the rainfall received during the "*Vuli*" season is much higher and occurs within a shorter period of time as opposed to the scenario experienced during the "*Masika*" rain season. However, the correlation levels stabilized considerably with decreasing temporal resolution (daily, monthly and seasonal), as shown in the Figures 4.11, 4.12 and 4.13 respectively. This is because when the time window is small, there is the likelihood of capturing less extreme precipitation events during TRMM overpass (Turk et al., 2002). However, the error margin differences between the seasons varied insignificantly (about 5%) and therefore considered acceptable especially for remote and ungauged catchments such as the Makanya.

4.5 Conclusion

Since the relationship between observations from the blended TRMM/MSG satellites sensors and ground surface rainfall intensities is indirect, the accuracy of the final product derived is often not guaranteed, and therefore continuous calibration and validation of the existing algorithms using ground information can greatly improve the accuracy of these near real-time rainfall distribution especially in developing countries where monitoring networks are scarce or do not exist at all. It is against this background that this study attempted to contribute towards this goal and subsequently greatly enhance the management of the water resources in these regions. Results obtained indicate that rainfall distribution in Makanya catchment is highly variable as one move from the lowlands to the highlands. This rainfall variability phenomenon was also observed between and within seasons.

Moreover, comparison of the results obtained during this study with the existing rainfall data from 3B42 products covering the same area revealed that the approach used improved their accuracy by about 10% thus complementing these products. This shows the robustness of the regression function that was derived to estimate the rainfall pattern in the study area.

In conclusion, the potential of remote sensing in accurate areal rainfall estimation is great but has not been fully exploited for remote and ungauged catchments particularly in the Sub-Saharan Africa where setting of an adequate weather monitoring network could be a challenging investment. This study therefore strongly embraces the fact that application of the remote sensing data for rainfall estimation is a prerequisite for water resources management in these regions.

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CHAPTER 5

Using satellite remote sensing to assess evapotranspiration: A case study of the Upper Ewaso Ng'iro North Basin, Kenya

This chapter is based on:

Mutiga, J.K., Su, Z. and Woldai, T., (2010). Using satellite remote sensing to assess evapotranspiration: case study of the Upper Ewaso Ng'iro North Basin, Kenya. *Int. J. Appl. Earth Observ. Geoinform, (12S): S100-S108.*

Abstract

Actual Evapotranspiration (ET_a) is one of the most useful indicators to explain whether the water is being used as "intended". ET_a variations, both in space and time and for different land use types are seen to be highly indicative for the adequacy, reliability and equity in water use; the knowledge of these conditions is essential for judicious water resources management. Unfortunately, ET_a estimation under actual field conditions is still a big challenge for both scientists and water managers. The complexity associated with the estimation of ET_a has led to the development of various methodological approaches for estimating ET_a over time.

During the past two to three decades, significant progress has been made in estimating actual evapotranspiration using satellite remote sensing. These methods provide powerful means for computing ET_a from a pixel scale to that of an entire basin. In this study, Surface Energy Balance Algorithm for Land (SEBAL) was used to compute a complete radiation and energy balance along with the resistances for momentum, heat and water vapor transport for each pixel in the Upper Ewaso Ng'iro North River Basin, in Kenya. This was then applied to assess the spatio-temporal distribution of ETa in the basin. The mean annual ET_a estimated from SEBAL for 2000, 2003 and 2006 were compared with the mean annual ET_a calculated from water balance method for the same periods and a good correlation of about 70% was observed.

It was further observed that ET_a increased gradually from 2000 to 2006 with an annual rate of about 15%. The estimated daily, monthly and annually ET_a distribution for the period of study were used to analyze water use patterns across the basin thus giving more insights into the underlying factors impacting on the water resources which could be used to facilitate the formulation of appropriate water resources management strategies for the basin.

Keywords: *Ewaso Ng'iro, SEBAL, Actual Evapotranspiration, Remote Sensing, Land cover/use, Energy Balance, and Water Balance.*

5.1 Introduction

Since water resource management strategies are usually implemented on a basin scale, understanding of the hydrological processes at this scale is a pre-requisite for the formulation of these strategies. As pressure on water resources increases, sound knowledge on where, when and how much water is used is required. Evapotranspiration *(ET)* in this case becomes an important factor for evaluating water productivity and monitoring of irrigation performance.

Evapotranspiration is a process governed by the energy and heat exchanges at the land surface, with the upper bound being constrained and controlled by the amount of available energy and water respectively (Hemukamara et al., 2003). However, direct measurement of actual evapotranspiration is difficult and in most cases only provides point values.

Although ET_a is one of the most important components of the hydrological cycle, it is one of the most difficult to measure especially under composite terrains (Wu et al., 2006). Traditionally, total evaporation (*ET*) from agricultural fields has been estimated by multiplying the potential evapotranspiration (ET_o) by crop coefficients (K_c) which is determined according to the crop type and the crop growth stage as highlighted in Allen et al., 1998 and Bos, et al., 2009.

Actual Evapotranspiration (ET_a) is one of the most useful indicators for explaining whether the water is being used as “intended” or not. ET_a variations, both in space and time and for different land use classes (particularly agricultural lands) are thought to be highly indicative for the adequacy, reliability and equity in water use; the knowledge of these conditions is essential for judicious water resources management. Unfortunately, ET_a estimation under actual field conditions is still a very challenging task for scientists and water managers. The complexity associated with the estimation of *ET* has led to the development of different methods for estimating this parameter over time (Allen et al., 1998).

Using recent developments in the field of remote sensing applications in water management, this paper shows how remote sensing tools can help improve water resources management by providing information on the existing patterns of water use, identifying the weaknesses in the approach to water management, and assisting in identifying potential areas providing opportunities for improving water use efficiency.

In semi-arid environments, *ET* from the land surface plays a critical role not only in water circulation within that surface, but also in many associated physical and ecological variables, such as atmospheric dynamics, subsurface water storage, and vegetation growth. Due to spatial variability in landuse, land cover, soil properties and water flows, most hydro-meteorological parameters exhibit an evident spatial variation, which cannot be obtained from a limited number of synoptic observations. This problem however, can be overcome by applying a semi-empirically based multi-step Surface Energy Balance Algorithm for Land (SEBAL) as formulated by Bastiaanssen (1995).

This study attempted to estimate the spatio-temporal distribution of evapotranspiration and other components (surface emissivity, albedo, temperature and normalized difference vegetation index) of the surface heat budget in the Upper Ewaso Ng'iro North Basin in Kenya (Figure 2.1B) during the rainy seasons of 2000, 2003 and 2006 by implementing SEBAL approach. This is because, evapotranspiration data enhances the understanding of the underlying factors which impact on water use and subsequently assist in decision making on appropriate interventions for different critical water uses, like irrigated agriculture (Bastiaanssen et al., 2001).

If reliable and consistent information regarding evapotranspiration can be accessed at low cost, it can be used to analyze the performance of, for example irrigation systems and thus devise better management strategies. Remote sensing is one such alternative, and over the last decade, methods for calculating ETa have been developed (Menenti, 1984; Jackson et al., 1988; Bastiaanssen, 1995; Kustas and Norman, 1996; Boegh et al., 2002; Su, 2002; Su, 2005). The main advantage of such an approach is that large areas can be covered, and that data is easily available without extensive monitoring networks in the field (Bandara, 2003; Chemin et al., 2004).

5.2 Materials and Methods

Archived MODIS L1B data with 36 channels of visible and near-infrared reflectance and radiance, as well as thermal-infrared radiance were used. Cloud free images covering the study area for 2000, 2003 and 2006, were downloaded from the satellite active archive's website http://edcimswww.cr.usgs.gov/pub/imswelcome/. The images were processed to provide the necessary data, (emissivity, vegetation index, surface albedo, and land surface temperature) required for the estimation of areal evapotranspiration using SEBAL approach.

5.2.1 Surface Energy Balance Algorithm for Land (SEBAL)

The Surface Energy Balance Algorithm for Land (SEBAL) is a relatively simple parameterization of the energy balance and surface fluxes based on spectral satellite measurements. SEBAL algorithm requires spatially distributed visible, near-infrared and thermal infrared input data, from satellite imageries. SEBAL parameterization is an iterative and feedback-based semi-empirical procedure, which deduces the radiation, heat and evaporative fluxes. The algorithm computes most essential hydro-meteorological parameters and requires little field information (only incoming solar radiation, air temperature and wind speed data are required) (Bastiaanssen, 1998a &b, 2000). The energy balance during the satellite overpass and the integrated 24 hour fluxes are computed on a pixel by pixel basis.

The model comprises of a number of computational steps for image processing and finally calculates ET_a as well as other energy exchanges between land and atmosphere. By ignoring energy required for photosynthesis and the heat storage in vegetation, SEBAL (in its most simplified form) reads: $R_n = G_0 + H + LE$ where R_n is the net radiation absorbed at the land surface (W/m2), G_0 is the soil heat flux to warm or cool the soil (W/m2), H is the sensible heat flux to warm or cool the atmosphere (W/m2) and LE is the latent heat flux associated with evaporation of water from soil, water and vegetation (W/m2). The applied SEBAL method consists of a physically based one-layer sensible heat transfer scheme and an empirical estimation scheme for soil heat flux. The soil heat flux is computed as an empirical fraction of the net radiation by using surface temperature, surface albedo and the normalized difference vegetation index (NDVI), as dependant variables (Figure 5.1).

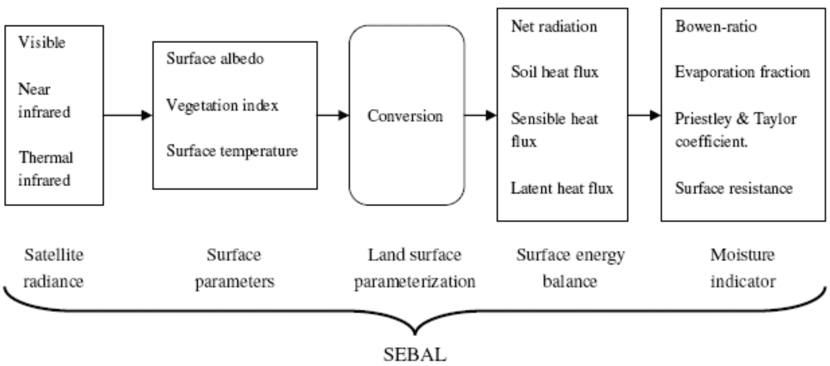

Figure 5.1: Conceptual scheme for SEBAL showing its principal components (Bastiaanssen *et al*., 1998).

5.2.2 Estimating Energy Balance Components

The surface energy balance is expressed as follows:

$$R_n = H + LE + G_o \tag{5.1}$$

where: R_n is the Net Radiation (W/m^2), H is the sensible Heat flux (W/m^2), LE is the Latent Heat flux (W/m^2) and G_o the Soil Heat flux (W/m^2).

5.2.2.1 Net Radiation (R_n)

Net radiation is the sum of all the incoming and outgoing heat fluxes (in both short wave and long wave) reaching and leaving a homogeneous flat surface (Verstraeten et al., 2005), usually expressed as follows:

$$R_n = K\downarrow - K\downarrow + L\uparrow - L\uparrow$$

where: ***K*** is the short-wave and ***L*** is the long-wave radiation respectively in W/m^2

$K_{net} = = K\downarrow - K\downarrow$ (Net short-wave radiation)

$L_{net} = = L\uparrow - L\uparrow$ (Net long-wave radiation)

$R_n = K_{net} + L_{net}$ can be expressed in terms of surface albedo, emissivity and temperature;

Thus $R_n = (1-\alpha)K\downarrow + \varepsilon_0\varepsilon_a\sigma T_a^4 - \varepsilon_0\sigma T_0$ (5.2)

where: ε_0 is the surface emissivity, ε_a is the air emissivity, σ is the Stefan-Boltzmann constant ($5.67*10^{-8}$ W/m^2K^4), T_a is the air temperature (K) and T_o is the land surface temperature (K) and α is the surface albedo.

5.2.2.2 Soil Heat Flux (Go)

The soil heat flux was computed using a relationship between net radiation, surface temperature, surface albedo and NDVI (Kustas et al., 2004).

$$G_o = c_G * \cos\theta * R_n * \exp\left(\frac{-\kappa LAI}{\sqrt{2*\cos\theta}}\right) \tag{5.3}$$

where: G_o is the soil heat flux, C_G and κ are constants 0.35 and 0.60 respectively, R_n is net radiation (W/m^2) as measured on the earth surface, θ is the solar zenith angle and LAI is Leaf Area Index

Koloskov (2007), however, observed that, over a 24 hour period, the soil heat flux is relatively small and can be ignored without introducing significant errors in the computation process.

5.2.2.3 Sensible Heat Flux (H)

This is the rate of heat loss to the air by convection and conduction, due to a temperature difference. Sensible heat flux is a function of the temperature gradient, surface resistance and wind speed and thus difficult to compute due to the fact that temperature gradient and surface resistance are a function of each other and hence at any time there are two unknowns in this functional relationship. The classical expression for sensible heat flux is given by Farah and Bastiaanssen, (2001) as:

$$H = \frac{\rho_a C_p}{r_{ah}} \partial T_a \qquad (5.4)$$

with

$$r_{ah} = \int_{Z_{down}}^{Z_{up}} \frac{1}{K_h} dz = \left[\frac{1}{ku_*} ln\left(\frac{Z_{up}}{Z_{down}} \right) \right] \qquad (5.5)$$

Where: ρ_a is the moist air density (Kg/m^3), C_p is the specific heat capacity of air at constant pressure (*J/KgK*), r_{ah} is the aerodynamic resistance to heat transport (s/m) and δT_a is the temperature difference between two heights Z_{down} and Z_{up} (m), K_h is the eddy diffusivity for heat transport, u_* is the friction velocity (m/s) and k is the Von Karman's constant.

The presence of hydrological extremes in the area covered by the image was crucial for specific solutions for the surface energy balance.

Assuming negligible sensible heat fluxes, $R_n = G_0 + LE$ was assigned to the wet pixels. This means that for the wet pixel, dT_a is 0, and for a dry pixel, dT_a is $((R_n + G_0)r_{ah})/\rho_a C_p)$. This relationship was used to determine dT_a for dry pixels using the initial estimate for r_{ah}.

It was also assumed that dT_a is linearly related to T_0 for all pixels thus a first estimate for the sensible heat flux was computed and subsequently used to obtain the integrated stability correction using the Monin–Obukhov similarity hypothesis (Eq. 5.6).

$$L = \frac{-\rho_a C_p u_*^{\ 3} T_o}{kgH} \quad (5.6)$$

This allowed for a second and improved estimation of $u*$ which, incorporated the stability correction for buoyancy effect on the momentum flux. The new value of $u*$ was then used to estimate r_{ah} by incorporating the stability correction for heat transport. This procedure was iteratively applied until H converged to the local non-neutral buoyancy conditions for each pixel. The energy balance was finally closed by considering the latent heat flux term as the residual term.

5.2.2.4 Latent Heat Flux (LE)

The latent heat flux represents the amount of energy required for evapotranspiration and is computed as the residual of the surface energy balance. By closing the energy budget on a pixel-by-pixel basis latent heat flux was obtained by inverting Eq. 5.1.
The instantaneous latent heat flux, *LE*, is the calculated residual term of the energy budget, and it is used to compute the instantaneous evaporative fraction (Λ).

$$\wedge \ = \frac{LE}{R_n - G} = \frac{LE}{LE + H} = \wedge_{day} \quad (5.7)$$

The instantaneous evaporative fraction (Λ) expresses the ratio of the actual to the potential crop evaporative demand when the atmospheric moisture conditions are in equilibrium with the soil moisture conditions. The instantaneous value can be used to calculate the daily value because evaporative fraction tends to be constant during daytime hours, although the *H* and *LE* fluxes vary considerably. The difference between the instantaneous evaporative fraction at satellite overpass and the evaporative fraction derived from the 24 hour integrated energy balance is marginal and may be neglected (Brutsaert and Sugita, 1992; Crago, 1996; Farah, 2001 and 2004; Nicholas and Cuenca, 1993; Akbari et al. 2007). For time scales of 1 day or longer, G_0 can be ignored and net available energy (R_n - G_0) reduces to net radiation (R_n). At daily time scales, LE_{24} (mm/day) can be computed as:

$$LE_{24} = \Lambda_{24} * (R_{n24}), \text{ since } G_{24} = 0 \quad (5.8)$$

Daily evapotranspiration (ET_{24}) in *mm/day* was determined from total daily available energy as:-

$$ET_{24} = \frac{86400 \times 10^3}{\lambda \rho_w} \Lambda R_{n24} \quad (5.9)$$

Where: R_{n24} (W/m^2) is the 24 hour averaged net radiation, λ (J/kg) is the latent heat of vaporization, and ρw (kg/m^3) is the density of water.

5.3 Results and Discussion

5.3.1 Spatio-temporal Distribution of Actual Evapotranspiration

The actual evapotranspiration (ET_a) was computed for July 12, 2000, 2003 and 2006 by solving the surface energy balance equation. ET_a values for each time period were extracted for different land cover/use types within the basin (Figure 5.3). It was observed that spatial variation of ET_a values ranged from 0 to 2 mm/day on bare or fallow lands, 3 to 4 mm/day on small scale farms, 3 to 5 mm/day on grasslands, 5 to 6 mm/day on large scale horticultural commercial farms and 7 to 8 mm/day on thick bushes and dense forests (Figure 5.2). Bare lands include rock outcrops and the degraded areas within the communal grazing lands for the pastoral communities found to the north of the basin and caused mainly by overgrazing. A discrepancy was however observed between ET_a values on small scale farms and those on large scale commercial farms with the latter exhibiting almost twice ET_a values compared to the former. This could be due to improved soil nutrient management strategy used by commercial farmers to enhance crop yields. Such strategies are absent on poorly managed small scale farms.

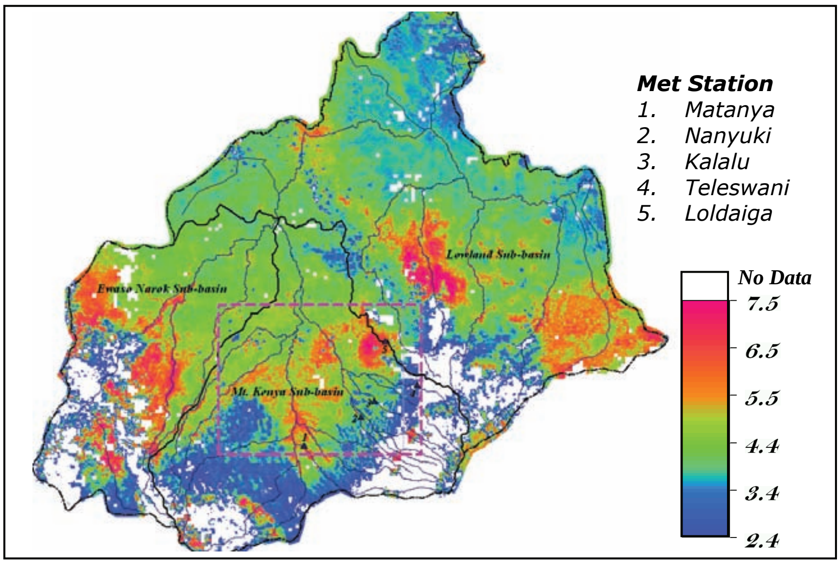

Figure 5.2: Spatial distribution of ET_a in the Upper Ewaso Ng'iro North Basin, Kenya, July 12, 2003 in mm/day.

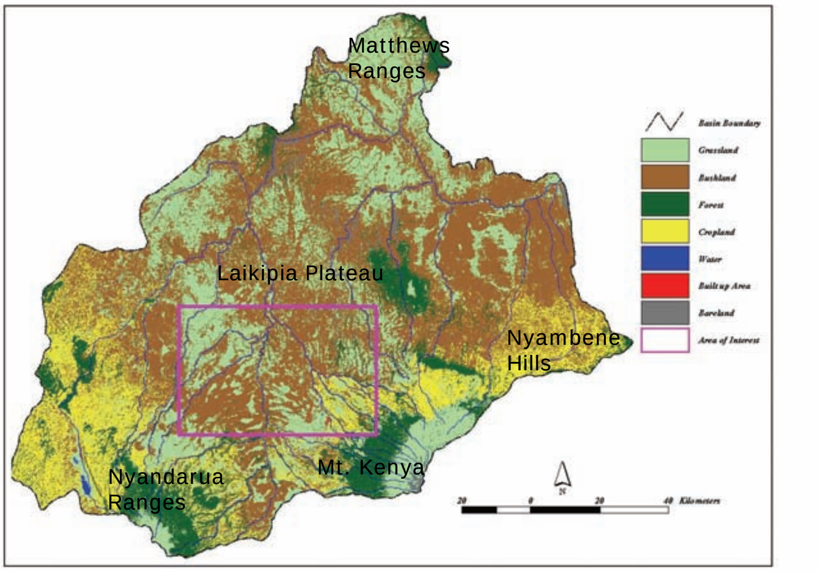

Figure 5.3: Land cover/use types in the Upper Ewaso Ng'iro North Basin, Kenya, 2003.

Spatial variation in ET_a values was observed from 2000 to 2006 (Figures 5.4, 5.5 and 5.6). The results show that ET_a values increased progressively from 2000 to 2006 with an annual increase rate of about 10%. This could be linked to the amount and distribution of rainfall for the same time periods. The year 2000 was indeed a dry year for the basin with annual average rainfall of about 600 mm/year which is below the annual average of the basin (700 mm/year) while the years 2003 and 2006 received a relatively higher annual rainfall of about 850 and 1050 mm/year respectively. Generally, the amount of rainfall received in the basin increases with increasing altitude.

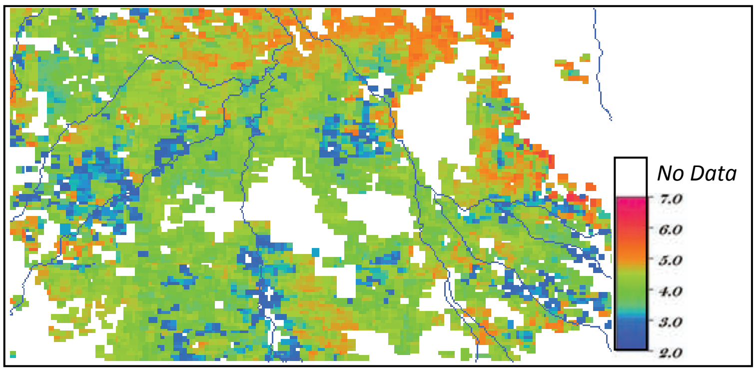

Figure 5.4: Daily *ETa* for July 12, 2000 in mm/day.

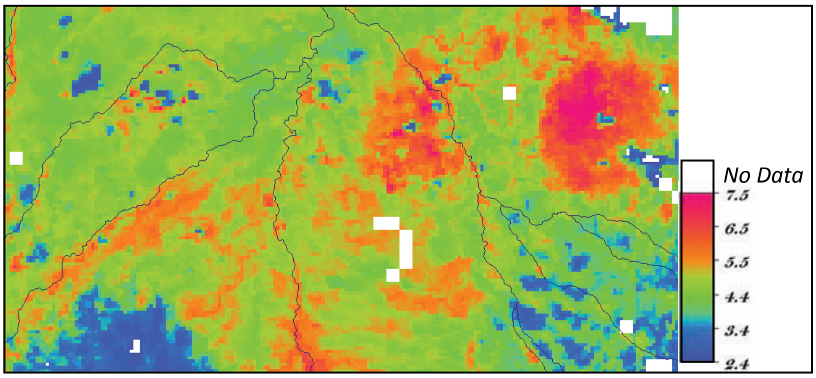

Figure 5.5: Daily *ETa* for July 12, 2003 in mm/day.

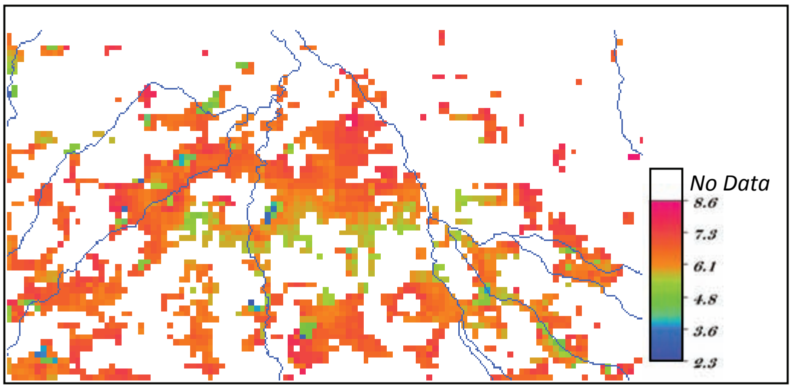

Figure 5.6: Daily *ETa* for July 12, 2006 in mm/day.

Daily ET_a values for the three time series were also compared with their respective NDVI values and a good correlation of about 60% was obtained (Figure 5.7A). NDVI is an indicator for vegetation and soil moisture conditions at the surface, and can be used to assess water stress levels in agricultural systems. It was observed that ET_a values increased with increasing NDVI values within the middle and low altitude areas (700 to 2,000 m a.s.l) of the basin (Figure 5.7A). This is because, at lower altitudes, water is the limiting factor and ET is controlled by water availability. However, in the higher altitude areas (2100 to 4000 m a.s.l), ET_a values tend to decrease with increasing NDVI (Figure 5.7B). The reason for this is that, at high altitude, temperature is the main limiting factor and this determines the different type of vegetation growing there and hence the negative relationship.

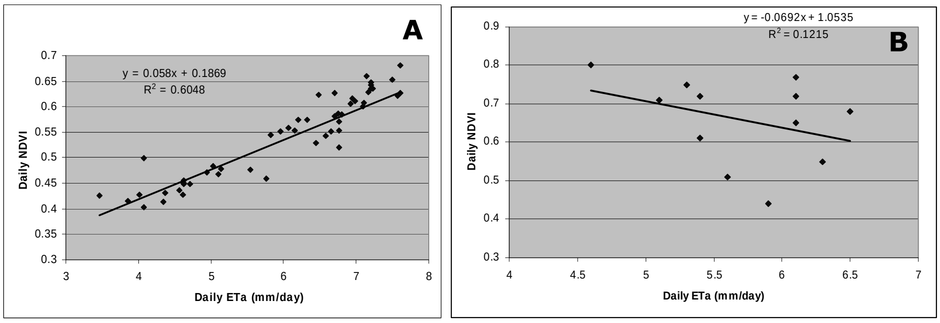

Figure 5.7: Daily *ETa* against NDVI at low altitude (A) and high altitude (B)

The highlands which are located on the foot zones of the mountain areas in the basin have lower ET_a values (3 to 4 mm/day) as compared to higher ET_a values (5 to 7 mm/day) found in the lowlands which have less vegetation cover and therefore experiencing higher rates of soil evaporation. The results further revealed that ET_a values increased with decreasing altitude (Figure 5.8), thus agreeing with the findings of Wiesmann et al., (2000). However, NDVI increased with increasing altitude (Figure 5.9) since vegetation density increases with altitude due to adequate rainfall and fertile volcanic soils found on the mountain slopes. Comparing ET_a results with in-situ values computed using FAO-56 approach, SEBAL tended to overestimate in most cases (Figure 5.10) although the values obtained from the two approches correlated relatetively well (Figure 5.11).

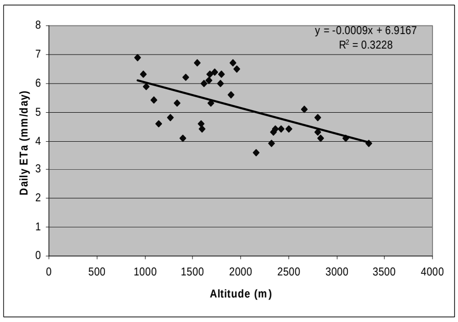

Figure 5.8: Daily *ETa* against altitude.

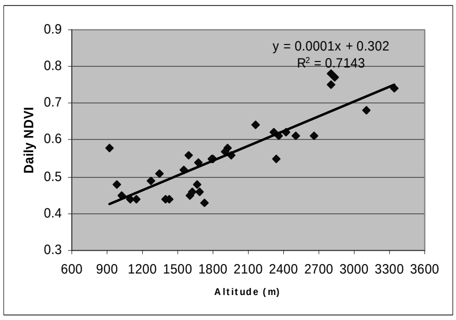

Figure 5.9: Daily NDVI against altitude.

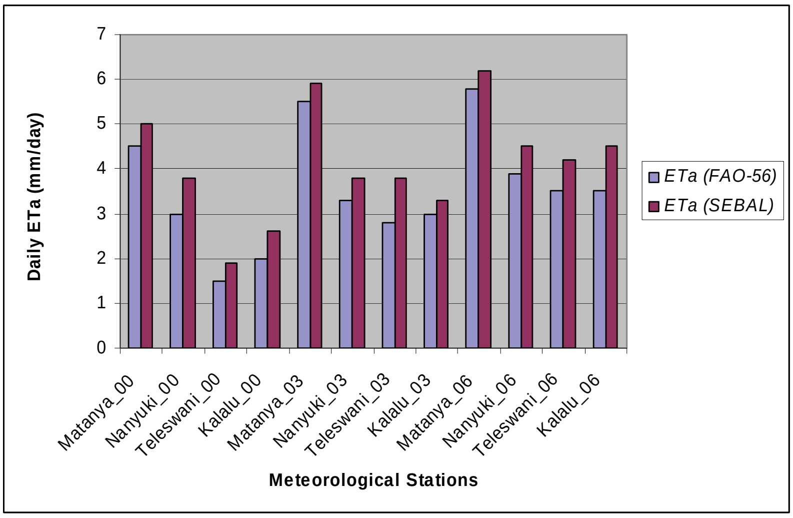

Figure 5.10: Comparing daily ET_a values from SEBAL and FAO-56 at different stations as shown in Figure 5.2.

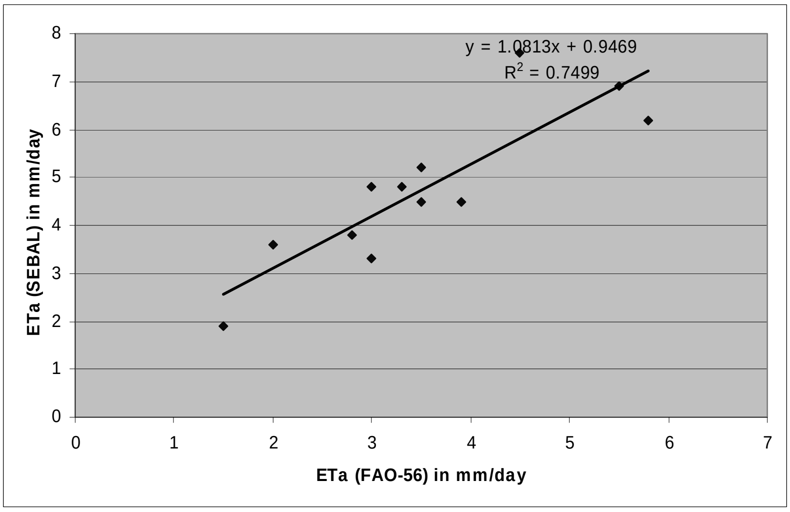

Figure 5.11: Comparing daily ET_a values from SEBAL and FAO-56.

5.3.2 Monthly and Annual *ETa* Estimation

Evapotranspiration is an important factor in a hydrological cycle and therefore it is crucial that this component is estimated accurately as it is an indicator of the available water resources in an area. The estimation of the monthly actual evapotranspiration from SEBAL (ET_{ms}) was done by spatially aggregating the daily mean actual evapotranspiration values derived from SEBAL (ET_{as}) proportionally to daily mean reference evapotranspiration (ET_o)

and daily cumulative evapotranspiration (ET_c) calculated from the meteorological measurements (Eq. 5.10). However, since ET_o and ET_c are only point estimates and do not represent the actual conditions at a specific pixel, the relationship was only used as an indicator of relative change in weather conditions within the area covered by the satellite image (Morse et al., 2000). Moreover, it was also assumed that soil moisture content will not change significantly within the month July since it is the end of the rainy season and so will the evaporative fraction (Farah et al., 2004). The mean annual ET_a was estimated by extrapolating the mean monthly ET_a (Eq. 11) to (Eq.12).

Thus $$ET_{si} = K_d{*}ET_{ds} \qquad (5.10)$$

Where: $K_d = ET_{oi} / ET_{ci}$ (daily evaporation rate)
ET_{si} = daily mean actual evapotranspiration from SEBAL for day i in July
ET_{ds} = daily mean actual evapotranspiration from SEBAL for July, 12
ET_{oi} = mean reference evapotranspiration from met station for day i in July
ET_{ci} = cumulative reference evapotranspiration from met station for day i in July

So monthly ET (ET_{ms}) $$= K_d \sum_{i=1}^{i=31} (ET_{si}) \qquad (5.11)$$

Where i = 1,2,3,……..31 for the month of July

and annual ET (ET_{as}) $$= K_a{*}ET_{am} \qquad (5.12)$$

Where: K_a = ET_{ms} / ET_{as} (monthly evaporation rate)
ET_{ms} = monthly mean *ET* estimated from SEBAL
ET_{am} = Annual mean *ET* measured at the met station

5.3.3 Water Balance of the Upper Ewaso Ng'iro North Basin

A simple water balance was computed for the basin by subtracting the mean annual evapotranspiration (ET_{as}) from mean annual precipitation (P). This was done for the three time periods under investigation assuming that the basin is closed and hence treating the water storage component as the closing factor of the water balance (Bastiaanssen and Chandrapala, 2003).

The annual rainfall distribution for each time period was obtained by performing simple kriging interpolation on the mean annual rainfall of 30 well distributed rain gauges across the basin and smoothing the results with the digital elevation model of the basin. Mt. Kenya sub-basin which is well gauged and contributes about 50% of the total surface runoff for the basin was used to compute the water balance.

The sub-basin is located in the upstream of the Upper Ewaso Ng'iro North basin and therefore treated as a closed basin taking precipitation as the only input. The results obtained were used to validate the ET_a derived from remote sensing products.

From the water balance concept, rainfall is partitioned as follows:

Precipation = Evapotranspiration - inflows + outflows ± change in storage

$$P = ET + R_{out} - R_{in} \pm \Delta W \qquad (5.13)$$

Where: P = annual precipitation,
ET = annual evapotranspiration
R_{in} = annual inflows
R_{out} = annual outflows
ΔW = change in water storage

However, for a complete hydrological period, a change in storage stabilizes and can be ignored.
Therefore, $P = ET + R_{out} - R_{in}$ and since the sub-basin is closed,

then $R_{in} = 0$

Therefore: $P = ET + R_{out}$ *and* $ET = P - R_{out}$ (5.14)

Where: R_{out} is the stream flow at the outlet of the sub-basin.

The annual mean ET_a was computed for the three time periods and compared with the annual ET_a computed from SEBAL. The results revealed that the two methods produced similar results with a correlation ratio of about 71% (Figure 5.12).

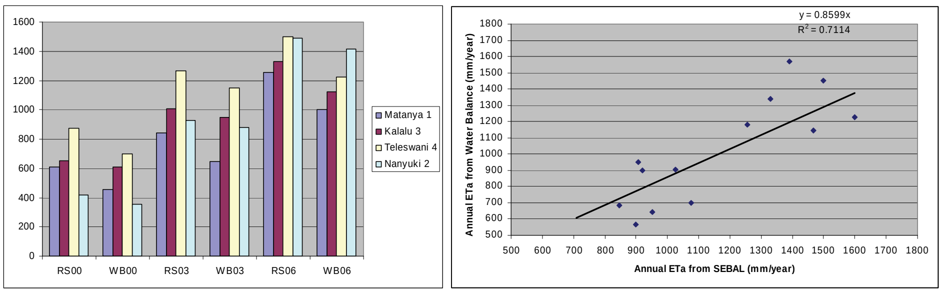

Figure 5.12: Comparing annual *ETa* values from SEBAL (RS) and Water Balance (WB).

The results obtained show a close correlation at the basin scale between ET_a values obtained from SEBAL (RS) and those from the water balance (WB) approach, clearly demonstrating the potential of the remote sensing based technique.

The total water storage in basin was also evaluated for the study period using Eq. 5.15

Thus: $P = ET + (R_{out} - R_{in} \pm \Delta W)$

where: $R_{out} - R_{in} \pm \Delta W$ = the total water storage (WS)

Therefore: $WS = P - ET$ (5.15)

where: P = Annual mean precipitation (mm/year)
ET = Annual mean *ETa* from SEBAL (mm/year)

The results revealed that the mean annual total water storage in the basin decreased with increasing annual mean ET_a from 2000 to 2006. Since the sub-basin is located in the upstream part of the Upper Ewaso Ng'iro North basin, it shows that water availability is becoming progressively less as one moves from upstream to downstream of the basin and this is currently a great concern especially to the water managers in the basin. To cater for the difference, farmers are adopting appropriate alternatives for water supply such as rainwater harvesting for supplementary irrigation. This practice is becoming more common especially in the middle reaches of the basin and need to be encouraged throughout the basin as a means of increasing water productivity.

Superimposing the total water storage with the existing water storage facilities in the basin shows that most of the water storage facilities are mainly concentrated in areas with more water storage (Figure 5.13). This is common particularly in the upstream areas, where both large and small scale irrigation farming are predominant. However, it was also observed that most of the storage facilities get their water supplies mainly from the rivers and streams causing their flows to greatly reduce especially during the dry season when irrigation is at its peak. This observation agrees with the findings by Kiteme et al., (1998b) that excessive water abstractions for irrigation in the upstream areas of the basin significantly contribute to increased water use conflicts between upstream and downstream water users.

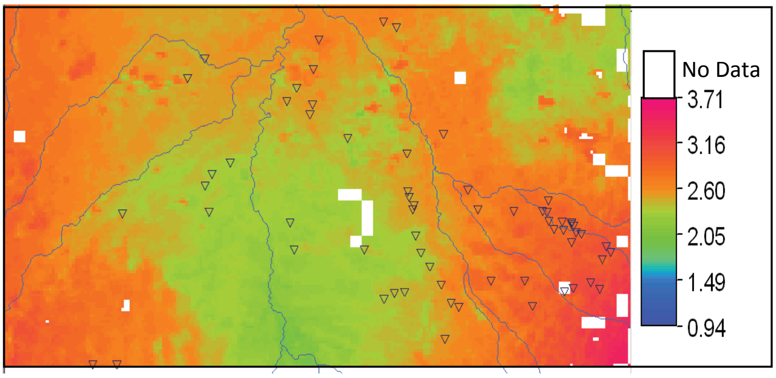

Figure 5.13: Annual total water storage, 2003 in mm/day.

5.4 Conclusion

The methodology used in this study enabled the estimation of the actual evapotranspiration (ET_a) in the Upper Ewaso Ng'iro North basin in Kenya using MODIS satellite images for 2000, 2003 and 2006. The estimated mean ET_a values (daily, monthly, annual) compared relatively well with those calculated using FAO-56 method. However, the correlation ratio improved from daily mean values to annual mean values (60% and 70% respectively).

Results from the study revealed that annual mean ET_a increased gradually from 2000 to 2006 at an annual rate of about 15% clearly demonstrating how water consumption has evolved over the years across the basin. Further, the spatio-temporal distribution of ET_a in different land cover/use types shows how water is being used. This information is particularly crucial for water resources planning and management because it shows when and where water is being used as intended.

In conclusion, SEBAL which is a remote sensing based technique has proved to be an effective means of assessing spatio-temporal patterns of water availability and consumption over large areas.

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CHAPTER 6

Water allocation as a planning tool to minimise water use conflicts in the upper Ewaso Ng'iro North Basin, Kenya

This chapter is based on:

Mutiga, J.K., Mavengano, S.T., Su, Z., Woldai, T. and Becht, R., (2010). Water allocation as a planning tool to minimize water use conflicts in the upper Ewaso Ng'iro North Basin, Kenya. *Water Resources Management, (24):3939-3959*.

Abstract

Inadequate water resources management and a general decline in rainfall have aggravated water scarcity problems in the Upper Ewaso Ng'iro North Basin in Kenya. Furthermore, water use conflicts in the basin have escalated in recent decades due to increased competition for available water resources. Excessive abstraction of the declining river water mainly for irrigation in the Mount Kenya and Nyandarua foot zones often leads to reduced water flow during the dry seasons, greatly affecting downstream water users. Increased water use in the basin coupled with deterioration of the vegetative cover has resulted in reduced water flows in the Ewaso Ng'iro river and its major tributaries. In addition, lack of sufficient knowledge about available water resources and current lack of coordination in water resources management in the basin often result in water deficits which have hampered development in the downstream catchment. The goal of this study was to match the water requirements of various competing sectors in the basin with the available water resources in order to attain both economic and ecological sustainability.

To achieve this, GIS techniques were used to quantify the spatial and temporal stream flow. The Water Evaluation and Planning (WEAP) model was applied to evaluate water resources development based on an equilibrium scenario of the current water demand. Water use was simulated for five different sectors (domestic, livestock, wildlife, irrigation and reserve). The analyses revealed that high water demand for irrigation was the main cause of excessive water abstraction particularly in the upstream catchments, giving rise to water shortages and consequently, water use conflicts downstream. The study, therefore, recommends that rainwater harvesting be promoted in the basin in order to improve water availability for productive use.

Keywords: *Water abstraction, Water Evaluation and Planning Model, Water demand, Water allocation, Water use conflicts, Scenario development, and Ewaso Ng'iro North basin.*

6.1 Introduction

Many countries in the world are facing formidable fresh water management challenges due to increased competition for the increasingly scarce natural resource. Overexploitation of water resources continues to be the greatest constraint on sustainable agricultural development, an important factor to poverty alleviation. Water has been recognized as an essential component of food security (UNWATER, 2006), with the World Summit on Sustainable Development in 2002 drawing more attention to the importance of water resources management in meeting the Millennium Development Goals (MDGs) (UN, 2002).

Water resources sustainability means using the natural resource wisely and protecting the complex ecosystems with future generations in mind. But sustainability will not be achieved with current patterns of resource consumption and use (UN, 2005). It is therefore of paramount importance to rational planning and decision making in equitable water management. This must be undertaken within the widely accepted integrated approach at all levels of the society.

Mountains often function as water towers of the earth and are rich in biological diversity, making them target areas for recreation. Approximately 12% of the world population depends directly on mountain resources (UNCED, 1992). Mountain environments are essential for survival of global ecosystems, but their function as water towers is rapidly under threat as competition for natural resources increases. They are susceptible to accelerated erosion, landslides and rapid loss of habitat and genetic diversity (Odermatt, 2004). There is therefore a need to focus more on these regions to preserve their status as major water sources.

The high plateau of the Upper Ewaso Ng'ro North Basin in Kenya and the mountain foot zones referred to as the "White Highlands" during the colonial period consisted of ranches and large farms. After independence in 1964, the basin experienced changes in land use as land was subdivided into smaller plots for agro-pastoralists as people resettled from overpopulated foot zone areas. As a result, growth points such as towns and densely populated small scale farms as well as with large scale technical horticulture farms have been formed in the mountain foot zones while game parks and tourist resort centres occupy the dry lowlands of the basin. The population increased from 50,000 in 1960 to 500,000 in 2000 and has put demand for water resources under pressure (Kiteme and Gikonyo, 2002). As more land is being converted to irrigated land to grow crops mainly for international markets, farmers now place their water intakes high up on the mountain in the tributaries of Ewaso

Ng'iro river. At the same time, pastoralists and small scale farmers are establishing small scale irrigation schemes (Wiesmann et al., 2000). These developments affect communities, wildlife and the ecology downstream of the basin as water becomes scarcer. For instance, 98 abstraction points within a 30 km river reach, provide water to about 30,000 people. About 97% of this abstracted water is being used to irrigate only 9% of the total basin area (Aeschbacher et al., 2005), and thus greatly contributing to water shortages downstream and hence conflicts.

The Upper Ewaso Ngiro North Basin has a high economic status in the country due to its intensified agriculture, forestry and game reserves attracting tourists from all over the world. It offers a great deal of beautiful scenery. Therefore, careful management and negotiation of water resources is a priority in order to mitigate growing water crises and conflicts at local and national levels. While a lot of research has been done in the basin on water resources aspects, focus has been around the Mt. Kenya area which is the main contributor of the Ewaso Ng'iro river (Aeschbacher et al., 2005; Ngigi et al., 2006; Notter et al., 2007) while no studies have been undertaken in the downstream catchments. Yet, in recent years (especially 1999 to 2002) the lower catchments have experienced water crises to an extent previously unknown (Aeschbacher et al., 2005).

Population growth and the intensification of irrigation on agricultural lands in the foot zones and along the rivers in the plateau have dramatically increased water demand over the past decade (Notter et al., 2007). As a result, water abstraction for irrigation, livestock and domestic use have severely stressed the water resources, particularly during dry seasons causing conflicts between upstream and downstream water users. There is therefore a need to understand the spatial and temporal water availability and to formulate a tool for planning and decision making in prioritisation of water allocation in the basin. However, given the complexity of the system and the interactions between water supply and demand, a large-scale water supply management tool would be useful for decision makers when formulating water management strategies for coping with future changes in water demands (Chung et al., 2008).

To contribute towards this goal, the current study adopted and applied Water Evaluation and Planning (WEAP) model as a decision support system (DSS) to assess water availability and investigate the impacts of different water allocation scenarios (water demand management strategies) aimed at meeting various sectorial water demands in the Upper Ewaso Ng'iro North basin in Kenya.

6.2 Materials and Methods

6.2.1 WEAP for Water allocation

WEAP, which is an object-oriented computer modeling package, is an Integrated Water Resources Management (IWRM) tool designed for simulation of water resources systems and trade-off analysis. The tool operates on the premise that water supply is defined by the amount of precipitation that falls on a watershed or a series of watersheds, with the supply progressively becoming depleted through natural watershed processes, human demands and interventions, or enhanced through watershed accretions. These processes are governed by a water balance model concept that defines watershed scale evaporative demands, rainfall-runoff processes, groundwater recharge, and irrigation demands (Yates et al., 2005 a&b; Purkey et al., 2007).

The model simulates water system operations within a river system with basic principles of water accounting on a user-defined time step, usually a month. Simulation allows the prediction and evaluation of "what if" scenarios and water policies such as water conservation programs, demand projections, hydrologic changes, new infrastructure and changes in allocations or operations (Raskin et al., 1992; Yates et al., 2005; Purkey et al., 2007; SEI, 2008). Thus WEAP is considered as an integrated water management tool for evaluating water use and allocation with a greater focus on balancing supply and demand in a swift and transparent way. Since no comprehensive work has been previously done on IWRM in the study area, adopting a user-friendly interface such WEAP could enhance building a shared understanding of the water supply and demand system, problems and their causes; exploring and expanding solution options; and developing and evaluating alternatives for the Upper Ewaso Ng'iro North basin (Ubbels and Verhallen, 2001).

WEAP model was applied by simulating recent base year or 'business as usual' account, for which water availability and demand was determined. This information was obtained from different water users/stakeholders in the basin through group discussions and individual interviews conducted during the fieldwork campaigns. The model was first configured for the whole Upper Ewaso Ng'iro North basin in form of a continuous set of three sub-catchments (Figure 6.1). It was then used to simulate alternative scenarios to assess the impacts of different development and management options. This was possible since the model has the ability to optimize water use in the catchment using an iterative linear programming algorithm with the objective of maximizing the water delivered to demand sites according to a set of user-defined rules (SEI, 2008).

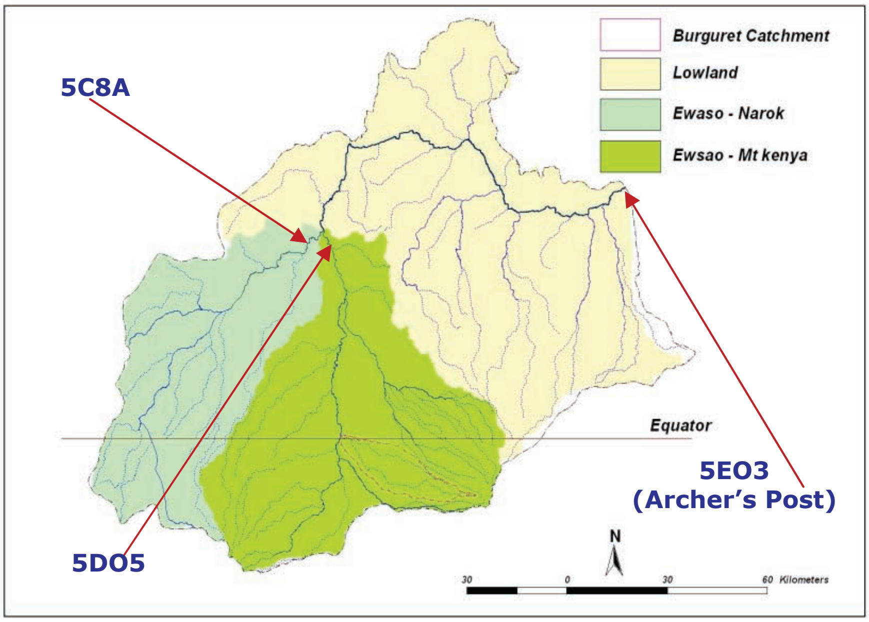

Figure 6.1: Main sub-basins in the Upper Ewaso Ngiro North Basin, Kenya.

The application was defined by time frame, spatial boundaries, system components and configuration of the problem. The Current Account, which is the calibration step of the model, provided the actual water demand, resources and supplies for the system. Scenarios built on the current account enabled the exploration of the impact of alternative policies on future water availability and use. Construction of different scenarios was based on alternative sets of policies, which were evaluated with regard to water sufficiency, costs and benefits (SEI, 2008). During this study, WEAP analyses were underpinned on the available data for the three sub-basins (Figure 6.1) on a monthly time step. Fieldwork carried out in the basin also provided some crucial data not found in the existing archives such as water abstraction points and crops types under irrigation

6.2.2 Surface water supply

The long-term variation in surface water at Archer's Post station of the Ewaso Ng'iro river shows clearly the reduction in the flow discharge. The minimum annual discharge at Archer's Post (5EO3) decreased proportionally to the increase of water abstraction in the upper catchments of the basin. For example, in low rainfall periods, February is one of the worst months of the year with the river reach upstream of Archer's Post drying up, clearly showing the limitations for further development potential of surface water.

6.2.3 Domestic water demand

The Domestic Water Supply requirement within the basin is primarily concentrated in the urban and rural centers which have been identified and lumped for the three sub-catchments (Figure 6.1). The centers are mainly concentrated in the sub-humid districts of Nyandarua, Nyeri, and Meru located on the slopes of Nyandarua ranges and Mt. Kenya. However, in the arid and semi arid districts (Isiolo and Samburu), urban and rural centers are generally concentrated close to major water sources such as permanent rivers, ephemeral streams, springs, wells and boreholes. About 70% of the total population in the basin is dispersed in rural communities. The total consumptive water requirement was based on 1999 population census, with a total human population of about 500,000 in the basin. A unit water requirement of 50 litres per person per day (Gleick, 1996) was used for WEAP domestic water demand calculations.

6.2.4 Livestock and wildlife water demand

A unit water requirement of 50 litres/ day for each livestock unit was given as the unit consumption rate to estimate the water demand for all livestock and wildlife in the basin. Livestock and wildlife figures were also based on 1999 census data, estimated to about 700,000 for the basin.

6.2.5 Reserve requirement

The key principles of the Kenya Water Act (2002) are sustainability and equity. The Act asserts that, in conjunction with using water resources to promote social and economic development, it is essential to protect the environment while ensuring that the water needs of present and future generations can be met. This is partly achieved by leaving enough water in a river, referred to as the "reserve", to maintain its ecological functioning and as such, it was assigned the highest priority over all other water uses and must strictly be met before water resources can be allocated to any other uses.

6.2.6 Irrigation water demand

Irrigation is the largest water user in the basin. The total area under irrigation in the basin is about 46 km^2 (commercial, small-scale and community schemes) with most of the farms being located on the north-western slopes of Mount Kenya. Most crops in the area are only irrigated in the dry season, (February to March and July to September). Since there is no data available on the exact amount of water used for irrigation and farmers do not know how much water they use for irrigation, irrigation water demand for the basin was calculated using the reference evapotranspiration (ET_o) and effective precipitation (P) concept as outlined in FAO-56 (Allen et al., 1998). Total water demand for irrigation was thus estimated by multiplying the total area under irrigation with the average water requirement for the main crops (Liu et al., 2010) in the basin using the following irrigation parameters (Reference potential Evaporation, ET_o, average crop factor, Kc = 0.80 (Table 6.1) and irrigation efficiency, ή1 = 40% ή2 = 85% for the reference (business as usual) and improved irrigation efficiency account respectively in the basin.

Table 6.1: Average crop coefficients for the common crops grown in the basin

Crop Name	**Average Kc for the total growing period**	**Average Kc For all crops**
Beans	0.88	
Cabbage	0.75	
Maize	0.88	
Onions	0.85	
Peas	0.88	0.80
Pepper	0.75	
Potatoes	0.82	
Tomatoes	0.82	
Wheat	0.85	
Rose flowers	0.70	

Adopted from FAO-33; Source: Allen et al., 1998.

6.3 Modelling water demand and supply

Decisions on water allocation require methods which allow for changes in water availability to be estimated spatially and temporally under a range of climatic conditions. Hydrological models provide the means to investigate the relationships between climate, human activity and water resources (Van Heerden et al., 2008). Supply-oriented simulation models are not always adequate for allocation of water resources, environmental and policy issues, therefore an integrated approach for water resources development has emerged, which places water supply projects in the context of demand-side issues, as well as issues of water quality and ecosystem preservation (Yates, 2005). WEAP model was selected for this study as it incorporates all these values into a practical tool for water resources planning (SEI, 2008). Water demand baseline data for the basin were obtained from the Water Resources management Authority (WRMA) regional office database for the year 2000 which was considered as the base year for this study.

Irrigation is the highest water consumer taking about 80% of the total water available in the basin. The total water demand in the basin is estimated to be about 950,000m^3/day. An important aspect of WEAP is its ability to distinguish between the "*business as usual*" scenario and the alternative policy scenarios. The "*business as usual*" also referred to in this study, as the reference scenario, incorporates current trends in both economic and demographic development, water supply available, water use efficiency and water pricing policies. Thus, the "*business as usual*" scenario analysis provides a reference against which the effects of alternative policy scenarios were be evaluated. A schematic diagram of the WEAP model for the Upper Ewaso Ng'iro North Basin in Kenya (Figure 6.2) shows all the demand sites and various water sources (streams, groundwater, and dams).

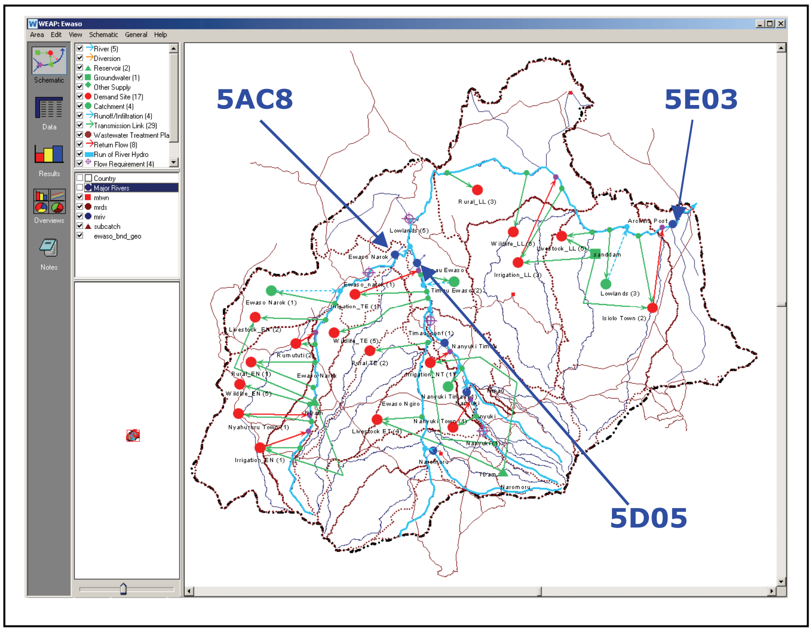

Figure 6.2: Schematic diagram showing the configuration of the *WEAP* model for Upper Ewaso Ng'iro North Basin in Kenya.

The model was calibrated and validated using the 1965 – 1980 data sets from three flow monitoring stations in the basin (Figure 6.1). This period was selected as it represents the naturalized flow of the basin since irrigation activities started in the early 1990s (Aeschbacher et al., 2005). Since there is no automatic calibration routine in the model, visual comparison of the observed and the simulated time series monthly flow was carried out for gauge 5DO5 which had adequate clean data for the selected period (Figure 6.5). Calibration was necessary in order to evaluate performance of the model. The percentage error in the simulated mean annual river flow using WEAP compared to the observed (measured) was found to be 0.18% with good simulations obtained during the dry seasons (Figures 6.3 and 6.4).

In general, the model simulation of the stream flow compared favourably well with the observed/ measured flow, exhibiting similar seasonal variability while capturing the general inter-annual trends. The model parameters were used to derive the discharge for all streams in the basin for the entire planning period (2000-2015) and subsequently allocate the available water to various existing demand sites in the basin (Figure 6.5).

The available data for the observed stream flow for the gauge station 5DO5 were used for simulation of discharge from the rainfall-runoff model within WEAP. Rainfall-runoff method was chosen since it best suited the characteristics of the basin, and required only one input variable (precipitation). Model simulation facilitated the assessment of water availability in the basin both in space and time.

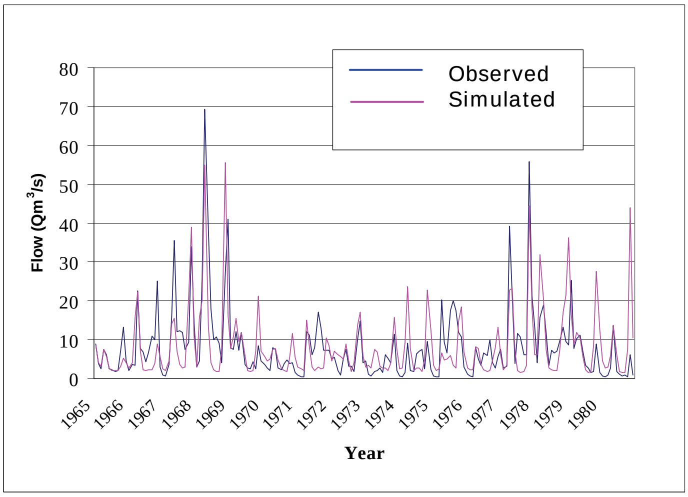

Figure 6.3: Simulated WEAP and observed flow at gauge 5DO5

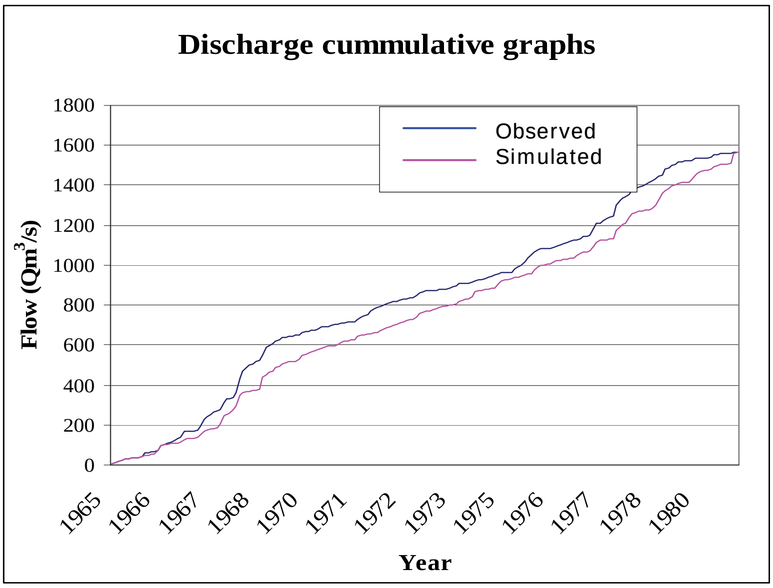

Figure 6.4: Cumulative WEAP simulated and observed stream flow at gauge 5DO5.

Estimated current water demands for the five different sectors were used for the reference scenario (Figure 6.6) from the "*naturalized*" stream flow (1965-1980). This period was selected because irrigation activities started in the early 1990s (Aeschbacher et al., 2005), which is believed to be the beginning of water use conflicts in the basin, as observed by Kiteme and Gikonyo (2002). Demands were fixed for the entire planning period representing an "*equilibrium*" type of scenario with a total annual water demand of 113 million cubic metres (MCM) for all sectors in the basin. Groundwater supply from 96 working boreholes was included to meet part of the demand. An average supply rate of 2 m^3/hr per borehole was used to meet part of the livestock and population demands, particularly in the basin lowlands. However, the total water demand almost double (220 MCM) by 2015 as a result of increase in both human and animal population in addition to changes in land use (increased area under irrigation) as illustrated in table 6.2.

Table 6.2: Water demand distribution for different sectors in the reference scenario

Sector	2000-Demand (MCM)	%	2015-Demand (MCM)	%
Domestic	11	10	23	10
Livestock	7	6	13	7
Wildlife	4	3	9	4
Reserve	1	1	3	1
Irrigation	90	80	172	78
Total	113	100	220	100

The reference scenario is helpful in understanding the current trend or the real situation in relation to water resources management in the basin. This scenario was used in designing future contingency plans for basin aimed at improving its environmental integrity.

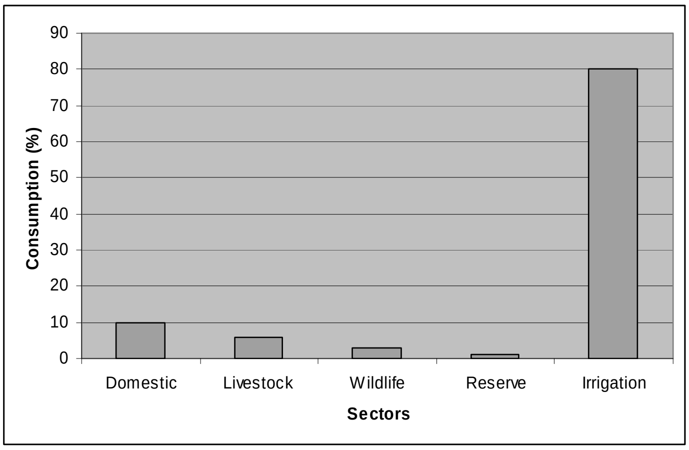

Figure 6.5: Water demand in different sectors for the reference scenario in the Upper Ewaso Ngi'ro North Basin, Kenya.

Water allocation models must accurately represent the significant features of water resource systems within any catchment. Ideally they should simulate water availability and demand (Etchells and Malano, 2005). Priorities for different demand sites in the basin were set on the basis of the true order of priorities that exist within any catchment (i.e. between different sectors) as well as the probable realities of upstream-downstream allocations.

Demand priority in this case, represented the level of priority for allocation of the available water resource (SEI, 2008; Al-Omari et al., 2009). This means, for example, that all the demand sites with the highest priority would be supplied first before moving to lower priority sites until all the demands are met or all the available resources are used, whichever comes first.
It was observed that water rights in some farms already do exist. For example, in the "*business as usual*" scenario, the Mt. Kenya and the Ewaso-Narok sub-catchments (Figure 6.1), supply priority was given as (1) since they are both located in the upstream of the basin but on different supply sources while the laikipia lowlands demand sites, a priority (2) was given as it is dependent on these two upstream catchments. This means that demand from all upstream activities would have to be met first, before the demands located in the lower reaches of the basin are met and this represent the "business as usual or the current account" scenario (Table 6.3). However, in order to promote equitable water allocation in sectors, prioritization of water use rights (Table 6.4) is a prerequisite in mitigating water use conflicts in the

basin. It should be noted that the current account provides a snapshot of actual water demand, resources and supplies to the system for the current or baseline year.

Table 6.3: Priorities for different demands in the "*Business as usual*" Scenario

Sub-Basin	Domestic	Livestock	Wildlife	Reserve	Irrigation
Mt. Kenya	1	2	4	9	3
Ewaso-Narok	1	2	4	10	3
Lowlands	5	6	8	11	7

Table 6.4: Priorities for different demands in accordance with the Water Act (2002)

Sub-Basin	Domestic	Livestock	Wildlife	Reserve	Irrigation
Mt. Kenya	1	2	1	1	3
Ewaso-Narok	1	2	1	1	3
Lowlands	1	2	1	1	3

Irrigation, which constitutes all irrigated farms in the mountain foot zones, had the largest annual water demand of 90 MCM, about 80% of the total water demand, while wildlife in the laikipia lowlands had the least demand of about 1%, (Figure 6.5). Stream flow during the dry season (February 2005) showed virtually no flow after the confluence of Ewaso-Narok and Mt. Kenya catchments. It was observed during fieldwork surveys that flow only occurred up to Ewaso-Narok swamp, located a few kilometres upstream of the gauge 5AC8 (Figure 6.1).

Other activities found downstream of the basin such as tourism, which depend on wildlife, are the most affected during this period and have to resort to alternative means of water supply. This scenario was used to replicate the present situation (present state of affairs) as much as possible and the results revealed that in February, when water use conflicts are highest, stream flow from the upper catchments did not get to the middle reaches of the basin (Ewaso-Narok and Mt. Kenya rivers confluence) meaning that, the stream flow at 5EO3 (Archer's Post) originated mainly from the Laikipia lowlands.

The total unmet demand for water (Figure 6.6) is of importance for planning purposes as it can easily be linked to the economy of an area. As a matter of fact, it forms the main reason for conflicts as other sectors are deprived of the economic benefit from the water resources. Unmet demand in this case is defined as the quantity of water that cannot be physically delivered from the river during a part of the year.

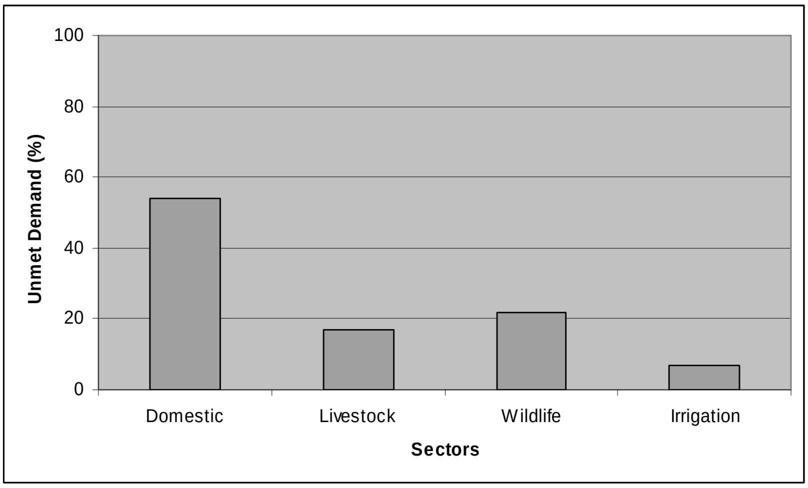

Figure 6.6: Unmet demand for different sectors in the reference scenario in the basin.

Through field assessment, it was observed that the Ewaso Ng'iro river often dried up for a considerable stretch from Archer's Post, when no rainfall was received in January, February, June and/or September, depending on the rainfall season. During these months, groundwater formed the main water supply for sectors in the lower catchments, and though boreholes yield 2 m^3/hr, this was still insufficient for other demands such as agriculture and wildlife. However, other alternatives such as deep wells not modeled in this study due to insufficient data available might be seen as alternative sources of supply. Nevertheless, the situation is likely to deteriorate in future due to ever increasing demand for water. Therefore, immediate action is required to address the declining stream flow, the main cause of the current water use conflicts in the basin particularly between upstream and downstream users.

6.3.1 Scenario Analysis

Scenarios are defined as alternatives or a set of assumptions (operating policies, pricing, and demand management strategies and alternative supply sources). Changes in these assumptions could either grow or decline at a varying rate over the planning horizon. Scenario projections for this study were established in WEAP based on economic, demographic, hydrological, and technological trends starting from a "*reference*" or "*business-as-usual*" point. For example, it was observed that increasing human, livestock and wildlife populations (doubling), caused a significant increase in water demand and hence an increase in unmet water demand if no appropriate measures are put in place to counter the effect.

Similarly, changes in land use such as increasing the area under irrigation (doubling) resulted in an increase in water demand and consequently increasing the unmet demand (Figures 6.7A & B). During the planning horizon (2000 – 2015), three different scenarios were constructed reflecting alternative paths for future water resources development in the basin. These scenarios included alternatives such as the construction of storage dams for flood harvesting, increasing water use efficiency, maintaining reserve flow, allocating water equitably and exploiting ground water (Figure 6.8). During scenario analysis, WEAP model was found to be sensitive to various input parameters (population growth, land use changes, groundwater storage, and irrigation efficiency) as shown in Figure 6.7.

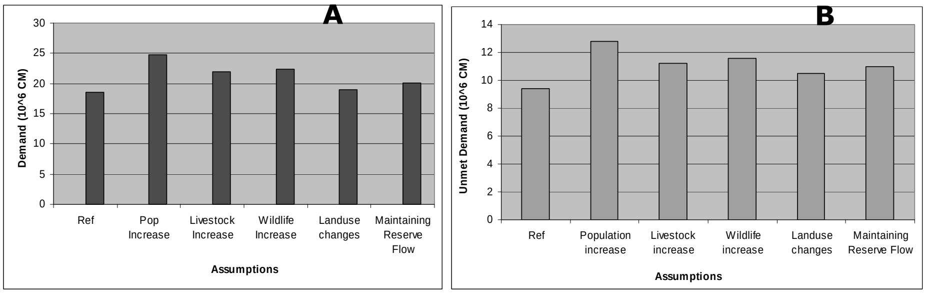

Figure 6.7: Water demand (A) and Unmet water demand (B) for different sectors with different assumptions in the basin.

6.3.2 Irrigation

Agriculture contributes about 30 % to the total regional gross domestic product (RGDP) while the other sectors (tourism, transport, communication, business services and community social services) contribute the remainder. Using irrigation water productivity rates of US$1.24/m^3 for crops (Sayeed, 2001) and US$0.06/m^3 for livestock and assuming that water productivity rate for both tourism and social services is US$2.4/m^3, the economic value, various services derived from the use of water was estimated. All these services are dependent on the "*Reserve*", which is defined as the quantity and quality of water required to satisfy basic human needs for all people who are or may be supplied from the water resources and to protect aquatic ecosystems in order to secure ecologically sustainable development and use of the water resource as defined in the Water Act (2002).

6.3.2 Water rights allocation

The Water Act (2002) provides an enabling environment for the implementation of water conservation and demand management measures. During this research, such measures were considered to be an important approach when reconciling water demands and water supplies in the Upper Ewaso Ng'iro North basin. When there is insufficient water, the allocation plan needs to promote equitable distribution to mitigate resource based conflicts by formulating strategies such as prioritization of water use. This process is guided by the priority as described in the Water Act (2002) which ranks the reserve and domestic water requirements above other uses (Table 6.4). In all the scenarios, therefore, domestic water use is given priority (1) as it is mandatory according to this legislation. Boreholes in the laikipia lowlands are set at supply priority (1) for domestic and livestock use, to augment water supplies during dry periods.

This scenario satisfies water demand downstream according to the water allocation hierarchy in the Water Act (2002).

6.3.3 Demand management strategy

WEAP model is unique in its capability to represent the effects of demand management strategies on water systems. Irrigation is the only activity that allows an evaluation of the effects of improved technologies. These strategies consist of measures, which farmers can take (e.g, switch crops, change planting dates, use water saving technologies or grow high value crops) to minimize water demand. This is important, particularly in the rapidly intensifying horticultural industry in the basin, where flowers such as roses fetch the highest profits as they are destined for the overseas markets.

6.3.4 Improving irrigation efficiency

Improving water use efficiency entails shifting from less efficient systems (flood or furrow, portable sprinklers) to more efficient ones (center pivot and drip irrigation) usually regarded as the gold standards of irrigation efficiency (Perry et al., 2009). The main water use in the basin is irrigation (80 % in the "*reference*" scenario). In this study, efficiency relates to water use at farm level and includes the efficiency of conveyance, distribution and application. Gravity pipeline systems are common in the upper catchments while furrow systems dominate in the lower areas where slopes allow for open channel water conveyance for flood irrigation methods. Gravity pipeline systems account for about 29% of the total abstraction points which translates to about 97% of the total abstracted volume, with the hydraulic structures said to be "*geared towards meeting the full water demand for the upstream abstractors*" before excess water is released downstream (Rural-Focus-Ltd, 2004). In this scenario, irrigation efficiency is assumed to have improved from the current 40% to 85%.

Improved irrigation efficiency can be achieved by managing demand through lining of the intake canals, proper maintenance of gravity pipelines and promoting water saving technologies for irrigation such as drip irrigation instead of the commonly used portable overhead sprinklers. It was observed during fieldwork, that some crops grown in the open would produce better yields if grown under greenhouse conditions in addition to good irrigation scheduling if high efficiencies are to be obtained. Implementation of this strategy significantly reduced daily irrigation water demand for the basin by about 18%, thus making more water available for the other sectors.

6.3.5 Groundwater use

Groundwater potential and safe abstraction rate in the Mt. Kenya sub-basin is estimated to be about 142.4 MCM (JICA, 1992) and can be used to complement surface water. It was established that if the existing boreholes (about 96 in good working condition) could be further developed, their average safe yield rate could improve to 10 m^3/hr and 6 m^3/hr in the Mt. Kenya and Ewaso-Narok sub-basins, respectively. This means that in order to take advantage of the existing groundwater potential, more boreholes need be drilled in the upstream part of the basin where recharge rates are high. The rate of replenishment of groundwater in this area is estimated to be about 120-220 MCM/year (JICA, 1992). The upper sub-basins can therefore produce sufficient water supply from groundwater abstraction to meet the total water demand by using only about 5% of the recharge. However, groundwater levels in these areas vary from 18 to over 200 m in depth resulting in high drilling, equipping and pumping costs.

6.3.6 Building storage dam

Development of reservoirs is part of the plan by the Ewaso Ng'iro North Development Authority (ENNDA) and other stakeholders in the basin for supporting socio-economic development activities. Analysis of results from this scenario showed that the water prioritization policy, would cause more water flow downstream leaving part of irrigation water demands unmet. For the "*business as usual*" scenario, water availability would increase when the demand was lowest and source development would only be possible if water could be stored into dams.

The results from this study indicate clearly, that an integrated approach for the development of water resources in the basin is necessary in order to meet the water requirements of all sectors to avoid competition and conflicts in water use and at the same time optimize the use of limited water resources. Dams can be multi-purpose and used for storage, domestic supply, flood regulation or irrigation. Suitable dam sites have been identified in the upstream of the basin, based on both bio-physical and socio-economic factors. Two dams were incorporated in this scenario and result analysis showed that building the dams would reduce the unmet water demand by about 5% (Figure 6.8). This is considered to be a significant contribution towards making more water available to the downstream users as well as reducing the current water use conflicts in the basin.

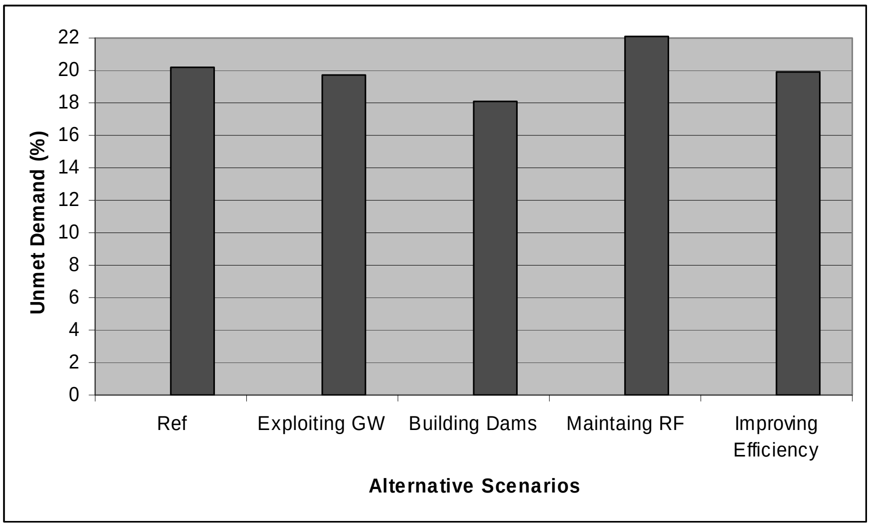

Figure 6.8: Unmet water demands for alternative scenarios**.**

It was observed that unmet water demand would decrease if groundwater was be used to complement the available surface water. Similarly, the building of flood water storage dams would significantly reduce currently unmet water demand. However, if reserve flow would be secured, the unmet demand would drastically increase thus escalating an already miserable situation. If implemented, this scenario would deny some economic sectors, particularly irrigated agriculture, substantial economic benefits (US$10M to US$62M).

Improving irrigation efficiency would improve supply, but in February, August, September, downstream water demand for wildlife would not be met (therefore affecting tourism) during low rainfall seasons unless the cropping calendar is changed. Improvement of farm technologies to achieve high crop yield and quality would improve the downstream flow while ensuring that water demands in Laikipia lowlands are met.

For example, in February 2005, stream flow improved at Archer's Post according to this scenario, but irrigated fields upstream experienced shortages and this affected the regional gross domestic product (RGDP) of the area.

6.4 Conclusion

Currently, forecasts on how water development or growth will change over time are only possible if reforms in the agricultural sector which constitutes 65% of the total water demand are implemented. During the fieldwork campaigns, it was observed that people are relocating from the mountain areas to the lowland areas, resulting in more land sub-divisions into small plots unviable for any agricultural activity. This has affected the growth of tourism and livestock in the basin which depends on the performance of the agricultural sector under the prevailing limited water resources. The scenario based on the current situation in the basin can provide insights in understanding the cause of water use conflicts and hence facilitate in formulating appropriate recommendations. By linking model outputs with water productivity data, it is possible to make preliminary estimates of the economic costs for each scenario. Based on simple assumptions, the estimates are believed to be indicative of the economic costs and benefits for different water management strategies.

Water allocation phase begins when available water resource is near depletion due to increased demand and managing it becomes very critical. Efforts to increase the productivity or value of every drop of water become so crucial. As competition for water increases, water is re-allocated from "*lower value*" uses (irrigation) to "*higher value*" uses (domestic and tourism). The Water Act (2002) sets priorities for water allocation with irrigation demand, being the lowest in the hierarchy. If this policy is enforced, it is believed that flow would improve downstream (even during the driest month of February) to an average of about 2.44 m^3/s. This scenario would ensure that in the event of low flows, downstream releases are given the highest priority.
Results from this study, have revealed that improving irrigation efficiency would significantly improve water supply for downstream areas and consequently reduce the unmet water demands. This can be achieved through improved control and timing of water application during irrigation, ensuring easy implementation of supplementary irrigation strategically to overcome seasonal dry spells. It is important to introduce suitable crops that can withstand the dry spells and encourage communities to practice crop rotation with a sense of economy in mind.

Nevertheless, a greater potential for better water resource management, to improve water use efficiency lies in soil and water conservation practices for rain-fed agriculture. Under rain-fed agriculture, water conservation aims at reducing runoff and evaporation losses while increasing water supply to the soil and thus to the plants. This would also increase the base flow from ground water especially in the downstream areas of the basin. Given the highly seasonal flow variability of the Ewaso Ng'iro river, which depends on rainfall occurrence, it would be necessary to install flood storage dams in strategic but suitable locations aimed at stabilizing its stream flow. Thus building dams upstream of the basin would help meet water demands in laikipia lowlands. Large commercial farms should also be encouraged to install reservoirs with at least three months storage capacity for the dry season in order to reduce demand from surface river water supplies. Release of stored runoff from these reservoirs during the dry season would support the downstream communities, thus achieving flow stabilization at Archer's Post through the middle reaches.

It is recommended that sand dams be constructed downstream since they are ideal for the lowland areas where evaporation losses are too high for a viable surface dam. Besides, sand dams could be used to increase the base flow and subsequently recharge the groundwater aquifers within the basin. For the basin to maximize its earnings, it is highly recommended that rainwater harvesting be promoted to improve water availability and reduce the current water use conflicts between upstream and downstream users.

Capacity building and promoting change in the attitude of users towards rainwater harvesting and water saving techniques are also crucial. Agriculture not only creates jobs but also contributes significantly to the GRDP of the area. Farm development incentives by the government could assist farmers in putting water infrastructure especially for irrigation in place. Furthermore, the formation of water user associations (WUAs) is of importance as it integrates ideas from different stakeholders who can freely discuss problems, set goals and define their solutions. These platforms will ensure a high level of stakeholder involvement and participation in designing and implementing development goals for the entire basin.

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CHAPTER 7

Spatial Multi-criteria evaluation process for selecting rainwater harvesting sites as mitigation measure in response to climate change in Sub-saharan Africa

This chapter is based on:

Mutiga, J.K., Su, Z., Woldai, T., (2009). Spatial multi-criteria evaluation process for selecting rainwater harvesting sites as a mitigation measure in responding to climate change in Sub-saharn Africa. Being revised for re-submission in the *Journal of Hydrology.*

Abstract

In most water scarce areas of Sub Saharan Africa (SSA), food security is not only threatened by increased water shortages particularly for crop production but also by climate change as predictions of increased rainfall variability are likely to make matters even worse. Generally, the water-related problems in rain-fed agriculture in these areas are often related to high intensity and short duration rainfall, with large spatial and temporal variability, rather than to the low cumulative amount of rainfall. Such irregular rainfall patterns result in high risk of meteorological droughts and intra-seasonal dry spells, leading to low crop yields and sometimes total crop failures. Although the situation appears desperate, rainwater harvesting (RWH) could serve as a remedy, since they have proven to be a promising potential technology for upgrading rainfed agriculture by improving water availability for crop production and increase groundwater levels.

This chapter presents results obtained from a weighted overlay analysis of a spatial Multi-Criteria Evaluation (MCE), a decision support tool used to identify suitable areas for adoption of appropriate RWH technologies in both the upper Ewaso Ng'iro North in Kenya and Makanya catchment in Pangani basin in Tanzania. During the evaluation process, a weighted linear combination (WLC) procedure allowing for full tradeoff among different factors (rainfall, topography, soils, land use and socio-economic) considered, was applied in the data rich Ewaso Ng'iro basin with the results obtained then being transferred to the data scarce Makanya catchment. Suitability maps showing suitable areas for RWH in both basins were produced with attributes that serve as indicators for targeted RWH interventions. It is evident that the information generated in this study can be used to raise awareness and guide policy decisions, in which case RWH may contribute towards meeting the Millennium Development Goals (MDGs) in SSA.

Keywords: *Food Security, Climate change, Dry spells, Rainwater Harvesting, WLC, Rain-fed Agriculture, Ewaso Ng'iro, Makanya, SSA.*

7.1 Introduction

Rain-fed agriculture will remain the dominant source of staple food production and livelihood foundation for the majority of the rural poor in Sub Saharan Africa (SSA) (Fox et al., 2003; Cooper et al., 2008). Moreover, food security in most of these regions is not only threatened by increased water shortages particularly for crop production purposes, but also by climate change which is likely to make matters even worse with increases in rainfall variability being predicted. The combined impact of climate change and population growth is expected to cause an alarming increase in water scarcity in many countries in the world, with many considered likely to face water scarcity or water stress by 2025 (UNECA, 1999; IPCC, 2007c). To counter such a scenario, greater emphasis will have to be placed on increasing productivity of the global rain-fed agriculture which currently provides 60% of the world's food. This is especially important in SSA, where currently nearly 90% of the staple food production continues to come from rain-fed farming systems (Rockström and Falkenmark, 2000; Rosegrant et al., 2002b).

The water-related problems in rain-fed agriculture in the water scarce areas of SSA are often related to high intensity and short duration rainfall with large spatial and temporal variability, rather than to low cumulative amount of rainfall. This results in a high risk of meteorological droughts and intra-seasonal dry spells, which lead to low crop yields and sometimes total crop failures (Rwehumbiza et al., 1999). The challenge is how to reduce the impact of such climatic disparities and cushion farmers against their effect on rain-fed agriculture (Barron et al., 2003).

Research in several semi-arid tropical regions (Tiffen et al., 1994; Rockström et al., 2001) shows that occurrence of dry spells lasting for 2 to 3 weeks can cause significant yield reduction. Mitigation of the impacts of such intra-seasonal dry spells (ISDS) is a prerequisite for improving water productivity in rain-fed agriculture in these areas (Boer et al., 1986; Rockström et al., 2001; Barron et al., 2003; Fox and Rockström, 2003; Hatibu et al., 2003; Motsi et al., 2004; Barron and Okwach, 2005). It has been increasingly recognized that in areas where agriculture is constrained by poor rainfall distribution in time and space, innovations that increase rainwater use efficiency and water management strategies have great potential to improve food security and livelihoods (Rockström, 2000 and 2001; Barron et al., 2003; Ngigi et al., 2005). Rainater harvesting (RWH) can contribute in reducing vulnerability to climate change and help minimize or even reverse land degradation (Fisher et al., 1995).

Previous studies show that, whilst the exact nature and extent of the impact of climate change on rainfall distribution patterns remains uncertain, it is the poor and the vulnerable that are most susceptible to changes in climate (Cooper et al., 2008; Ingram et al., 2008). This is particularly true for those communities in SSA who rely mainly on rain-fed agriculture or pastoralism for their livelihoods, as is the case in both the Upper Ewaso Ng'iro North basin in Kenya and Pangani basin in Tanzania. Adaptation to climate change therefore becomes a priority to ensure long-term effectiveness of investment in poverty eradication and sustainable development. However, adaptation should not be treated as a standalone issue, but in the context of poverty reduction and the millennium development goals (MDGs).

There are major untapped synergies between the poverty reduction and climate change agendas, especially in the area of adaptations such as rainwater harvesting (IPCC, 2007c). For example, local storage of water is increasingly being seen as an important adaptation for ensuring water availability and food security to rural and urban populations (Kashyap, 2004; Lasage et al., 2008). In this regard, RWH is one of the most reliable options for increasing agricultural water use efficiency in the water-scarce areas of SSA, as it can be used to bridge dry spells through supplementary irrigation (SIR) of rain-fed crops (Oweis, 1996; Rockström, 1999; SIWI, 2001; Oweis and Hachum, 2003; Barron et al., 1999 and 2003; Mupangwa et al., 2006; Kahinda et al., 2007; Ngigi et al., 2008).

However, Rockström, (2001) observed that, the existing RWH innovations appeared insufficient in providing adequate water to produce the necessary biomass for food security. This is mainly due to lack of knowledge on both bio-physical and socio-economic conditions under which RWH can be adopted by smallholder farmers, which then leads to low adoption rates as is the case in the upper Ewaso Ng'iro North Basin (Ngigi et al., 2008). It is against this background that this study attempted to identify suitable areas for RWH by applying a multi-criteria evaluation (MCE) approach, aimed at bridging the gap in knowledge, and hence improving adoption rates of successful RWH innovations. This approach is considered as an effective tool that can support decision makers in formulating sound and well informed strategies for water resources planning and management.

7.2 Materials and methods

7.2.1 GIS Data processing in relation to RWH suitability

Expert knowledge, which was mainly obtained from the existing literature on the main bio-physical and socio-economic factors (criteria) that influence suitability for RHW, was complemented by rich indigenous knowledge. In order to tap this knowledge, key stakeholders (farmers, pastoralists, policy makers, interest groups, NGOs, CBOs) in the basin participated through various group discussions. Firstly, they were asked to identify major factors (stipulated below), which according to their view influence the suitability of RWH and then assign weights to all identified factors depending on their relative importance to RWH suitability, (Figure 7.2) through consensus building. Furthermore, all the identified criteria were classified as either constraints (limiting the alternatives under consideration) or factors (enhancing or detracting from the suitability of a specific alternative under consideration).

7.2.1.1 Land cover/use

Vegetation is an important parameter that affects surface runoff. An increase in vegetation density results in a corresponding increase in interception losses, retention and infiltration rates consequently decreasing the volume of runoff generated. It is evident that effective utilization of rainfall, particularly in arid and semi-arid lands (ASALs), depends on land characteristics such as land cover/use and management practices (Rwehumbiza et al., 1999). Land cover data for the Upper Ewaso Ng'iro basin was obtained from supervised classification of landsat 7 ETM+ images of 2003, with a 30 m pixel resolution. Seven main land cover classes (grassland, bushland, forest, wetland, cropland, built-up areas and bareland) were obtained from this classification, which were subsequently grouped into two classes according to their suitability for RWH, (suitable and not suitable). For example, cropland was classified as suitable while forest and wetland areas as not suitable.

7.2.1.2 Agro-ecological zones

Agro-climatic zones are an indicator of the inherent risks to rain-fed crop production and therefore are useful in setting up criteria for RWH systems. This is because the zones are created by combining important climatic variables (rainfall, relief, temperatures). The data was used as a constraint particularly when differentiating between areas that are suitable for micro-catchment to those suitable for macro-catchment systems.

7.2.1.3 Rainfall

Hydrological processes relevant to RWH practices are those involved in the production, flow and storage of runoff from rainfall within a given area. Rain falling in a particular catchment area can either be effective (as direct runoff) or ineffective (as evaporation, deep percolation) (Prinz et al., 1998) and the quantity of rainfall, which produces runoff, is a good indicator for suitability for RWH. Water harvesting techniques which collect runoff are not feasible below certain rainfall thresholds particularly in ASAL environments. Usually, runoff generated from rainfall below this threshold is negligible as such rain either infiltrates the surface or evaporates (Oberle, 2004). Based on this fact, weights were assigned to different areas in the basin, depending on the amount of annual rainfall they received with respect to the threshold (600 mm/year). Areas that received higher rainfall than this threshold were assigned higher weights than those with lower values. Spatial rainfall layer was obtained by performing a simple kriging interpolation on the mean annual rainfall data (over the past 30 years) from the existing 30 rain gauging stations spread across the basin, and smoothing the results based on a digital terrain model of the area (Mutiga et al., 2010).

7.2.1.4 Slope

Topographic features are significant to hydrological parameters as they play a key role in the distribution and flux of both water and energy within a natural landscape. Slope gradient for example is considered as a major parameter for determining the type of water harvesting possible. Terrain analysis was carried out using a Digital Elevation Model (DEM) with a 20 m resolution. In this regard, the basin to be grouped into four main slope classes (very steep slope: 30 – 100%, steep slope: 15 - 30%, medium/undulating slope: 5 - 15% and flat: 0 – 5%). Different slope classes were assigned different weights depending on their relative importance to RWH suitability. Slope length was also determined as it is regarded as highly important for ascertaining the suitability for macro-catchment RWH, because runoff volume increases with increasing slope length (Prinz et al., 1998).

7.2.1.5 Soils

Runoff, a major parameter influencing the potential for RWH does not only dependent on rainfall characteristics but also on the infiltration capacity of the soil (Oberle, 2004). The suitability for RWH will depend strongly on its soil characteristics such as surface structure, drainage and depth (Prinz et al., 1998). Soil texture for example influences its infiltration capacity. Information obtained from the soil layer include soil type, texture, drainage and depth and depending on the RWH type being considered (macro or micro-catchment) different weights were assigned these factors based on their degree of influence.

7.2.1.6 Socio-economic factors

The socio-economic conditions of a region being considered for RWH play a very important role in planning, designing and implementation. Some of the socio-economic factors considered for the evaluation criteria include: distance to roads, rivers, market places, and settlements. To achieve this, a 2 km buffer zone was created around the roads, rivers and settlements in the basin. Areas classified as most suitable for RWH and falling within the buffer zones of the roads, rivers and settlements, were given highest priority for the implementation of RWH. Proximity to roads was considered a benefit as roads generate runoff which can be diverted to either cultivated (Figure 7.8) or grazing land or to a dam for storage at minimal cost. Similarly, proximity to settlements implies that time spent in search of water is minimized and can instead be used for other, more productive activities such as income generating.

7.2.3 Multi-criteria Evaluation Process (MCE)

MCE is a procedure for evaluating several criteria in order to arrive at a specific objective (Voogd, 1983). The evaluation can be achieved either by using a Boolean overlay or weighted linear combination (WLC). In a boolean overlay, all criteria are reduced to logical statements of suitability and then combined by means of one or more logical operators such as intersection ("*AND*") and union ("*OR*"), while in WLC, continuous criteria (factors) are first standardized to a common scale and then combined by means of a weighted average. During this study, land use, rainfall, slope, soils and socio-economic factors were used to determine the suitability for RWH, whereas vegetation cover types were used as constraints. In this case, both Boolean overlays for constraints and WLC for factors were used to obtain a continuous mapping of RWH suitability. The WLC procedure played a major role since it allowed for a full tradeoff among all factors, while at the same time offering much more flexibility during the evaluation process (Mahini and Gholamalifard, 2006).

A constraint in the context of the current study was used to limit the alternatives under consideration. In this case, constraints (forests and wetlands) were expressed in the form of a Boolean map with areas excluded from consideration being assigned a value of zero and those open for consideration a value of one (Figure 7.3). As opposed to a constraint, a factor is defined as a criterion that enhances or detracts from the suitability of a specific alternative under consideration. All factors (land cover/use, rainfall, slope, soils and socio-economic) were first standardized to a common scale and then combined by means of a weighted average on a continuous scale to produce a final factors map (Figure 7.4).

7.2.3.1 Determining factor weights

Prior to integration of all the factors, weights were assigned to each factor by taking the opinion of key stakeholders involved into consideration, thus complementing the already existing expert knowledge (Prinz et al., 1996). During this process, the factors were rated after all the stakeholders reached a consensus on their different opinions/views. A nine point importance scale, (Figure 7.1) was used to assign a commonly agreed relative importance weight (RIW). Later, RIWs for all the factors were subjected to a pair-wise comparison matrix (Table 7.1), based on the principles of the Analytical Hierarchical Process (AHP) developed by Saaty (1977) as a decision making process (Eastman et al., 1995 and Al-awar et al., 2000). This process allowed for tradeoffs between the different factors under consideration.

Principal eigen-vector of the pair-wise comparison matrix generated was used to compute a best fit for the weights set for all factors (Table 7.1). Since a complete pair-wise comparison matrix contains multiple paths by which relative importance of criteria can be assessed, a degree of consistency in developing the weights was also determined. The consistency ratio (probability that matrix weights were randomly assigned) for this procedure stood at 0.06, enabling the adoption of the assigned weights (Saaty, 1980) for the evaluation process.

Each factor map was then multiplied by its corresponding weight and summed to produce a final factors map (Eq. 7.1) which was merged with the final constraints map to produce the final suitability map for RWH (Eq. 7.2). The summary of the whole procedure is as presented in Figure 7.2.

Thus:

Final factors map = 0.420*Soil + 0.168*Rainfall + 0.247*Slope +0.091*LCLU +0.048*Distance to water storage + 0.026*Socio-Economic (7.1)

and;

Final suitability map for RWH = Final constraint map * Final factors map (7.2)

I/9	I/7	I/5	I/3	I	3	5	7	9
Extremely	Very Strongly	Strongly	Moderately	Equally	Moderately	Strongly	Very Strongly	Extremely

◄– – – – – – Less Important | More Important – – – – – –►

Figure 7.1: Nine point importance scale (Saaty, 1977).

Table 7.1: Pair-wise comparison matrix used for different factors with *CR* = 0.06

	Soils	Rainfall	Slope	LCLU	Distance to existing Storage	Socio-Economic	Weight
Soil	I						0.420
Rainfall	I/3	I					0.168
Slope	I/3	3	I				0.247
LCLU	I/5	I/3	I/3	I			0.091
Dist to Existing Storage	I/7	I/5	I/5	I/3	I		0.048
Socio-Economic	I/9	I/7	I/7	I/5	I/3	I	0.026

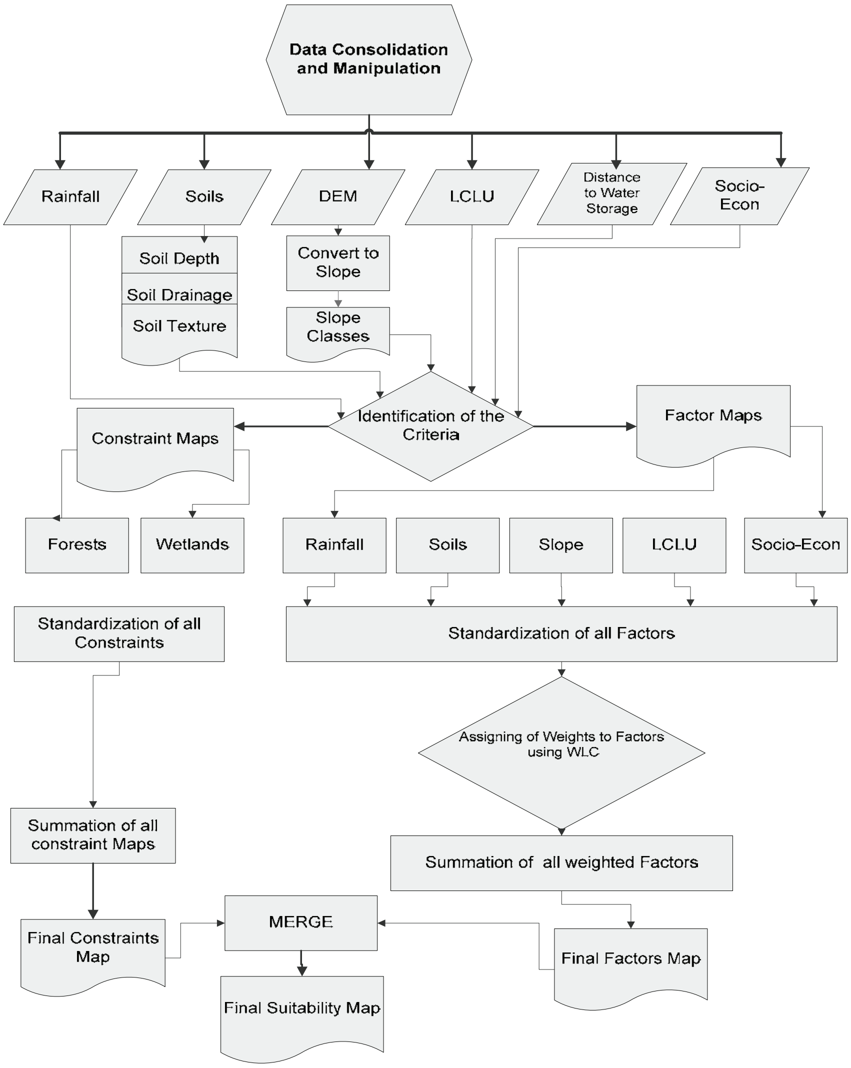

Figure 7.2: MCE process used to identify suitable areas for RWH in the basin.

7.3 Results

7.3.1 Final suitability map

The evaluation criteria developed produced a suitability map for RWH in the upper Ewaso Ng'iro North basin in Kenya. The accuracy of this map improved significantly (from 70 to 80%) when rich indigenous knowledge was used to complement the existing expert knowledge.

The final suitability map for RWH for the basin was superimposed on the 2 km buffer zones created around roads, schools, dispensaries, cattle dips, settlement points and rivers in the basin, (Figure 7.5), facilitating identification of priority areas. For example, most suitable areas which were found within intersecting regions of all the buffer zones, were given a higher priority (1) than those found close to only settlement points or roads (priority 2) as shown in Figure 7.6, for both micro and macro-catchment systems. It should be noted that the difference between these two systems is that in micro (also referred to as the in-situ systems), water is collected in an upland area and released onto an area immediately below it (Figure 7.8), while in macro-systems, water is collected from an area at an appreciable distance from the area it is used, sometimes requiring an intermediate storage (Figures 7.11, 7.12 & 7.14).

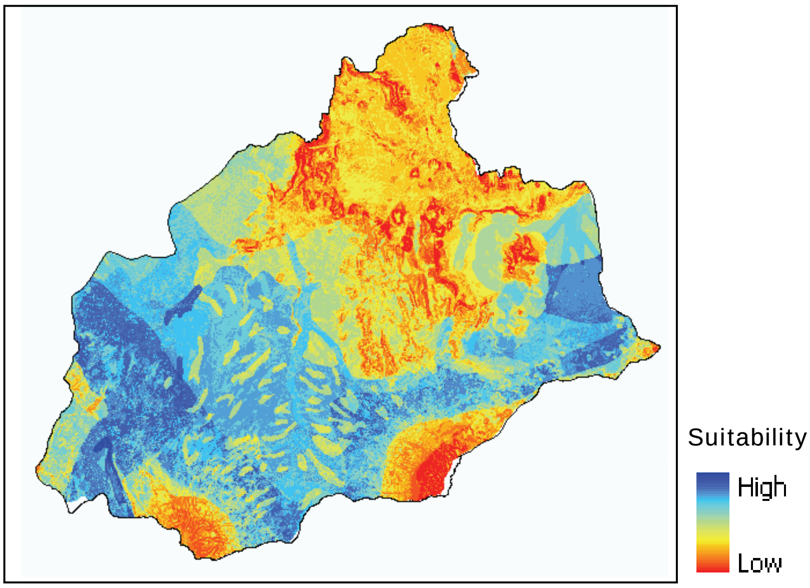

Figure 7.3: Final factors map.

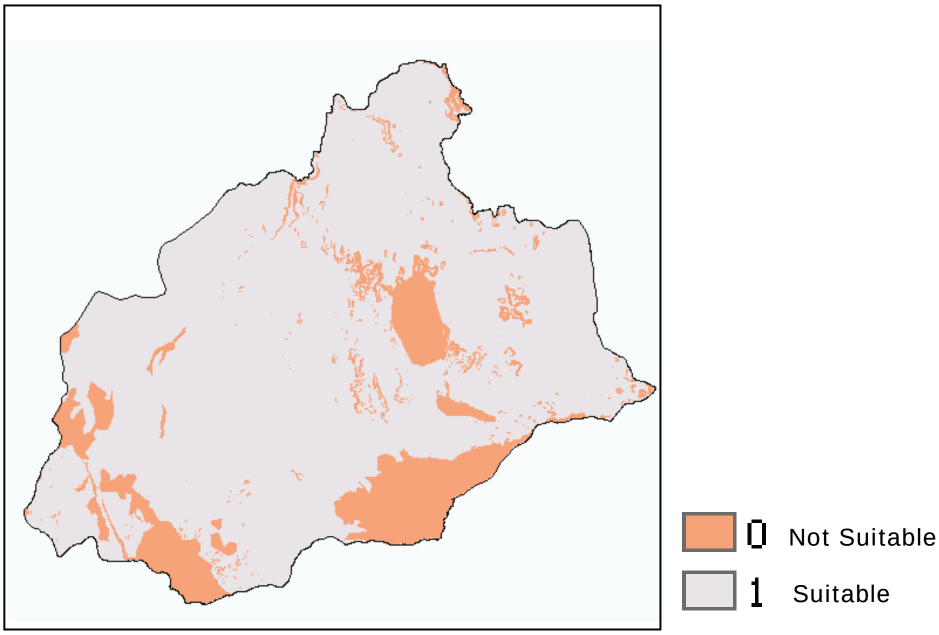

Figure 7.4: Final constraints map.

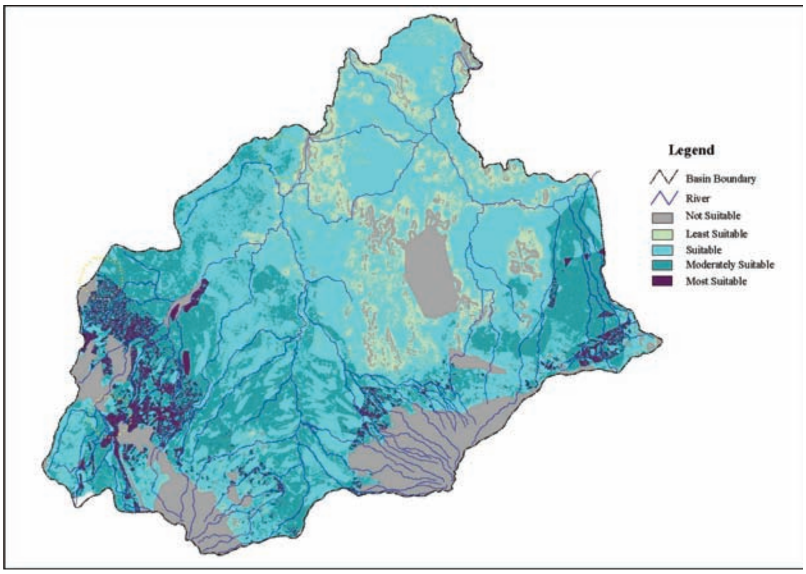

Figure 7.5: Final suitability map for RWH in the Upper Ewaso Ng'iro North Basin.

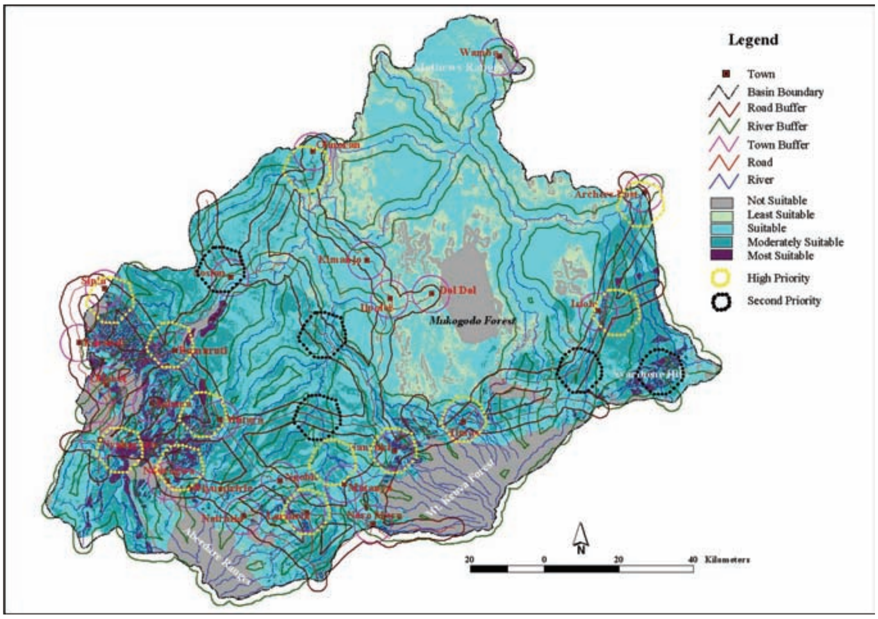

Figure 7.6: Suitability map showing priority areas for RWH intervention in the Upper Ewaso Ng'iro North Basin.

7.3.2 Suitable areas, land uses and population density

The results obtained showed that areas identified as most suitable and assigned the highest priority (1) for intervention were found in densely populated areas with small scale farming being the most dominant. The reason for this is that these areas are located on the foot zones of the Aberdare ranges, Mt. Kenya and the Nyambene hills, which receive sufficient rainfall for farming activities (Figure 7.7). Areas under open shrubs and grass, mainly used for grazing, have a suitability rating second to agriculture. These areas are generally occupied by pastoral communities with livestock production as their main livelihood. However, the areas are prone to droughts and severe land degradation as a result of over-grazing (Figure 7.10).

It was further observed that, areas classified as most suitable and assigned priority (1) or (2) were found close to the roads and settlements. Roads coud be used for generating runoff, which could then either be channelled directly to croplands or to storage facilities, (Figure 7.8). This would consequently reduce damage to such roads by water erosion as well as make water available for other productive use such as supplementary irrigation (SIR) or livestock watering, (Figures 7.11 & 7.13).

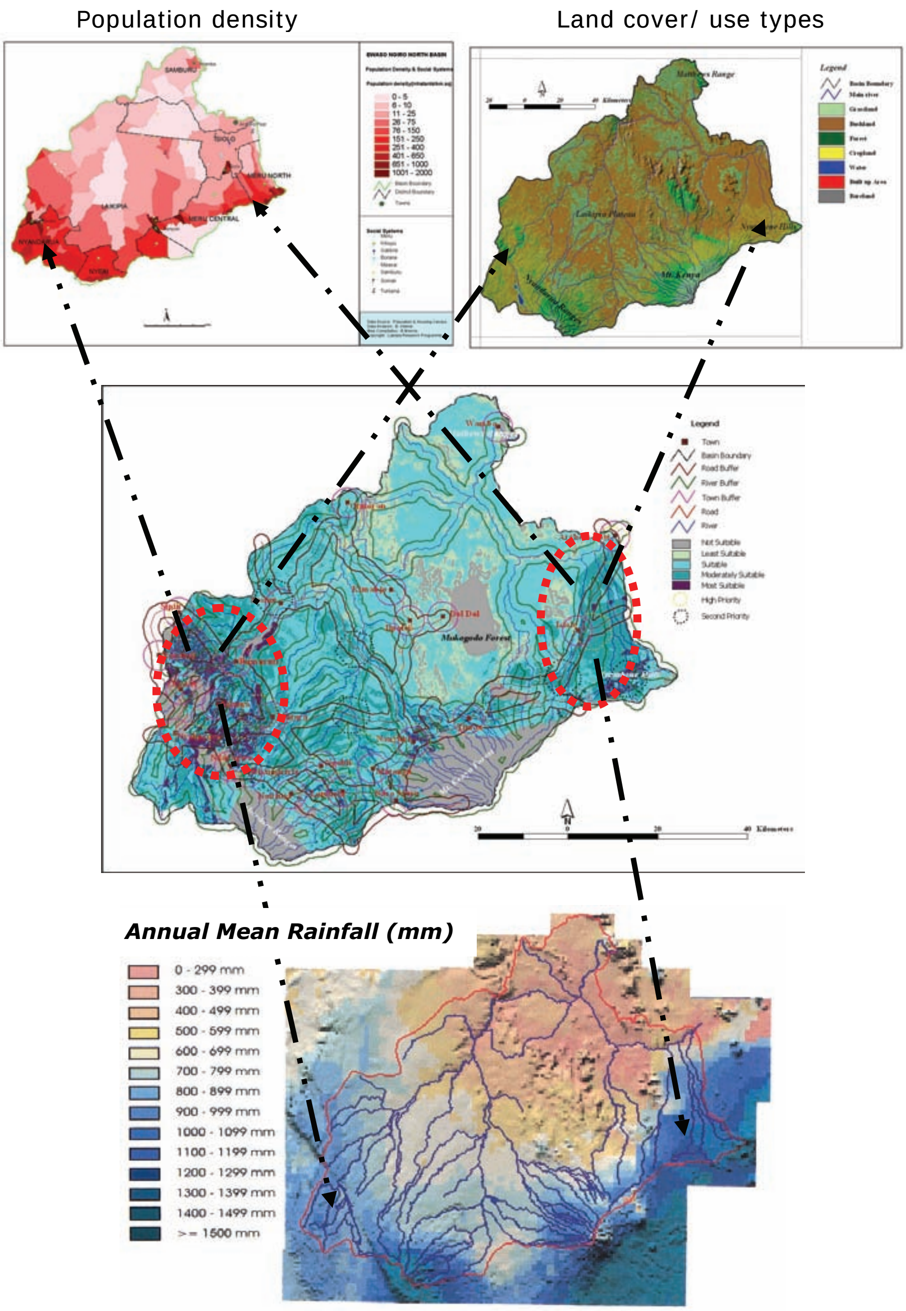

Figure 7.7: RWH suitability in relation to population, land use and rainfall amount.

7.3.3 RWH for sustainable Agriculture

The results produced show that areas classified as most suitable (about 20%) for the micro-systems (conservation tillage, terraces, and furrows) (Figure 7.9) are found mainly in the south western part, upstream of the basin (Figure 7.16). These areas have a high potential for agricultural activities and hence attract high population densities. This is because they receive a mean annual rainfall of between 800 and 1,000 mm/year, which is sufficient for crop and livestock production. Implementing the appropriate RWH systems in these areas according to the identified priorities (Figure 7.6) could make more water available for productive use in the downstream areas of the basin. Areas suitable for macro-systems, on the other hand were found mainly in the lowlands, including the Laikipia Plateau with a mean annual rainfall of between 400 and 600 mm/year, which in most cases in not sufficient for crop production. Implementing RWH systems in these areas with high rainfall variability can provide an alternative source of water, supplementing the available rainfall and hence improving agricultural production, food security and reducing rural poverty.

7.3.4 RWH and Gender

Priority areas for implementation of RWH were found close to settlements, which mean that time normally spent in search of water by women and children can be saved and put to more productive use such as income generating activities or children spending more time on advancing their education.

7.3.5 RWH for groundwater recharge

Competition for the limited water resources between agriculture and ecosystems is increasingly becoming a serious problem in the upper Ewaso Ng'iro North basin. This has resulted to catchment degradation (Figure 7.10) as the water scarcity crisis intensifies. For example pastoralists, who live in the lowland areas of the basin, usually move upstream with their livestock in search of both pasture and water to the forested areas which form the source of water for many tributaries of Ewaso Ngi'ro River. This migration of livestock, which normally take palce during the dry periods, degrades the upper catchments, mainly through over-grazing (Figure 7.10). Similarly, small scale farmers in the lowland areas of the basin who practise irrigation also move their water intake points higher up the mountains in search of water to irrigate their crops, thus exposing these areas to further degradation through encroachment. One of the reasons why, during the evaluation process to identify suitable areas for RWH, forests and wetlands were considered as constraints was to counteract this encroachment aspect. From the results obtained during the study, micro-catchment systems tend to be dominant in the upstream areas, where farming is the main source of livelihood for the inhabitants and if promoted, such systems could significantly contribute towards conservation of these areas.

In the highlands (upstream of the basin), soil erosion is a major concern, especially on the mountain slopes of Mt. Kenya where soils are prone to erosion. Micro-catchment systems (mainly soil and water conservation practices on croplands) therefore need to be promoted in these areas in order to reduce their degradation. In addition, soil cover needs to be improved in order to minimize surface runoff and evaporation losses and instead store this water for crop production. It is generally believed that, if flood water can be harvested and stored in the upstream areas of the basin, and utilized during dry spells to complement rainfall, more water could be made available to downstream users, minimizing the persistent water use conflicts currently being experienced in the upper Ewaso Ng'iro North basin.

Water storage could either be within the soil profile (micro-systems) or built-up structures (macro-systems), like community dams or individual water pans. However, most of the existing macro-systems in the basin are not efficient enough due to their high rates of water losses (through seepage and evaporation), which has a negative effect on any attempt to increase their uptake among the small scale farmers. To minimize such losses, lining up of dams/ water ponds and covering their tops with polythane paper (Figure 7.12) is becoming common among able farmers, which means added expenses to already over burdened poor farmers. This shows clearly that there is a need to adopt appropriate methodology to help identify areas suitable in the basin for various RWH techniques to assist the farmers with their current predicaments, an issue which the study has adequately addressed.

The lowlands (comprising of arid and semi-arid areas) mainly dominated by agro-pastoralists, but have insufficient soil moisture to support any meaningful crop or pasture production. Maintaining good grass cover especially on communal grazing lands is therefore a big challenge. However, if water loss through surface runoff is to be reduced in these areas, then maintaining adequate vegetation cover is necessary. Harvesting surface runoff would minimize land degradation and at the same time enhance agricultural production.

Figure 7.8: Directing runoff from a road reserve (A) to a RWH storage (Macro-systems) for SIR downstream (B).

Figure 7.9: RWH storage (micro-systems) common in the upstream of the basin

Figure 7.10: Land degradation (B) caused by soil erosion due to over-grazing (A).

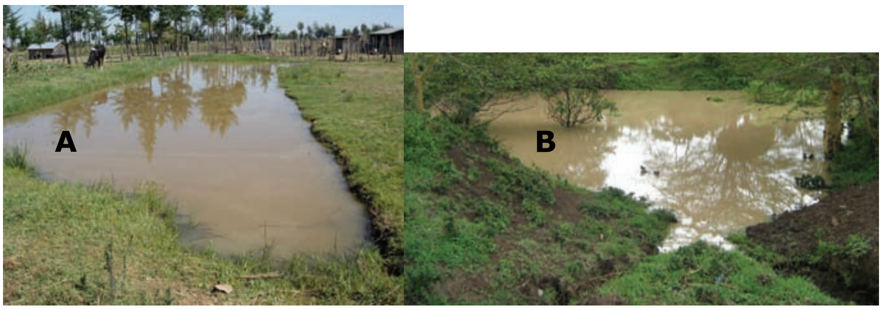

Figure 7.11: RWH storage (macro-systems) for SIR (A) and livestock watering (B) in the downstream part of the basin.

Figure 7.12: Measures for minimizing water losses from RWH storage systems for SIR in the lower part of the basin.

Figure 7.13: RWH storage systems for watering livestock found downstream of the basin

7.3.6 Sensitivity Analysis of the Evaluation Criteria

Sensitivity analysis was performed to assess the effect of changing weights of the input factor criteria on the total area classified as suitable and the degree of its suitability. The first scenario involved assigning equal weights to all factors under consideration, followed by evaluation of the areal extent of suitability. The other scenarios involved assigning of a higher weight to each input factor in turn, while keeping the weights of all other factors constant. The observations obtained revealed that only soil properties (texture, drainage, depth) and slope factors significantly affected the result of the outcome (by about 20%) of the extent of areas suitable for RWH.

Changing of the weights for the other factors (rainfall, slope, soils, land cover/use) did not have a significant effect (only about 2%) of areas suitable for RWH. It was therefore concluded that soil characteristics and slope are the main factors influencing the suitability for RWH interventions. This finding is in agreement with Oberle (2004) and Ngigi et al. (2006) who also observed that soil properties and slope characteristics are the most important criteria when selecting potential areas for micro/macro-catchment water harvesting systems.

7.3.7 Validation of RWH suitability mapping

Validity of the final suitability map for RWH in the basin was tested by overlaying the map with data on existing and working water pans spread across the basin. The results revealed that, a significant number of the existing water pans (80%) was found within areas classified as most suitable for RWH (Figure 7.14). This indicates that the suitability map produced, matches the existing RWH facilities.

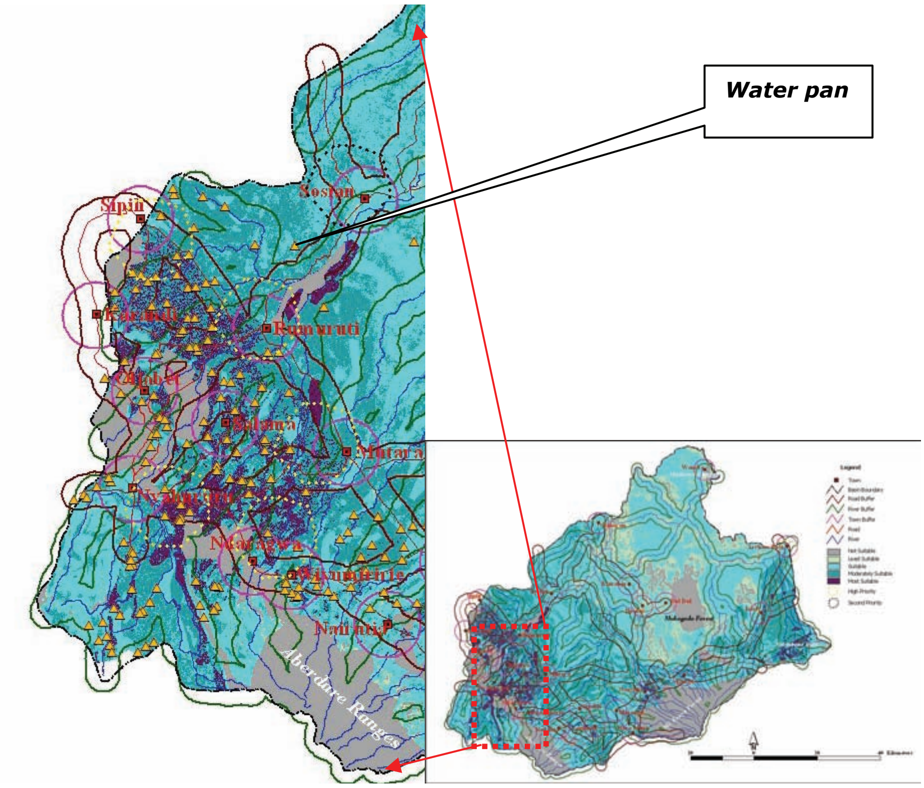

Figure 7.14: Map showing overlapping areas between suitable areas for RWH and the existing water pans in the upper Ewaso Ng'iro North Basin.

Results also revealed that existing water pans which have been abandoned by the community as inefficient, were located in areas classified as not suitable (Figure 7.15) agreeing with findings of Ngigi et al. (2008) who observed that low efficiency levels of existing RWH systems contributed significantly to the low rate of their adoption. Soils in these areas are characterized by high infiltration rates, rendering water pans here inefficient for storing water for longer periods since most of the water is lost through seepage.

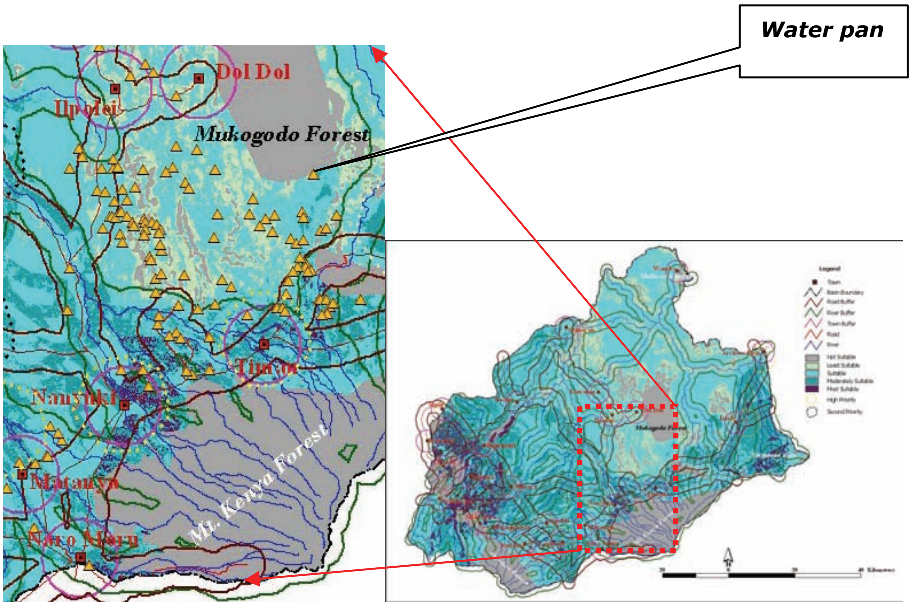

Figure 7.15: Map showing overlapping areas between areas unsuitable for RWH and the existing inefficient water pans.

7.3.7 Adopting the MCE in the Makanya Catchment in Tanzania

The developed decision support system (DSS) for identifying RWH sites in the upper Ewaso Ng'iro North basin was adopted and applied to Makanya catchment, located upstream of the Pangani river basin in Tanzania. Since this catchment has scanty spatial information, it was difficult to develop a similar comprehensive evaluation to that undertaken in the upper Ewaso Ng'iro North basin. However, since the two basins exhibit similar bio-physical and socio-economic characteristics, the developed MCE/DSS for the Ewaso Ng'iro North basin was adopted in the Makanya catchment and used to identify suitable areas for RWH (Figure 7.16B).

The results obtained indicate that the adopted MCE produced an accuracy of about 75% which was considered significant taking into account that the area had minimal spatial data. About 35% of the total catchment area was found to be suitable for RWH interventions. It was further revealed that about 10% of the areas identified as suitable were located on flat to gentle undulating slopes (0-2%) comprised of clay to silt clay soils and 25% of the areas were on gentle to moderately undulating slopes (3 - 10%) with silt clay to sandy clay soils (Figure 7.16A), which is in agreement with findings of Mbilinyi et al. (2007). This procedure demonstrates clearly, how results from a data rich area can be effectively transferred to a data scarce area with similar characteristics when performing similar tasks.

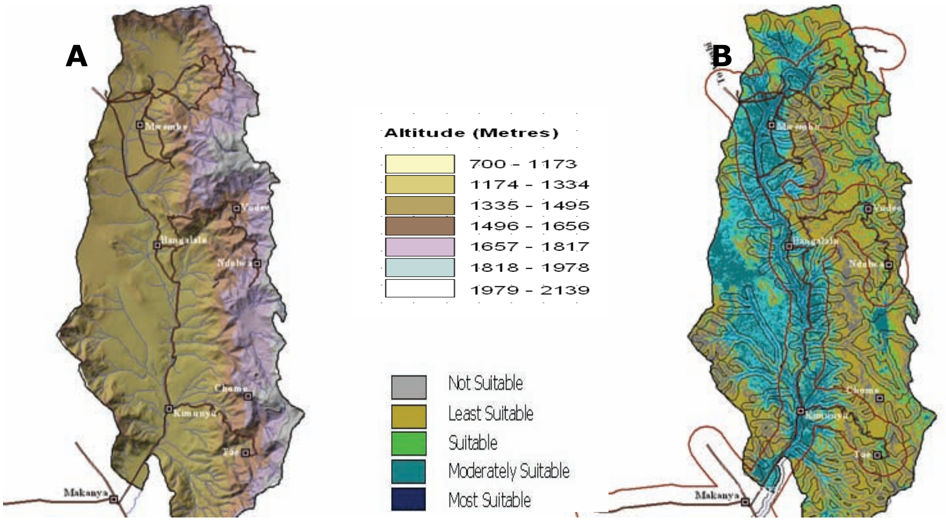

Figure 7.16: Suitability map for RWH in the Makanya Catchment, Tanzania.

7.3.8 Cost benefits analysis of RWH

An experiment was carried out in one of the sites identified suitable for RWH in the Upper Ewaso Ng'iro North basin with the aim of assessing the overall economic returns obtained from using a micro-system RWH such as conservation tillage. This system was selected as it can be easily implemented and is cheap. Conservation tillage is actually, one of the most promising soil moisture conservation practices used by farmers in the region (Kihara, 2002). A maize crop, which is the preferred food crop in both basins, was used for this evaluation using different treatments (Table 7.3).

The experiment was conducted in an area located in the famous Laikipia Plateau (1,900 m a.s.l) with semi-arid to semi-humid climatic characteristics. The area receives a mean annual rainfall of about 500 mm/year which is not sufficient to support a maize crop to maturity. This experiment was conducted during the long rains (March-July) in 2008. The area has mainly deep clay soils with a high water storage capacity (Liniger et al., 1991). The results obtained revealed that, provision of additional soil moisture through RWH in the root-zone, can dramatically enhance water availability for the crop, leading to increased crop yields (Table 7.2). The results further show that, the potential of conservation tillage in the area is high, and if incentives (inputs, credit facilities) are provided especially for smallholder farmers, this could lead to increased adoption rates.

The the results indicate that conservation tillage improved the yields by 45-190%, with higher yields being produced with nutrient management (Table 7.3) is applied. This is in compliance with the findings of Barron et al. (2004) and Rockström (1999), who showed that upgrading rain-fed production systems through supplementary irrigation (SIR) during dry spells can lead to large increases in water productivity and subsequently crop yields. These results thus provide a basis for farmers to make informed decisions on agricultural investments under hydrological risks and uncertain production systems as in the dry areas of SSA since the sustainability of RWH interventions depends on the perceived tangible benefits (Vishnudas, 2006). In this regard, RWH can be considered as an option for making more rainwater available for crop production in dry areas as such an important key to unlocking the potential in rain-fed agriculture.

Table 7.2: Returns from conventional and conservation tillage

	Cost Item	**Description**	**Conventional Tillage**	**Conservation Tillage**
Expenditure	Inputs	Maize (13.3 Kgs, Hybrid seed)	2,146	2,146
		Beans (16.5 Kgs, Local seed)	578	578
		Planting fertilizer (79 Kgs)	3,168	3,168
		Herbicide (1.6 Litres)	0	1,312
	Labour	Ploughing with tractor	7,413	0
		Harrowing with tractor	3,706	0
		Ridging	2,225	0
		Ripping with oxen	0	2000
		Planting / fertilizer application	1,970	1,970
		Herbicide application	0	800
		1st Normal weeding (see note)	7,413	0
		2nd Normal weeding	7,413	0
		Shallow weeding	0	792
		Harvesting	2,050	2,050
Income	Crop yields	Maize yield value	60,000	59,300
		Bean yield value	10,025	7,095
Net profit		***Total Income***	***70,025***	***66,395***
		Total Cost	38,076	14,816
		Net profit (Income – Cost)	**(45%) 31,949**	**(78%) 51,579**

Table 7.3: Returns from different treatments

Farmers Name	Treatment	Main Crop	Input & Labour Cost/ Ha (US$)	Total Cost (US$)	Value of main crop/ Ha (US$)	Net Profit (US$)
A	Ripping, Herbicide fertilizer	Maize	Inputs 460 Labour 80	540	950	410 (76%)
B	Ripping, Herbicide	Beans	Inputs 50 Labour 60	110	320	210 (190%)
C	Ripping, Herbicide fertilizer	peas	Inputs 250 Labor 270	520	1200	680 (130%)
D	Ripping Herbicide Fertilizer	Garden peas	Inputs 500 Labour 800	1300	3740	2440 (190%)

7.4 Conclusion

This work provides a case study on how indigenous knowledge can be used to complement an expert knowledge base in identifying suitable areas for RWH as an adaptation measure for minimizing the impacts of climate change such as flooding and drought. This was achieved through the involvement and participation of various stakeholders (farmers, agro-pastoralists, pastoralists, conservationists, development agencies, government line ministries, NGOs, CBOs) in the basin who were instrumental in identifying major factors influencing suitability for RWH. In carrying the evalution process to identify suitable areas fpr RWH, their efforts were complemented by existing expert knowledge. Sensitivity analysis conducted to assess the reliability of assigning weights to different factors, revealed that only soil properties (texture, depth, drainage) and slope characteristics significantly influenced the suitability (20%) for RWH in the area.

Moreover, since competition for the limited water resources between agriculture and ecosystems is increasingly becoming a serious problem in both the Upper Ewaso Ng'iro North and Pangani River Basins, RWH is considered an alternative and viable water supply system, particularly during the dry periods. Since about 40% of the total area was found suitable for RWH systems, its potential needs to be carefully and strategically harnessed in order to improve food security in the basin. In this regard, RWH is seen as an important key to unlocking the potential in rain-fed agriculture not only in these basins, but also in other dry areas of SSA.

In conclusion, this study recommends that agricultural and water policies need to be modified to accommodate RWH technologies aimed at improving water productivity (crop-per-drop) not only in these basins but in other similar regions within SSA. However, since the impacts of upscaling of RWH technologies on hydrology at basin scale are not yet known, further assessment is recommended to determine to what extent upscalling is sustainable.

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CHAPTER 8

Impacts of agricultural intensification through upscaling of suitable rainwater harvesting technologies in the upper Ewaso Ng'iro North Basin, Kenya

This chapter is based on:

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Abstract

Changes in land cover and land use can lead to significant impacts to hydrology by affecting the amount of runoff, soil moisture and groundwater recharge over a range of temporal and spatial scales. However, hydrologic effects of these changes are still an unknown at watershed scale. Moreover, predicting the effects of land cover/use and climate change on hydrological cycle has remained a major challenge. This is because of the complexity and uncertainty of future climate changes making it difficult to predict the consequences. It is against this backdrop that, for sustainable water resources management, assessment of the impacts of land cover/use change on hydrological regime at all scales becomes critical.

During this study, we applied the SWAT model to assess the impacts of area hydrology between baseline and alternative scenario (upscaling of rainwater harvesting technologies). Specifically, our overall objective was to quantitatively evaluate the effects of land use changes on watershed hydrology in the upper Ewaso Ng'iro North basin in Kenya. This was achieved by estimating hydrological responses under historical land use scenarios obtained from the multi-temporal satellite imageries of 1987, 1995 and 2003.

The model performance was found to be relatively good (Nash and Sutcliffe efficient of 70%). Stream flow analysis was carried out for different parts of the basin to understand its hydrological responses, especially, the behavior of base flow. The results show a decrease in base flow during 1987 – 2003 period with decreasing forest, bush and grass covers, which can be attributed to poor natural vegetation emanating mainly from overgrazing and deforestation for agricultural activities. In conclusion, the study clearly shows that, assessment of hydrologic effects of land use changes is critical for a sustainable water resources planning and management of the basin.

Keywords: *Land cover/ use change, SWAT, rainwater harvesting, upscaling, hydrological regime, rain-fed agriculture.*

8.1 Introduction

Global water demand for food production for the growing world population is expected to rise and part of this increase will result in escalating water scarcity (Wisser et al., 2009; Rockström et al., 2007). As fresh water resources are limited, the question arises of whether there will be sufficient water per capita available in the 21st century to fulfill the demand generated by increasing population. Moreover, over exploitation of the useable water resources has already threatened the sustainability of the fresh water availability (Zalewski, 2000).

Studies on water demand for food, environment and industries indicate that more developing countries would experience chronic and physical water shortage by 2025 (Bastiaanssen, 2000). Already some countries mainly in the Middle East and Africa are confronted with water supply shortage (Al-Weshah, 2002). Therefore, the challenge to manage the scarce water resources in a sustainable manner is growing.

Hydrological processes inside river basins are complex due to the combined nature of the natural processes and man made features. Moreover, properties of media forming hydrological systems display a degree of heterogeneity at various scales (Wolski, 1999; Bronstert and Bardossy, 2003). Therefore, attempts to obtain quantitative description of hydrology in river basins must consider these spatial and temporal heterogeneities.

Land cover/use changes (LUCs) alter the hydrological cycle of a catchment by modifying its rainfall, evaporation and runoff, particularly in small catchments (Cao et al., 2006). Furthermore, they can affect the amount of runoff, soil moisture and groundwater recharge over a range of temporal and spatial scales (Calder 1992; Im et al. 2003). However, predicting the effects of LUCs on hydrological cycle has remained a major challenge (Sivapalan, 2003).

In recent years, different hydrological models have been applied to quantify the effects of land use changes on the hydrological cycle (Fohrer et al., 2001; Lørup et al., 1998; Beven, 1989; Refsgaard, 1997; Chen and Li, 2004; Quilbe, et al., 2008). Generally, hydrological modelling is an attempt to describe the physical processes (canopy interception, evapotransiration, overland flow) controlling the transformation of precipitation to runoff (Al-Sabbagh, 2001). For example, Fohrer et al., (2001) who applied SWAT model on a meso-scale catchment observed that, surface run-off is most susceptible variable to LUCs though its influence is difficult to quantify particularly at large scale with complex interactions.

Nevertheless, recent developments of decision support systems based on geographic information systems (GIS) and distributed hydrological models have provided practical and useful tools to achieve this goal (Fohrer et al., 2001).

Land use changes, especially those arising from intensification of rain-fed agriculture, are usually driven by the need to improve agricultural production and hence livelihoods (Ngigi, et al., 2008). To enhance productivity of rain-fed agriculture, supplemental small-scale irrigation infrastructure through RWH is important for increasing evapotranspiration, particularly given growing environmental and social concerns about large scale irrigation projects (de Fraiture et al., 2007) that rely heavily on abstractions from either groundwater or river flows.

Due to the complexity of the climate system and its interactions with the hydrological cycle, it is extremely difficult to detect the causes of climate and land use change that are responsible for changes in the rainfall–runoff relationship (Pfister et al., 2004). Difficulties in predicting these changes can arise from the limit of data quality, the short period of measurements, and the gaps in time series, etc. This makes hydrological models useful tools for extrapolating data in space and time and to simulate the effects of changing climate and land use conditions on the hydrological processes in a river basin.

In this study, we applied the soil and water assessment tool (SWAT) model to estimate spatial variations of surface runoff resulting from upscaling of rainwater harvesting (RWH) in the upper Ewaso Ng'iro North basin in Kenya. Impacts were assessed on the area hydrology between baseline and alternative scenario such as upscaling of suitable RWH technologies. Our overall objective however, was to quantitatively evaluate the effects of land use changes on watershed hydrology of the basin (Figure 8.1). This was achieved by estimating hydrological responses under historical land use scenarios obtained from multi-temporal satellite imageries.

8.2 Materials and Methods

8.2.1 Study Area

The major challenges facing the upper Ewaso Ng'iro North basin include rapidly growing population and degradation of natural resource base resulting to declining land productivity and consequently insecure livelihoods. Farmers migrating from adjacent high agricultural potential districts due to increased pressure on land have caused land use changes particularly in the lower zones from natural vegetation to small scale agriculture, which have led to increased water abstraction and subsequently decreased river flows (Gichuki, 2002).

Land use changes in the basin, and especially from the intensification of rain-fed agriculture, have become inevitable due to increased food demand. Such changes are bound to have positive socio-economic impacts geared towards improving livelihoods, but may also lead to negative impacts downstream, consequently affecting their livelihoods and natural ecosystems that depend on sustained river flows (Ngigi et al., 2006). Generally, upstream watersheds play an important role on controlling the stream flow regime, and its hydrologic behaviour (water yield and runoff generation) depends mainly on their vegetation cover, soil and geological setting (Tangtham, 1998).

Low rainfall reliability and occurrences of dry spells in the basin are responsible for persistent crop failure in the upper Ewaso Ng'iro North basin. Studies by Ngigi et al. (2006) indicate that, there is 60% probability of occurrence of below average rainfall and 50-80% of agricultural droughts in the basin. However, it was also observed that, on-farm storage RWH systems can adequately address major critical water deficits by storing runoff for supplemental irrigation (SIR), thus bridging the dry spell period.

Water demand is continuously increasing in the basin due to population growth and irrigation development. About 60 to 95% of the available river water in the upper reaches of the basin is abstracted during the dry season with up to about 90% of the total abstraction being illegal (Kiteme and Gikonyo, 2002; Notter et al., 2007). This has negatively affected downstream populations and natural ecosystems leading to water use conflicts (Mutiga et al., 2010).

However, all is not lost since RWH can play a vital role in easing competition for the scarce water resources and consequently enhance food security. RWH is increasingly being recognized as a viable strategy for improving food production, especially by small-scale farmers in semi-arid environments. Rockström and Falkenmark, (2000) observed that RWH can provide the opportunity to maximize soil water holding capacity and mitigate dry spells in order to increase water productivity. Therefore, RWH need to be promoted significantly to enhance their adoption rates.

8.2.2 Description of the SWAT Model

SWAT is an acronym for Soil and Water Assessment Tool, a river basin model developed originally by the USDA Agricultural Research Service (ARS) and Texas A&M University that is currently one of the worlds leading spatially distributed hydrological models. The model is a physically based semi-distributed rainfall-runoff model that operates on a daily time step. It comprises of a GIS interface that outlines the sub-basins and stream networks from a Digital Elevation Model (DEM) and calculates daily water balances from meteorological, soil and land-use data (Arnold et al., 1998; Srinivasan et al., 1998). The model has the capability to predict the impact of management on water, sediment and agricultural chemical yields in large basins (Fontaine, 2002). The main components of the model include hydrology, weather, sedimentation, soil temperature, crop growth, nutrients, pesticides and agricultural management. However, fundamental strength of SWAT is the combination of upland and channel processes that are incorporated into one simulation package. The model has been widely used for both agricultural and water resources applications (Gassman et al., 2007).

Conceptually, the model divides a catchment into smaller discrete calculation units (hydrological response units - HRUs) for which the spatial variation of the major physical properties are limited, and hydrological processes can be treated as being homogeneous. The total catchment behaviour is a net result of manifold small sub-basins. The model operates on a daily time step, and can be used to predict the impacts of land management practices on water, sediment and agricultural chemicals in catchments (Neitsch et al., 2002; Chaplot, 2004).

The upper Ewaso Ng'iro North basin was subdivided into sub-basins and a river network based on a digital elevation model (DEM). Based on the unique combinations of soil and land use, the sub-basins were further detailed into hydrological response units (HRUs), which are the fundamental units of calculation. In total, 40 sub-basins and 128 HRUs were delineated for the basin.

8.2.3 Data requirements

SWAT model requires detailed spatial and temporal input data, as it is a highly detailed physical model. The most important spatial information used includes Digital Elevation Model (DEM), weather variables, land use, soil properties and land management practices. The DEM, which forms the basis for delineating the catchment boundary, stream network and created sub-basins, was obtained from the interpolation of 20 m interval contours. For temporal data, daily rainfall and potential evapotranspiration were used as climatic input data. Rainfall records were collected from five meteorological stations within the basin (Figure 8.1) while potential evapotranspiration was calculated by using the FAO Penman-Monteith method (FAO, 1998) which requires air temperature, relative humidity, wind speed, and radiation data.

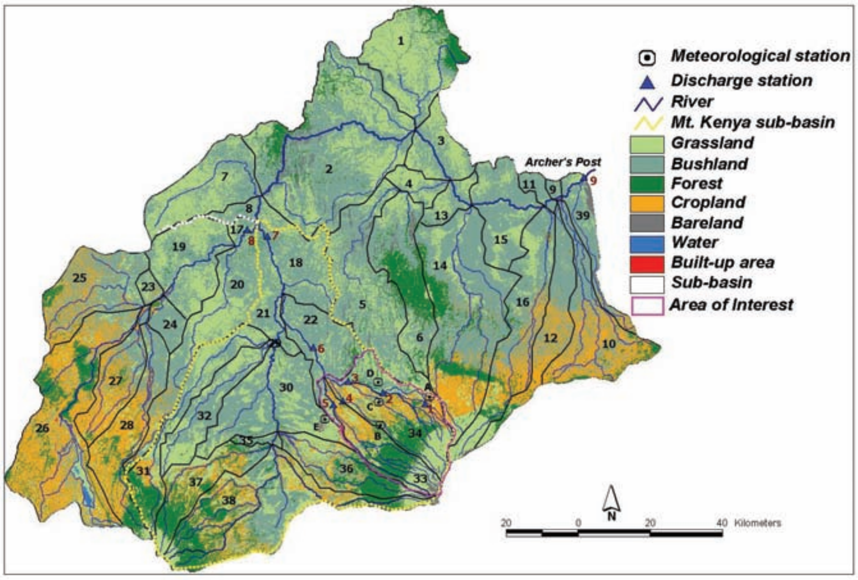

Figure 8.1: SWAT model configured for the upper Ewaso Ng'iro North Basin, Kenya with **1-9** discharge gauging stations.

The soil and land cover/use layers for the basin were used to generate unique combinations, each considered as having a homogeneous physical property called Hydrological Response Unit (HRU) which form the fundamental units for modelling. Hence, SWAT was used to distribute the river basin into units with similar characteristics in soil, land cover and that are located in the same sub-basin. The water balance for every HRU was computed on a daily time step.

8.2.4 Model calibration and Validation

The SWAT hydrological model was run on a daily time step, with model calibration, validation and analyses computed on a monthly basis for the basin. Calibration was performed manually by varying the ten most sensitive parameters (Table 8.1) in the model. This process was applied to examine the influence of various model parameters, step by step with an aim of improving simulated results as measured variables may not always be readily available for the area under investigation. The calibration and validation were done using the flow records from 1970 through 1990 for Mt. Kenya sub-basin (Figure 8.1), where we had adequate data. The period was split into two periods; 1970 – 1980 for calibration and 1980 – 1990 for validation.

8.3 Results and Discussions

8.3.1 Model calibration and validation

The initial model runs, after calibration, resulted in reasonable agreement between monthly observed and simulated discharge with a Nash-Sutcliffe efficiency of 0.75 indicating that the model performed well and could therefore be applied for discharge prediction. In general, model performance efficiency, determines how well the probability distributions of simulated and observed data fit each other.

The performance efficiency (R^2) value for simulated versus observed daily stream flow for the basin was 0.75 for the calibration period and 0.70 for the validation period (Figure 8.2). Visual comparison of simulated and observed stream flow during the calibration period shows that the model performed well in terms of the rainfall and runoff relationships.

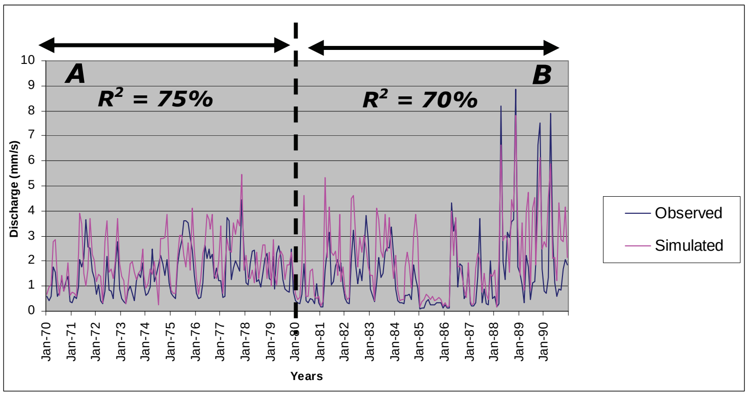

Figure 8.2: Calibration (A) and validation (B) phase of the SWAT model.

8.3.2 Model simulations

The SWAT model divides contributions to river flow into three categories; surface overland flow, lateral flow (quick flow within the upper soil profile) and groundwater flow (return flow from shallow aquifers), Table 8.1.

Major components of the hydrologic budget were simulated to determine the impacts of proposed land management (RWH) and LUC changes. This was done for 2003-2015 period. It was assumed that during the base year (2003) there is no RWH, and that it would be implemented sufficiently to meet crop requirements by 2015. The soil conservation service curve number (SCS, CN) approach and Penman-Montheith methods were used to calculate runoff and potential evapotranspiration respectively (Table 8.1).

Table 8.1: Sensitive SWAT parameters in Ewaso Ng'iro North Basin

SWAT Parameter	*Parameter Description*
CN2	Curve number
SURLAG	Surface Runoff lag coefficient
SOL_K	Soil Conductivity
SOL_AWC	Soil Water Capacity
EPCO	Plant Evaporation compensation factor
ESCO	Soil Evaporation coefficient
GW_REVAP	Groundwater "revap" coefficient
REVAPMN	Threshold depth of water in shallow aquifer
GW_DELAY	Groundwater Delay
ALFA_BF	Base flow alpha factor

8.3.3 Land cover/use changes and Population

Land cover/use types for the three time periods were obtained from classification of multi-spectral landsat images of 1987, 1995 and 2003, each with a spatial resolution of 30 m. Proportional changes in land use during the study period were determined by visually comparing classification results of multi-temporal images. Four main land cover/use types (forest, grassland, bushlands, and cropland) were identified in the upper Ewaso Ng'iro basin and used for SWAT simulations. However, it was observed that the upper catchments experienced the highest forest cover loss due to encroachment from people migrating from the neighbouring high potential areas with dense population (Kohler, 1987; Wiesmann, 1998). This resulted in catchments deterioration, making them prone to erosion and flooding. The population in the basin grew from 250,000 to about 650,000 in 1987 and 2003 respectively (more than double).

Table 8.2: Different land cover/use types in the basin

Land cover/ use class (%)	1987	1995	2003
Bare	19.2	22.5	24.1
Grassland	20.5	19.5	18.0
Cropland	12.1	17.4	24.3
Bushland	19.1	13.1	8.2
Forest	29.8	25.2	23.2
Water	1.2	1.2	1.0
Built-up area	0.1	0.1	0.2

The dominant land cover types in the area include forest, grassland, bareland and cropland (Table 8.2). Forest cover decreased by about 7% between 1987 and 2003. Similarly bushaland and grassland areas reduced drastically during the same period while bareland increased. The decrease could be associated with the need to clear more land for agricultural activities to feed the growing population as indicated by an increase in cropland. However, the increase in bareland witnessed over the same period could be associated to overexploitation of the soils through continuous poor farming practices with minimum soil nutrient in the area in addition to overgrazing. There was a 100% increase in urban area in the same period.

8.3.4 Runoff generation

Surface runoff generally occurs when the rate of water application to the ground surface exceeds the rate of infiltration. SCS curve number method was used to estimate surface runoff. Based on land use change scenarios, model parameters (Table 8.1) were recalculated and the model was re-run to deliver the modified flows. Figure 8.3 gives the simulated flow hydrographs for the three years (1987, 1995 and 2003) and land cover/use scenarios in the catchment. Analysis from running the model under different land cover/uses, revealed that runoff significantly increased (Table 8.3) leading to a decrease in evapotranspiration (*ET*) in relation to rainfall.

It was observed that surface runoff constitutes about 20% on average of the annual water balance in the basin with a higher component being converted to evapotranpiration (about 60% on average) leading to less groundwater recharge and consequently less water availability (Table 8.3). This observation tends to agree with the findings of Rockström (1999) on how rainfall is partitioned in the dry areas of SSA (10-25%, runoff and 45-80%, evapotranpiration). Further, the results also revealed that upscaling of RWH increased base flow by about 5% and reduced surface runoff by 2% with no significant effects in the downstream areas. The principal areas with relatively high runoff generation include the headwaters in the Mt. Kenya and the Aberdare ranges.

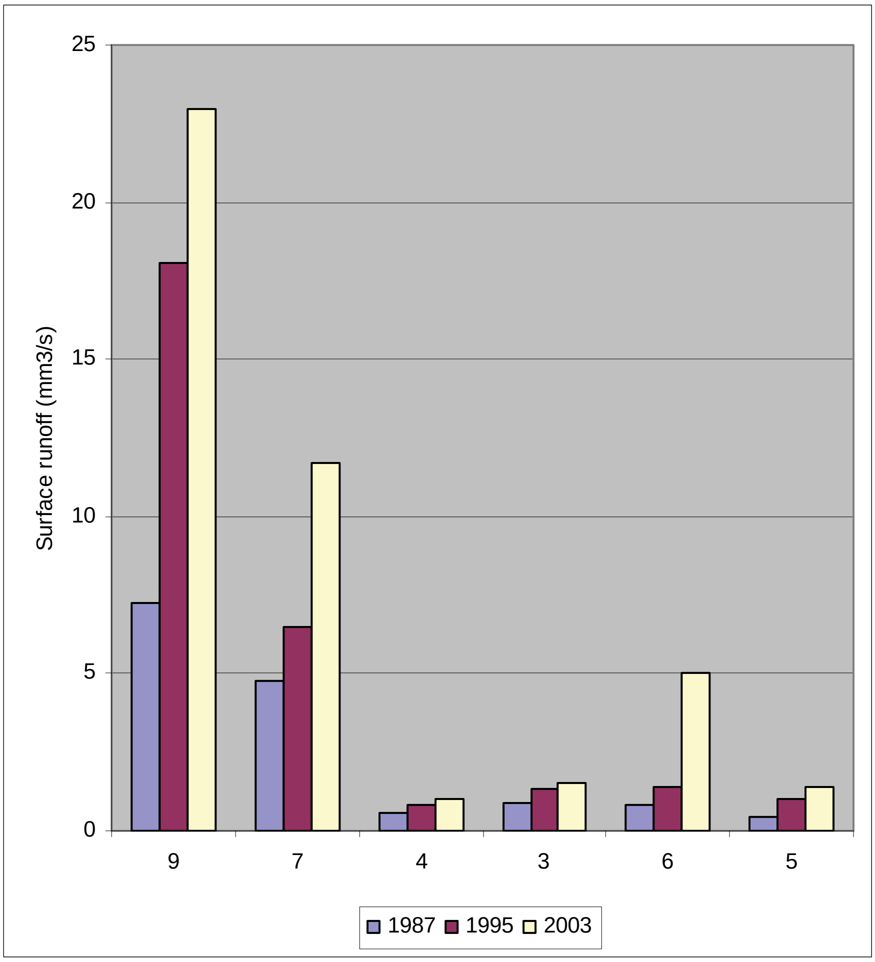

Figure 8.3: Generated surface runoff under different land cover/use types at various stations within the basin as shown in Figure 8.1.

Table 8.3, shows the average annual values of modelled hydrological components and changes attributed to land cover/use changes over the last 15-year period in the basin. The results indicate that there were slight increases in surface runoff and lateral flow as a response to the land cover/use change. The percent increase in surface runoff over the 15-year period (1987-2003) was about 4% per year while shallow ground water flow decreased by about 1% per year (Table 8.3). This situation was primarily due to the changes in land cover/use experienced during this period (Table 8.2)

Table 8.3: Rainfall partitioning under different LUC scenarios in mm/year

	1987	1995	2003	RWH
Precipitation	760	920	940	940
Surface runoff	143	212	224	210
Lateral soil flow	24	27	28	25
Shallow GW flow	62	56	53	55
REVAP	64	62	63	65
Deep Aquifer Recharge	12	13	14	16
Total aquifer recharge	126	140	146	152
Total water yield	260	354	380	348
Soil percolation	64	58	60	73
Evapotranspiration	480	542	545	592
Transmission losses	26	29	33	21

Nortcliff et al., (1990) observed that major changes in runoff occur between 0 to 30% vegetation cover, with higher vegetation cover having relatively smaller impacts. This tends to agree with the findings of the current study which show that the observed surface runoff increased gradually during 1987 – 2003 period (Table 8.3) with decreasing forest, grassland and bushland covers (Table 8.2). This can be attributed to poor natural vegetation resulting from overgrazing and deforestation for agricultural activities. This is because, infiltrated water reduces with decreasing vegetation cover.

Expansion in cropland resulted in higher surface runoff and consequently higher annual water yields (Table 8.3). Since an increased water yield percolates through well-drained soils, the primary implications include flooding in the downstream areas of the basin, and if this flood water can be diverted and stored to supplement irrigation activities, could reduce the downstream impacts significantly.

8.3.5 Downstream impacts of upscaling RWH

The results revealed that there are insignificant effects on downstream flow (Figure 8.3) resulting from the upscaling suitable RWH technologies in the upstream part of the basin. The annual total water yields, quick flow and base flow decreased moderately in the two scenarios when compared with flow at the current land cover/use (2003). The flow duration curves shows the temporal variation of flow over the three periods which could also be related to climate variability in addition to LUCs.

Land cover/use changes, especially those emanating from the intensification of rain-fed agriculture within the basin are inevitable due to the need to meet increasing food demand. Such changes could have either, positive socio-economic impacts such as those improving yields and hence livelihoods, but could also lead to negative impacts downstream, such as reduced water availability thus affecting both people and the natural ecosystems. Figure 8.4, gives the simulated flow hydrographs for the three land cover/use scenarios of the basin during 1987 – 2003 periods. Moreover, it was noted that the upstream part of the catchment, played an important role of controlling stream flow with its hydrologic behaviour (water yield and runoff generation) depending mainly on the vegetation conditions agreeing with the observations made by Tangtham (1998).

Furthermore, the results from this study indicate that an increase in *ET* as a result of intensifying agricultural activities using RWH technologies led to a decrease in the amount of water penetrating into the soil profile to replenish the shallow groundwater storage during the wet season. This change caused a reduced contribution of groundwater to the river flow and hence the overall discharge.

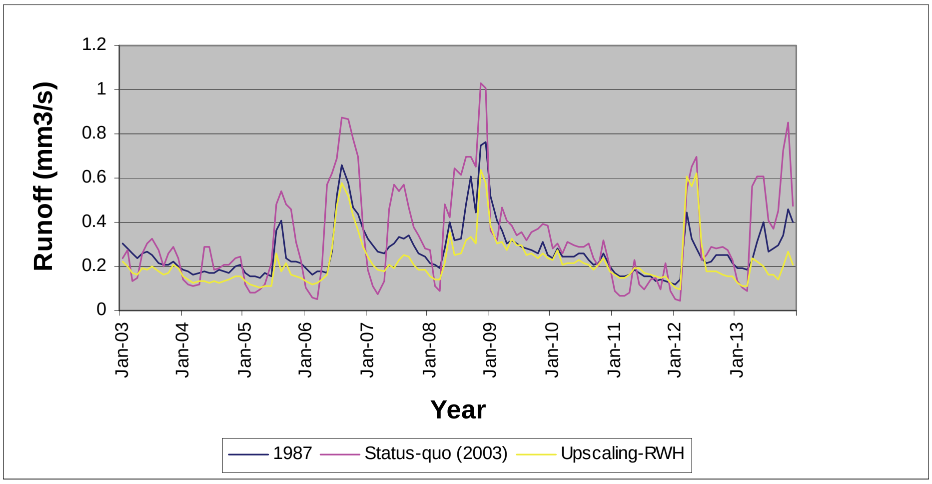

Figure 8.4: Simulated surface runoff for three different scenarios at the basin outlet (Archer's Post as shown in Figure 6.1).

Monthly average surface runoff tends to follow the rainfall pattern with higher values being observed when rainfall amounts are also high, clearly distinguishing between the two rainfall peaks (April-May and October–November) in the basin with relatively low values during the dry seasons (January-February and August–September).

8.4 Conclusion

SWAT model was applied to investigate the watershed-scale hydrologic impacts of land use changes within a 800 km^2 watershed. Simulated stream flow at the watershed outlet was found to be close to observed values with respect to low flow, and partly peak flows for the study period. The model however often underestimated some rainfall events. This could be due to the poor quality of input data. Nevertheless, a good agreement was also observed between simulated and the observed total runoff volumes during the simulation period.

Moreover, the results obtained also show that basin hydrology was found to be relatively sensitive to changes in land cover/use attributes, with a general pattern of increasing surface runoff with a decrease in forest, bushes and grasses with a subsequent decrease in evapotranspiration. However, intensification of rain-fed agriculture particularly in the upstream of the catchment does not significantly lower water availability in its downstream. Further, it was noted that the upstream part of the catchment plays an important role in controlling stream flow with its hydrologic behaviour (water yield and runoff generation) depending mainly on the vegetation conditions, which is in agreement with with the observations made by Tangtham (1998).

The performance of the model was assessed using the Nash and Sutcliffe efficient model performance evaluation criteria, and after verification, the model was applied for different scenario analyses (status quo and upscaling of RWH). Simulation of different scenarios demonstrates the implications of increased evapotranspiration (due to RWH upscaling) particularly to the contribution of groundwater to river discharge. Confidence can therefore be placed in asserting that irrespective of the level of future changes in RWH, the change in proportion of runoff that contributes to Ewaso Ng'iro river discharge through groundwater flows is insignificant and does therefore not affect the downstream flow significantly as a result of increasing *ET*.

The results also revealed that upscaling of RWH increased base flow by about 5% and reduced surface runoff by 2% with no significant effects in the downstream areas. In conclusion, assessment of the hydrologic effects of land cover/use changes is crucial for water resource development and management in the basin. Rapid population growth in addition to the effects of climate change has adversely impacted on the already limited resources (mainly water, arable land and pasture) leading to overwhelming conflicts over their use and management.

Smallholder agro-pastoralists have become the main agents of resource degradation in the recent past as they engage themselves in survival and coping strategies that are incompatible with prevailing ecological conditions in the basin. In addition, unregulated land subdivision has resulted in small and unviable land parcels that cannot support any meaningful livelihood. All these factors combined, have led to resource use conflicts especially in the dry areas of the basin (lowlands). This situation has been escalated by the increasing effects of climate change. Resource use conflicts in the Upper Ewaso Ng'iro Basin have now become as unpredictable as the weather over the past two decades with violence reaching unexpected levels in the 2007/2008 period. This consequently resulted in loss of human lives and property worth millions of shillings as witnessed during the post election violence not only in the basin, but also in most parts of the country (Kenya).

To minimize these effects, innovative natural resource (water and pasture) management remains crucial, calling for formulation of policies in relation to natural resource use and management that provide efficient mechanisms to address the situation while ensuring their sustainability. From the findings of this study, upscaling of RWH could play this critical role by providing more water for use, especially during the dry seasons when the user conflicts are at their peak.

8.5 References

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CHAPTER 9

Conclusions and recommendations

9.1 Conclusions

Water-related problems in rain-fed agriculture within dry river basins like the Upper Ewaso Ng'iro North Basin in Kenya and the Pangani River Basin in Tanzania are often related to large spatial and temporal rainfall variability rather than low cumulative volumes of rainfall. The overall result of rainfall unpredictability in these regions is a high risk of meteorological droughts and intra-seasonal dry spells. Therefore bridging crop water deficits particularly during dry spells through supplementary irrigation (using the harvested rain) can stabilize production in these areas, by increasing water productivity, especially if the water is applied at the moisture-sensitive stages of crop growth. It was also revealed that yields could be improved further if rainwater harvesting is applied together with nutrient management. This study therefore recommends that more resources should be made available to promote optimal utilization of available rainwater by adopting appropriate water related innovations in order to alleviate water scarcity and improve livelihoods of the rural communities in the upper Ewaso Ng'iro North and the Pangani where most people live below the poverty line. This could be achieved by empowering the rural poor to manage and sustainably use the available rainwater, in order to effectively deal with climate variability.

9.1.1 Water use situation in the study areas

The two basins (Pangani and Ewaso Ng'iro) can be classified as water scarce since they produce less than 1000 m^3 per capita per year (Chapter 2). The main source of water in the basins is surface water, which can only meet total user demand during the rain season. Critical shortages were found to occur during the dry season when more water is required especially for irrigation purposes. The degree of water abstraction for irrigation purposes increases downstream. This is attributed to the existing land use systems with the upper parts being predominantly covered with forests while the lower parts are smallholder parcels under subsistence cultivation (Figures 2.2 and 2.11).

It was also revealed that most of the water abstracted in the Upper Ewaso Ng'iro North Basin is taken illegally and this makes planning and management of the resource extremely difficult. The underlying issue is scarcity, and in order to maximize user benefits, efficient water resource management in the basin is therefore crucial. In an attempt to address the issue of water scarcity with minimal user conflict, communities along either the river systems (for Ewaso Ng'iro North) or the furrow systems (Pangani) have formed water user associations (WUAs) with the mandate of creating and raising awareness of water situations in the basin in general, resolve any water use related conflicts, regulate water use allocation, especially during the dry season and ensure fair water sharing between upstream and downstream users, enhancing cooperation among different users. This is complemented with various rainwater harvesting technologies being practiced in the area (Figure 2.7).

However, the success of improving water resource management activities in the two basins depends totally on the willingness and collaboration of the communities as well as the political will to enforce the existing water laws. The study further shows that many farmers perceive supplementary irrigationto be a solution to their water-related problems and since the two basins exhibit a high potential for rainwater harvesting and if harnessed and complemented with improved water saving technologies and nutrient management, RWH could significantly contribute to enhancing their livelihoods. Agricultural water management is seen as the key to food security and income for the rural communities in the two basins.

9.1.2 Potential of Remote Sensing

In order to promote sustainable development and conservation of environmental flows, estimation of the catchment water balance is required to give an overview of periodic water availability for the purpose of water resources planning and management. Moreover, quantification of individual components of the hydrologic cycle, especially at catchment scale is a crucial step in integrated watershed management. In order to achieve effective water resources planning and management, timely, accurate and comprehensive related information is required to facilitate informed decision making. Furthermore, since water resource management strategies are usually implemented at a basin scale, understanding of the hydrological processes at this scale is a pre-requisite for the formulation of these strategies. As pressure on water resources increases, sound knowledge of where, when and how much water is used is required. Remote sensing has proved to be an effective means of assessing spatio-temporal patterns of water availability and consumption over large areas. This is because the technology has the capability of obtaining consistent and frequent observations about the land surface processes.

However, remote sensing products need to be validated before they are used with in-situ data from different regions with different climatic and environmental characteristics in order to minimize systematic errors that could be propagated during the processing period or to improve their accuracy (Chapter 3). This would consequently enhance a good understanding of various environmental processes across different spatial and temporal scales. During the study, validation of remotely sensed derived products (land surface albedo and temperature) acquired from LSA SAF of the EUMETcast archive was conducted before being used to estimate regional evapotanspiration within the SSA region covering the East African (Chapter 4) countries, where the study basins are located, using the Surface Energy Balance System (SEBS).

Results obtained show that, there is a strong agreement (r^2 of 70% and 50%; RMSE of 2.4K and 0.005) between the remotely sensed and in-situ measurements for surface temperature and albedo, respectively. This shows the great potential that remote sensing technology has in providing valuable and timely information on spatial variations in flux partitioning and thus making it an indispensable means for monitoring vegetation conditions and ecosystem health over large land surfaces particularly in data scarce areas of Sub-Saharan Africa such as the two study basins.

Once the reliability of these remote sensing products was ascertained, it was now in order to apply this novel technology to estimate spatio-temporal rainfall distribution (Chapter 4) and evapotranspiration (Chapter 5), which is an indicator of water use levels in the basin. For the estimation of rainfall distribution in the Makanya catchment located in the upstream part of the Pangani River Basin in Tanzania, a multi-channel and multi-sensor data integration from both MeteoSat Second Generation (MSG) and Tropical Rainfall Measuring Mission's (TRMM) Microwave Imager (TMI) was used. A polynomial relationship (Figure 4.7) developed was applied to transform the precipitating clouds top temperatures into their corresponding rainfall intensities across the catchment.

The results obtained from this application revealed that rainfall in the catchment is highly variable as one moves from the lowlands to the highlands (Figure 4.10) with the lowlands receiving low rainfall amounts (400-500 mm/year) while the highlands receive relatively higher amounts (800-900 mm/year), agreeing with the findings of Enfors and Gordon (2007). It was observed that rainfall was highly variable between and within seasons in any particular year (Figures 4.12 and 4.13).

Since actual evapotranspiration (ETa) is one of the most useful indicators to explain whether the water is being used as "intended", its variations, both in space and time and for different land use types at any scale, are crucial. Unfortunately, estimation of ETa under actual field conditions is still a big challenge for both scientists and water managers. The complexity associated with the estimation of this variable has led to the development of various remote sensing based approaches over time. During this study, a semi-empirically based multi-step Surface Energy Balance Algorithm for Land (SEBAL) was used to assess the spatio-temporal distribution of ETa in the Upper Ewaso Ng'iro North Basin in Kenya. Archived cloud free MODIS L1B data with 36 channels of visible and near-infrared reflectance and radiance, as well as thermal-infrared radiance covering the area were used.

The results indicate that ETa values increased progressively between the years 2000 and 2006 (Figures 5.4, 5.5 and 5.6) with an annual increase rate of about 10%. This could be linked to the amount and distribution of rainfall for the same time periods. The year 2000 was indeed a dry year for the basin with an annual average rainfall of about 600 mm which is below the annual average of the basin (700 mm/year) while the years 2003 and 2006 received a relatively higher annual rainfall of about 850 and 1050 mm respectively.

Generally, the amount of rainfall received in the basin increases with increasing altitude. It was also observed that the mean annual total water storage in the basin decreased with increasing annual mean ETa from 2000 to 2006 with the lowlands experiencing high water deficits. This study demonstrates clearly that water availability becomes progressively less as one moves from upstream to downstream in the basin (Figure 5.13). This situation is currently a major concern especially for the water managers in the basin. To cater for this difference in water availability, farmers are adopting appropriate alternatives for water supply such as rainwater harvesting for supplementary irrigation. This practice is becoming more common especially in the middle reaches of the basin and should to be encouraged throughout the basin as a means of increasing water productivity and improving its availability.

9.1.3 Water allocation

Inadequate water resource management and a general decline in rainfall have aggravated water scarcity problems not only in the Upper Ewaso Ng'iro North Basin in Kenya but also in dry regions of SSA. Water use conflicts especially in this basin have escalated in recent decades due to increased competition for available water resources, resulting in excessive abstraction of the declining river water flow. This has led to reduced water flow particularly during the dry seasons, greatly affecting downstream water users. The goal of this study was to match the water requirements of various competing sectors in the basin with the available water resources in order to attain both economic and ecological sustainability.

To achieve the above goal, the Water Evaluation and Planning (WEAP) model, a decision support system (DSS), was adopted and applied to assess water availability and investigate the impacts of different water allocation scenarios (water demand management strategies) aimed at meeting various sectorial water demands in the Upper Ewaso Ng'iro North Basin in Kenya (Chapter 6). The model was first configured for the whole Upper Ewaso Ng'iro North basin in the form of a continuous set of three sub-catchments (Figure 6.1). It was then used to simulate alternative scenarios to assess the impacts of different development and management options. This was possible since the model has the ability to optimize water use in the catchment using an iterative linear programming algorithm with the objective of maximizing the water delivered to demand sites according to a set of user-defined rules (SEI, 2008). Estimated current water demands for the five different sectors were used for the reference scenario (Figure 6.6) based on the "naturalized" stream flow (1965-1980). This period was selected because irrigation activities started in the early 1990s, which is believed to be the beginning of water use conflicts in the basin.

The results from this study indicate clearly, that an integrated approach for the development of water resources in the basin is necessary in order to meet the water requirements of all sectors to avoid competition and conflicts in water use and at the same time optimize the use of limited water resources. To promote equitable water allocation in all sectors, prioritization of water use rights (Table 6.4) is a prerequisite in mitigating water use conflicts across the basin.

Since dams can be multi-purpose (used for storage, domestic supply, flood regulation or irrigation), suitable dam sites have been identified in the upstream of the basin, based on both bio-physical and socio-economic factors. Two dams were incorporated in this scenario and result analysis showed that building the dams would reduce the unmet water demand by about 5% (Figure 6.8). This is considered to be a significant contribution towards making more water available to the downstream users as well as reducing the current water use conflicts in the basin.

Results from this study revealed that improving irrigation efficiency would significantly improve water supply requirements downstream and consequently reduce the unmet water demand. This can be achieved through improved control and timing of water application during irrigation, ensuring implementation of supplementary irrigation strategically to overcome seasonal dry spells. It is important to introduce suitable crops that can withstand the dry spells and encourage communities to practice crop rotation with a sense of economy in mind.

Nevertheless, a greater potential for better water resource management to improve water use efficiency lies in soil and water conservation practices for rain-fed agriculture. In rain-fed agriculture, water conservation aims at reducing runoff and evaporation losses while increasing water supply to the soil and thus to the plants. This would also increase the base flow from ground water especially in the downstream areas of the basin. Given the highly seasonal flow variability of the Ewaso Ng'iro River, which depends on rainfall occurrence, it would be necessary to install flood storage dams in strategic but suitable locations aimed at stabilizing its stream flow. Thus building dams upstream of the basin would help meet water demands in Laikipia lowlands. Large commercial farms should also be encouraged to install reservoirs with at least three months storage capacity for the dry season in order to reduce demand from surface river water supplies. Release of stored runoff from these reservoirs during the dry season would support the downstream communities, thus achieving flow stabilization at Archer's Post through the middle reaches.

Capacity building and promoting change in the attitude of users towards rainwater harvesting and water saving techniques are also crucial. Agriculture not only creates jobs but also contributes significantly to the Gross Regional Domestic Product (GRDP) of the area. Farm development incentives by the government could assist farmers in putting water infrastructure especially for irrigation in place. Furthermore, the formation of water user associations (WUAs) is of importance as it integrates ideas from different stakeholders who can freely discuss problems, set goals and define their solutions. These platforms ensure a high level of stakeholder involvement and participation in designing and implementing development goals for the entire basin.

9.1.4 Potential of RWH

It has been increasingly recognized that in areas where agriculture is constrained by poor rainfall distribution in time and space (such as the Upper Ewaso Ng'iro North and Pangani River Basins) innovations that increase rainwater use efficiency and water management strategies have great potential to improve food security and livelihoods. Water management strategies such as rainwater harvesting (RWH) can be used to bridge dry spells through supplementary irrigation (SIR) of rain-fed crops.

However, most of the existing RWH innovations in the study basin are insufficient in providing adequate water to produce the necessary biomass for food security. This is mainly due to lack of knowledge about both bio-physical and socio-economic conditions under which RWH can be adopted by smallholder farmers, which then leads to low adoption rates. It is against this background that this study attempted to identify suitable areas for RWH by applying a spatial multi-criteria evaluation (MCE) approach, aimed at bridging the gap in knowledge, and hence improving the adoption rate of successful RWH innovations (Chapter 7).

During the evaluation process, a weighted linear combination (WLC) procedure allowing for full tradeoff among different factors (rainfall, topography, soils, land use/cover and socio-economic factors), was applied in the data rich Upper Ewaso Ng'iro North Basin with the results obtained then transferred to the data scarce Makanya catchment, which lies in the upper reaches of the Pangani River Basin in Tanzania. Suitability maps showing suitable areas for RWH in both areas were produced with attributes that serve as indicators for targeted RWH interventions. Sensitivity analysis performed to assess the effect of changing weights of the input factor criteria (rainfall, slope, soils, land cover/use) revealed that soil properties and slope characteristics are the most important criteria to be considered when selecting potential areas for various rainwater harvesting systems.

The results obtained indicate that the adopted MCE for the data scarce area (Makanya catchment) produced an accuracy of about 75%, which was considered significant taking into account that the area had minimal spatial data, with about 35% of the total catchment area being suitable for RWH interventions. This procedure demonstrates clearly how results from a data rich area can be effectively transferred to a data scarce area with similar characteristics when performing similar tasks.

A cost benefit analysis carried out in one of the sites identified as suitable for RWH in the Upper Ewaso Ng'iro North Basin to assess the overall economic returns obtained from using a micro-system RWH such as conservation tillage revealed that the yields improved by 45-190%, with higher yields being produced with nutrient management (Table 7.3). These findings demonstrate clearly that upgrading rain-fed production systems through SIR during dry spells can lead to large increases in water productivity and subsequently crop yields. These results thus provide a basis for farmers to make informed decisions on agricultural investments under hydrological risk and uncertain production systems in the dry areas of SSA like the Upper Ewaso Ng'iro North and Pangani Basins, since the sustainability of RWH interventions depends on the perceived tangible benefits. In this regard, RWH can be considered an option for making more rainwater available for crop production in dry areas and as such forms an important key to unlocking the potential in rain-fed agriculture.

This approach is considered to be an effective tool that can support decision makers in formulating sound and well informed strategies for water resource planning and management. The study therefore recommends that agricultural and water policies be modified to accommodate RWH technologies that aim to improve water productivity, not only for the basin but for the entire country.

9.1.5 Impacts of upscaling RWH

Land use changes, especially those arising from intensification of rain-fed agriculture, are usually driven by the need to improve agricultural production and livelihoods. To enhance productivity in rain-fed agriculture, supplemental small-scale irrigation infrastructure through RWH is important for increasing evapotranspiration, particularly given the growing environmental and social concerns about large-scale irrigation projects that rely heavily on abstractions from either groundwater or river flows. These changes can result in significant impacts on hydrology by affecting the amount of runoff, soil moisture, and groundwater recharge over a range of temporal and spatial scales. For sustainable water resources management, assessment of the impact of land cover/use change on a hydrological regime at all scales becomes critical.

In order to quantify the impact of these changes on the area hydrology, SWAT, an acronym for Soil and Water Assessment Tool model, was used to evalute the spatial variations of surface runoff resulting from upscaling of rainwater harvesting (RWH) in the Upper Ewaso Ng'iro North Basin in Kenya. An assessment was made based on the baseline and an alternative scenario (upscaling of rainwater harvesting technologies) by estimating hydrological responses under historical land use /cover scenarios obtained from the multi-temporal satellite imageries of 1987, 1995 and 2003. The model performance was found to be relatively good (Nash and Sutcliffe efficient of 70%) as shown in Figure 8.2B. Stream flow analysis was carried out for different parts of the basin to understand its hydrological responses, especially, the behavior of the base flow.

Analysis obtained from running the model under different land cover/uses, revealed that runoff significantly increased (Table 8.3) translating to a decrease in evapotranspiration (ET) in relation to rainfall. It was also observed that surface runoff constituted about 20% on average of the annual water balance in the basin with a higher component being converted to evapotranpiration (about 60% on average) leading to less groundwater recharge and consequently less water availability (Table 8.3). Further, the results also revealed that upscaling of RWH increased the base flow by about 5% and reduced surface runoff by 2% without having a significant effect in the downstream areas.

The principal areas with relatively high runoff generation included the headwaters in the Mt. Kenya and the Aberdare ranges (Figure 5.3 and Table 2.1).

In conclusion, the results obtained show that basin hydrology was found to be relatively sensitive to changes in land cover/use attributes, with a general pattern of increasing surface runoff with a decrease in forest, bushes and grasses, with a subsequent decrease in evapotranspiration. However, intensification of rain-fed agriculture particularly in the upstream of the catchment does not significantly lower water availability in its downstream areas. Further, it was noted that the upstream part of the catchment plays an important role in controlling stream flow with its hydrologic behaviour (water yield and runoff generation) depending mainly on the vegetation conditions. Upscaling of RWH increased base flow by about 5% and reduced surface runoff by 2% without having a significant effect in downstream areas. Assessment of the hydrologic effects of land cover/use changes is crucial for water resources development and management in the basin.

9.2 Recommendations

Inadequate water resources management and rainfall variability in general are the main causes of water-related problems (user conflicts due to scarcity, food insecurity, and poor rural livelihoods among others) in both the Upper Ewaso Ng'iro North Basin in Kenya and the Pangani River Basin in Tanzania. For example, water use conflicts in these basins have escalated in recent decades due to increased competition for available water resources. Excessive abstraction of the declining river water mainly for irrigation in the upstream areas with high potential for agriculture, often leads to reduced water flow during the dry seasons, greatly affecting downstream water users.

Population growth and the intensification of small scale irrigation on agricultural lands in these basins have dramatically increased water demand over the past decade. As a result, water abstraction for irrigation, livestock, and domestic use have severely stressed the water resources, particularly during dry seasons, causing conflict between upstream and downstream water users. Considering the existing water resources' situation in these basins, the following recommendations can be made:

9.2.1 Cost Recovery

Although water is a highly valuable resource in the two basins (Chapter 2), it is generally supplied for free (with low and highly subsidized cost). Water pricing has been widely accepted as a means of alleviating the water use crisis to improve productivity with the hope of ensuring better investments in the sector. It is strongly believed that if water is equitably charged, then its use would be more sustainable. Cost recovery is therefore critical for preserving the physical integrity of a system and thus it is necessary to come up with innovative solutions for water valuation aimed at improving its efficiency, while at the same time ensuring the protection of the peoples' rights to access. Managing water as an economic good is an important way of achieving efficient and equitable use and of encouraging conservation and protection of the resource (Dublin, 1992). However, failure to recognize water as an economic good has led to wasteful and environmentally damaging uses of the resource in the two basins. Since higher water charges will definitely reduce farmers' net revenues, it might prompt them to shift towards either low water consuming crops or high value crops to maximize the benefits of the available water resources. Farmers in both basins may be encouraged and motivated to shift from maize crops to sorghum, millet, cassava, cowpeas (low water consuming crops) or to cabbage, carrots, onions and French beans (high value crops), in order to maximize on their returns.

9.2.2 Promoting of water saving Technologies

If appropriately used, water saving technologies such as drip and sprinkler irrigation can significantly enhance water productivity and hence increase crop yields. These technologies can be implemented in combination with appropriate soil and water conservation practices with the aim to improve water application and distribution efficiency. Moreover, to promote these technonologies, incentives must be given to farmers who are already using them.

9.2.3 Promoting of vitual water trade

Addressing water scarcity related issues in the two basins will remain a major challenge. This means that other water supply alternatives must be identified in addition to RWH. Since the upper catchments were found to have more water than the lower catchments, which are suitable for livestock keeping, we suggest that virtual water trade between the upstream and downstream catchments be encouraged and promoted. This way, upstream farmers can provide cereal and vegetable products to downstream farmers in exchange for animal products. This kind of arrangement may be more efficient than cultivating crops in areas where opportunity costs of using water for other purposes are very high. This would significantly reduce water use conflicts currently being experienced in the area.

Samenvatting

In Sub-Saharan Africa (SSA) is 95% van de landbouw overwegend regen afhankelijk. Dit betekent dat de meerderheid van de bevolking afhankelijk is van op regenval gebaseerde landbouw voor hun bestaan. In veel landen in SSA is de groei in de landbouw sector het laatste decennium zwak geweest, ondanks het feit dat aan deze sector prioriteit is toegekend ten behoeve van armoede bestrijding. Deze trage groei wordt veroorzaakt door slechte landbouw methodes en de gevolgen van klimaat verandering.

Hoewel de situatie wanhopig lijkt, zijn er technieken om regenwater op te vangen die misschien uitkomst kunnen bieden. Dergelijke technieken hebben veelbelovend potentieel getoond wat betreft het verhogen van de opbrengst in de landbouw. De meeste in de regio bestaande technieken zijn echter weinig effectief, waardoor ze ook weinig worden toegepast. Het doel van dit onderzoek was om bij te dragen aan bestaande kennis en strategieën te formuleren ten behoeve van duurzaam water- en landbeheer in de water arme rivier bekkens in SSA. Hiermee zou de water productiviteit verbeterd kunnen worden, zo bijdragend aan de voedsel zekerheid en de wereldwijde discussie over water, voedsel en het milieu, met het doel de reeds gestelde milennium ontwikkelings doelen (MDGs) te bereiken.

Om dit doel te bereiken is in deze studie een snelle analyse methode, gebaseerd op GIS, gehanteerd om de geschiktheid te bepalen van een aantal water systeem innovaties (WSIs), zoals regenwateropvang (rainwater harvesting, RWH) technieken, die de landbouwkundige productiviteit van deze droge gebieden in SSA kunnen verbeteren. Remote sensing technieken werden gebruikt om de meeste gegevens te verzamelen (via verschillende multi-sensor missies), die nodig waren voor de verschillende ‘decision support tools (DSTs)’ die in deze study zijn gebruikt. Dit werd aangevuld met de bestaande rijke lokale kennis.

Om in gebruik name van deze innovatieve waterbeheers technieken op grotere schaal te bevorderen, speciaal onder kleine landbouwers, is een ruimtelijk multi criterium evaluatie process (SMCE) toegepast, een DST dat geschikte gebieden identificeert om bepaalde RWH technieken door te voeren in de stroomgebieden van de Upper Ewas Ng’iro North in Kenia en de Pangani Rivier in Tanzania. Een gewogen, lineaire combinatie procedure, die de verschillende factoren van invloed op de geschikheid van een gebied volledig afwoog, werd toegepast in het gebied rijk aan data van de Ewaso Ng’iro. De verkregen resultaten zijn vervolgens overgebracht naar het data arme Makanya stroomgebied, bovenstrooms in het Pangani Bekken in Tanzania.

Kaarten met gebieden geschikt voor RWH werden aangemaakt, met aangegeven de plekken waar RWH toepasbaar zou zijn. Deze informatie kan gebruikt worden ter bewustmaking en om beleids beslissingen te sturen wat betreft RWH en het halen van de MDGs.

Hoewel de voordelen van het implementeren van RWH (verhoogde opbrengst door verbeterde water productiviteit, verbeterde rurale levensomstandigheden) worden erkend, was het ook van essentieel belang wat het gevolg zou zijn als RWH op grote schaal zou worden toegepast door veel kleine boeren in het gebied. Dit is gedaan door een bodem en water evaluatie methode (soil and water assessment tool, SWAT) toe te passen, een hydrologische mehode om de invloeden op de hydrologie vast te stellen van veranderingen in land bedekking/gebruik door uitgebreidere RWH technieken. De situatie van 2003 is geëvalueerd en vergeleken met het mogelijke alternatief (uitgebreidere RWH) voor 2015.

De hydrologische respons werd geschat op basis van historische grond bedekking/gebruik scenarios, verkregen via multi-temporale sateliet beelden uit 1987, 1995 en 2003. De resultaten lieten een toename in totale oppervlakte afwatering zien gedurende deze periode en een afname in bos, struiken en grass in het gebied. Het op grote schaal toepassen van RWH als water beheer's strategie verlaagde de algehele oppervlakte afwatering, tegelijkertijd de grondwater stroming in bijna gelijke mate verhogend, zo de vermindering in bovengrondse afwatering compenserend. Ook is vastgesteld dat het uitbreiden van al in gebruik zijnde, geschikte RWH technieken de evapotransporatie (ET) verhoogde, aantonend hoe water productief kan worden aangewend ter verbetering van de opbrengst.

De studie concludeert dat de meest haalbare en kost effectieve manier om de water schaarste en gerelateerde water problemen in deze droge gebieden in SSA het hoofd te bieden, het promoten en aanmoedigen is tot in gebruik name van innovaties in waterbeheer, zoals RWH, dat bewezen heeft meer water beschikbaar te kunnen maken om zo de voedsel productie en dus de leefomstandigheden in het gebied te verbeteren. Dit kan worden bereikt door boeren te motiveren door krediet mogelijkheden en markten voor hun producten te bieden. Capaciteits uitbreiding door middel van het via agrarische voorlichtingsdiensten aanbieden van keuze mogelijkheden, gebaseerd op de eigenschappen van het gebied, kan hier aan bijdragen.

Author's Biography

Jeniffer Kinoti was born on 25 December 1969 in Gaitu, a small rural village in Meru district, Kenya. She received her primary education at Njuthine Pry, a local school, and later joined Nyeri Technical School for her secondary education in 1984 graduating with a distinction in 1987. This enabled her to secure admission to Moi Forces Academy, Nairobi, Kenya for her higher secondary education specializing in a science based subject cluster (Mathematics, Physics, and Chemistry), which she successfully completed in 1989.

In early 1991, Jeniffer joined Moi University Eldoret, Kenya, to pursue a Bachelor's degree in Education Technology (Motor Vehicle Engineering Option). After graduating with Honours, in 1994, she immediately joined DT Dobie workshop in Ruaraka Nairobi, Kenya, as a motor vehicle mechanic, working in both in the Nissan and the Mercedes Benz units of the company. In 1994, she joined Othaya Boys High School as the Head of Department (Power Mechanics Technology), where she was instrumental in setting up this department.

After working for about 2 years, Jeniffer left to start a Master of Philosophy degree course in Environmental Science, at Moi University Eldoret, Kenya, specializing in Environmental Information Systems. She majored in Remote Sensing (RS) and Geographical Information Systems (GIS) and graduated in 2001 with a thesis entitled "*Land-use Dynamics and their Impacts on the Environment: A case study of Muthengera Location, Laikipia District, Kenya".* After graduation, Jeniffer joined the Laikipia Research Programme (now the Centre for Training and Integrated Research in ASAL Development – CETRAD) as a GIS Analyst/ Environmental Scientist, where she worked until 2002 when she left to join the International Livestock Research Institute (ILRI) in Nairobi as a Remote Sensing and GIS Specialist. While working in these two reknown research oriented institutions, Jeniffer was mainly engaged in Spatial Data Analysis, Database Management and GIS/ RS training for interns (MSc. and PhD students). This earned her immense experience in various aspects of research and development projects.

In 2005, Jeniffer obtained a Dutch scholarship (NFP) to undertake PhD studies at ITC, Enschede, in the Department of Water Resources. Her study topic was "Planning of System Innovations in Watersheds: Spatial Mapping of Environmental and Hydrological Determinants in Pangani and Ewaso Ng'iro North River Basins, Africa". Jeniffer began her studies in April 2006 culminating into several peer reviewed scientific journal articles and international conference papers. Her research interests include spatial hydrology, quantitative remote sensing and IWRM. Currently Jeniffer is working at CETRAD as the Head of Research and Training and as a Post-doc Researcher with NCCR-North-South Initiative on Mapping of Landscape transformations in East Africa Region.

Author's publications

Msc Thesis/Dissertation

1. **Kinoti, J., (2001)**. Land-use Dynamics and their Impacts to the Environment: A case study of Muthengera Location, Laikipia District, Kenya. *M.Phil Thesis, Moi University, Eldoret, Kenya*.

ISI Journal Articles

1. **Mutiga, J.K., Su, Z. and Woldai, T., (2010)**. Using Satellite Remote Sensing to assess Evapotranspiration: A case study of the upper Ewaso Ng'iro North Basin, Kenya. Int. J. Appl. Earth Observ. *Geoinform., (12S): S100–S108.*

2. **Mutiga, J.K., Su, Z., Woldai, T. and Maathuis, B.H.P., (2010)**. Estimation of spatial temporal rainfall distribution using remote sensing techniques: A case study of Makanya catchment, Tanzania. Int*. J. Appl. Earth Observ. Geoinform., (12S): S90–S99.*

3. **Mutiga, J.K., Mavengano, S. T., Su, Z., Woldai, T. and Becht, R., (2010)**. Water allocation as a planning tool to minimise water use conflicts in the upper Ewaso Ng'iro North Basin, Kenya. *Water Resources Management, (24):3939-3959.*

4. **Mutiga, J.K., Su, Z. and Woldai, T., (2010)**. Spatial Multi-criteria evaluation process for selecting rainwater harvesting sites as a mitigation measure in responding to climate change in sub-saharan Africa. *Being revised for re-submission to Journal of Hydrology.*

5. **Mutiga, J.K., Su, Z., Woldai, T. and Maathuis, B.H.P., (2010)**. Validation of satellite derived albedo and surface temperature for regional estimation of evapotranspiration in data scarce areas in sub-saharan Africa. *Being revised for re-submission to Remote Sens. Lett*.

6. **Mutiga, J.K., Su, Z. and Woldai, T., (2010)**. Impacts of agricultural intensification through water systems innovations in the upper Ewaso Ng'iro North Basin, Kenya. *Hydrology and Earth System Sciences, (Under Review).*

International Conference Proceeding (Full Papers, peer reviewed)

1. **Mutiga, J.K., Su, Z. and Woldai, T., (2008)**. Application of Spatial Multicriteria evaluation process (MCE) to select suitable rainwater harvesting sites as a mitigation measure in responding to climate change in water scarce basins of sub-saharan Africa. A case study of the upper Ewaso Ng'iro North basin, Kenya. *8th EMS Annual meeting/ 7th European conference on Applied Climatology (ECAC), Amsterdams, The Netherlands.*

1. 2. **Mutiga, J.K., Su, Z. and Woldai, T., (2008)**. Using Satellite Remote Sensing to assess Evapotranspiration: A case study of the upper Ewaso Ng'iro North Basin, Kenya. *In: ISPRS 2008: Proceedings of the XXI congress: Silk road for information from imagery: the International Society for Photogrammetry and Remote Sensing, Beijing, China.*

2. **Mutiga, J.K., Su, Z. and Woldai, T., (2006)**. Estimation of spatial temporal rainfall distribution using remote sensing techniques: A case study of Makanya catchment, Tanzania. *8thWaterNet/WARFSA/GWP-SA Symposium on Integrated Water Resources Management: From Concept to Practice, Lusaka, Zambia.*

3. **Mutiga, J.K., Woldai, T. and Su, Z., (2006)**. Application of Expert knowledge based multi - criteria evaluation (MCE) process to select suitable areas for water harvesting systems in Sub-Saharan Africa. A case study of Tanzania. *6th AARSE International conference on Earth Observation and Geo-information Sciences in support of Africa's Development, Cairo, Egypt.*

Research Projects

1. Principal Investigator, ESA Tiger Project: Planning of Systems innovations in the upper ewaso Ng'iro and Pangani Basins (2005-2010).

2. Principal Investigator, IFS Project: Improving rural community livelihoods through adoption of rainwater harvesting in Ewaso Ng'iro (2009-2010).

3. Principal Investigator, GEO Project: Application of Earth Observation for sustainable water resources management in Ewaso Ng'iro basin (2010-2013).

ITC Dissertation List

http://www.itc.nl/Pub/research/Graduate-programme/Graduate-programme-PhD_Graduates.html