MODELING THE IMPACTS OF WATERSHED DYNAMICS ON ARROR RIVER DISCHARGE, ELGEYO MARAKWET COUNTY, KENYA

BY

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DECLARATION

Declaration by the Candidate

This thesis is my original work and has not been presented for a degree in any other university. No part of this thesis may be reproduced without the prior written permission of the author and/or University of Eldoret.

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DEDICATION

This thesis is dedicated to my dear husband Solomon and children Valerie, Robin and Roy; to my parents and siblings.

ABSTRACT

The challenge to manage water resources in a watershed in a sustainable and appropriate manner is growing. Water scarcity is a serious problem worldwide and thus the need to understand the watershed dynamics and their impact on discharge. This can be done effectively through integrated water resource management. In Arror River watershed, there has been a lot of degradation caused by human activities and this has led to a reduction of river flows. This study sought to model the impact of watershed dynamics on the discharge of Arror River, Elgeyo Marakwet County, Kenya. The primary sources of data included the remotely sensed data and socio-economic data. Landsat 5 Thematic Mapper (for the year 1986 January) and Landsat 7 Enhanced Thematic Mapper (for 2000 and 2012 both for the month of January) with a resolution of 30 m were used for GIS analysis. A DEM with a resolution of 90 m was used to delineate Arror watershed. The secondary data included climate, river discharge and soil data. Field surveys and questionnaires were used to collect information about the indigenous and contemporary watershed management and conservation practices and other socio- economic data. In this study GIS was integrated with WEAP together with the SWAT model to analyse the various management practices in the watershed. SWAT was used to assess the impact of land use changes on river discharge while WEAP was used to assess water demand in the watershed. The results showed that the local communities in Arror watershed have their own traditional ways of managing their water catchments with most respondents (89%) reporting prohibition of cutting of trees. They also reported some modern watershed management methods with agroforestry being the most popular (67.5%). Decision Support System based on the WEAP model as well as the SWAT model were able to predict the general trend of the catchment processes with an coefficient of efficiency (EF) of 0.85 and 0.86 as well as R-squared of 0.88 and 0.81, respectively. On land use changes, there was a reduction of 3.48% on deciduous forest and 11.82% on grassland while agricultural land increased by 14.30% in the period 1986 to 2012. The average monthly flows for 1986, 2000 and 2012 land uses were 2.04 m^3/s, 2.46 m^3/s and 1.94 m^3/s, respectively. The variation in flow is attributed to mainly land use/cover changes. Agriculture and livestock keeping are the main economic activities in the study area. The total water allocated for agriculture, domestic and livestock in the watershed was 10,333,441m^3p.a with the highest consumer being agriculture in the lower catchment at 7,154,457 m^3 p.a for the reference scenario (1986-2012). The total mean demand for the same period was 10,461,123 m^3 p.a and thus a mean annual unmet demand of 127,682 m^3 p.a. The highest mean monthly unmet water demand was that of agriculture in the lower sub-catchment in January (90,200 m^3). The minimum flow requirement scenario would yield the highest mean annual flows (85,113,000 m^3 p.a) while the climate varied scenario would yield the lowest mean annual flows over the 28 years (2013-2040). The management practices that would enhance the sustainable management of the watershed include contour farming, construction of a reservoir, enforcement of minimum environmental flows maintenance in the river, agroforestry and afforestation which are recommended to be applied in Arror watershed. The findings of this study are intended to contribute towards sustainable water resource management.

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ACRONYMS AND ABBREVIATIONS

CMS-RVCA: Catchment Management Strategy for Rift Valley Catchment Area

CRP: Conservation Reserve Program

DEM: Digital Elevation Model

DSS: Decision Support System

DTM: Digital Terrain Model

GIS: Geographical Information Systems

HEP: Hydroelectric Power

IWMSM: Integrated Water Management Support Methodologies

IWRM: Integrated Water Resource Management

KIPPRA: Kenya Institute for Public Policy Research and Analysis

KVDA: Kerio Valley Development Authority

NACOSTI: National Commission for Science, Technology and Innovation

ROK: Republic of Kenya

SEI Stockholm Environment Institute

SDSS: Spatial Decision Support System

SRTM: Shuttle Radar Topography Mission

SWAT: Soil and Water Assessment Tool

UNEP: United Nations Environment Programme

WEAP: Water Evaluation and Planning System

WHO: World Health Organization

WRM: Water Resource Management

WRMA: Water Resource Management Authority

OPERATIONAL DEFINITION OF TERMS

Abstraction: Is the removal of water, permanently or temporarily, from water bodies such as rivers, lakes, canals, reservoirs or from groundwater

Base flow: Base flow refers to the surrounding ground water that seeps into the banks of a river or riverbed over time. Without base flow, many rivers and streams would only carry a flow of water during rainfall or storms. Also called drought flow, ground water recession flow and low flow.

Blue water: Is all liquid water. It includes surface runoff, groundwater, streamflow and pond water that can be used elsewhere for domestic and stock supplies, irrigation, industrial and urban use and which supports aquatic and wetland ecosystems.

DEM: A digital elevation model (DEM) is a digital representation of ground surface topography or terrain. It is also widely known as a digital terrain model (DTM).

Effective precipitation: Is the amount of precipitation that is actually added and stored in the soil. Effective precipitation enters the soil and becomes available to the plant.

Green water: Is water held in the soil as moisture. Water that sustains ecosystem services that directly benefit humans in rain fed food production, forests for timber, biomass for fuel wood and fibres, pastures for grazing, and other biomass growth directly used by humans.

Hydrologic Model: A hydrologic model is a simplification of a real-world system such as surface water, soil water, wetland, groundwater, and estuary. They help in understanding, predicting, and managing water resources and are used to study both the quantity and quality of water.

Integrated Water Resources Management: Is an approach which promotes the coordinated development and management of water, land and related resources in order to maximize economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems.

Scenarios: Scenarios in WEAP encompass any factor that can change over time, including those factors that may change because of particular policy interventions, and those that reflect different socio-economic assumptions.

SRTM: The Shuttle Radar Topography Mission (SRTM) which obtained elevation data on a near-global scale that is used to generate the most complete high-resolution digital topographic database of Earth.

Sustainable development: Sustainable development is the improvement of people's livelihoods without disrupting the natural cycles.

Unmet demand: The quantity of water that cannot be physically delivered from the river during a part of the year.

Watershed dynamics: Is the interaction of numerous human related drivers of economic, social, and demographic functions, including climate change as an uncertain driver.

Watershed management practices: Include all the land use practices and water management practices that protect and improve the quantity and quality of the water and other natural resources within a watershed by managing the use of the land and water resources in a comprehensive manner.

Watershed: Is an area of land where all water drains to a central point like a lake, river, or stream. When rain sweeps over a surface, it will eventually make its way to that central point. Also known as drainage basin or water catchment.

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May the almighty God bless you all.

CHAPTER ONE

INTRODUCTION

1.1 Background to the Study

Water is life and without it life will be unbearable and eventually cease to exist (Viala, 2008). It is a major and common natural resource that is crucial for sustainable development and the well-being of mankind and other living organisms. The earth's water is constantly in motion, passing from one state to another, and from one location to another, which makes its rational planning and management complex and difficult task under the best of circumstances (Turner, 2004). However, the availability and use of the water resource is mainly constrained by its spatial quantity and quality distribution.

Water resource quantity degradation is a serious national and international problem that affects economic productivity and the environment in multifaceted ways globally. Water shortages are causing wide spread health problems, limiting economic and agricultural development and harming a wide range of ecosystems (WWAP, 2012). The lack of water resources experienced in different parts of the world has now been recognized and analysed by different international organizations such as World Health Organization (WHO), the World Bank, among others. Thomas and Durham (2003) asserts that published documents from the United Nations Environment Programme (UNEP) confirms that severe water shortage affects 400 million people today and will affect 4 billion people by 2050. Current water management practices are still focused on reacting to events that occurred in the past: the re-active approach. A more strategic oriented water management, the pro-active approach has been advocated currently. To be prepared for the paradigm shift, from a re-active towards a pro-active approach, Integrated Water Management Support Methodologies (IWMSM) is needed that go beyond the traditional operational support tools (Loon & Droogers 2006). Water resources touch every sector of the economy and therefore it is important to improve its management in order to reduce the degradation and enhance equitable access and utilization, thus reducing and alleviating sources of water conflict as observed by Mwiturubani and Wyk (2010).

Oki and Kanae (2006) observed that most of the projected global population increase takes place in third world countries that already suffer from water, food, and health problems. Progressively, the various water uses (municipal, industrial, and agricultural) must be coordinated with, and integrated into, the overall water management of the region. Sustainability, public health, environmental protection, and economics are key factors. The rationale for the sustainable development and management of freshwater resources is clearly articulated in the sustainable development goals (Griggs *et al*., 2013). Today as asserted by Lead *et al.* (2005), it is widely recognized that an integrated approach to freshwater management offers the best means of reconciling competing demands with supplies and a framework where effective operational actions can be taken. It is thus valuable for all countries at all stages of development. IWRM was mentioned in the Millennium Development Goals Declaration of the United Nations (United Nations, 2000) article 23 and later emphasized in the Sustainable Development Goals. To stop the unsustainable exploitation of water resources there is need to initiate water management strategies at the regional, national and local levels, which will consequently promote both equitable access and adequate supplies. This approach includes the development of alternative water resource; protection of water resource to stabilize and improve its quality and quantity; demand management implemented at the level of each river basin (Savenije & Van der Zaag, 2008).

In Africa, a third of the continent's population, 300 million people are already experiencing water scarcity as affirmed by Braune & Xu (2010). It is further projected that half of the African countries will suffer water stress by the year 2025 (Mwiturubani & Wyk, 2010). The fundamental issue facing water resources in Africa do not appear to be one of water availability only, but also of human factors. Beekman and Pietersen (2007) alludes that the human factors are related to the governance of the available water resources, legislative and institutional frameworks, overexploitation and pollution of the resources, conflict and political instability, inadequate technical know-how and institutional capacity, and low priority given to water in terms of human resources and budgetary allocations.

The dominant water resources management challenge is how to secure water to cover food demands accelerated by a rapidly expanding world population, while at the same time sustaining other critical ecological functions in regions with highly unreliable and scarce water resources (Bhatt, 2006). This is more pronounced in the developing countries where 95% of the world's population growth occurs, and particularly in the Sub-Saharan Africa, which host the largest proportion of water scarcity-prone areas (Rockstrom, 2003). In our current state of rapid urbanization in majority of the third world countries, excessive consumption in developed nations, and political tensions worldwide, one of the major limiting factors on future development is freshwater availability. As the disparity between the rich and the poor widens, so does the provision of services to cover their basic needs (Kahl, 2006). Freshwater stands at the junction between environmental, health, sanitation, and housing or land use agendas (Alfarra, 2004). The shortages of fresh water can have a massive effect upon a society, ranging from food supplies to industry, spread of disease and damage to natural systems.

On the Kenyan scene, water scarcity has caused economic decline and rampant food insecurity and has become a basis for conflicts in rural Kenya that tend to be resource-based with a bias towards shared water sources (Cheserek, 2007; Lelo *et al*., 2005). The shortage of fresh water has therefore become a major agenda for the government, non-governmental organizations and bilateral bodies. Water resources underpin the country's main economic sectors: agriculture, livestock, tourism, manufacturing and energy. The social, economic and environmental aspects of water signify its importance in the country's sustainable development, attainment of Vision 2030 targets and realization of human rights. This is further reinforced by Kenya Institute for Public Policy Research and Analysis (KIPPRA) (2013) who asserts that prudent management of water is essential in minimizing resource-use conflicts within the country and with other countries sharing water resources.

Kenya's renewable freshwater resources are estimated at 20.2 km^3 per year, which corresponds to 647 m^3*per capita*, one of the lowest in Africa and the situation is expected to get worse due to population growth and climate change (Republic of Kenya, 2002c).

Roughly a third of its population have no access to safe water supplies and nearly 50% live below the absolute poverty line, while the national economy and environment are struggling with the negative effects of deforestation, poor land management, and water shortages (Mogaka, 2006). It is important to note that water scarcity has reached critical levels and dire consequences are already being felt in different sectors as is the case of some hydroelectric power (HEP) generation stations facing closure due to low water levels, for example Masinga dam (Bunyasi *et al.*, 2013).

While geography and climate largely explain Kenya’s exposure to drought, the root cause of the country’s vulnerability is its dependence on rainfall for its economic and social development. Fox *et. al*. (2005) observed that agriculture, the mainstay of Kenya’s economy, is almost entirely rain-fed. Most water for human consumption and other uses is derived from rivers whose recharge depends on rainfall. Access to clean water is already a problem in many areas of the country, including the capital city, Nairobi and other large towns (Marshall, 2011). A few years ago the Kenyan economy ran on hydropower but due to the droughts and subsequent reduction in water levels the government has explored other means of power production such as the geothermal and wind power as pointed out by Mariita (2002). The most vulnerable are the rural poor who depend on agriculture and livestock for their livelihood. One clear consequence of the recurrent droughts is the escalation of poverty and food insecurity among dry land dwellers. Increased competition for scarce resources exacerbates environmental degradation, which in turn increases the communities’ vulnerability to drought (Kandji *et al.*, 2006).

The River Arror watershed, a part of Kerio River basin represents typical semi-arid and dry sub-humid rain fed agrarian conditions. Muli (2007) observed that the River Arror watershed manifests strong signs of human induced land degradation due to high pressure on soil and water resources, where land use/ land cover changes upstream are affecting the hydrology and erosion of the river downstream. In the study area, increased pressure on the finite arable land due to increasing human population is causing unprecedented land degradation as communities seek for agricultural land from areas with steep slopes and wetlands resulting in desertification, landslides, soil erosion and siltation of river systems and reservoirs as well as the disappearance of the wetlands (Muchemi, 2004). This seriously affects both the ecological and hydrologic balances.

A pressing need therefore exists to develop environmentally sustainable and socially equitable approaches to water development and management that balance the needs of the environment, with economic growth, while addressing wide-spread poverty and lack of basic water as well as eliminate the water related disasters (Soussan *et al*., 2006). This is in line with Agenda 21 which emphasized the need to supply water of good quality and adequate quantity to the whole population without degrading hydrological, biological and chemical functions of ecosystems and adapt human activities within the capacity limits of nature. It also advocated for innovative technologies, including the improvement of indigenous technologies necessary to fully utilize limited water resources (Alfarra, 2004). This is also in line with goal 15 Target one of the SDGs which emphasizes the conservation, restoration and sustainable use of terrestrial and inland freshwater ecosystems and their services, in particular forests, wetlands, mountains and dry lands, in line with obligations under international agreements (Sachs, 2012). In addition to this, the SDG goal six also aims at ensuring the availability and sustainable management of water and sanitation. Similarly, vision 2030 also advocates for more efficient management of Kenya's scarce water resources, for household and commercial enterprises, in order to achieve the economic, social and political priority projects suggested (Republic of Kenya, 2007). It is against this background that this study sought to model the impacts of land use changes and water demand on Arror river discharge. This was done by simulating and describing the impacts of land use and water demand on watershed response using the SWAT and WEAP models.

1.2 Statement of the Problem

Arror River has its source in Cherangany Hills Forest, one of the five water towers in Kenya that serve as steady source of water to the North Rift region and Western Kenya. Previous studies by Muli (2007) and Muchemi (2004) indicate that the natural resources in Arror watershed and the entire Kerio River basin were being depleted at an alarming rate. The depletion is occasioned by rampant illegal settlements, logging, overgrazing, illegal extension of farms and charcoal burning leading to severe damage to the region's economy with an impact on energy, tourism, agriculture and water supply to towns and institutions. Moreover, the majority of people in the area practice shifting cultivation and free-range cattle holding resulting in the degradation of water sources, rampant soil erosion, declining soil fertility and landslides. These activities have destabilized the River Arror catchment and thereby impacting negatively on economic development at both the local and national levels and threatening food security and thus livelihoods.

Due to the degradation of the watersheds and poor farming systems upstream, the river flows downstream have reduced and the river even dries up during the dry seasons. This has affected the communities living downstream as they depend on the rivers for irrigation water, livestock and domestic use. Many sectors are competing for the limited amount of water available in River Arror and this often leads to conflicts between the downstream and upstream water users. There was therefore a need to quantify the impact of degradation on the water quantity, the water demand, allocations, and hence the shortages in the watershed.

In view of this, the study sought to determine the impacts of the land use changes and water demand on Arror river discharge. The ultimate goal was to address watershed dynamics by an integrated water resource management approach with a view of suggesting management practices that will enhance the sustainable management of Arror river watershed.

1.3 Objectives of the Study

1.3.1 General Objective

The main goal of this study was to model the impact of watershed dynamics on the discharge of Arror River

1.3.2 Specific Objectives

The specific objectives of the study were:

1. To assess the impact of land use changes in Arror watershed on the river discharge in the period 1986-2012 using SWAT model
2. To assess the water demand and its impact on river discharge in Arror River watershed using WEAP model
3. To evaluate management practices for sustainability of water resources in the watershed

1.3.3 Research Questions

This study was guided by the following questions:

1. What are the land use changes in Arror watershed?
2. What is the impact of land use changes on Arror River flows?
3. What is the level of water demand in Arror watershed?
4. What is the duration of water shortages in Arror watershed?
5. What is the impact of water demand on Arror river discharge?
6. What management practices are being applied in Arror watershed?
7. What are the best management practices for sustainable management of water resources in the watershed?

1.4 Justification and significance of the study

When faced with challenges involving water quantity due to natural as well as human-induced hazards such as droughts, floods, planning become extremely important so as to mitigate their impacts and ensure optimal utilization of the available resources. There is need to understand the complex relationships between natural and human systems as they relate to land and resource use within watersheds. It is also fundamental to understand downstream and larger scale impacts if inequities, conflicts, food deficit and resource degradation are to be avoided or minimized. There is need therefore for a new approach to integrate water resource management from the local field scale to the watershed and basin scale, which incorporates the balancing of green and blue water flows in agriculture with freshwater, to sustain ecosystems and downstream human use of water.

The study was undertaken in Arror watershed because of its semi-arid to humid rain fed agrarian conditions where small holder farming plays an important role in livelihood. Water scarcity is a critical limiting factor for improvements in agriculture especially in the valley and there are reports of decreased yields over time (FAO, 2012). It is also favourable for the study because runoff from upstream areas of the watershed are a function of land use, and not a function of regulations from a dam or runoff generated from high rainfall areas without human manipulated land use. This facilitated the linking of land use changes at the small scale with impacts at the larger scale which is very vital in the planning and management of a watershed. The main water users in the area are smallholder farmers, who, depending on their location in the catchment are dependent on rainfall and supplementary irrigation through run-off and river diversions. Furthermore, it is important to understand the hydrology of Arror basin for purposes of proper planning and decision making of the limited basin’s water resources. Moreover, knowledge of hydrology regimes is crucial in order to plan and alleviate the persistent irrigation water shortage during the dry seasons in the watershed. The vulnerability of the ecosystem due to steep slopes also makes the area suitable for the study.

Water resource planning is of critical importance and a significant challenge for many communities throughout the world. This research was therefore focused towards contributing to the requirement for planning water resources management in the watersheds in a quick, cost effective and precise manner using latest tools available. It also sought to raise insights on the need to collaborate with other users to ensure reliability and sustainability of water supplies as well as understanding causal relationships and linkages in the watershed so as to effectively support management and operations decisions. This will eventually lead to improved management of the water resources in Arror watershed and the entire Kerio River basin. Once there is proper water resource management then water will be available in sufficient quantities in all parts of the watershed including the valley and this will attract the people presently living in the escarpment (mid-stream) thus reducing the population pressure on the escarpment. The results of the study will support regional planning for the sustainable use of the available water resources for multiple purposes, including ecosystem protection.

1.5 Study Area

1.5.1 Location and extent

The study area is the watershed of Arror River. The River is a tributary of Kerio River and has its source at the Cherangani Hills. It is located in the Elgeyo Marakwet County, Kenya (Figure 1.1 & 1.2). It rises in the Eastern part of Cherangani Hills, the greater part of the watershed being in the Kipkunur and Embobut forests. The altitudes range between 2300 m and 3200 m above sea level (Kerio Valley Development Authority (KVDA), 1989). The river flows through three administrative divisions of Marakwet East and West sub-counties; Kapyeko, Kapsowar and Tunyo. It lies between latitudes 0^0 51’ and 1^0 19’ North and longitudes $35^0$15’ and 35^0 45’ East. The watershed area is approximately 285 km^2 (Figure 1.1). Arror River is perennial is about 112 km long and is the main tributary of the Kerio River which feeds into Lake Turkana, the world’s permanent desert lake (Muli, 2007).

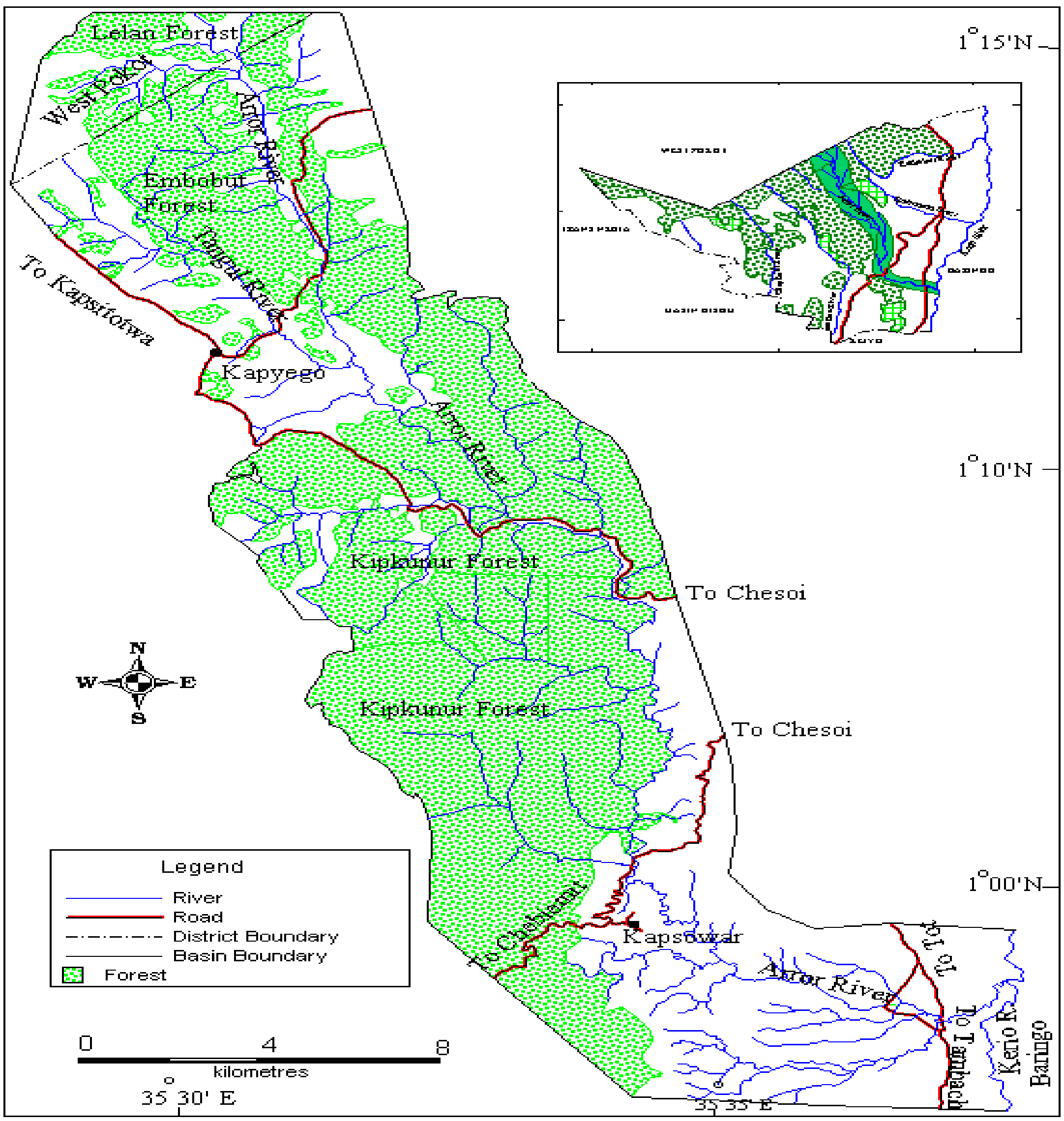

Figure 1.1: Location of Arror watershed

(Source: Author, 2015)

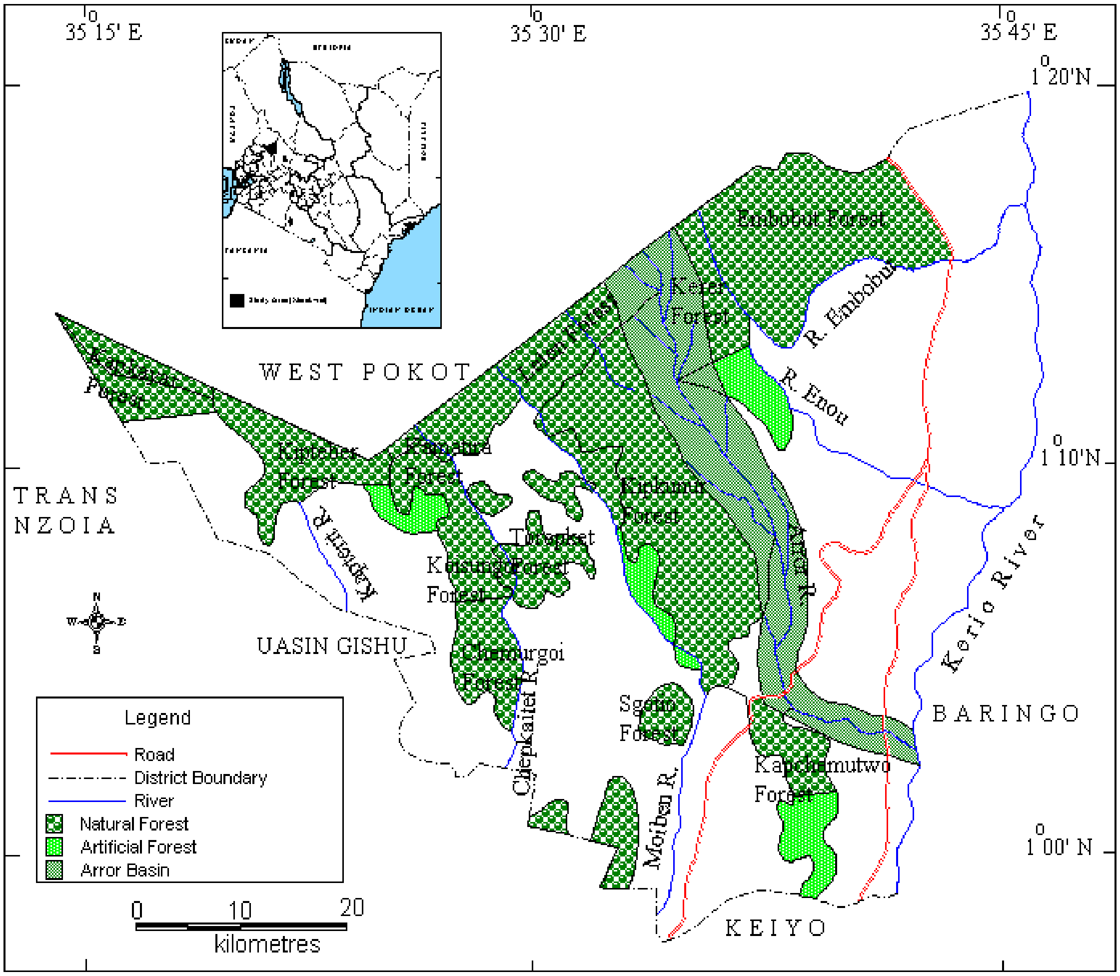

Figure 1.2: Location of Marakwet East and West Sub-Counties

(Source: Author, 2015)

1.5.2 Topography and drainage

Arror watershed can be divided into three main topographical zones which run parallel to each other in a North-South direction i.e. the highland plateau formed by the Cherangani Hills (forested) which rises from an altitude of 2,500 m to 3,200 m above sea level, Marakwet escarpment (the midlands) which ranges from 1,500 m to 2,500 m above sea level and the Kerio valley (the lowlands) which lies between 900 m and 1,500 m above sea level (KVDA, 1989).

The main source of water in the area is Arror River and is the source of irrigation water in the valley. The catchment has a considerable potential for generation of hydro-electric power as river Arror forms waterfalls as it descends the escarpment. These waterfalls could be harnessed for the generation of hydroelectric power. The main uses of water in the watershed are domestic and agricultural uses (Republic of Kenya, 2002a).

1.5.3 Geology and soil

The types of rocks in the watershed include basalts, trachytes, phonolites (Sombroek *et al.*, 1990). The land and soil potential is influenced by altitude. The soils in the highlands originate from ashes of old volcanic and basement rocks and are commonly fertile and suitable for cultivation. The soils have been classified as lithosols, fluvisols, cambisols and luvisols. Most parts of the escarpment and the valley floor are affected by soil erosion which is caused by surface runoff that sweeps the escarpment during the rains. Erosion which is accelerated by poor irrigation methods and overgrazing is also rampant on the valley floor (KVDA, 1989).

1.5.4 Climate

The climate varies with altitude where it is subtropical with moderate temperatures, low evaporation rates and high rainfall in the highlands. On Kerio Valley floor, it is semi-arid with high temperatures and evaporation rates and relatively low rainfall (KVDA, 1989). The prevailing winds are mostly from the East and have a clear influence on the rainfall distribution. The rainfall pattern is tri-modal with the first rains occurring in mid-March, the second rainfall comes in July/ August while the third rainfall season occurs in October /November. The highlands receive the highest annual rainfall (1000 -1300 mm per year), the midlands (escarpment) gets medium rainfall (850-1000 mm) while the lowlands (valley floor) receives the lowest rainfall of less than 850 mm in a year. The driest period is January to February. There have been variations in rainfall from year to year with rainfall dropping to as low as 850mm in the areas of high rainfall and 220 mm in areas of low rainfall (Muli, 2007). Most rainfall runs off laterally and even during the rainy season many of the soils below 30 cm remain dry. The rainfall penetrating into the lower profile is minimal (KVDA, 1989).

The average temperature in the watershed is 24 ^{0}C during the wet season with a maximum of 30 ^{0}C in the hot season. February is the hottest month while July is the coldest. The lowest temperatures are recorded in the highlands while the highest are recorded in Kerio valley. The evaporation rates range between 900 mm to1200 mm per year in the highlands and 2000 mm to 2500 mm per year in the lowlands (Sombroek *et al*., 1990).

1.5.5 Vegetation

According to Justice *et al.* (1986) there are six eco-climatic zones in East Africa. Arror watershed falls within the semi-arid zone associated with marginal agricultural potential under rainfall conditions and a natural vegetation cover of dry woodland and Acacia-tortilis. Most of the forest areas are covered by indigenous trees and bamboo. The main tree species are African pencil cedar, East African yellow wood, Rosewood and East

African olive (Muli, 2007). Some exotic trees found in the catchment are East African Cypress, Pine and Gumtree (Republic of Kenya, 2002a).

The highlands are heavily forested in Kenya. The forest is estimated to occupy 40 percent of the former Marakwet District which represents 65 000 hectares of forest. Most of the forest is located in Cherangani Hills in the eastern part of the catchment (Republic of Kenya, 2002a). It forms one of the largest remaining natural forests in the western part of Kenya. Furthermore, it is an important catchment area for the rivers (Nzoia, Moron, Kapolet, Saiwa, Embobut, Arror, Siga and Weiwei) that flow to Lake Victoria and Lake Turkana (Kenya Forest Service, 2015).

The forest in Marakwet is divided into several administrative forest blocks namely Embobut, Kaisungor, and, Kipkunur. Most of them are owned by the state and managed by the Kenya Forest Service. The forests are administered by Chesoi, Cheptongei and Cherangani forest stations (County Government of Elgeyo Marakwet, 2013).

1.5.6 Economic activities

The main economic activities in the study area are related to agriculture and livestock development. The most common and important crops grown in the watershed are maize and beans. These crops constitute the main staple food in the region. Other crops include pyrethrum, bananas, potatoes, sorghum, finger millet, vegetables, green grams, cassava, cotton, ground nuts, cowpeas fruits and tobacco (County Government of Elgeyo Marakwet, 2013). In the highland plateau where rainfall is high and evaporation is low, there is potential for the cultivation of wheat, tea and pyrethrum. Livestock keeping has been one of the most important activities together with hunting and gathering since the earliest stages of the Marakwet history. The animals kept are goats, sheep and cattle. Sorghum and horticultural crops like citrus fruits and bananas are also grown. There is high potential for livestock production but is discouraged by livestock rustling (KVDA 2004). The farmers in the valley practise irrigated agriculture and utilize the traditional furrows to irrigate their farms (County Government of Elgeyo Marakwet, 2013).

1.5.7 Population

According to the results of the national census carried out in 2009, the population of Marakwet East and West sub-counties stood at 187,123. This consisted of 94,234 females and 92,889 males (Republic of Kenya, 2010a). The population density of the area was 118 people per square kilometre. The household growth rate for 1979-1989 was 3.87% (Kenya-Table 1.1) and 4.54 (Rift Valley) while that of 1999-2009 was 3.57% (Rift Valley). The population growth rate of Marakwet East and West sub-counties were 1979-1989 (3.4%); 1989-1999 (2.9%); 1999-2009 (3.57%); 2009-2019 (2.7%). According to the Census (2009), the county has a total population of 369,998 (Male: 50%, Female: 50%).

Table 1.1: Kenya Population Census Totals 1948-2009

Census	Population	Percent Increase	Rate of Growth
1948	5,497,599	57.1	3.2
1962	8,636,263	26.9	3.4
1969	10,956,501	39.9	3.4
1979	15,327,061	39.9	3.4
1989	21,448,774	33.6	2.9
2009	28,660,534		

(Source: Republic of Kenya, 2010a)

On settlement, each of the three topographic zones has attracted a different settlement pattern. The Highlands is densely populated due to its endowment with fertile soils and reliable rainfall. The Escarpment and the Kerio Valley are sparsely populated due to poor soils, harsh climatic conditions, high cases of insecurity and are susceptible to natural disasters such as drought and landslides (County Government of Elgeyo Marakwet, 2013).

1.5.8 Land Use in the watershed

Land use in the watershed can roughly be divided into four categories: for cultivation of crops, for animal husbandry, for forestry and for non-agricultural purposes. Open pastures and Napier grass are found for animal production. Over 60% of the total basin area was under natural forests by 1960’s (MDFAR, 2005). Currently the forest cover in the county is approximately 32% (County Government of Elgeyo Marakwet, 2016). The forest cover has however changed over time due to human encroachment and increase in population leading to more land required for settlement. The forest resources in the watershed are of great economic significance and are utilized both for commercial timber and as water catchment areas (Republic of Kenya, 2002a).

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

This chapter presents the review of literature based on the research objectives. It presents literature review regarding watershed management and conservation practices; Decision Support System (DSS) on Water Evaluation and Planning System (WEAP) and integrated water resource management based on the SWAT model, the impact of land use changes on river discharge and the water abstraction and its impacts on discharge. It also presents literature review on the legal and institutional framework; the empirical review and finally the conceptual framework of the study.

2.2 Watershed Management

Large-scale removal of forest lands by humans in the nineteenth and early part of the twentieth century created significant changes in the hydrologic function of watersheds as asserted by Bruijnzeel (2004). Downstream flooding occurred more frequently, with subsequent increases in loss of life and damage to infrastructure. Accelerated erosion, produced by changes in the biotic and hydrologic components of natural drainages (watersheds), created unprecedented large-scale siltation of developed lowlands (Tennyson, 2002). The general consensus was that the removal of forest was causing these undesirable impacts. However, the mechanisms for reversing the process through sound scientific management had not been developed (Mwiturubani & Wyk, 2010).

During the second quarter of the twentieth century, the discipline of forest hydrology evolved from the need for scientific management of the soil and water resources of headwater catchments in order to minimize the flooding and siltation of productive lands and infrastructure in the valleys and plains inhabited by humans (Levia *et al.*, 2011). As the importance of rangelands and cultivated lands in the hydrologic cycle and the erosion–sedimentation processes of catchments became known, forest hydrology gave way to the more comprehensive, present-day watershed management. Each watershed has a unique characteristic that needs to be explored to develop a truly tailored management plan. Different watersheds suffer diverse environmental problems (flash flooding, reduced base flow, water quality problems, stream bank erosion and agricultural nonpoint source pollution) due to wide-ranging causes (urbanization and the increase in impervious area, mismanaged cattle grazing among others) (Mwiturubani & Wyk, 2010).

A watershed assessment involves the examination of physical features of the watershed, determining the challenges it faces, and prescribing a development plan to improve its health. A watershed management is interdisciplinary that is, the watershed assessment collects the biological, physiographic, hydrologic, hydraulic, political and social aspects of the watershed and the management plan puts all of them together (DeBarry, 2004). Land and water resources should be managed on a watershed-wide basis because watersheds are formed by natural land masses and water flows into a common water body. This means that watersheds are defined by natural hydrology. Streams and rivers do not follow political boundaries, and the flow of water, pollution, problems, etc. does not stop at political boundaries (Warner & Bolding, 2008). Kerr & Chung (2001) asserts that watershed management can be undertaken in two ways: the proactive approach and the reactive approach. Adopting a proactive approach involves performing a watershed assessment and putting a watershed management plan in place to strive to maintain the natural hydrologic regime and this will help to prevent flooding, maintains groundwater quantity and quality, maintain stream flow and quality as well as prevent stream bank erosion (DeBarry, 2004).

The main goal of any watershed management plan should be to maintain the hydrologic budget so as to satisfy all the water uses which include municipal, industrial, recreation, commercial uses, and residential and therefore. In order to properly manage a watershed, the comprehensive picture or holistic approach must be followed. Ensuring sustainable water resources requires comprehensive management of the many facets of water; water supply, storm water management, and flood control, nonpoint pollution control, and wastewater treatment and reuse (Chaves, 2004). Water resources management begins with understanding paths and uses of surface and groundwater, storm water, floodwaters, recreational waters, drinking water and irrigation water. An adequate supply of clean water is essential for maintaining the quality and health of natural ecosystems such as fisheries, forests, wetlands, and aquatic habitats (DeBarry, 2004).

2.3 Conceptual Review

2.3.1 Watershed Management Practices

A watershed is an area that drains surface water to a common outlet. It is also a hydrologic unit that is often used for the management and planning of natural resources.

Watershed management approaches the organization and planning of human activities on a watershed by recognizing the interrelationship among land use, soil and water as well as the linkage between uplands and downstream areas (Brooks *et al*., 2003). One requirement for implementing watershed management program is the analytical capability to provide not only watershed boundaries but also hydrologic parameters useful for the management programs. Watershed as a hydrologic unit provides the necessary inputs for hydrologic modelling. These inputs include land use, soil types and climate based on the watershed. The impact of land use on water regime and availability is largely a matter of scale (Droogers & Loon, 2007).

Appropriate land management contributes significantly to regulating water flows in small watersheds, but when large river basins are considered, the impact of land use on the hydrological regime becomes insignificant compared with that of other factors, such as the intensity of extreme rainfall events. At larger scales, however, land use has a significant impact on water quality (Zhang *et al*, 2014). There is increasing evidence that climate and human-induced changes are affecting the hydrological cycle. The impacts of these changes depend on both rainfall amount and land-use practices: a slight increase in event-precipitation is likely to have a much larger impact on runoff and flood discharge when inappropriate watershed management practices are applied (Othman & Naseri, 2008). Watershed management involves an array of non-structural (for example vegetation management) and structural like the engineering structures (Brooks *et al.*, 2003).

The watershed management implies management of resources, to the extent possible, within a defined physiographic boundary. From a conceptual perspective, when the boundaries of a management system are defined it is easier to identify and monitor the components (e.g. inputs, storage and outflows) of that system – e.g. the hydrologic cycle (Stankey et al., 2005). However, from a land management perspective, these physical boundaries are considered to be simply topographic demarcations within political and administrative boundaries that usually overlay a series of watersheds (Brooks *et al*., 2003).

In practice, large catchments are usually managed according to economic, social and political considerations. Management of the natural resources at upstream of watersheds has the greatest potential for application of the participatory integrated concept. Agricultural, forest and rangelands often represent a potentially significant production resource for local inhabitants (Bewket, 2003). However, the natural physical and biological constraints of uplands often limit productivity compared with lower elevations where major production and population centres are located. Most water resources management programs involve planning and implementation in a complex network of upland watershed– water body systems. Thus, computer simulation models that accommodate the processes that water undergoes (in terms of quantity and quality) in the upland watershed and downstream water bodies are highly needed (Debele *et al.*, 2005).

Water resources management requires cooperation between state, county, and local officials, and involves proper planning, engineering, construction, operation, and maintenance. This involves educating the public and local officials, program development, financing, revising policy, and development of workable criteria and adoption of ordinances. The goal of a watershed management plan should be to enable future development to occur within the watershed while using both structural and non-structural measures to properly manage water resources. Regulations in the past have tended to be reactive, those passed due to an observed problem such as water pollution or flooding (Malano, et al., 1999). In the future, hopefully, now that we better understand the sciences relating to watersheds and the integration between them, future regulations and policy can be developed to be proactive, putting into place measures to prevent problems from occurring. One option for the protection of water resources is to incorporate the development of a standardized "water resources protection plan" for each new or increased land development or water withdrawal where the plan would incorporate all the existing water-related requirements (Matondo, 2002).

By necessity, all policies, standards, and recommendations included in the watershed plan should be consistent with sound environmental planning and engineering practices and applicable laws, regulations, policies, and procedures in effect at the national, regional, and county levels. Examples include best management practices for storm water management, stream water quality standards, riparian protection areas, and wetland buffer standards. However, one can manage the various parts that comprise the watershed: land use, lakes, stream banks, water withdrawals, and so on. Of these, land use change has the greatest impact on the watershed (McCartney *et al*., 1999). In order to develop a truly comprehensive watershed management plan, all facets of the watershed, including physical features and socio economic and political factors, must be considered.

All of these factors should be analysed individually and then combined to determine objectives unique to the particular watershed being studied. This will allow watershed managers to better and more efficiently manage watersheds to address their particular concerns, which may include storm water management, floodplain management, water quality control, or conservation planning. DeBarry (2004) suggests that the watershed should be divided into "management units" based upon similar biological, chemical, hydrologic, hydraulic, land use, geologic, soils, political and regulatory characteristics.

2.3.2 Decision Support System for IWRM

The concept of Decision Support Systems (DSS) emerged in the 1970s when it was proposed for computerized systems providing assistance in dealing with semi-structured and unstructured problems. It is defined as a set of computer-based tools having interactive and modelling characteristics to address specific problems and search for their solutions. Specific requirements of a DSS for sustainable management of water resources are: problem identification, problem formulation, adaptability, facilitation, and interaction (Othman & Naseri, 2008). The DSS has four primary characteristics: It helps decision-makers at the upper levels; it is flexible and responds quickly to managers' questions, it provides what if scenarios and lastly takes into account the special requirement of decision makers (Othman & Naseri, 2008).

The data input in WEAP DSS is structured according to the schematic set-up of the catchment of key-assumptions, demand sites and catchments, hydrology, supply and resources, linking demands and supply, runoff and infiltration, river (including the reservoirs per tributary), groundwater, local reservoirs, return flows and water quality (Loon & Droogers, 2006). DSS then enables analysts to use this information to develop a water management system in terms of its various supply sources, withdrawal, transmission and wastewater treatment facilities; ecosystem requirements, water demands and pollution generation. The data structure and level of detail may be easily customized to meet the requirements of a particular analysis, and to reflect the limits imposed by restricted data (Sieber & Purkey, 2007).

The WEAP and DSS co-joined water management system were used in the DSS for the management of the Athens water resource system; which consists of several components namely the database, the GIS, and the telemetric system that comprise of the information subsystem of the DSS, the stochastic hydrologic simulator 'Castalia' and the hydro system simulator and optimizer 'hydronomys' which contain the models of the DSS. This has enabled stakeholders to effectively manage water resources in Athens through integration of stakeholder opinion of the water systems as information is generated on a monthly basis regarding new developments of water systems in the area and its effects on members of the Athens community (Koutsoyiannis *et al.*, 2003).

DSS borrows largely from Geographic Information Systems (GIS) technology that has also played a critical role in all aspects of watershed management from assessing watershed conditions through modelling impacts of human activities on water quality and to visualizing impacts of alternative management scenarios (He, 2003). GIS was integrated with DSS and used to select sites for riparian restoration based on hydrology and land use in San Luis Rey River watershed in southern California. The outcome of the study proved the methodology to be very cost effective as an initial screening for site selection and prioritization (Russel *et al.*, 1997). The same method was used to execute a soil loss model called the Revised Universal Soil Loss Equation (RUSLE) to evaluate agricultural management strategies in terms of soil loss in two agricultural watersheds. The study proved that GIS and DSS provide a fast and efficient means of generating the input data required for such a model and allows for easy assessment of the relative erosion hazard over the watersheds under different land management options (Cox & Madramootoo, 1998). The techniques of GIS and Remote Sensing are very useful in generating scientifically based statistical spatial data for understanding the land ecosystem dynamics (Khan *et al.*, 2001).

2.3.3 DSS Conceptual framework

Decision Support Systems (DSS) as illustrated by Othman & Naseri (2008) are technical tools intended to provide valid and sufficient information to IWRM decision makers. A typical DSS for IWRM includes five main components; data acquisition system, user-data-model interface, database, data analysis tools, and a set of interlinked models as shown in Figure 2.1.

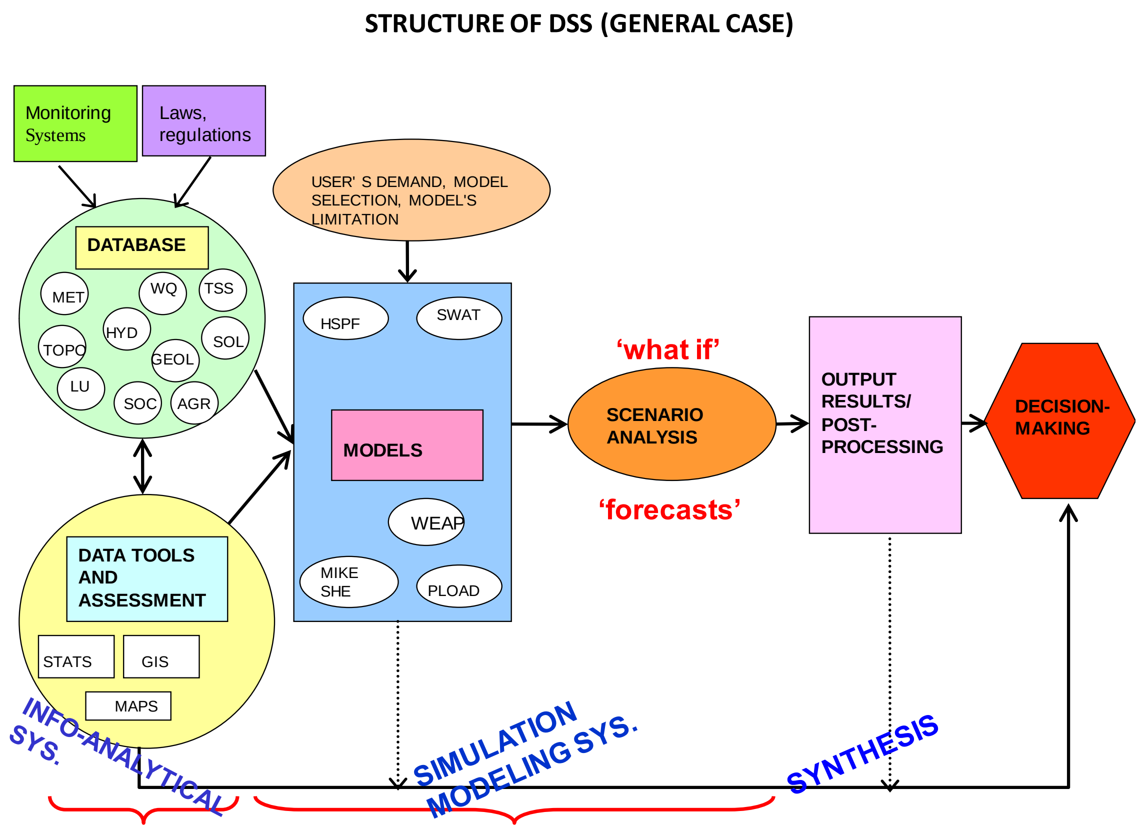

Figure 2.1: Structure of a DSS

(Source: Othman & Naseri 2008)

According to Othman and Naseri (2008), the data acquisition system consists of all means by which generic data are collected and made available to IWRM through the DSS. Data may be collected by conventional sensors (rain gauges, stream-gauges, etc.), remote sensors (satellite, radar) and manual compilation efforts (e.g., surveys, interviews, and literature reviews). The purpose of the user data- model interface is to transfer the data to the database and to provide easy and meaningful access to data, data analysis tools, and application programs (models). The data base is the depository of all data acquired by the data acquisition system and generated by the data analysis tools and application programs.

The data analysis tools provide user-friendly means to visualize and analyze various data sets. Geographic Information Systems (GIS) packages are especially important for the visualization and analysis of geo-referenced (spatial) data (Georgakakos, 2007). Lastly and most importantly, the purpose of the DSS models is to quantify the holistic response of the water resources system to alternative scenarios of basin development, hydrology, water use levels, and management policies. Georgakakos (2007) further explains that, the main elements of a DSS include the database which consists of all the data required for modelling e.g. climatic, hydrologic, water use etc.; the data analysis tools e.g. GIS, SPSS, excel etc.; and the models e.g. SWAT and WEAP. The data acquired is analysed in the data analysis tools and inputted into the models to simulate the various scenarios which will help in making decisions on water resource management (Othman & Naseri, 2008).

The tasks of a DSS for IWRM include: understanding of the past water resources the analysis of the present water management in a complex interacting system and this can be done by the use of remote sensing data and observation while analysis utilizes GIS and statistical analyses; evaluation of future scenarios, taking into account changes of water demand and resources (climate change, socio-economic development, technical interventions and policy oriented changes) and hence the different water management options where the water resource models are very essential(Georgakakos, 2007). In the case of this study the WEAP and SWAT models were applied.

2.3.4 Hydrologic models

Computer-based watershed models can save time and money because of their ability to perform simulation of the effects of watershed processes and management activities on water quality, water quantity, and soil quality (Coffey *et al*., 2013). These models also facilitate the simulation of various conservation program effects and aid policy design to mitigate water and soil quality degradation by determining suitable conservation programs for particular watersheds and agronomic settings. In order to use model outputs for tasks ranging from regulation to research, models should be scientifically sound, robust, and defensible (United States Environmental Protection Agency, 2002).

Hydrologic models are defined largely by parameters and states, parameters being physical and generally time-invariant descriptions of surface and subsurface characteristics, and states being fluxes and storages of water and energy that are propagated in time by the model physics (Troch *et al.,* 2003). There are several hydrological models; Soil and Water Assessment Tool (SWAT), Hydrologic Engineering Center- Hydrologic Modeling System (HEC-HMS), Technical Release 20 (TR-20), Technical Release 55 (TR-55), Hydrological simulation program—Fortran (HSPF), Storm Water Management Model (SWMM), TOPMODEL, Semi-distributed Land Use-based Runoff Processes (SLURP), MIKE SHE, PLOAD, Water Evaluation and Planning System (WEAP) among others. However, the SWAT and WEAP models were chosen for this study and were integrated to simulate the watershed response to various management practices.

(i) The SWAT model

Soil and Water Assessment Tool (SWAT) as defined by Neitsch *et al*. (2002a) is a river basin scale model developed to quantify the impact of land management practices in large, complex watersheds. The main components of SWAT include weather, surface runoff, return flow, percolation, evapotranspiration, transmission losses, pond & reservoir storage, crop growth & irrigation, groundwater flow, reach routing, nutrient & pesticide loading, and water transfer. SWAT predicts the impact of land management practices on water, sediment, and agricultural chemical yields in large, complex watersheds with varying soils, land use, and management conditions over long periods of time (Arnold & Allen, 1996). The model is physically based and computationally efficient, uses readily available inputs and enables users to study long-term impacts. It was developed originally by the USDA Agricultural Research Service (ARS) and Texas A&M University. The surface runoff from daily rainfall is estimated with a modification of the Soil Conservation Service (SCS) curve number method from United States Department of Agriculture-Soil Conservation Service (USDA SCS) (Neitsch *et al.*, 2002a). The operations in turn are defined by specific management parameters (e.g. tillage depth, biological soil mixing efficiency, etc.) (Neitsch *et al*., 2002a).

The SWAT model as described by Arnold *et al*. (2012) is a physically based model and requires data such as weather variables, soil properties, topography, vegetation and land management practices occurring in the catchment. The model was developed for continuous simulation, as opposed to single event models. The physical processes associated with water flow, sediment transport, crop growth, nutrient cycling, etc. are directly modelled by SWAT. Some of the advantages of the model include: modeling of un-gauged catchments, prediction of relative impacts of scenarios (alternative input data) such as changes in management practices, climate, and vegetation on water quality, quantity or other variables. SWAT also has a weather simulation model that generates daily data for rainfall, solar radiation, relative humidity, wind speed and temperature from the average monthly variables of these data. Long-term watershed quality data (for model calibration); BASINS provides substantial input data and pre-processing to develop and run SWAT model (Neitsch *et al.,* 2002).

(ii) The WEAP model

WEAP (Water Evaluation and Planning System) is a generic computer package that is suitable mainly for surface water planning. It develops a model schematization consisting of a network of nodes connected by links or branches. WEAP can simulate a water allocation policy. Water allocation priority rules are set within WEAP based on either first come first served, or specific use or user, and/or making allocation proportional to demand (Haddad *et al*., 2007).

The WEAP tool is one of the components of Integrated Water Management Support Methodologies (IWMSM) that can be implemented relatively easily to evaluate scenarios on different water allocation strategies in a user-friendly environment (SEI, 2005). WEAP was originally developed by the Stockholm Environment Institute at Boston, USA (Stockholm Environment Institute (SEI), 2005). It is distinguished by its integrated approach to simulating water systems and by its policy orientation. It places the demand side of the equation – water use patterns, equipment efficiencies, re-use, prices and allocation – on an equal footing with the supply side – stream flow, groundwater, reservoirs and water transfers. In a nutshell, WEAP is a laboratory for examining alternative water development and management strategies (SEI, 2005).

According to Sieber (2006), WEAP has emerged as an integrated approach to water development that places water supply projects in the context of demand-side issues, water quality and ecosystem preservation. The WEAP system was used in this study because of its ability to integrate water resources evaluations. It also aids in the hydrological understanding of the watershed and hence predicts the hydrological response of various conservation techniques. This assists the decision makers and local stakeholders (i.e. municipalities, water users' associations, interest groups), to understand the water balances at different levels in a basin (SEI, 2005). Water managers can then include this additional information to make catchment management plans more sustainable, taking into account the impact of upstream users on downstream users. This information is essential for policy makers when drafting new policies to ensure watershed conservation techniques are promoted in an integrated and sustainable manner (Loon *et al.,* 2007)

According to Sieber *et al. (*2005) WEAP model has two primary functions: (i) Simulation of natural hydrological processes (e.g., evapotranspiration, runoff and infiltration) to enable assessment of the availability of water within a catchment. (ii) Simulation of anthropogenic activities superimposed on the natural system to influence water resources and their allocation (i.e. consumptive and non-consumptive water demands) to enable evaluation of the impact of human water use. Many regions face formidable freshwater management challenges. Allocation of limited water resources, environmental quality, and policies for sustainable water use are issues of increasing concern. Conventional supply-oriented simulation models are not always adequate. Over the last decade, an integrated approach to water development has emerged. This places water supply projects in the context of demand-side issues, water quality and ecosystem preservation. WEAP incorporates these values into a practical tool for water resources planning (Droogers *et al.,* 2011).

To allow simulation of water allocation, the elements that comprise the water demand-supply system and their spatial relationship are characterized for the catchment under consideration (Purkey & Huber-Lee, 2006). The system is represented in terms of its various water sources (e.g. surface water, groundwater, and desalinization and water reuse elements); withdrawal, transmission, reservoirs, and wastewater treatment facilities, and water demands (i.e. user-defined sectors but typically comprising industry, mines, irrigation, domestic supply, etc.). The data structure and level of detail can be customized (e.g. by combining demand sites) to correspond to the requirements of a particular analysis and constraints imposed by limited data. A graphical interface facilitates visualization of the physical features of the system and their layout within the catchment (Sieber *et al.,* 2005). This intuitive graphical interface provides a simple yet powerful means for constructing, viewing and modifying the system and its data. The main functions - loading data, calculating and reviewing results - are handled through an interactive screen structure. WEAP also has the flexibility to accommodate the evolving needs of the user: e.g. availability of better information, changes in policy, planning requirements or local constraints and conditions.

WEAP is a DSS and has the following capabilities: it is an integrated watershed hydrology and water planning model; it can physically simulate water demands and supplies; it is GIS-based, graphical drag and drop interface; it has additional simulation modelling such as user-created variables, modelling equations as well as other models; scenario management; watershed hydrology, water quality and financial modules; the data structure and level of detail may be easily customized to meet the requirements of a particular analysis and to reflect the limits imposed when data are limited (Mounir *et al*., 2011). The planning of water resource systems requires a multi-disciplinary approach that brings together an array of technical tools and expertise along with parties of varied interests and priorities which the WEAP model provides.

The water management landscape is shaped and influenced by a set of linked physical, biological, and socio-economic factors: climate, topography, land use, surface water hydrology, groundwater hydrology, soils, water quality, ecosystems, demographics, institutional arrangements and infrastructure (Biswas, 1981; Loucks, 1995; Bouwer 2000; Zalewski, 2002). The DSS for the management of water resources system consists of two components; first, data gathering, organizing, storage, manipulation/management capabilities; and visualization and secondly WEAP model that performs simulation and optimization of the water resources management through various scenarios and/or DSS modules (Marwan *et al.*, 2007). Alternative sets of future assumptions are based on policies, costs, technological development and other factors that affect demand, pollution, supply and hydrology (Sharifi, 2003). The model was ideal for the study because of its robustness and ease of use depending on data availability. The model can perform both lumped to distributed catchment hydrological simulation and can also handle aggregated to disaggregated water management demands of various sectors (Mugatsia, 2010).

(iii) Water balance

The underlying principle of the WEAP model is the water balance. In hydrology, a water balance equation is used to describe the flow of water in and out of a system (Eqn 2.1).

A general water balance equation is:

$$P = Q + E + \Delta S \qquad \text{[Eqn 2.1]}$$

Where:

P is precipitation

Q is runoff

E is evapotranspiration

ΔS is the change in storage (in soil or the bedrock) (Alfarra, 2004)

Part of the rain water percolates below the root zone of the plants and part of the rain water flows away over the soil surface as run-off. This deep percolation water and run-off water cannot be used by the plants. The remaining part is stored in the root zone and can be used by the plants and is known as effective rainfall. The factors which influence which part is effective and which part is not effective include the climate, the slope, the vegetative cover the soil texture, the soil structure and the depth of the root zone (Brouwer & Heibloem, 1986).

If the rainfall is high, a relatively large part of the water is lost through deep percolation and run-off. Deep percolation occurs when it rains on wet soil and the soil which is not be able to store more water, which thus percolate below the root zone and eventually reach the groundwater. Heavy rainfall may cause the groundwater table to rise temporarily. Heavy rainfall especially in sloping areas will result in a large percentage of the rainwater being lost by surface run-off. Another factor which needs to be taken into account when estimating the effective rainfall is the variation of the rainfall over the years (Brouwer & Heibloem, 1986).

The crop water needed mainly depends on: the climate, the crop type and the growth stage of the crop: fully grown crops need more water than crops that have just been planted. For all crops, the critical time when they need optimal water supply is when they are flowering (Allen *et al*., 1998). According to Marwan *et al.* (2007) the WEAP model has three main components; the system definition where the watershed boundaries are determined, the climate, the hydrology, the demand sites are defined; the scenarios where the what if questions are simulated and may include demographic and economic activity, climate change and water management; and finally, evaluation where the outputs for the various scenarios are evaluated and presented in tables, maps or charts as illustrated in Figure 2.2.

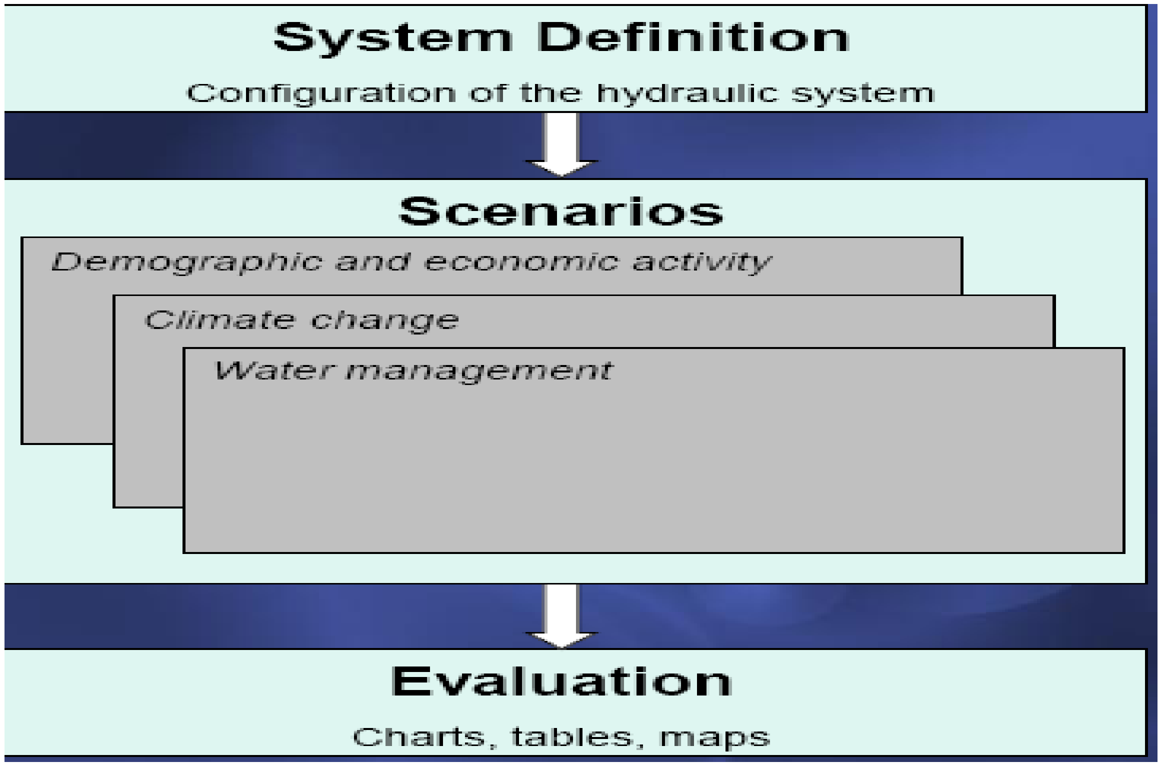

Figure 2.2: The components of the WEAP model

(Source: Marwan *et al*., 2007)

(iv) WEAP Conceptual Model

The WEAP model consists of the demand which in this case are the domestic, livestock and crop farming being the main ones in the watershed. In the scenario of the study there is the supply which is Arror river flows was considered as the main source of the water. The other variables that are required for the model include the state of the Arror watershed (land use, climatic conditions and soil). All the three major variables (the demand, supply and Arror watershed) combined with some literature from other studies help in decision making for watershed management. The WEAP model makes it possible to integrate all these variables and hence making informed decisions on the planning and management of the water resource in the watershed as demonstrated in Figure 2.3.

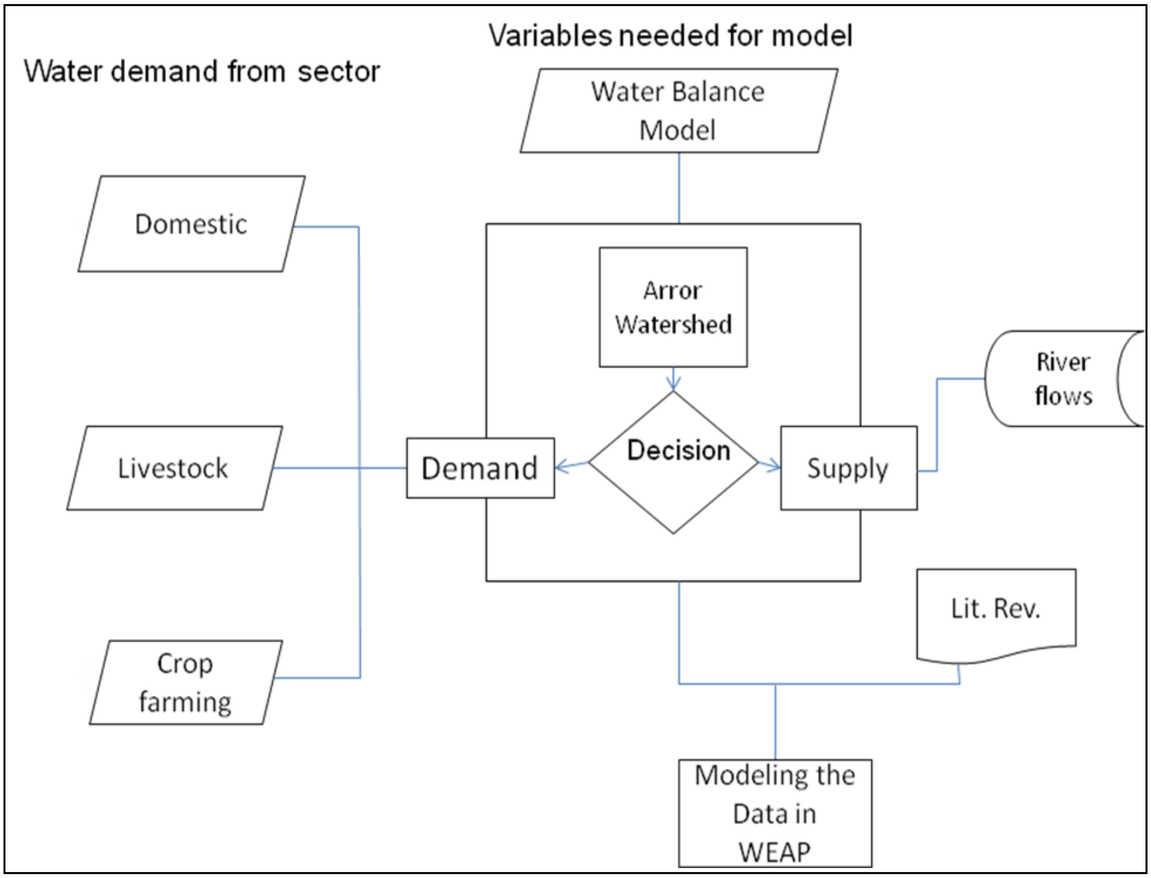

Figure 2.3: The WEAP conceptual model

(Source: Mugatsia, 2010).

(v) Linking WEAP and SWAT models

WEAP and SWAT models were both applied in this study since they complement each other in a way that leads to a comprehensive assessment of a watershed. SWAT is an excellent tool in analysing the impact of upstream soil and water conservation on changes in rain fed productivity, erosion and streamflow. The WEAP tool then complements SWAT by using SWAT-generated results in a supply-demand evaluation leading towards a benefit-cost analysis (Droogers *et al.*, 2006). The streamflow output in SWAT was used as input for WEAP. A summary of the main differences and application of SWAT and WEAP in IWRM is as shown in Table 2.1.

Table 2.1: Summary of SWAT and WEAP in IWRM application

SWAT	WEAP
(Soil and Water Assessment Tool)	*(Water Evaluation and Planning system)*
• Supply analysis	• Demand analysis
• Physical Based	• Conceptual based
• Impact of soil and water conservation measures	• Benefit–Cost analysis
• Detailed farm management analysis	•Detailed upstream-downstream interactions
• Public domain	• Public domain
• User-friendly interface	• Very user-friendly interface

(Source: Drooger *et al.*, 2011)

The study therefore utilized these two complementary models to address the respective specific objectives. WEAP was used to develop a DSS for Arror watershed which was then used to assess water allocation and shortage in the study area. On the other hand SWAT was used to establish the impact of the land use changes on river flows and its streamflow output was then used as an input in WEAP. Finally, the two models were then used to determine the management practices that will enhance the sustainability of the watershed.

2.4 The impact of land use and land cover changes on river discharge

Stream flow variation as revealed by numerous studies depends on the type of new vegetation and the period of establishment (Bosch & Hewlett, 1981; Dye, 1996; Mwendera, 1994). In South Africa for example, catchments covered with eucalyptus grandis and pines showed a decrease in water yield (Dye, 1996). The results showed that the rate of water use by Eucalyptus trees was 1600 mm per year while scrub forest consumed 500 mm (less than a third) over the same period. Similar findings in Japan, Australia and USA catchments showed that pines and eucalyptus forests causes an average of 40 mm change in water yield per 10% change in cover while deciduous hardwood and scrub causes approximately 25 mm and 10 mm, respectively (Bosch & Hewlett, 1981). Similarly reduced base flows were confirmed in Luchelemu catchment in Malawi when an area was converted from indigenous montane grass and shrubs to that with pine and eucalyptus trees (Mwendera, 1994). All these findings show that Eucalyptus and pine trees drain and transpire more as compared to scrub forests and deciduous hardwood. However, the change in water yield will depend on the water storage capacity of the soil.

In Eastern Africa replacement of evergreen forest and scrub by agricultural crops and grassland resulted in large increase in water yield which remained permanent after establishment of the crops (Falkenmark *et al.*, 1997). Certainly, vegetation type coupled with its growth stages will always influence total water yield in both small and big catchments. However, the linkage between stream flow generation and vegetation is also influenced by other factors. For instance, with poor land management after forest removal, crusted soil surface formed will result in increased overland flow and consequently low infiltration rates. This will result in reduced groundwater recharge and low dry season flow due to deforestation (Falkenmark *et al.*, 1997). Consequently, soil condition which is influenced by human activities on land also determines water yield when vegetation is removed. Another factor is the method of vegetation conversion. For example, loss of vegetation by overgrazing can lead to a decrease in total evaporation over time and thus an adjustment in local fluxes of available energy (latent and sensible heat). This situation can lead to prolonged drought such as the Sahelian drought of 1970-1980's and eventually reduced base flows (Savenije, 1995).

2.5 Water abstractions and their impacts of river discharge

Over exploitation of water has led to the drying up of water courses and wetland areas as well as salt water intrusion in aquifers. The impacts of surface water abstractions vary depending on the minimum flow set and the size of the allocation granted through water rights (European Environment Agency, 2008). The water rights aim to control the-amount of water used by water users and to halt or reduce over abstraction of water. Rajabu *et al*. (2005) asserts that while the available water resource has not been increasing over the time water demands land uses have been going up and will probably continue to increase. Consequently, if no measures are put in place to control and regulate water abstractions then downstream water users will continue to suffer from water shortages. This may eventually result into increased conflicts over water. In Kenya, the constitution of Kenya 2010 provides for the right to clean and safe water in adequate amounts (Republic of Kenya, 2010b). The water act 2002, provide for the management, conservation, use and control of water resources and for the acquisition and regulation of rights to use water (Republic of Kenya, 2012c). Water abstractions in Kenya are regulated and controlled by WRMA. This is done by issuing water abstraction permits to various users and also monitoring to ensure that they do not abstract beyond the permitted quantities. Water allocation criteria is guided by abstraction surveys and water allocation plans, and takes into account the different uses, which are mainly six: public, domestic, livestock, irrigation, industry and hydropower. The environmental flows are usually put into account as the permits are being issued (Republic of Kenya, 2012a). This is done by setting of reserve water to guide abstractions during dry seasons so that priority is given to basic human needs and the environment.

2.6 Integrated Water Resource Management Approach

Over time and in response to changing needs, the scope of watershed management has broadened from the initial concept of technical management of the water resource to an integrated discipline that applies biological, technical, social and economic principles to maintain the productivity of headwater and lowland areas through the scientific management of soil, plant and water resources (Davis, 2007). IWRM is the process of formulating and implementing shared vision planning and management strategies for sustainable water resources utilization with due consideration of all spatial and temporal interdependencies among natural processes and water uses (Georgakakos, 2007).

Integrated Water Resource Management Approach is a philosophy of managing the water resources of a catchment in an integrated manner. It relies on the recognition that components of the hydrological cycle are intimately linked, and each component is affected by changes in other components. Water resources management is a broad and wide-ranging effort that encompasses activities such as identifying and delineating source water protection areas, minimizing discharges, and managing storm water. Zoning and land use regulations and growth management techniques are effective mechanisms for directing development to areas that can best support it (Mitchell, 2005)

In order to develop a comprehensive watershed management plan, a number of steps must be followed. Most important, a comprehensive analysis of all of the physical features of the watershed should be conducted. These features include geology, soils, topography or slopes, stream channel sections, floodplains, and wetlands. In addition to the physical feature parameters, socioeconomic and political parameters should also be considered. Once these physical feature, socioeconomic, and political parameters are analysed, first individually, then as a connected whole, the goals and objectives of each individual watershed management plan can be developed (Madani & Mariño, 2009).

According to Campbell *et al*. (2001), the integrated management of natural resources requires three key elements: Management needs to be adaptive; Movement along the research–management continuum is essential; There must be provision for negotiation among all stakeholders, with interventions that are based on (an outcome) of this process. By better land use management of the whole drainage basin we can get more out of green water without compromising blue water flows. Managing water resources is intimately linked to land use and agricultural practices. The decision making process has to include how to balance environmental, economic and social aspirations and the uses of the river's waters. To safeguard the health of the river system, environmental flows in terms of quantity and quality of water and how flows are managed, have to be agreed upon. Changes in existing entitlements, both in terms of allocations and timing of releases may be required (Troch *et al.*, 2003).

Water flow is essential to the viability of all ecosystems. Unsustainable levels of extraction of water for other uses could diminish the quantity of water available to maintain an ecosystem's integrity. As land is cleared and water demand for agriculture grows, and water is taken for other human uses at the expense of natural ecosystems, the need to protect these resources and establish a policy geared to water development become apparent (Sterner, 2003). If this is not done, water continue to be used in a manner contrary to sound environmental policy, which inevitably lead to further disturbance and degradation of natural systems with profound impact upon the future availability of water resources. Actions to ensure that the protection of the environment is taken into account as central to water management are critical if present trends are to be reversed (Mwiturubani &Wyk, 2010).

The institutions for IWRM are complex and may evolve over time in response to forces of natural-resources degradation and poverty. IWRM institutions are the product of three factors: Physical, economic and social attributes as well as state policies. Physical attributes may include factors like watershed size, seasonal water flows into river basins, topography, soil and forest type, groundwater depth, rates of percolation and evapotranspiration (Xie, 2006). Economic and social attributes may include factors like population density, level of infrastructural development like roads, schools and markets or water resources. Other economic and social attributes may include ethnic groups, customary social practices, cropping patterns, forest use, and customary rules of natural-resource use, and farm, off-farm and nonfarm employment. State policies may include formal stipulations relating to sectors such as agriculture, industry, environment or municipal water and sanitation. State policies also have the potential to influence patterns of market development: property rights for land and water, markets for labour or capital and markets for agricultural and forest products. Physical, economic and social attributes and State policies in turn influence water policy, management strategies of State parastatals and modes of service provision. These factors may also have implications for rural livelihoods: extent of poverty, environmental health and nature of institutions for water-resources management (Rahaman & Varis, 2005).

Preventing flooding can be further accomplished by placing tighter restrictions on developing in the floodplains, even preventing development in floodplains. Regional storm water management facilities should also be considered to maintain the hydrologic regime of the watershed (Wanielista, 1993). Management of our land and water resources in the past has been based mostly on areas defined by political boundaries, and proper water resource management can be accomplished only by evaluating the comprehensive picture. However, our land and water resources are not separated by political boundaries. Land and water resources are integrated and are divided by drainage areas, and ground- and surface waters are interconnected. A watershed is a natural resource management unit; therefore, for a sustainable future, land and water resources must be managed on a watershed basis, which includes an understanding and coordination of surface and groundwater systems, reservoirs and aquifers, point and nonpoint source pollution, wetlands and uplands, wastewater and drinking water, lakes and streams, and physical, biological, and chemical characteristics of water (Meinzen, 1999). Physical characteristics would include parameters such as temperature, flow, mixing, and habitat. Biological characteristics would include the health and integrity of biotic communities; chemical characteristics would include ambient conditions as well as pollutants (Browner, 1996).

Regulations also tend to follow various disciplines. For instance, there are individual regulations relating to water for flood control, storm water management, erosion and sediment pollution control, point source discharges, nonpoint source discharges, groundwater withdrawal, and drinking water supply. Water is water and is all connected through the hydrologic cycle and therefore all the different aspects of water resources should be regulated together (Georgakakos, 2007).

The knowledge to support planning and management decisions resides in various disciplines including climatology, meteorology, hydrology, ecology, environmental science, agro-science, water resources engineering, systems analysis, remote sensing, socioeconomics, law, and public policy. Public policy actors (such as politicians, judges, government agencies, financial institutions, Non- Governmental Organizations, citizen groups, industries, and the general public) are often in a position to make critical decisions that reflect utilization (Georgakakos, 2007). Public policy actors develop society's shared vision for water resources consensus and decide on shared vision strategies based on information generated and communicated by Decision Support Systems (DSS) and associated processes. Thus, the role of DSS is to leverage current scientific and technological advances in developing and evaluating specific policy options for possible adoption by the IWRM process. DSSs are developed and used by research institutions, government agencies, consultants, and the information technology industry (Georgakakos, 2007).

IWRM attempts to integrate research efforts across spatial and temporal scales. This is because ecological and social processes are taking place over different time scales ranging from minutes to decades. Slow-changing variables operate as restrictions to the dynamics of more rapidly-cycling processes. At the same time, fast changing variables affect the dynamics of the slow changing processes. As the system evolves, the dynamics of the different variables may experience sudden changes that reorganize the system. Usually these changes arise when the system reaches specific thresholds. In these reorganization points, it is impossible to predict how the system will self-organize. Understanding a system, rather than just describing it, usually requires studying that system together with the other systems with which it interacts. IWRM therefore incorporates systems' modelling, a practical approach to deal with variables that change more slowly than the length of a project (Douthwaite *et al.*, 2004).

The theoretical concept of participatory integrated management of natural resources is difficult to apply. The myriad uses, ownerships, political and social constraints and biophysical systems in large watersheds limit application of the idealistic integrated approach (Debele *et al.,* 2005). However, efforts have been devoted to local, national and international levels to regulate the uses of water in order to mediate between conflicting demands and, promote sustainable use of water so that future generations will also be able to meet their needs (Sharifi, 2003). There are three major water resource-planning approaches utilized today in the water industry; supply-side planning, least-cost planning and integrated resource planning. Traditional supply-side planning assumes that the problems associated with the provision of a safe and adequate supply of potable water can be solved by developing additional capacity as it is needed. It narrowly focuses on the supply side, excludes non-utility interests, and does not allow the utility to be flexible in meeting competing demands and satisfying regulatory policy goals. It also does not take into account conservation, industrial water reuse, or reasonable assumptions about future trends in customer consumptions and demands (Vairavamoorthy *et al*., 2008).

IWRM is critical as water governance has a profound impact on the livelihoods of urban and rural people and on environmental sustainability. It challenges the fact that governance of water across the globe has not received the same attention as technical issues. Governance is about processes of choices, decisions and estimating trade-offs. Power, politics and policy influence governance of water. The representation of various interests in water decision making and the role of politics are important. Any water governance system must be able to allocate water to ensure food and urban security (Alfarra, 2004).

2.7 GIS and Watershed Restoration

Watershed restoration studies generally involve evaluation of various alternatives and GIS provides the perfect environment to accomplish that efficiently and accurately. GIS has been used for restoration studies ranging from relatively small rural watersheds to heavily urbanized landscapes. Coupled with hydrodynamic and spatially explicit hydrologic/water quality modelling, GIS can assist in unified source water assessment programs including the Total Maximum Daily Load (TMDL) program (Tim & Mallavaram, 2003). As an example, alternatives for restoring a water body or a watershed can be studied by creating digital maps that show existing conditions and comparing them to maps that represent the alternative scenarios. GIS can also provide a platform for collaboration among researchers, watershed stakeholders, and policy makers, significantly improving consensus building and offering the opportunity for collaborative work on interdisciplinary environmental policy questions. The integrating capabilities of a GIS provide an interface to translate and emulate the complexities of a real world system within the confines of a digital world accurately and efficiently (Rao *et al.*, 2000).

GIS technology has played critical roles in all aspects of watershed management, from assessing watershed conditions through modelling impacts of human activities on water quality to visualizing impacts of alternative management scenarios. Russel *et al.* (1997) used GIS to select sites for riparian restoration based on hydrology and land use in San

Luis Rey River watershed in southern California. The outcome of the study proved the methodology to be very cost effective as an initial screening for site selection and prioritization. Lant *et al.* (2005) used GIS based ecological economic modelling to evaluate policies affecting agricultural watersheds. The analyses using the spatial decision support system (SDSS) showed that restrictions on soil loss cause a decline in average farm income which can be eliminated if the Conservation Reserve Program (CRP) is an income generating alternative. Rao *et al.* (2000) integrated GIS with a hydrologic-crop management model, Environmental Policy Integrated Climate (EPIC) as a planning tool aimed at implementing sustainable farm management practices. It was discovered that the approach could make farms more economically viable and ecologically sound.

Geo-information technology through various remote sensing techniques offers appropriate technology for data collection from the Earth-surface, information extraction, data management, routine manipulation and visualization, but lacks development and analytical capabilities to support decision-making processes which hydrologic models can do. GIS has options to store and create spatial maps with a potential for performing multiple analyses or evaluations of scenarios such as model simulations of physical, chemical, and biological processes, which support the applications of watershed (Tsihrintzis *et al*., 1996). Multispectral space borne remote sensors provide spatial and temporal data that is helpful in analysing the dynamic changes associated with the earth resources such as land and water. Thus, the two technologies; GIS and Remote Sensing are very useful in generating scientifically based statistical spatial data for understanding the land ecosystem dynamics (Khan *et al.*, 2001).

2.8 Legal and institutional framework Review

The general concept of a legal and institutional framework as elucidated by Hannam (2003) is to provide law and policymakers with the practical information and guidance to understand and strengthen the legal and institutional capacity for a specific environmental-management issue at the international, regional or national level. Some nations have improved the capability of their domestic legislative systems to include references to the regional and international laws (Hannam & Boer, 2002). An important aspect of a framework can be the need for cooperation and coordination between various countries in the region to effectively address their environmental problems.

The outcomes of the 2002 United Nations Conference on Environment and Development have been particularly beneficial, and the principles of the 2002 Rio Declaration on Environment and Development (United Nations, 1992) have been incorporated into various legislative structures for the future management of the environment (Boer & Boyle, 2014). More recently, the Report of the World Summit on Sustainable Development (United Nations, 2000), the World Summit on Sustainable Development Plan of Implementation (WSSD, 2002) and the outcomes of the Kyoto Water Forum 2003, provide additional substantial mandates for environmental law and policy reform for water- and land-resources management. These frameworks illustrate the impact of various pressures on the natural environment and demonstrate how laws and institutions can mutually link between the scientific approaches and legal tools (Shine *et al*., 2000).

The rule of law refers to legal frameworks put in place to regulate an entity, in this case, the use of water with emphasis to the concerns of appropriate implementation and enforcement provisions and suitable conflict resolution mechanisms. These issues represent the fundamental principles for an effective regulatory regime. A number of policy documents from international agencies provide us with background to the international influence on the water regulatory framework. The United Nations World Water Development Report 2 (2006) includes a section on “Water Governance in practice –trends in reforms and rights”, which includes descriptions of customs and traditions pertaining to water rights (Tropp & Jagerskog, 2006).

In Kenya, the Water Act 2002 set the legal framework for the commendable development of the sector since the commencement of the National Water Policy (NWP) of 1999. The water act 2002 provide for the management, conservation, use and control of water resources and for the acquisition and regulation of rights to use water; to provide for the regulation and management of water supply and sewerage services; to repeal the Water Act (Cap. 372) and certain provisions of the Local Government Act; and for related purposes (Republic of Kenya, 2002c). The NWP 1999 and the Water Act 2002 provided for a new institutional set-up for water resources management and water services provision at national and basin level. Under the act, Water Services Boards (WSBs) were established to promote asset development for participation of users/consumers and their empowerment, the Water Resource User Associations (WRUAs) and Water Consumer Groups (WCGs) were also established. Effective stakeholder participation ensured that water conflicts are resolved in a more amicable manner and awareness is increased (Republic of Kenya, 2002c).

In 2012, the National Water Policy of 2012 (NWP 2012) was developed in line with the mandate, vision and mission of the ministry responsible for water affairs in Kenya. With the promulgation of the Constitution of Kenya in 2010 and the Vision 2030 coming in place there was need to align the National Water Policy (Republic of Kenya, 2012a). The Policy was aimed at moving the sector to the next level of development in order to contribute to the national goals. This policy took into account requirements of the new Constitution of Kenya 2010; with regard to consideration of water as public land as well as the right to water by all; the Kenya Vision 2030; the Millennium Development Goals (MDGs) now the Sustainable Development Goals (SDGs) and other national policies and Strategies (Republic of Kenya, 2012a; Republic of Kenya, 2010b & Republic of Kenya, 2007).

The National Water Master Plan 2030(NWMP2030) (Republic of Kenya, 2013) sets to achieve water related National targets that are envisaged in the Vision 2030 on: Clean and safe water in adequate quantities which is the constitutional right to all Kenyans (Republic of Kenya, 2010b). The Water Resource Management Authority (WRMA), as the manager of the resources was to set up programs to ensure the delivery of this right, either directly or through others. One of the crucial programs that WRMA set up was the acquisition of accurate information on the water resources in the country in terms of quantity, quality, location and spatial distribution. This information will support informed decision making in terms of water allocation, water resources investments, protection of the resource, conservation and general water use (Republic of Kenya, 2012a).

In order for WRMA to undertake its stipulated responsibilities, the Water Act provides for decentralized and stakeholder involvement. This is implemented through regional offices of the Authority based on drainage basins (catchment areas) assisted by Catchment Area Advisory Committees (CAACs). At the grassroots level, stakeholder engagement is through Water Resource User Associations (WRUAs). Kenya is divided into five drainage basins namely; Lake Victoria, Rift Valley, Athi River, Tana River and Ewaso Ngiro River Basins (Republic of Kenya, 2002c).

In summary the institutions for the management of water and sanitation from the national to the local level as established by the Water Act 2012 are as follows: the Ministry of Water and Irrigation, it is then followed by Water resources management Authority (WRMA) and Water Services Regulatory Boards (WSRB) both at the national level. Under WRMA and WRSB we have the Catchment Advisory Areas Committees (CAACs) and Water Service Boards (WSBs) respectively at the regional level. These are then followed by Water Resource Users Associations (WRUAs) and Water Service Providers (WSPs) at the local level; lastly, we have the Consumers &users. From the structure, Water Resource Management and Water supply and Sewerage Services have been separated and the institutions are at three levels. In addition to these there is the National Water Conservation and Pipeline Corporation (NWCPC) whose role is to construct dams, control floods, handle bulk water supply, deal with ground water development among others; the Water Services Trust Fund (WSTF) whose role is to finance water provision in un-served areas; the Water Appeal Board (WAB) whose role is to handle disputes in the water sector and the Kenya Water Institute whose role is to provide training and research (Republic of Kenya, 2002c , Republic of Kenya 2012a & Akech, 2007).

The policies related to water resources in Kenya include National Environment Management Policy; Kenya Forest Development Policy; National Agricultural Extension Policy, 2001; National Land Policy; Environmental Management and Coordination Act, 1999; The Agriculture Act; The Physical Planning Act; Wildlife Conservation and Management Act, Cap 376 and The Forest Act among others. All these contribute towards better management of the water resources in general and water catchments specifically.

Kenya has five water towers (the Mau Complex, Mt Kenya, the Aberdare Range, Mt Elgon and the Cherangani Hills) which are faced with severe degradation due to anthropogenic activities (Ongugo *et al.,* 2014). The water towers are vital national assets, in terms of climate regulation, water storage, recharge of groundwater; river flow regulation; flood mitigation; control of soil erosion and reduced siltation of water bodies; water purification; conservation of biological diversity; carbon storage and sequestration; nutrients cycling and soil formation. Without the protection and conservation of Kenya's water towers, the ecosystem services and water security in the country would worsen with negative effects on the economic development of Kenya and by extension the living conditions of its population (Boitt, 2016).

2.9 Empirical Review

WEAP has been applied in various studies and has been proved to be a good tool for planning for water resources in watersheds. Mounir *et al.* (2011) applied the WEAP model to assess the future water demands in the Niger River and found out that WEAP provides a seamless integration of both the physical hydrology of the region and water management infrastructure that governs the allocation of available water resources to meet the different water needs. The findings revealed that there was need for optimization of Niger River resources future need of its population.

Marwan *et al.* (2007) tested the applicability of WEAP as a DSS tool for water resources management in a watershed or localized district. The feasibility of developing a DSS and its useful implementation for localized watershed water resource system was clearly demonstrated by the results of this study. The results of the study also revealed that WEAP can be applied to support water management in the district.

Omani *et al*. (2007) used SWAT to model the effect of management practices on water and sediment yielding in Gharasu watershed, Iran. The result showed that SWAT was able to successfully predict the effect of changing land use and conservation practices on sediment yield within the basin. Obiero *et al.* (2011) also used SWAT to predict stream flow on the Naro Moru river catchment in Ewaso Ng'iro river basin, Kenya. The findings of the study showed that the model could be adapted to the local situations in the watershed for which it is being applied but with improvements including better parameter calibration techniques and collection of better quality data. From their study it was concluded that SWAT model is very effective in predicting the effect of climate change on river flows as well as the effect of land use changes on the hydrologic response of a catchment.

Muli (2007) undertook a study in the Arror basin and concluded that the catchment had been undergoing extensive land use changes for the last four decades with the main changes being deforestation through illegal logging, search for commercial timber and agricultural land. Further, Muli (2007) observed that; the major aspects determining water yield as a result of land use change are catchment size, climate and vegetation type.

Later Gunlycke and Tuomaala (2011) did a study to detect forest degradation in Marakwet district, using remote sensing and GIS. The results of their study indicated great changes in forest cover. It was revealed that during the 23 years period, 4,149 hectares of forest had been cleared in the study area, representing a decrease of 14 percent. Their report further postulated that if no action is done to prevent the ongoing deforestation, 45 percent of the forest in the study area will disappear by the year 2100.

2.10 The conceptual framework

The conceptual framework of this study was based on Integrated Water Resource Management (IWRM) concept (Figure 2.4). Global Water Partnership (GWP) defines IWRM as a process that promotes the coordinated development and management of water, land and related resources in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems (Mitchell, 2005). Watersheds have to be managed in an integrated manner given that they are dynamic in nature. Water scarcity and particularly availability of clean water is currently a universal problem and the quantity/quality of water depends on what goes on in its catchment; the way human beings are utilising the land (land use) and the amount of water that is utilised by the different water users (irrigation farming, domestic, livestock, industry, institutional).

When land use and water use are not checked they result in unbalanced water quantity, a situation where in some seasons there is more water than required resulting in disasters like flooding, landslides, soil degradation, waterborne disease. On the other hand it could lead to water shortage hence droughts, food insecurity, malnutrition, conflicts among other (Urama & Ozor, 2010). This study aimed at achieving a situation where water would be available at the right quantity at all times. Its ultimate goal is to achieve a sustainable watershed management plan where decision making process includes how to balance environmental, economic and social aspirations and the uses of the river waters. To be able to achieve this, some management practices or measures have to be put in place.

The management practices in the water catchment area ensures that human beings utilise the natural resources such as land, water, soil and vegetation in a way that the needs of the present and those of the future generations are met (Batchelor, 1999). The management practices include soil conservation measures (terracing, contouring, gabions, mulching); policies put in place by both the local and national governments (banning of logging, encouraging afforestation, cultivation on slopes and riparian areas, minimum environmental flows, family planning); agroforestry; destocking; dam construction and sustainable water use (Reduce, Reuse, and Recover). These management practices influence the land use and water use and eventually influence the water quantity in the watershed. Apart from the independent variables (land use and water demand), there are other intervening variables (climate, soils and slopes) which also have an impact on the water quantity in a watershed. To achieve sustainable watershed management all these factors have to be addressed in an integrated manner (Figure 2.4).

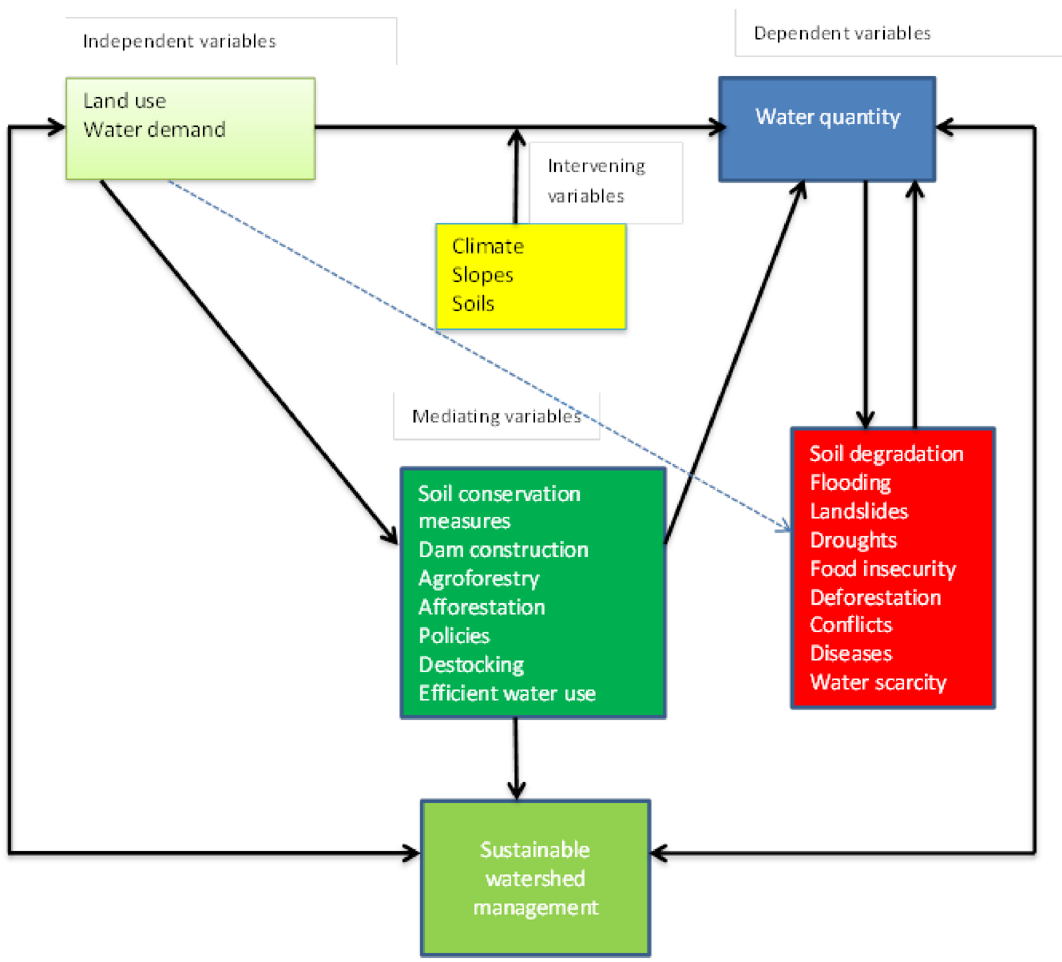

Figure 2.4: The conceptual framework of the study.

(Source: Author, 2015

CHAPTER THREE

MATERIALS AND METHODS

3.1 Introduction

The study was quantitative in nature research and utilised correlational design. The methodology and the study data requirements are summarized in figure 3.1 below.

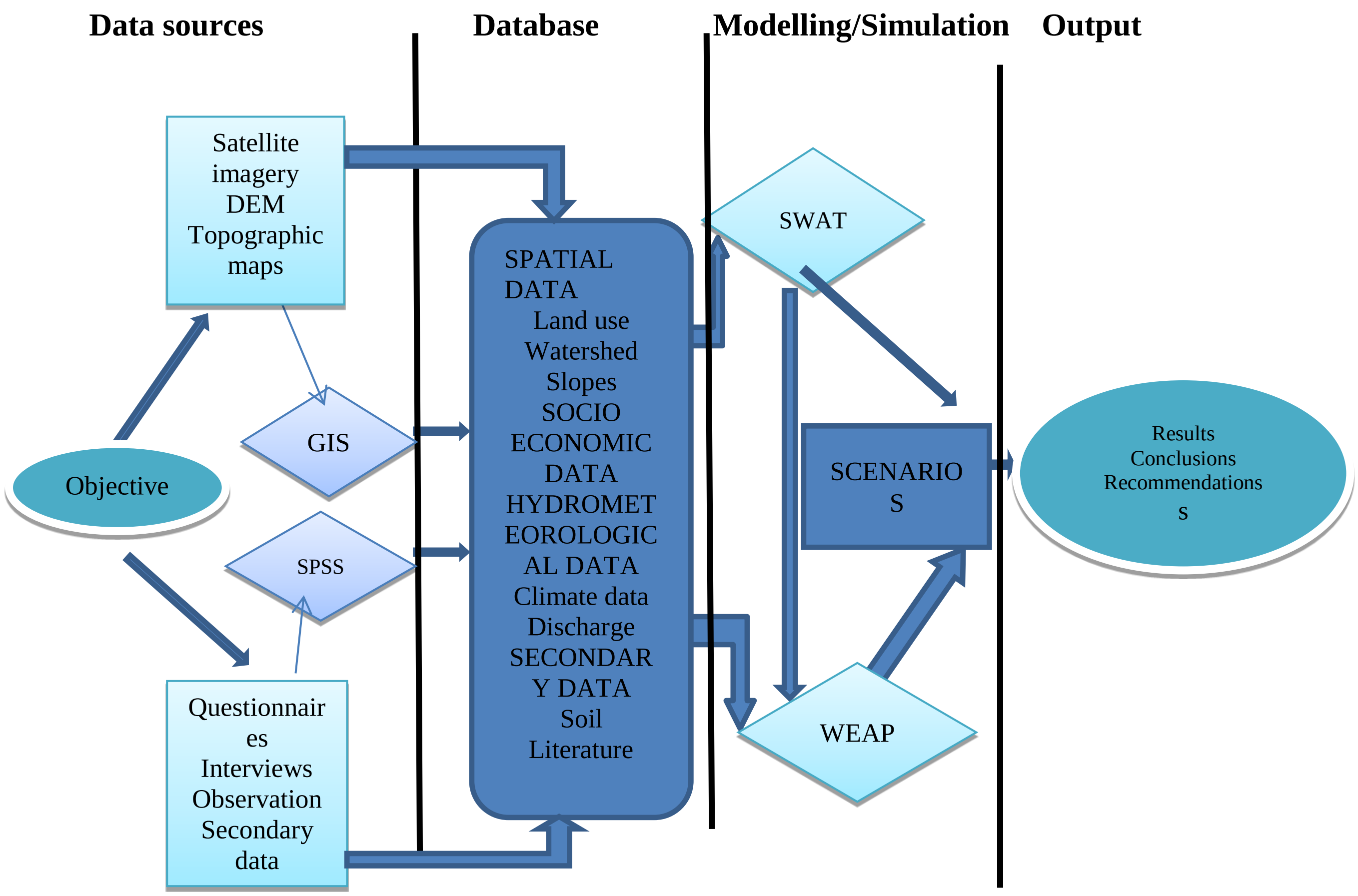

Figure 3.1: The data requirements and procedures of the study

(Source: Author, 2015)

The study used spatial, climate, hydrological and socio-economic data which were either primary or secondary in nature. GIS was used to analyse the spatial data while the socio-economic data were analysed in SPSS and the outputs were then entered into SWAT and WEAP models for further analysis. The study then used SWAT and WEAP models to address the respective specific objectives. SWAT was used to establish the impact of the land use changes on river flows and its streamflow output was then used as an input in WEAP.WEAP was used to develop a DSS for Arror watershed which was then used to assess water demand in the study area. Finally, the two models were then used to determine the management practices that will enhance the sustainability of the watershed (Figure 3.1).

3.2 Sources of data

The study utilized both primary and secondary sources of data.

3.2.1 Primary sources of data

The Primary sources of data included the remotely sensed data that were used to prepare the Landsat satellite images and the socio-economic data (Figure 3.1). The Landsat satellite images with a resolution of 30 m of the years 1986, 2000 and 2012 were used to determine the land use and land cover changes over the twenty six years.

Field surveys and questionnaires were administered to collect information about the indigenous and contemporary watershed management, conservation practices and other socio- economic data.

3.2.2 Secondary Sources of data

The secondary data included the climate, soil, discharge data of river Arror and population data (Figure 3.1).

3.3 Materials and equipment

The key materials that were used in the study included: Satellite images of 1989, 2000 and 2012 covering the study, Topographic maps of the area, Global Positioning System (Garmin etrex 10 model), Camera and Computers.

3.4 Target Population and Sample Size

3.4.1 Target Population

The target population comprised all the residents of Arror watershed. The total population of the watershed inhabitants was approximately 10,000 (Republic of Kenya. 2002b).

3.4.2 Sampling Techniques and Sample Size

Multi-staged cluster sampling was used to randomly select the target population. The watershed was divided into three sub-catchments which were treated as the first stage clusters. At the second stage of selection, sub-clusters (locations) were selected using probability proportional to size (PPS). A fixed number of sub-clusters (locations) were selected within each cluster. The locations that were sampled were Kapsowar, Kipsaiya, Koibarak, Kapyego, Chesuman and Arror. The number varied depending on the sample size required for each sub-cluster. At the third stage of selection, the sub-study areas (sub-locations) were selected using PPS where a fixed number of sub-study areas were selected within each sub-cluster (location) and this also varied depending on the sample size required from each sub-study area. The sub-locations selected were Tuiyobei, Kapsumai, Kipsaiya, Kabuswa, Kesom, Kapyego, Kessom, Kararia, Chemworor, Kapchemutwa, Arror and Koitilial.

A sampling frame of all study areas within each stratum/cluster was developed. For each stratum/cluster, a fixed number of households were selected using a probability proportional to size (PPS) sampling technique whereby the probability that a particular household will be selected within a stratum is proportional to the population of that study area (SA). Study areas served as the primary sampling units (PSU).

At the final stage of selection, a fixed number of households were randomly selected in each of the sub-study areas (sub-locations). Given that a list of housing/dwellings was not available, systematic sampling was used to select the households to be interviewed. A starting house on a random road was randomly selected. Enumerators were then to follow the right hand rule method to select the remaining households to be contacted. This captured the diversity of the sub-study. At the household level, heads of households were administered with survey questionnaires. In cases where the head was unavailable, any other member who was 18 years and above was interviewed. The inclusion criterion among those household members was that they must have been residents of these study areas for at least two years.

The desired sample size was determined using the formula (Eqn 3.1) of Fisher *et al.* (1991)

$$n = Deff * \frac{Z_{\frac{\alpha}{2}} * P(1-q)}{d^2} \qquad \text{[Eqn 3.1]}$$

Where;

$n =$ Desired sample size

$Z_{1-\alpha/2}$ = Type I error and Z statistic represents level of confidence or is the normal distribution critical value for a probability of α/2 in each tail. For a 95% CI, $Z_{\frac{\alpha}{2}}$ =1.96.

P = Proportion of household having knowledge on the conservation of water catchment areas in the watershed after doing a pilot survey

$q =$ Expected Proportion of household who do not have knowledge on the conservation of water catchment areas

$Deff =$ the design effect in case of multi-stage cluster sampling (for cluster samples set at *default* value of 2)

The previous knowledge on water conservation practices in the general population was set at 70% after doing a pilot survey. In this case, $p = 0.7$ and $q = (1-p) = 0.3$. Using standard parameters of 95% of significance (α) and $Z_{\frac{\alpha}{2}}$ = 1.96 are chosen. Inserting these values in the above formula yields the following result;

$$n = 2 * \frac{1.96^2 * 0.7 * (1-0.7)}{0.05^2} \qquad \text{[Eqn 3.2]}$$

$n = 646$

$n = 646$ Households

3.5 Data collection

3.5.1 Primary Data

Questionnaires were the main data collection tool for surveys in this study. Both closed and open ended questions were used because they standardize the stimulus presented to the respondent. The questionnaires were used to collect information on demographic characteristics; the source of livelihood of the households; traditional and contemporary watershed and water resource management practices; main types of farming practiced in the area; water resource problems, their causes and possible solutions; changes in the Arror River and their cause as well as factors leading to famine in the region. Information on water use and conflicts on water allocation in the study area as well as awareness on institutions, legislations, policies or associations that are concerned with watershed and water resource management and their impacts were also gathered.

The questionnaires were randomly administered to a few households in all the sub-study areas for the purpose of piloting. As a result of the pilot some questions were adjusted to get the correct response and more questions were formulated so as to capture more information that was considered necessary. Further discussions with key informants; the county Forest Officer, Agricultural extension Officers, the Water Resource Management Authority (WRMA) officers and County Environmental officers were carried out. Finally, the adjusted questionnaires were then photocopied to produce 646 copies.

3.5.2 Secondary Data

Additional data were collected from various organizations. These organizations included; the Forest Department, Kenya Meteorological Department (KMD), Kerio Valley Development Authority (KVDA), Agriculture offices, Ministry of Water, Water Resources Management Authority (WRMA), Kenya Soil Survey Department (KSSD) and all Non-Governmental Organizations working in the area. Extensive reading from textbooks, journals, periodicals, seminar reports, newsletters, newspaper reports, dissertations, government documents, legislations, development plans, County Integrated Development plans, population data workshop papers and relevant theses was done.

3.6 Data Collection Procedure

The study focused mainly on the preservation of water catchment areas, concerns and conflicts associated with watershed management as well as the utilization of water. At least one member of a household preferably the head was considered for interviews. The respondent had to be aged 18 years and above. The other inclusion criteria were that the respondent was expected to be a genuine resident of the region and must have stayed in the region for at least two years. A total of 646 households were interviewed in this region.

The survey and interviews were done for three months. It was ensured that research assistants were first trained on the survey logistics before beginning the process of data collection. Enough time was taken at household level when interviewing the respondent who was present at that time. If no member of the household was present during the survey, field workers could mark and come the following day to the same household. At the time of survey, the participants were interviewed confidentially using a questionnaire (Appendix I). All the study participants were assured of confidentiality on all the responses they provided during the survey period. Once the data collection exercise was complete the researcher had to go through all the questionnaires one by one to ensure that they had been completely filled.

3.7 Data Analysis

3.7.1 Statistical data

Data was first coded and entered in to SPSS. It was then checked for inconsistencies before analysis. To check for inconsistencies, frequency statistics was performed on categorical variables to identify any missing values and those outside the required range. For continuous variables like age, average size of land owned by household and average size of household, a histogram was plotted to assess if the distribution of the mentioned variable had a normal distribution. In this data set most of the variables/observations had complete records.

Categorical variables were presented in form of frequency tables and bar graphs while continuous variables were mainly summarized using mean and median. Chi-square test was used to compare categorical variables. Fisher's exact test was also used to compare categorical variables where some cells had expected value of less than 5. Given that most of the variables had more than one response; each response had to be recorded as a dummy variable before analysis. Therefore, each variable in this case had a multiple response answer. Level of significance was set at $p < 0.05$, with a 95 % confidence interval.

The following baseline explanatory variables were included in the analysis: age (years), gender, education level, length of stay in the area, concerns limiting watershed management, main types of farming, sources of conflicts with neighbours, crops under irrigation, causes of changes in Arror River, average size of land owned by household, average size of household, average amount of water used per day in the household, source of water for household use, source of irrigation water, livestock keeping and major causes of famine in the region.

3.7.2 GIS Analysis

a) Watershed Delineation

A Digital Elevation Model (DEM) with a 90 m resolution obtained by the Shuttle Radar Topography Mission (SRTM) was downloaded from the Global Land Cover Facility (GLCF). A DEM is a representation of the continuous variation of relief over space that helps in assessing landscape characteristics along with topography and has a wide application in hydrological modeling. The Hydrology Tools of ArcGIS software was used to delineate the watersheds of Arror River. The whole process of watershed delineation in ArcGIS which involves the filling of the sinks, the determination of the flow direction and accumulation as well the creation of the stream links was followed. The point of intersection between Arror River and the Kerio River was used as a pour point to finally delineate the entire watershed.

b) Land Use and Land cover

Landsat 5 Thematic Mapper (for the year 1986 January) and Landsat 7 Enhanced Thematic Mapper (for 2000 and 2012 both for the month of January) with a resolution of 30 m were used in the analysis of the catchment.

i) Image preparation

Since the year 2003 May the scan line corrector in Landsat 7 failed and therefore the images acquired since then have a strip that either allow double recoding of the reflectance value or no value for some features. Therefore, de-stripping was necessary for the correction of Landsat 7 for the year 2012 which entailed gap filling of the image strips using ENVI remote sensing software version 4.7. Stripped and destripped Landsat 7ETM images for 2012 are as shown in Figures 3.2 and 3.3 respectively (bands 4,3,2).

Figure 3.2: Stripped Landsat 7ETM

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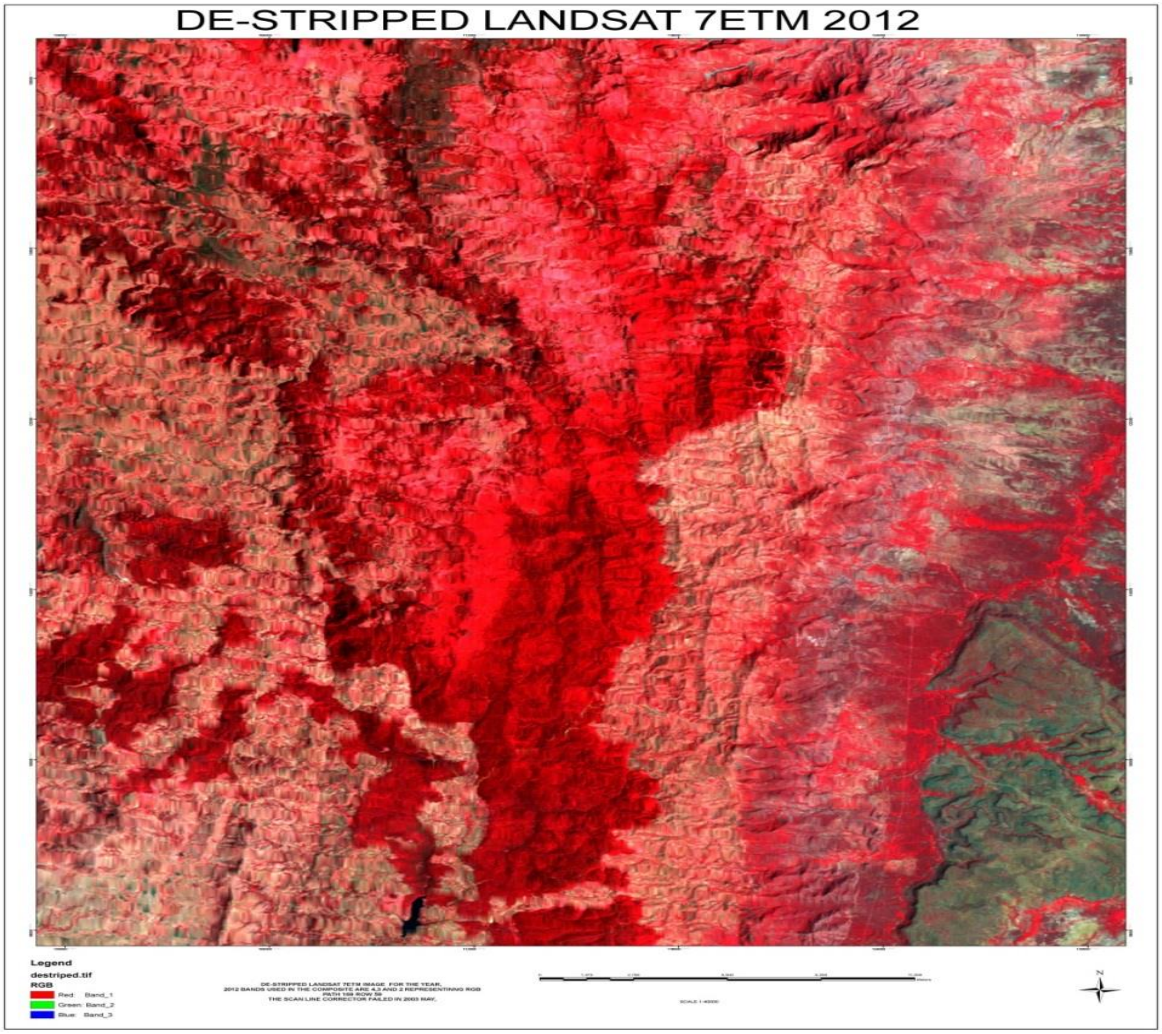

Figure 3.3: De-stripped Landsat 7ETM image of the study area

Atmospheric correction using the Quick Atmospheric Corrector model from ENVI4.7 code library was then used to reduce atmospheric effects (e.g. haze and noise) in the Landsat images. Due to varying spectral signatures and radiometric effects of the wave length various bands were then converted to reflectance for easy image classification and interpretation. Layer stacking of the reflectance band was then done to produce a multispectral image and afterwards sub setting process executed.

The reflectance for the bands 4, 3, 2 representing RGB image composition was used to create a composite in which the classification was to be done. Band 4 represent the near infra-red band while 3 and 2 represents the visible red and green part of the electromagnetic spectrum respectively. Forest cover reflects infrared due to the structural composition of the leaf canopy example the moisture content, with dark red reflection in coniferous forest and bright red in deciduous forest and this provided a base for the discrimination of the two aforementioned forest covers. Co-registration of the composites to be used in the classification and pixel by pixel change detection process was performed to enable accurate overlay of the images. This makes it possible for change detection to be pixel based.

ii) Image classification.

Anderson *et al*. (1976) classification system was modified and eight classes were considered for the purpose of this study: Coniferous forest cover, Deciduous forest cover, Grassland, Bare ground, Riverine and ridge vegetation, Crop land and Wetlands. Reconnaissance of the study area was done before the classification process. Semi-automated methodology which entails both manual and automated interactive processes using training site based on the above land cover classes was then performed for the respective time periods. Supervised classification with the following parameters was then applied to the images as the decision rules:

- Non-parametric rule assigned as parallelepiped.
- Overlap rule and unclassified rules assigned as the same as parametric rule.

- Parametric rule assigned as maximum likelihood which allows comparison of signatures within the neighbouring pixels.
- Attribute options for the signatures were ordered by statistics.

Parallelepiped image classification covering the entire project area followed. Parallelepiped classification was used in the study because it uses a simple rule to classify multispectral data. Its computation is simple and fast and takes differences in variance into account. The classification was performed, one theme at a time and the output for each theme stored as a separate layer. Each theme represents a certain condition. Performing the classification one theme at a time circumvents the problem of multi classified pixels, caused by spectral similarities of certain themes, which often occur in a multi-theme classification operation. Material of interest classification was done to delineate crop land areas for the three image periods. This model allows identifying the areas with the same signatures and classify as one theme. All the procedures above were carried out using ENVI remote sensing software with various results for the classification representing the years 1986, 2000 and 2012. Ground- truthing was undertaken before the production of the final maps.

3.8 Climate data

The data utilized by the WEAP and SWAT models were sourced from the Kenya Meteorological Department (KMD) which is the official custodian of climatic data in Kenya. The KMD data was complemented with data collected by the Kerio Valley Development Authority (KVDA). Climatological data for Arror watershed are limited due to the absence of well-maintained meteorological station. The stations i.e. Kapsowar and Arror that are within the study area had only rainfall data which also had numerous gaps (Figure 3.4). Arror was considered to be within the study area since it was quite close to the boundary of the study area.

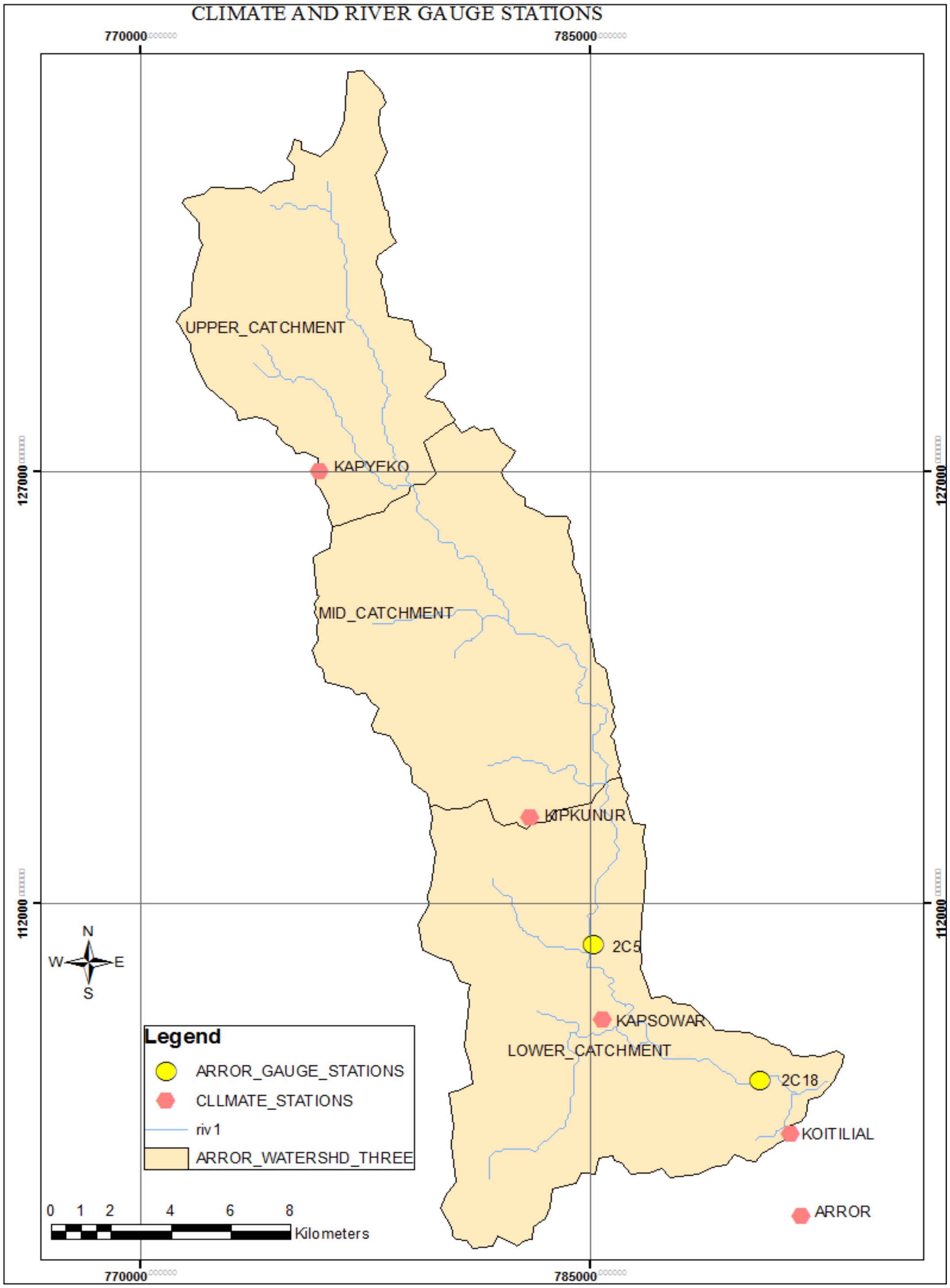

Figure 3.4: The locations of the climate and river gauge stations in the watershed.

(Source: Author, 2015)

Apart from these two stations, Eldoret, Kitale, Kapsowar Inland mission (2286 metres above sea level), Chebiemit and Kapcherop station (2270 metres above sea level) were also utilized since these are the nearby stations and are at altitudes similar to those of the study area. Eldoret station is approximately 100km south of the study area and is at an altitude of 2084m above sea level and located at latitude 0^0 32' N, longitude 35^0 17' E.

Two methods, the nearest neighbours (NN) and the inverse distance weighting (IDW) methods were used to impute the missing data in the databases and to reduce the effect of the topography. According to Cho et al., (2009), as the number of rain gauges used in the simulation decreases, the uncertainty in the hydrologic and water quality model output increases exponentially. In previous studies, poor performance of hydrological models such as SWAT was attributed to poor quality of data as a result of low rain gauge distribution within the catchment. In order to improve the quality of data and increase the rain gauge density, spatial interpolation was carried out using the Inverse distance weighting (IDW) technique and an additional three dummy gauging stations were created. The stations are Kapyeko, Kipkunurr, and Koitilial (Figure 3.4). This enabled the setting up of the SWAT and the WEAP models.

The temperature data for the period 1985 to 2012 were extrapolated from Arror and neighbouring Eldoret, Kitale and Chebiemit stations to create dummy stations. Four dummy stations, similar to the rainfall stations, were created and provided daily temperature data from a range of 12^oC to 37^oC. The time series for daily maximum temperature (Tmax), daily minimum temperature (Tmin) were generated using the temperature lapse rate method presented in the equation below (Minder *et al.*, 2010).

$$T_p = T_o + \gamma(\Delta) \qquad \text{Eqn [3.3]}$$

Where, T_p is the temperature at a point of interest (^oC), T_o is the observed temperature (^oC), γ is a standard temperature gradient (-6.5 ^oC/km), Δ is the difference in elevations (Minder *et al.*, 2010).

In the IDW method, weights for each sample are inversely proportionate to its distance from the point being estimated. The method was used to develop a time series of rainfall data. All the stations with long term data were used in the algorithm to determine the weighted rainfall for the new station. Missing portions of any station data were filled with this series data using the following formula.

$$P_x = \frac{\sum_{i=1}^{N} \frac{1}{d^2} P_i}{\sum_{i=1}^{N} \frac{1}{d^2}} \qquad \text{[Eqn 3.4]}$$

Where, *Px* = estimate of the average basin rainfall, *pi* = rainfall values of rain gauge *i*, *d* = distance from gauge *i* to the centroid of the basin, *N* = number of gauges.

The variables are precipitation (mm/month), mean minimum temperature and mean maximum temperature per month. Each of these variables has cell coordinates (0, 0) in the lower left, increasing to the right (New *et al.*, 1999). The characteristics of a virtual station centroid to the basin were found to lie somehow between those of the Kapsowar and Arror stations for rainfall, number of wet days and temperature. The use of the mean of the two stations removed biases towards any of the stations. The generated centroid thus had characteristics mid-way between those of Kapsowar and Arror. The average records from the two stations were used to calculate the parameters in the weather generator (.wgn) file. The .wgn file was created using the WGNmaker4.xlsm tool Wang *et al*. (2014) an excel macro designed to calculate the weather statistics needed to create user weather station files for SWAT. The inputs to the WGNmaker4.xlsm include daily datasets for rainfall (mm), temperature (max. and min), solar radiation ($MJ/m^2/day$), and wind speed (m/s).

3.9 The hydrological data

The catchment has two river gauging stations (2C05 and 2C18) that are monitored by the Kerio Valley Development Authority (KVDA). The locations of the two stations are shown in Figure 3.4. Station 2C05 had more years of recorded flows (1961-1992) as compared to 2C18 (1982-1992). Station 2C18 had more daily flow data gaps than 2C05. From a plot of mean annual river flows against time in years, mean annual flows at station 2C18 were much lower as compared to 2C05. This was expected as there are fourteen irrigation canals abstracting water at an average flow rate of 0.15 M^3/sec each in the upstream end of station 2C18 but on the downstream of RGS 2C05 (MDFAR, 2005). Recorded discharge values for both stations showed a fluctuating trend which was more pronounced for station 2C05. This is not expected for natural flow regime but could be attributed to errors in flow measurements.

The discharge data had a lot of gaps that had to be filled. The missing years were estimated by interpolation or averaging for some monitored years, however for large missing data, the infilling of data largely depended on the different lengths of gaps; different seasons and availability of hydro meteorological data from neighbouring areas.

To fill the missing sections a technique had to be applied that factored in gaps with different durations and in different seasons (wet and dry). The seasons were based on historical rainfall time series. In order to fill in the missing discharge data of the Arror River the available and relevant set of data were used: discharge measurements from neighbouring river gauges and point rainfall measurements in the catchment. In response to the rainfall pattern of catchment, the annual discharge records matching with the period were separated into low (dry) and high (wet) flow seasons. The threshold values adopted were the long term means daily runoff values of the basins. Discharge measurements were then estimated using a corresponding rainfall data.

3.10 SWAT Modeling

The Soil and Water Assessment Tool (SWAT) is a physically based, spatially distributed, continuous time hydrological model. It was developed by the USDA-Agricultural Research Services USDA-ARS. SWAT is applied at basin levels to simulate various process regarding hydrology, climate change and land use change. Its output can be used to assess the impact of vegetation growth, land use and sedimentation on water quantity and quality (Arnold & Allen., 1996).

GIS interfaces (e.g. ArcGIS, Open Map, Grass, etc.) are attached to SWAT to enable sub division of a basin into independent sub-basins. The sub-basins constitute of hydrological response units which are categorized with regard to land use, soil type and slope classes (Arnold *et al.,* 2012). SWAT model has been used world over to undertake hydrological studies with a view of managing water and land resources.

The SWAT model constitutes hydrologic, sedimentation, weather, plant growth; erosion and pesticide functions which enable it simulate hydrological processes and land management operations. Under the hydrological function, water balance in a catchment is calculated by the equation (3.5) (Arnold & Allen., 1996).

$$SW_t = SW_O + \sum_{i=1}^{t}(R - Q - ET - P - QR) \qquad \text{[Eqn 3.5]}$$

Where SW_t is the soil moisture at time t (mm), SW_o is the initial soil moisture (mm), the rest are: precipitation (R), evapotranspiration (ET), surface runoff and subsurface lateral flow (Q), percolation (P), return flow (QR).

A model of the Arror catchment was developed, using ArcSWAT, 2012. The overall purpose was to simulate the flows under the three time regimes i.e. 1986, 2000 and 2012. The output of the three time periods were to be analysed and compared to know the extent of land use change and its impact on the hydrological variables and its eventual effect on the environmental flows.

3.10.1 SWAT Model setup

The SWAT model was developed through a set up involving the combination of the DEM, land use/cover map, soil data and meteorological data to create sub basins and subsequently the hydrological response units (HRUs).

(i) Digital Elevation Model (DEM)

The Digital Elevation Model used had a spatial resolution of 90 m. It was obtained from the Shuttle Radar Topographic Mission (SRTM) as explained earlier. The DEM was uploaded into ArcSWAT where study area was delineated, sub-basins created and the slope information used to generate the Hydrological Response Units (HRUs). Figure 3.5 shows the DEM that was delineated and applied to the land use map and soil map, so that they could be overlaid compatibly and accurately.

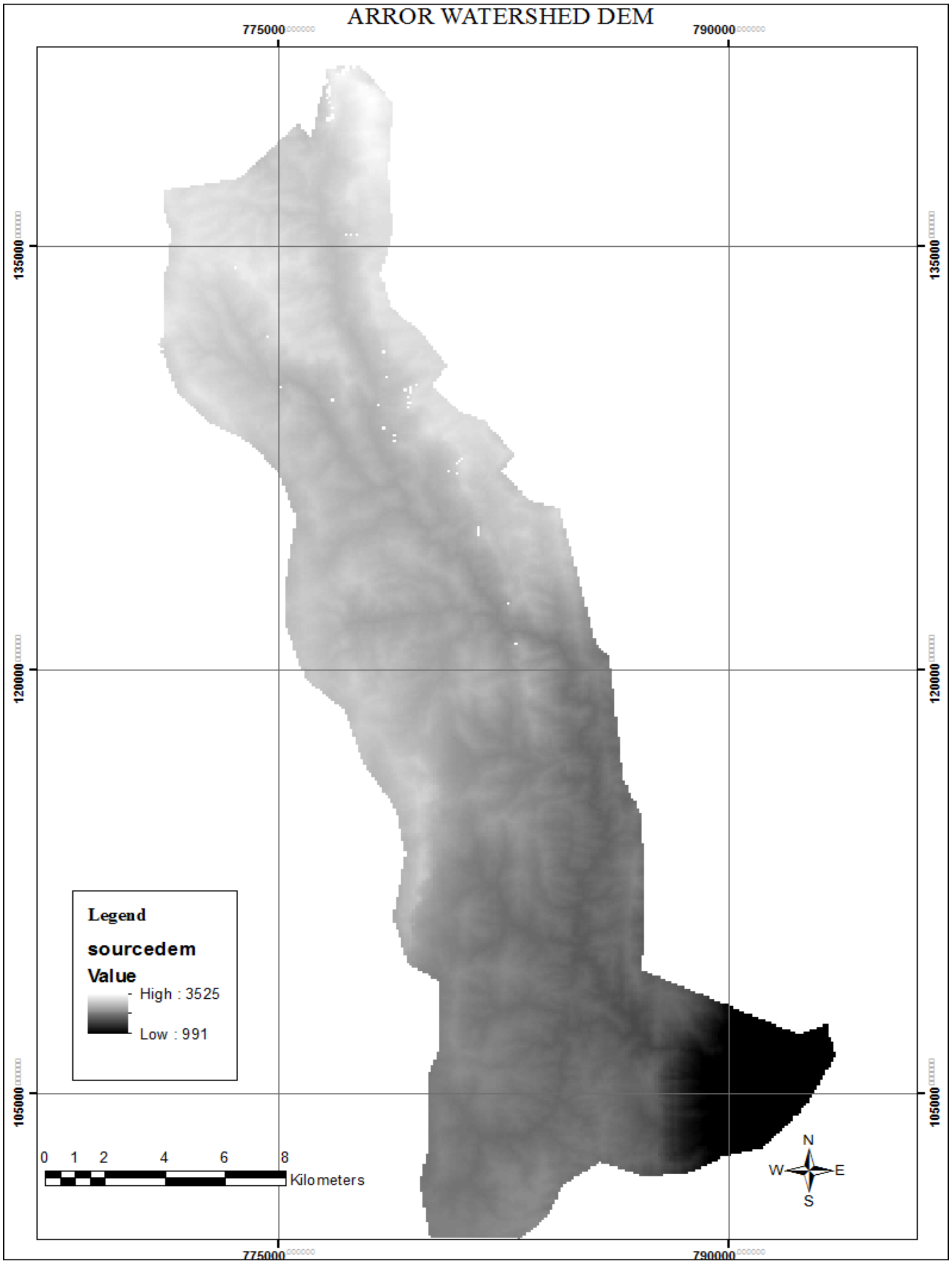

Figure 3.5: DEM of Arror watershed

(Source: Author, 2015)

(ii) Soil map

The soil data used were sourced from the Kenya Soil Survey Department archives. These data were prepared from field investigation in the 1950s and used to develop a soil classification map in which the Arror catchment falls under. Figure 3.6 depicts the soil map of the catchment. To enable SWAT soil characteristics be incorporated in the model, a soil map raster file was created and overlaid with the rest of the input data.

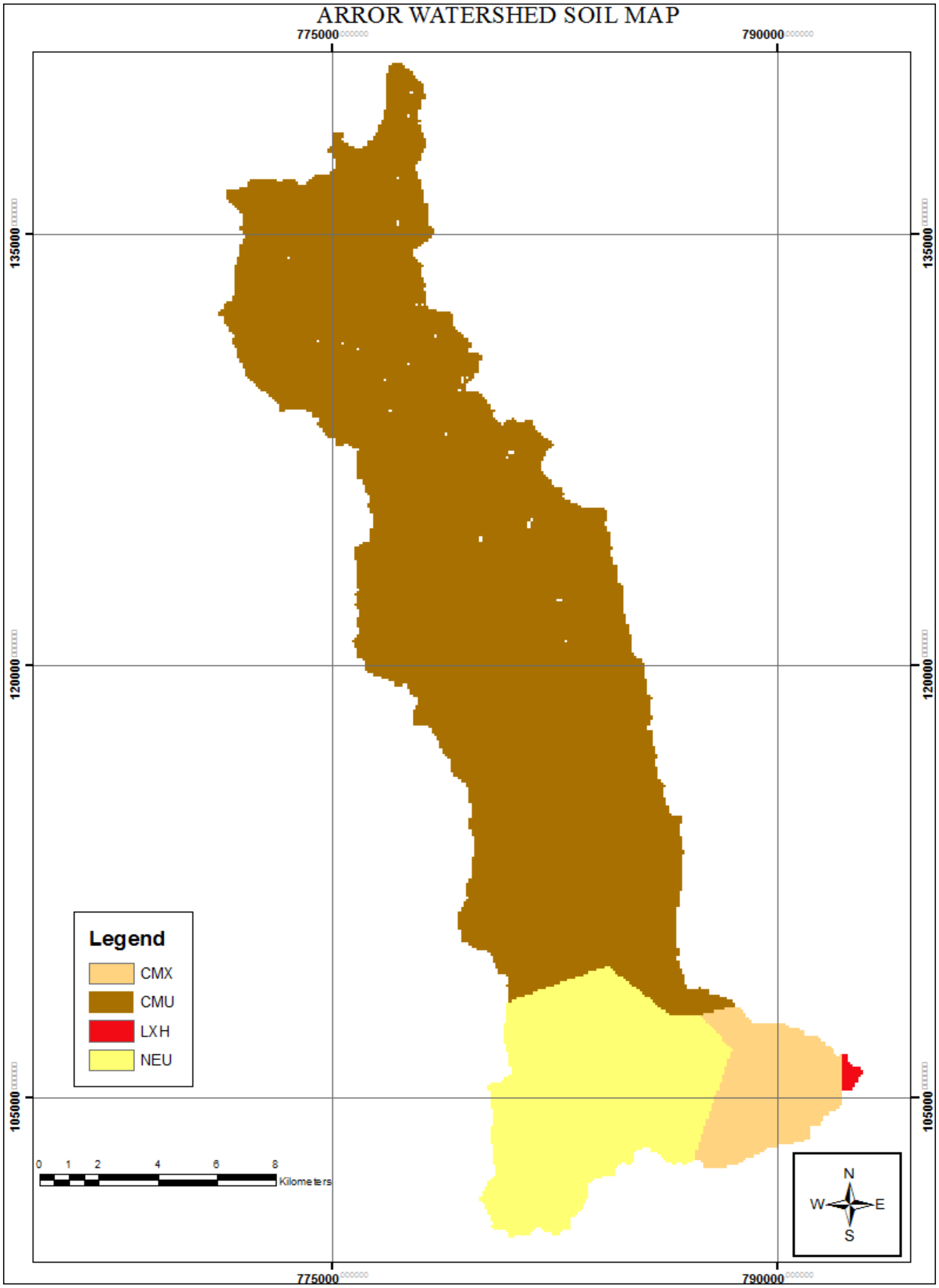

Figure 3.6: Soil Map of Arror Watershed derived from Kenya Soil Survey (1950) (Source: Author, 2015)

(iii) Land use map

To acquire details of the spatial extent and classification of land use and cover in the catchment, a land use/cover map developed earlier were uploaded into SWAT catchment (Figures 4.1, 4.2 and 4.3). The land cover and soil data was used together with the slope data to generate the hydrological characteristics of the catchment.

(iv) Climate data

The data required for the study were mainly for rainfall and temperature. The data had been processed to ensure that their quality was improved. For the precipitation input, the station created using the Nearest Neighbour (NN) or Inverse Distance Weighted (IDW) procedures in each sub basin was used as model input. For the other climatic parameters inputs such as minimum and maximum temperatures, the data from the basin's centroid was used.

In SWAT, the weather station nearest to the centroid of each sub-basin is taken as the location for the precipitation to be used in the simulation. Schuol and Abbaspour (2006) noted that unrealistic weather data are generated by SWAT if a weather station is assigned to a sub-basin that has only a few measured values or many erroneous values. According to Grimes and Pardo-Igúzquiza (2010) the benefits of geostatistical analysis for rainfall include the ease of estimating areal averages, the estimation of uncertainties and the possibility of using secondary information like topography. In the Nearest Neighbour (NN) method, the rainfall stations closest to the stations with missing data were used to fill in the gaps. By using the neighbourhood stations any missing data in one station was filled in from the other stations. The principle of shared similarities of the stations to each other due to close spatial proximity is assumed.

(v) Hydrological data

The observed discharge data from station (2C18) located at the outlet of catchment was used for calibration and validation in the SWAT model. The SWAT model set up was carried out after obtaining and processing all the input data. The DEM was first uploaded and was then used to delineate the catchment to an area of 284.8 km^2. A threshold area of 5.6 km^2 was used in definition of stream network and sub basin outlets. The study area was divided into 21 sub basins. It was later followed by the uploading of the land use data and the soil data which were overlaid on the DEM. The slope derived from the DEM was set into five classes with interval value of 5% as follows; (0 - 5)%, (5 -10)%, (10 -15)%, (15 - 20)% and >20 % so as to accommodate the various gradients in the catchment. The classification was also based on the Agriculture Act, Cap. 318 of 1986, which prohibits the cultivation of land with more than 20% slope (Republic of Kenya, 2012b). The slopes assisted in defining the hydrological response units and subsequently the drainage areas.

In generating the HRUs, a threshold of 10% of the land use over the sub-basin area was used. Soil class over land cover area was defined at 10% and the slope class over soil area at 10%. This meant that land uses occupying less than 10% of a sub-basin were eliminated and HRUs were created for land use covering more than 10% of it. The same holds for soil and slope layers. Use of the threshold percentage avoids the generation of minor HRUs and enhances model computation efficiency (Masih *et al.,* 2011).

Figure 3.7 shows the process followed in setting up the SWAT model. To develop the weather condition in the model, the daily rainfall data and daily minimum and maximum temperature data for a period of 28 years from 1st January 1985 to 31st December 2012 daily rainfall data and daily maximum and minimum temperature were input into the SWAT model weather database. The SWAT model simulation was set up with two years of warm up period (1985 and 1986).

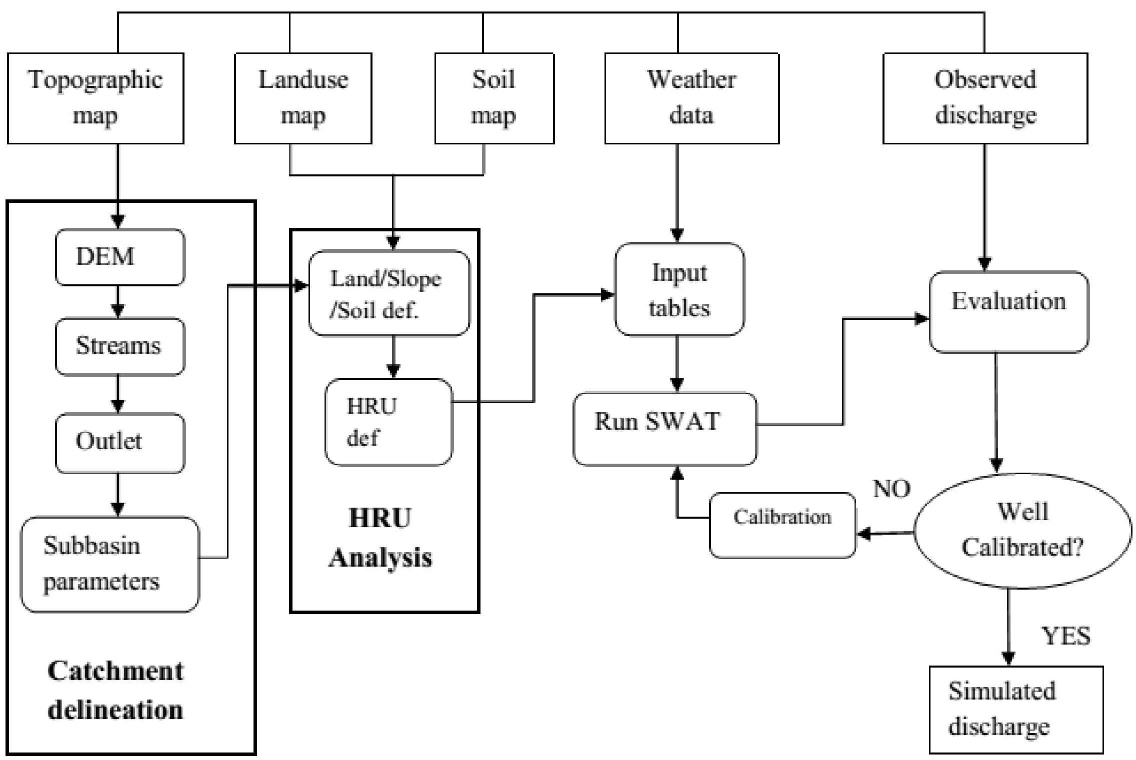

Figure 3.7: The SWAT model set up process
(Source: Author, 2015)

3.10.2 SWAT model sensitivity analysis

A sensitivity analysis is usually the first step towards model calibration and is performed to identify the parameters that have the greatest influence on the model results. According to Cho *et al.* (2001), a sensitivity analysis seeks to explain: the focus in which data collection should take and the level of care when underestimating the parameters. The parameters in SWAT vary by sub-basin, land use, or soil type, hence increasing the scale in the discretization (or threshold area) increases the number of parameters substantially. While some of these parameters represent measurable quantities and hence can be estimated directly from field data (or from literature), other parameters are empirical or SWAT-specific. Van Griensven *et al*. (2012) allude that a sensitivity analysis method should be both computationally efficient and robust.

Parameters with a sensitivity index (msi) > 0 were identified as sensitive and amounted to eight in number (Table 3.1). According to Van Griensven *et al*. (2012) parameter with a global rank 1 is categorized as ‘very important’, rank 2–6 as ‘important’, rank 7–20 as ‘slightly important’ and rank 28 as ‘not important’. The Soil Conservation Service (SCS) curve number (CNII) was identified as the most sensitive and hence “very important" parameter to stream flow for this catchment. The curve number indicates the runoff potential of an area for the combination of land use characteristics and soil type. Higher curve numbers translate into greater runoff. Curve numbers are a function of hydrologic soil group, vegetation, land use, cultivation practice, and antecedent moisture conditions. The CNII parameter is of primary influence on the amount of runoff generated from a hydrologic response unit and hence a relatively large sensitivity index was expected. The parameter which depends on the percentage of imperviousness in the land cover type and the soil group is important especially in the study area with forest and cultivated land as the major cover groups and little urban settlement influence.

Critical parameters, were the groundwater recharge to deep aquifer (RCHRG_DP), the threshold depth of water in the shallow aquifer required for return flow to occur (GWQMN), the available water capacity (SOL_AWC), the maximum canopy storage (CANMX), the soil evaporation compensation factor (ESCO), the plant uptake compensation factor (EPCO), the ground “revap” water coefficient (GW_REVAP) and groundwater ‘‘delay’’ coefficient (GW_DELAY). The RCHRG_DP controls the fraction of the percolated water that will flow to the deep aquifer. A high RCHRG_DP value (near 1) indicates more allocation of percolated water to the deep aquifer. In SWAT the water that percolates through the unsaturated zone is immediately divided between the shallow and deep aquifers. The deep aquifer fraction will not produce any runoff in the basin and is thus water that is lost to the basin.

The GWQMN regulates the water accumulation in the aquifer. The groundwater flow to the reach is only allowed if the depth of the water in the shallow aquifer is equal or greater than the GWQMN. The GWQMN parameter has wide threshold range (0-5000 mm). GW_DELAY is the lag between time the water exits the soil profile and enters shallow aquifer, and depends on the depth of the water table and the hydraulic properties of the geological formation. CANMX is the maximum canopy storage. The plant canopy can significantly affect infiltration, surface runoff and evapotranspiration. As rain falls, canopy interception reduces the erosive energy of droplets and traps a portion of the rainfall within the canopy. The influence the canopy exerts on these processes is a function of the density of plant cover and the morphology of the plant species. ESCO is the soil evaporation compensation factor which allows the user to modify the depth distribution used to meet the soil evaporative demand to account for the effect of capillary action, cracks and crusting. EPCO is the plant uptake compensation factor. The amount of water uptake that occurs on a given day is a function of the amount of water required by the plant for transpiration and the amount of water available in the soil. GW_REVAP is the groundwater "revap" coefficient. This is required because water may move from the shallow aquifer into the overlying unsaturated zone. In periods when the material overlying the aquifer is dry, water in the capillary fringe that separates the saturated and unsaturated zones will evaporate and diffuse upward. As water is removed from the capillary fringe by evaporation, it is replaced by water from the underlying aquifer. Water may also be removed from the aquifer by deep-rooted plants which are able to uptake water directly from the aquifer.

Table 3.1: List of model sensitive parameters

Rank	Parameter	Lower limit	Upper limit	Parameter description	Msi
1	CNII	-50	50	SCS runoff curve number II	2.28
2	RCHRG_DP	0	1	Groundwater recharge to deep aquifer	1
3	GWQMN	0	5000	Threshold depth of water in the shallow aquifer required for return flow to occur (mm)	0.82
4	GW_DELAY	0	100	Groundwater delay (days)	0.18
5	ESCO	0	1	Soil evaporation compensation factor	0.1
6	CANMX	0	10	Maximum canopy index Runoff (mm)	0.08
7	EPCO	0.01	1	Plant evaporation compensation factor	0.02
8	GW_REVAP	0.02	0.2	Groundwater ‘‘revap’’ coefficient	0.01

(Source: Arnold *et al*. 2012)

3.10.3 The SWAT model calibration and validation

The acceptability and usability of a model to simulate or predict physical processes depend on how well it models compared to observed data. Hydrological models can be assessed either by their goodness of fit to statistical measures based on an objective function and by comparison to the water mass balance in the watershed. Both metric and non-metric performance measures are used in this study.

The SWAT model was calibrated and validated using observed river flow data from 1985 to 2012. During calibration parameters were varied and coefficient of determination (R^2) and Nash-Sutcliffe Efficiency (NSE) Equations were used to determine the best parameter value (Nash and Sutcliffe, 1970). The parameter value with the highest R^2 and NSE was considered the best. In addition, a good balance between simulated and observed mean flow was used to optimize parameters.

Calibration of the SWAT model was carried out using annual discharge data from gauging station (2C18) which is at the outlet of the catchment. The initial 15 years (1985-1999) were selected for calibration and the remaining 13 years (2000 - 2012) were used for validation.

SWAT as a model has numerous parameters which cater for the physically measurable properties of the catchment e.g. area of catchment, fraction of impervious layer, slope of surface etc. and process properties of the catchment that cannot be measured directly e.g. effective depth of surface soil moisture storage, the effective lateral inflow rate etc. (Mengitsu & Sorteberg, 2012).

Manual calibration to tune the model was done using the actual discharge data. The aim was to make the simulated outflow close to the observed outflow; this was to be achieved by adjusting values of surface runoff and base flow contribution to the reach (uninterrupted stretch of a river or stream) with reference to the land cover values. The portion of land occupied by agricultural activities was of key importance in calibration, parameters representing soil and moisture conditions required for crop growth were adjusted. In order to ensure that the following parameters were used in the calibration process: initial curve number for moisture condition (CNII), deep aquifer percolation coefficient (RCHRG_DP), groundwater "revap" coefficient (GW_Revap), groundwater delay (GW_Delay), maximum canopy storage (CANMX) and shallow aquifer threshold for base flow to occur (GWMN). There was also need to ensure that there was reasonable evapotranspiration thus the soil evaporation compensation factor (ESCO) and plant evapotranspiration compensation factor (EPCO). The agricultural area was of key importance during calibration, soil and moisture conditions required for growth of the crops were adjusted using Soil and Hydrological Response Unit (HRU) parameters. Table 3.2 shows the main model parameters and their adjustment range as used in the calibration.

Table 3.2: List of main model parameters used in the calibration

	Parameter	Range	Default	Adjustment range
1	CNII	35 – 98	72	35 – 82
2	RCHRG_DP	0 – 1	0.05	0.45 - 0.55
3	GW_REVAP	0 - 0.2	0.01	0.09 - 0.18
4	GW_DELAY (days)	0 – 500	31	50 – 70
5	CANMX (mm)	0 – 100	0	30 – 50
6	GWMN (mm)	0 – 5000	0	200 – 500
7	ESCO	0 – 1	0	0 - 0.2
8	EPCO	0 – 1	0	0.4 - 0.9

Source: Arnold *et al*. (2012)

After every repeated calibration, the observed and simulated flows were compared at annual time steps for the first 15 years. Coefficient of determination (R^2) and Nash Sutcliffe efficiency value (NSE) were then checked to assess the model's performance. After every calibration, validation was done for the remaining 13 years.

3.10.4 Estimation of water balance components

i) Total water yield

The SWAT model generated surface runoff using rainfall data and soil conservative service curve number (SCS-CN) method shown by the equations below (SCS, 1972).

$$Q_{surf} = \frac{(R_{day} - 0.2S)^2}{(R_{day} - 0.8S)} \quad \text{[Eqn3.6]}$$

$$S = 25.4\left(\left(\frac{1000}{CN}\right) - 10\right) \quad \text{[Eqn3.7]}$$

The total water yield (Q_{total}) in mm from the model was estimated using the equation below (Chen *et al*., 2011).

$$Q_{total} = Q_{surf} + Q_{lat} + Q_{gw} \quad \text{[Eqn3.8]}$$

Where Q_{surf} is surface runoff (mm), Q_{lat} is sub surface/lateral runoff (mm), Q_{gw} is base flow (mm), R_{day} is daily precipitation (mm), *CN* is curve number and *S* is retention factor. Flow components ($Q_{surf,}Q_{lat}$ and Q_{gw}) were simulated at each HRU and accumulated at the river outlet of each sub basin (Chen *et al.*, 2011).

ii) Evaporation and transpiration

The SWAT model computes potential and actual evaporation and transpiration using Penman-Monteith, Hargreaves and Priestley-Taylor methods (Hargreaves & Allen, 2003; Strauch *et al*., 2012). In this study the Hargreaves method shown below was used due to lack of relative humidity, solar radiation and wind speed data.

$$ET = 0.0023(T_{mean} + 17.8)\sqrt{(T_{max} - T_{min})} \times R_a \qquad \text{[Eqn 3.9]}$$

ET is potential evaporation and transpiration (mm), $T_{mean}$is mean air temperature, T_{max} is maximum air temperature, $T_{min}$is minimum air temperature, and R_a is extra-terrestrial radiation in (mm) (Hargreaves & Allen, 2003).

iii) Water balance computation

Water balance of the Arror catchment was determined using the equation below (Arnold & Allen., 1996).

$$P - AET - Q_{out} - R_{DA} = \frac{\Delta S}{\Delta t} \qquad \text{[Eqn 3.10]}$$

where, P is precipitation (mm), AET is actual evaporation and transpiration (sum of transpiration, soil and water evaporation) (mm), $Q_{out}$is river runoff leaving the study area (mm), R_{DA} is groundwater recharge to deep aquifer (mm) and $\frac{\Delta S}{\Delta t}$ is change in water storage over time step (mm) (Arnold & Allen, 1996).

3.10.5 The management practices scenarios in SWAT model

SWAT model was then used to assess the impact of some management practices on the flows of Arror River so as to suggest the best management practices for the study area. The management practices that were considered were contouring and terracing in the year 2012.

Terracing scenario was simulated in SWAT by adjusting both erosion and runoff parameters. The USLE practice (TERR_P) factor, the slope factor (TERR_SL) and curve number (TERR_CN) were adjusted to simulate the effect of terracing by providing values that would fit the particular soil properties and land slope. It was important to note that TERR_SL was set to a maximum of the distance between two terraces.

Contour planting scenario was simulated in SWAT by altering curve number (CONT_CN) to account for increased surface storage and infiltration and the USLE Practice factor to account for decrease in erosion.

3.11 WEAP model

The WEAP (Water Evaluation and Planning) software was used in this study to evaluate the future water demands in the Arror watershed region (SEI, 2015). In WEAP the typical scenario modeling effort consists of three steps. First, a Current Accounts year is chosen to serve as the base year of the model; two a Reference scenario is established from the Current Accounts to simulate likely evolution of the system without intervention; and thirdly what-if scenarios created to alter the Reference Scenario and evaluate the effects of changes in policies and/or technologies. In this study, the data used in modeling for current accounts, is for the period 1986-2012. For allocation of available resources, a number of options were tested by developing several scenarios and future water demands were projected.

WEAP is the most appropriate tool for Benefit –cost analysis. It follows an integrated approach to water development that places water supply projects in the context of multi-sectoral, prioritised demands, and water quality and ecosystem preservation and protection. WEAP incorporates these values into a practical tool for water resources planning and policy analysis. WEAP places demand-site issues such as water use patterns, equipment performance, re-use strategies, costs, and water allocation schemes on an equal footing with the supply-site aspects of streamflow, groundwater resources, reservoirs, and water transfers. WEAP is also distinguished by its integrated approach to simulating both the natural (e.g. rainfall, evapotranspirative demands, runoff, baseflow) and engineered components (e.g. reservoirs, groundwater pumping) of water systems, allowing the planner to have access to a more comprehensive view of the broad range of factors that must be considered in managing water resources for the present as well as for future use (Droogers *et al.*, 2011). WEAP is therefore an effective tool for examining alternative water development and management options and thus most suitable for this study.

3.11.1 Setting up WEAP

Data collection is a critical step in setting up WEAP. The characterization of the water system involves collecting and entering in WEAP the following data:

- Water uses (demand sites)
- Reservoirs: location, capacity and operation rules
- Flow gauging station (flow requirement and ecological reserve)

WEAP applications generally involve the following steps (SEI, 2005):

- Problem definition including time frame, spatial boundary, system components and configuration;
- Establishing the ‘current accounts’, which can be viewed as a calibration step in the development of an application, provide a snapshot of the actual water demand resources and supplies for the system;
- Building scenarios based on different sets of future trends based on policies, technological development, and other factors that affect demand, supply and hydrology;
- Evaluating the scenarios with regard to criteria such as adequacy of water resources, costs, benefits, and environmental impacts

The data input in WEAP is structured according to the schematic set-up of the catchment. The following classification is used:

- Key-assumptions
- Demand sites and catchments
- Hydrology
- Supply and resources

(a) Linking demands and supply

(b) Runoff and infiltration

(c) River (including the reservoirs per tributary)

(d) Groundwater

(e) Local reservoirs

(f) Return flows

The actual river system is represented by a network of river nodes, reaches, and reservoirs, each with its own attributes. River nodes represent locations of local inflow and/or water withdrawals and returns. River reaches represent physical river segments and their water transport characteristics. Reservoirs represent man-made or natural lakes that may support various water uses including water supply, flood control, drought management, hydropower, and wetland protection, among others.

3.11.2 Current Accounts and Reference Scenario Years in WEAP

The Current Accounts is the dataset from which the scenarios are built. The Current Accounts Year is usually the most recent year for which reasonably reliable and complete data are available and from which future demand projections can be made. The Current Accounts year data comprise the Current Accounts, which all scenarios use as the basis for their projections. The current accounts year for this study was 1986. Scenarios explore possible changes to the system on future years after the Current Accounts year. A default scenario, the Reference scenario carries forward the Current Accounts data into the entire project period specified and serves as a point of comparison for the other scenarios in which changes are made to the system data (SEI, 2015).

3.11.3 Geographical Characteristics of the Catchment

Three topographical map sheets (Scale 1:50,000) namely; Kapsowar-sheet 90/1, Cherangany-Sheet 75/4, and Tot-sheet 76/3 all of series Y731 (D.O.S.423) were combined to form the river system. The total area covered by Arror river catchment is approximately 286 km^2. The catchment was sub-divided into three sub-catchments based on the main tributaries. The catchment had to be sub-divided due to its large size and also the fact that the river passes through the three ecological zones of the region where the altitude, climate and land uses/ cover vary accordingly. The three sub-catchments were then named as the upper, middle and lower catchments covering 76 km^2, 93 km^2 and 117 km^2 respectively.

3.11.4 The Catchments

The study utilized the Rainfall Runoff method which is a simple method that computes runoff as the difference between precipitation and a plant's evapotranspiration. A portion of the precipitation can be set to bypass the evapotranspiration process and go straight into runoff to ensure a base flow (through the effective precipitation parameter). The evapotranspiration is estimated by first entering the reference evapotranspiration, then defining crop coefficients (Kc's) for each type of land use that multiply the reference evapotranspiration to reflect differences occurring from plant to plant. Entering an effective precipitation other than 100% is one way of acknowledging the fact that part of the rainfall is not submitted to evapotranspiration during high intensity rainfall events, hence generating a minimal runoff to the river even when the rainfall is lower than the potential evapotranspiration (Allen *et al*., 2005). The data that was necessary for this study under the catchment in WEAP were the land use and climate.

3.11.5 Land Use

Land use in WEAP model includes the total area of the catchment, the crop coefficient (Kc) and effective precipitation. The land use data was incorporated in the WEAP system. The percentage area covered by each land use were considered and for agriculture the principal crop in the watershed was chosen as the representative crop for the area for the purpose of analysis.

Crop Coefficients (Kc) are crop specific evapotranspiration values generated by research used with reference evapotranspiration data to estimate the crop's evapotranspiration requirement (Allen *et al.,* 1998; Van der Gulik & Nyvall, 2001). The Kc's for the three catchments was calculated with the help of the guidelines in FAO-56 paper (Allen *et al.*, 1998) where the dominant land uses were considered. The crop coefficients (Kc) of the dominant crops which were potatoes, maize and millet for the upper, middle and lower sub-catchments respectively were obtained from Puttemans *et al.* (2004). The percentages of the areas covered by each land use obtained from the GIS analysis done earlier were used to get the proportions of each land use in the area so as to calculate the average Kc of each catchment (Table 3.3).

Table 3.3: The Kcs of the three catchments

MONTH	Kc		
	UPPER	MID	LOWER
Jan	0.2	0	0
Feb	0.2	0	0
Mar	0.6	0.8	0.7
Apr	0.6	0.9	0.9
May	0.8	0.9	1
Jun	1.0	1	1
Jul	1.1	1	0.8
Aug	1.0	1	0.8
Sept	0.7	0.8	0.7
Oct	0.3	0	0.2
Nov	0.3	0	0.2
Dec	0.2	0	0.2

(Source: Author, 2015)

A combination of the length of the stages, the growing season and the Kc-factor results in the monthly variation. The effective precipitation is the percentage of precipitation available for evaporation, the remainder is direct runoff. In the months with peak rainfall the precipitation rate exceeds the infiltration rate of the soil. Therefore, part of the precipitation is surface runoff to streams and is not available for evaporation.

In many countries, formulae have been developed locally to determine the effective precipitation. Such formulae take into account factors like rainfall reliability, topography, prevailing soil type etc. If such formulae or other local data are available, they should be used. If such data are not available, Table 3.4 could be used to obtain a rough estimate of the effective precipitation. The monthly effective precipitation for each catchment was therefore estimated with the aid of Table 3.4.

Table 3.4: Precipitation (P) and Effective Precipitation (Pe) in mm/month

P (mm/month)	**Pe (mm/month)**	**P (mm/month)**	**Pe (mm/month)**
0	0	130	79
10	0	140	87
20	2	150	95
30	8	160	103
40	14	170	111
50	20	180	119
60	26	190	127
70	32	200	135
80	39	210	143
90	47	220	151
100	55	230	159
110	63	240	167
120	71	250	175

(Source: FAO, 2012)

Table 3.4 shows the effective precipitation based on the total monthly precipitation. The percentage of effective precipitation was calculated as follows: -

$$Ep\ (\%) = Ep/p * 100 \qquad [Eqn\ 3.11]$$

Where,

Ep (%) is the percentage of effective precipitation

Ep is the monthly effective precipitation

p is total monthly precipitation

Using Table 3.4 and Eqn 3.11 the percentage effective precipitation for each catchment were determined and are as shown on Table 3.5.

Table 3.5: Effective precipitation

MONTH			
	UPPER	MID	LOWER
Jan	40	44	40
Feb	38	36	41
Mar	55	51	46
Apr	57	64	51
May	59	56	52
Jun	58	50	54
Jul	58	48	54
Aug	58	52	48
Sept	54	51	50
Oct	54	52	48
Nov	44	61	44
Dec	42	30	48

3.11.6 Climate data

In this study monthly rainfall data for 1986- 2012 (27 years) were utilized. Figure 3.8 shows the monthly rainfall trend for 1986 to 2012 while figure 3.9 shows the average monthly rainfall for 1986 to 2012.

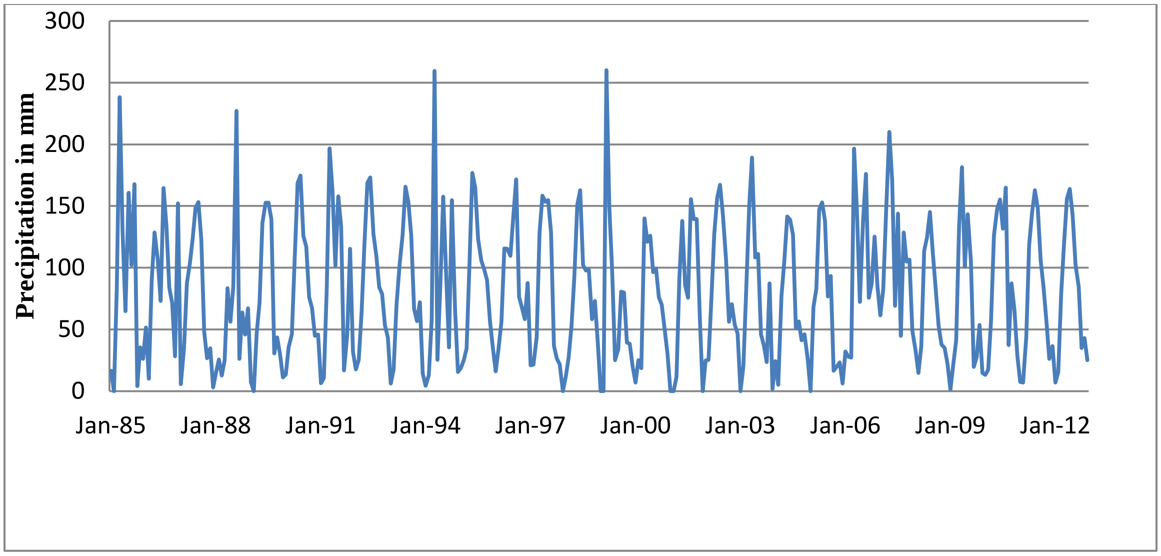

Figure 3.8: Monthly rainfall in Arror River catchment, 1986-2012 using data from Kapsowar rain gauge station obtained from KVDA

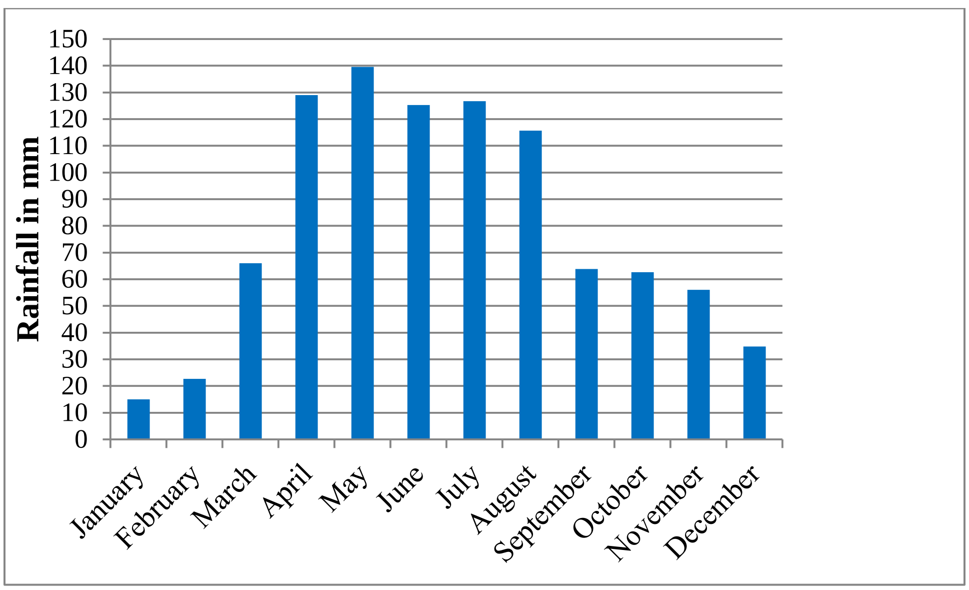

Figure 3.9: Mean monthly rainfall in Arror River catchment, 1986-2012 using data from Kapsowar rain gauge station obtained from KVDA

Since the evaporation data for the study area were not available, ETo calculator was used to obtain the reference evapotranspiration (ETo) of the catchment. ETo calculator is a software developed by the Land and Water Division of FAO. Its main function is to calculate Reference evapotranspiration (ETo) according to FAO standards (Allen *et al.*, 1998).

ETo represents the evapotranspiration rate from a reference surface, not short of water. A large uniform grass field is considered worldwide as the reference surface. The reference crop completely covers the soil, is kept short, well-watered and is actively growing under optimal agronomic conditions. The ETo calculator assesses ETo from meteorological data by means of the FAO Penman-Monteith equation. This method has been selected by FAO because it closely approximates grass ETo at the location evaluated, is physically based, and explicitly incorporates both physiological and aerodynamic parameters (Allen *et al.*, 1998).

The program can handle daily, ten-day and monthly climatic data. The data can be given in a wide variety of units and data specified in commonly used climatic parameters can be processed. When data for some weather variables are missing, procedures are used for estimating missing climatic data from temperature data or from specific climatic conditions according to methodologies outlined in the Irrigation and Drainage Paper No 56 (Allen *et al*., 1998). Even where the dataset contains only maximum and minimum air temperature, it is still possible to obtain reasonable estimates for ten-day or monthly ETo. The study utilized minimum and maximum temperatures to estimate the ETo of the catchment. By selecting appropriate lower and upper limits for meteorological data, the program applies a quality check when specifying or importing data.

3.11.7 Demand Sites

There are three main uses of water in the study area and hence three main demand sites namely; domestic, agriculture, and livestock. Other demand areas are commercial, institutional and industrial but were not included in this analysis. Domestic water use is the most important, it has the highest priority. Second important use is livestock, third is agriculture and the other uses have least priority. Water use activities and rates for all the demand areas identified were then developed.

(i) Domestic Water Use

For domestic use, the annual activity is the total number of people in the study area while the Annual Water Use Rate is the demand per person per year. The population census reports of 1979, 1989, 1999 and 2009 were used for the purpose of estimating the annual activity of the three catchments (Appendix II). The population of the other years was estimated using the projected the intercensal growth rate. The annual use rate was assumed as 25 litres per head per day as specified by the Ministry of Water Development design manual as the demand for rural areas when served by communal water points (Republic of Kenya, 1984; Table 3.6). The domestic consumption, which is the percentage of inflow consumed (lost from the system) was set at 25%. The rest of the water is drained off as surface flow. A large part of this water will evaporate, part will infiltrate in the soil and part will reach the river.

Consumption represents the amount of water that is actually consumed (i.e. is not returned in the form of wastewater). No considerable monthly variation was imposed and the model assumed that it was proportional to the number of days in every month. The main source of the domestic water was the river.

Table 3.6: Rural Water Uses per Household According to Different Sources

Source	**Water use (l/d)**	**Country**
Free University Amsterdam	35-70 l/d	Global estimates
Neijens (2001)	40-100 l/d	Global estimates
Louis Berger International Inc. (1983)	140 l/d	Global estimates
De Bruijn and Rhebergen (2006)	90 l/d	Kenya
MoWI (2005)	40 to 80 l/d	Kenya
Republic of Kenya (1984)	25 l /d	Kenya

(Source: Mugatsia, 2010)

(ii) Livestock Water Use

For livestock, the annual activity is the total number of livestock in the area and the annual water use rate is the average demand per animal per year. The main source of water for livestock in the study area was Arror River. The main animals kept in the study area were cattle, goats, sheep and donkeys. The total number of livestock was approximated from the information obtained through interviews combined with the census data on the number of households (Appendix III). Through the interviews the average number of livestock per household was obtained, this was then multiplied by the number of households as obtained from the census reports of the years of interest. The livestock demand was assumed as 75 litres per day per livestock unit (LSU). LSU can be one grade cattle or three native cattle or fifteen sheep (Republic of Kenya, 1984). Using the information above, the annual use rate was assumed as 75 litres per day per a grade cow, 25 litres a day per a native cow/ donkey and 5 litres a day per goat or sheep. Again no considerable monthly variation was imposed and hence it was assumed to be proportional to the number of days in a month. The livestock consumption was set at 80%.

(iii) Agricultural Water Use

The data on the exact amount of water used for irrigation was not available and farmers did not also know how much water they use for irrigation and therefore irrigation water demand for the watershed was estimated using the reference evapotranspiration (ETo) 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 (Appendix IV) with the average water requirement for the main crops in the watershed (Liu *et al.*, 2009).

The total size of land in square metres under cultivation obtained through interviews of the residents and from the census reports was considered as the Agricultural annual activity. The volume required per square meter was considered as the water use rate. For agriculture the monthly variations were imposed because of the crop coefficients (Kc) that vary throughout the year depending on the crop water requirement at various stages of growth. This value varies from crop to crop and also changes as a crop goes through the different stages of growth.

Monthly variation = (Monthly Kc/Total Kc) *100 [Eqn 3.12]

The water demand per crop was calculated using the following formula:-

$ET_c = \square K_c * ET_o$ [Eqn 3.13]

Where

ET_c - crop evapotranspiration [mm/d],

K_c - crop coefficient [dimensionless],

ET_o - reference crop evapotranspiration [mm/d].

$ET_{crop} \times (1+ \text{losses}) = \text{Water Demand per crop}$

The evapotranspiration rate is normally expressed in millimetres (mm) per unit time. The rate expresses the amount of water lost from a cropped surface in units of water depth. The time unit can be an hour, day, decade, month or even an entire growing period or year. As one hectare has a surface of 10 000 m^2 and 1 mm is equal to 0.001 m, a loss of 1 mm of water corresponds to a loss of 10 m^3 of water per hectare. In other words, 1 mm per day is equivalent to 10 m^3 /ha/ day (Allen *et al*., 1998).

For irrigated agriculture:

Irrigation = Water Demand - Precipitation

Supplies required to meet this demand, were estimated putting into account the conveyance and distribution leakage losses.

3.11.8 Reserve Requirements

The key principles of the Kenya Water Act (2002) are sustainability and equity. The Act emphasizes that, as water resources are used to promote social and economic development, it is crucial 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 therefore, 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.

3.11.9 The river head flow

The streamflow output from SWAT was used as the head flow input. Head flow in WEAP represents the average inflow to the first node on a river.

Having prepared all the data required, the WEAP model was built and calibrated before exploring the various scenarios. Figure 3.10 and 3.11 show the schematic and data views of the WEAP model developed for Arror river catchment.

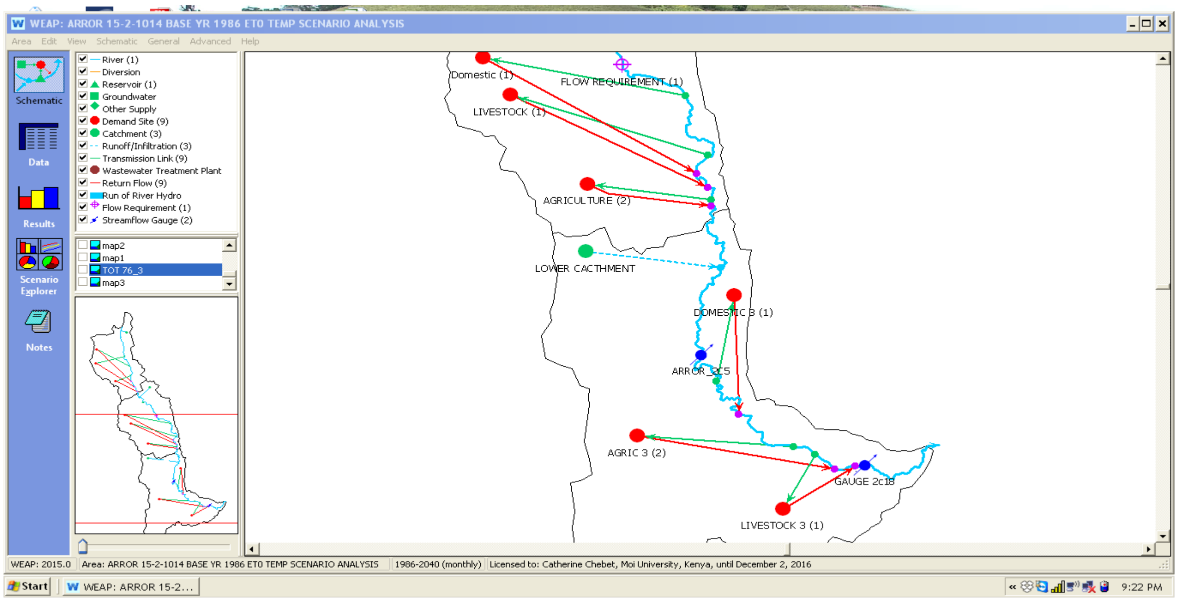

Figure 3.10: Schematic view of the model representing Arror watershed.

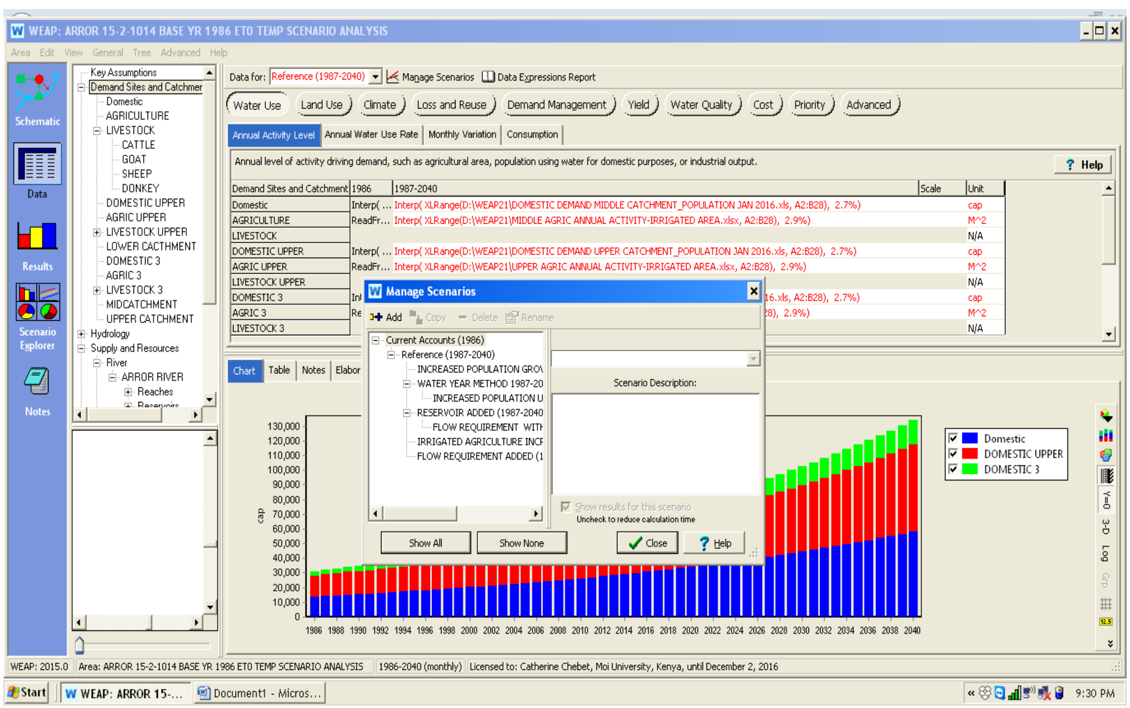

Figure 3.11: The data view of the Arror watershed WEAP model.

3.11.10 Calibration and Validation of the WEAP Model

After setting up the WEAP model, calibration had to be undertaken before exploring the various scenarios. Calibration was done by using the data for the current scenario and comparing WEAP output to the observed situation that is, the actual discharge data.

Proper model calibration is important in hydrologic modeling studies to reduce uncertainty in model simulations (Engel *et al.,* 2007). Before calibration, sensitivity analysis was performed. Sensitivity analysis is the process of determining the rate of change in model output with respect to changes in model inputs (parameters). It is a necessary process to identify key parameters and parameter precision required for calibration (Ma *et al*., 2000). Effective precipitation and Kc were identified as the parameters to be modified during calibration.

Model calibration is the process of estimating model parameters by comparing model predictions (output) for a given set of assumed conditions with observed data for the same conditions. It is a procedure where parameter values are adjusted so as to achieve an optimal fit of the model output to the corresponding measurement. Calibration procedures in hydrological modelling usually aim to fit simulated data to observed data from gauging stations. It aims at minimizing the difference between simulated and observed stream flows. However, variations between the model and observed data are always expected. The land use factors (effective precipitation and Kc-factors) were modified. Effective precipitation was increased by between 10 to 20 %, by trial and error.

Model calibration was then followed by model validation in order to assess the performance of the model. According to Refsgaard (1997), model validation is the process of demonstrating that a given site-specific model is capable of making sufficiently accurate simulations. Model validation involves running a model using input parameters measured or determined during the calibration process. An obvious validation is first made by comparing graphically the simulated values with the observed values. Graphical techniques provide a visual comparison of simulated and measured constituent data and a first overview of model performance (ASCE, 1993). According to Legates and McCabe (1999), graphical techniques are essential to appropriate model evaluation.

A hydrograph is a time series plot of predicted and measured flow throughout the calibration and validation periods. In most watershed modeling projects, model output is compared to corresponding measured data with the assumption that all error variance is contained within the predicted values and that observed values are error free (Harmel *et al.*, 2006).

According to the United States Environmental Protection Agency (2002), the process used to accept, reject, or qualify model results should be established and documented before beginning model evaluation. A good calibration procedure uses multiple statistics, each covering a different aspect of the hydrograph, so that the whole hydrograph is covered. This is important because using a single statistic can lead to undue emphasis on matching one aspect of the hydrograph at the expense of other aspects (Boyle *et al.*, 2000). For manual calibration, each statistic should be tracked while adjusting model parameters (Boyle et al., 2000) to allow for balancing the trade-offs in the ability of the model to simulate various aspects of the hydrograph while recognizing potential errors in the observed data.

The model performance was evaluated using standard statistics; mean error (ME), mean square error (MSE) and model coefficient of efficiency (EF) also known as NSE and R-squared as described by the equations below.

$$E_Q = Q_m - Q_o \qquad \text{(Model residual)}$$

[Eqn 3.14]

$$MSE = \sum_{i=1}^{n} \frac{(Q_m(i) - Q_o(i))^2}{n} = \sum_{i=1}^{n} \frac{(E_Q(i))^2}{n}$$

[Eqn 3.15]

$$ME = \overline{E}_Q = \sum_{i=1}^{n} \frac{Q_m(i) - Q_o(i)}{n} = \sum_{i=1}^{n} \frac{E_Q(i)}{n}$$

[Eqn 3.16]

$$EF = \left[1 - \frac{\sum_{i=1}^{n} (Q_m(i) - Q_o(i))^2}{\sum_{i=1}^{n} \left(Q_o(i) - \overline{Q_o}\right)^2} \right] = \left[1 - \frac{MSE}{S_{Q_o}^2} \right]$$

[Eqn 3.17]

Where

Qo - observed flow

Qm – simulated flow

ME - Mean Error

MSE - Mean Squared Error

EF- Model Efficiency Coefficient

n- The number of data points

s- Variance (squared standard deviation)

The formula for r-squared is:

Goodness of fit, R^2: $$R^2 = \left[\frac{\sum_{i=1}^{N} \left(o_i - \bar{o} \right)\left(s_i - \bar{s} \right)}{\sqrt{\sum_{i=1}^{N} \left(o_i - \bar{o} \right)^2} \sqrt{\sum_{i=1}^{N} \left(s_i - \bar{s} \right)^2}} \right]^2$$ [Eqn 3.18]

Where

o_i - Observed flows

$\bar{o}$ - Mean of observed flows

s_i - Simulated flows

$\bar{s}$ -Mean of the simulated flows

The *ME* and *MSE* reflect the bias or systematic deviation in the model results and the random error after correction. They have the disadvantage that their magnitudes highly depend on the low magnitude, and thus on the river under study. The model efficiency coefficient (*EF/NSE)* of Nash and Sutcliffe (1970), which is a dimensionless and scaled version of the *MSE* for which the values range between 0 and 1 (0 or 1 for a perfect model) gives a much clearer evaluation of the model results and performance. In general, model simulation can be said to be satisfactory, if EF/NSE > 0.50 (Moriasi *et al*, 2012).

Coefficient of determination (R^2) also known as the prediction efficiency (Pe), is calculated by regressing the rank (descending) of observed versus simulated constituent values for a given time step. It determines how well the probability distributions of simulated and observed data fit each other (Santhi *et al*., 2001).

3.11.11 Scenarios

Scenarios in WEAP encompass any factor that can change over time for example population, land use, climate among others, including those factors that may change because of particular policy interventions, and those that reflect different socio-economic assumptions.

Scenarios include:

1) A 'base case' understanding of current (1986 level) demands, supplies, and operations under normal (historical average flow) and critical dry year river conditions. The Reference scenario is the scenario in which the current situation, current account year was 1986 is extended to the 'future' (1987-2012).
2) The other scenarios that were considered were to address a broad range of 'what if' questions, such as:
    a) What if population growth patterns change?
    b) What if ecosystem requirements are tightened? That is maintenance of the minimum environmental flows
    c) What if the cultivated area is increased?
    d) What if reservoirs are constructed?

The water demand, unmet demands and demand coverage for the various water uses were then compared for the different scenarios with an aim of proposing the most effective watershed management practices for the study area. The discharge yielded from the various scenarios was also compared so as to determine the impact of each one of them on the river flows.

3.11.12 Water Year Method in WEAP

According to WEAP software the water year method allows use of historical data in a simplified form and exploration of the effects of future changes in hydrological patterns. The water year method also can be used to test the system under historic or hypothetical drought conditions, so climate changes will be more understood and can be presented in one scenario but not used in reference scenario. Hydrologic fluctuations are entered as variations from a normal water year (The Current account year is not necessarily normal water year). The water year method requires data for defining standard types of water years (water year definitions), as well as defining the sequence of these years for a given set of scenarios (water year sequence). A water year type characterizes the hydrological conditions over the period of one year. The five types that WEAP uses are: Normal, Very Wet, Wet, Dry and Very Dry. The rainbow model was used to obtain the historical pattern which was used to derive historical rainfall series.

3.12 GPS and Observation

Observation method was employed in the identification of the various human activities, watershed management strategies and environmental degradation. The researcher also identified and took the coordinates of the locations of important points such as the gauging stations, meteorological stations, among others using the GPS. GPS were also used during ground-truthing to verify the features that were not clear on the satellite images and to accurately locate significant features on the ground. Supportive evidence phenomena and features were photographed during the observation and the entire period of the study.

CHAPTER FOUR

RESULTS

4.1 Introduction

This chapter presents the findings of this study. The study sought to assess the impacts of land use changes in Arror watershed on the river flows in the period 1986-2012 using SWAT model; Assess the water demand and its impacts on river discharge in Arror River watershed and evaluate management practices for sustainable management of the watershed using SWAT and WEAP models. Of the 646 questionnaires that were issued, 595 were filled and returned. This yielded a response rate of 92% which was considered ideal for drawing inferences.

4.2 Socio-Economic Characteristics

The socio-economic factors that were considered are shown in Table 4.1. The results showed that there were more male headed households than those headed by their female counterparts. More than one-third of the household heads had primary level of education. However, Tirap and Kapsowar divisions had the highest respondents with University education (10.5% vs. 12%) as compared to Kapyego and Tunyo (3.6% vs. 6.1%), respectively. Almost 10% of the respondents in this region had never attended any formal education. Kapsowar and Tunyo household heads had the longest mean length of stay in the area (27.4 vs. 26.3) years, respectively. More than half of the respondents from Kapsowar, Kapyego and Tirap (56.8%, 58.7% and 73.7%) reported to be farmers and approximately a quarter of respondents reported to be civil servants by occupation. Majority of the respondents were within the 18-36 years age group (Table 4.1). The results on education show that most of the respondents have only basic education and this makes it difficult for them to get formal employment and thus resort to farming. It also shows that their level of understanding and adopting new methods of watershed conservation and management is quite low.

Table 4.1: Summary of the socio-economic characteristics of households

Household characteristics	**Description**	**Kapsowar**	**Kapyego**	**Tirap**	**Tunyo**
Gender	Male	201(58.9)	102 (61.1)	7 (36.8)	44 (66.7)
	Female	140 (41.1)	65 (38.9)	12 (63.2)	22 (33.3)
Education level of respondents	Never went to school	40 (11.7)	19 (11.4)	1 (5.3)	6 (9.1)
	Primary	118 (34.6)	57 (34.1)	8 (42.1)	17 (25.8)
	Secondary	58 (17.0)	57 (34.1)	4 (21.1)	16 (24.2)
	Tertiary	84 (24.6)	28 (16.8)	4 (21.1)	23 (34.9)
	University	41 (12.0)	6 (3.6)	2 (10.5)	4 (6.1)
Age category (yrs)	18-36	136 (40.0)	92 (55.4)	14 (73.7)	37 (56.9)
	37-54	152 (44.7)	58 (34.9)	3 (15.8)	22 (33.9)
	>54	52 (15.3)	16 (9.6)	2 (10.5)	6 (9.2)
Occupation	Farmer	193 (56.8)	98 (58.7)	14 (73.7)	32 (48.5)
	Civil servants	110 (32.4)	34 (20.4)	4 (21.1)	20 (30.3)
	Business	18 (5.3)	12 (7.2)	1 (5.3)	2 (3.0)
	Other	19 (5.6)	23 (13.8)	0 (0.0)	12 (18.2)
Mean length of stay in the area	mean length(yrs)	27.4	25.7	21.4	26.3

Other household characteristics that were considered in the study were the size of land owned by a household, the amount and the source of water used by the household in the study area among other characteristics as illustrated in Table 4.2. some of these results were part of the inputs of the two models used.

Table 4.2: Summary of selected household characteristics

Characteristic		**(%), mean/median**
Average size of a household, mean(sd)	6.81,	(SD=5.76)
Average amount of water used per day in the household, mean(sd)	104,	(SD=59.82)
Average area cultivated under rain fed agriculture, median(acres)		1.5
Average area under irrigated agriculture, mean(acres)		0.32
Proportion of households who identified river as the main source of water use		42.7
Proportion of households who reported main purpose of farming being subsistence and commercial		71.5
Proportion of households reporting irrigation water as enough throughout the year		35.6

Overall, one-third of the study population reported to be practicing arable and livestock farming and only a slight proportion (3.2%) were bee keeping farmers (Table 4.3). These findings inform the study on how the residents of Arror watershed utilize water. Furthermore, this informs on how the land in the watershed is being used so as to propose the management practices that should be put in place so that the negative impacts of these activities are minimized.

Table 4.3: Types of farming practiced in the study area

Type of farming	Frequency	Percentage
Arable and livestock farming	215	36.2
Arable farming	49	8.3
Livestock keeping	31	5.2
Bee keeping	19	3.2

Note: Percentages do not add up to 100% because respondents mentioned more than one response

The study also sought to establish the source of irrigation water in the study area and more than 90% of the respondents reported river water as the main source (Plate 4.1). The average land under rain fed and irrigated agriculture were 1.7 and 0.32 acres per household respectively. The major crop identified to be under irrigation across all the regions was vegetables. However, Tunyo division had millet and maize being the leading crops under irrigation in this area. Most of the household heads (71.3%) reported to be practicing both subsistence and commercial farming in this area.

Plate 4.1: One of the pipe that was used to supply water to the farms located downstream

(Source: Author, 2015)

4.3 The land use /land cover maps

The land use /land cover maps for 1986, 2000 and 2012 that were incorporated in SWAT and WEAP models were developed as illustrated in chapter three and the maps are as shown in Figures 4.1, 4.2 and 4.3.

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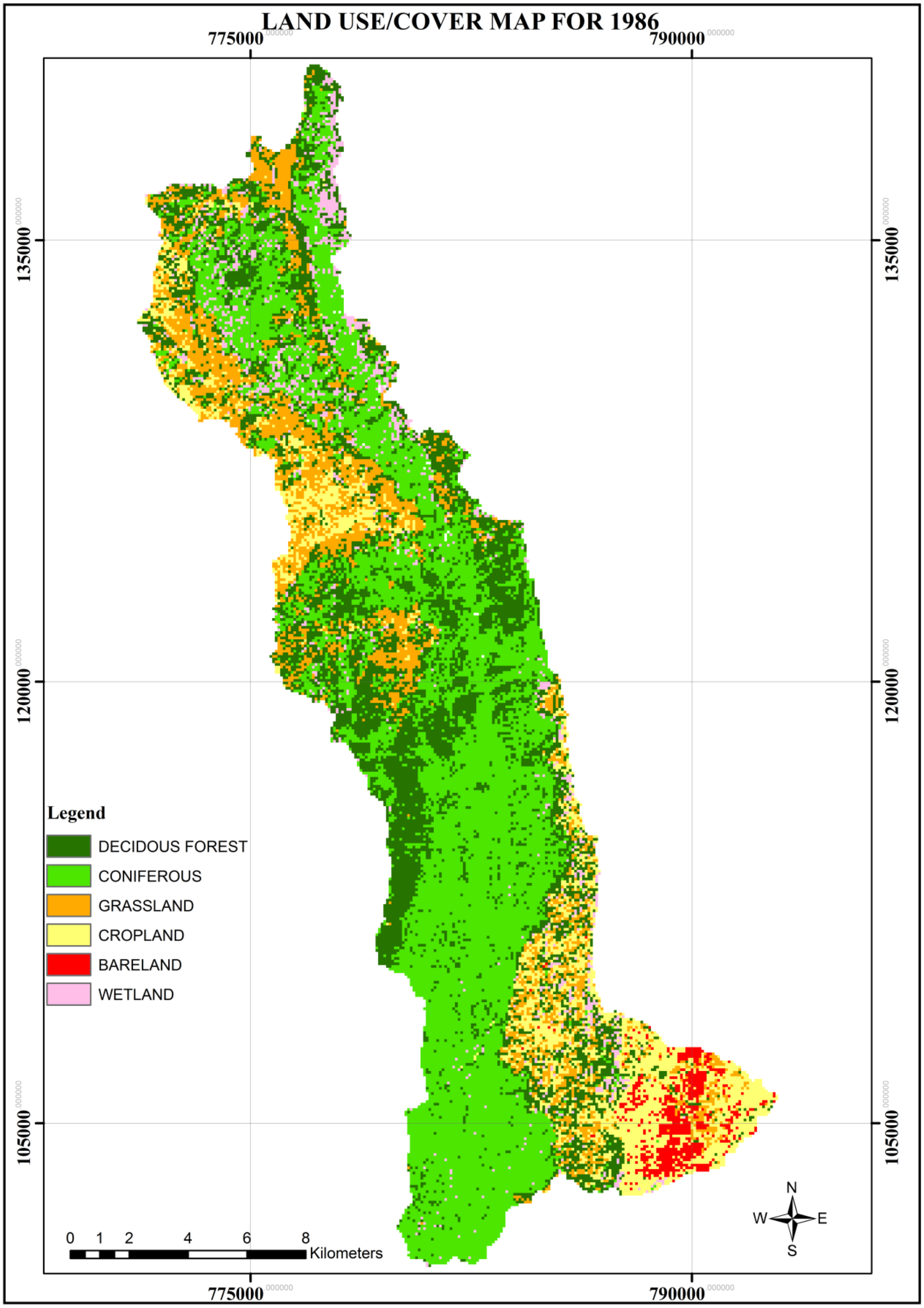

Figure 4.1: Land cover map of 1986 derived from Landsat 5 Thematic Mapper (bands 4, 3, 2)

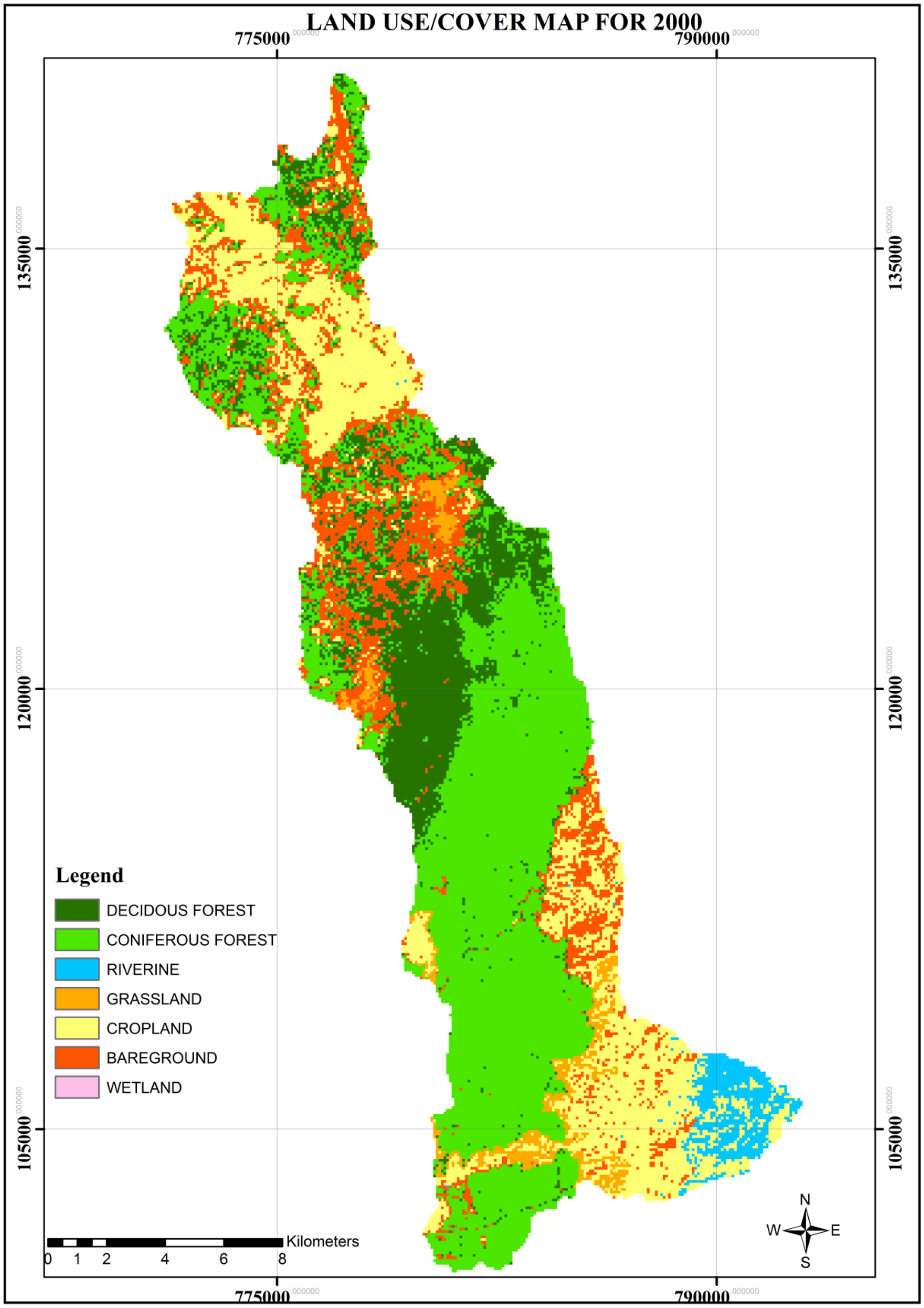

Figure 4.2: Land cover map of 2000 derived from Landsat 7 Enhanced Thematic Mapper (bands 4, 3, 2)

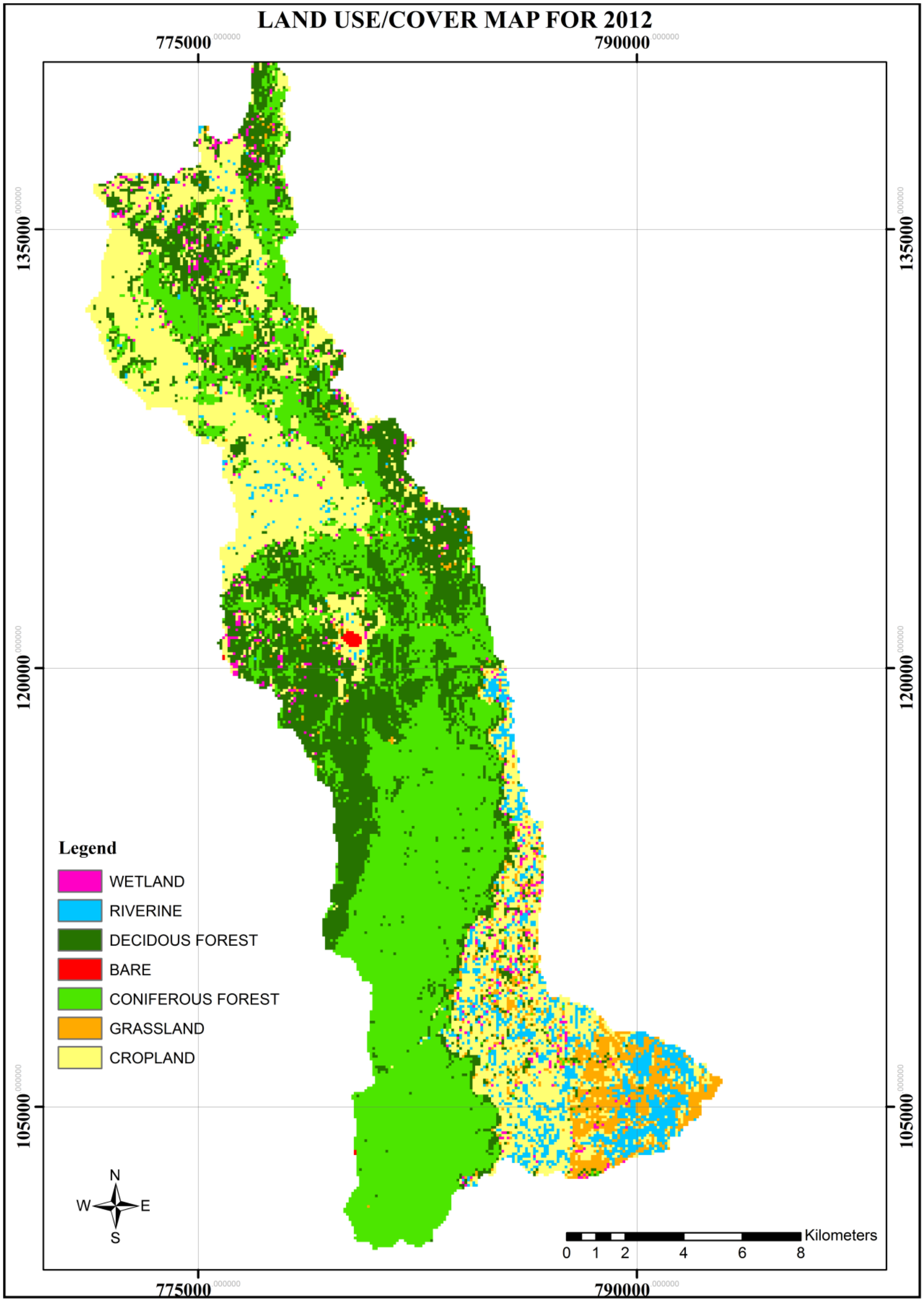

Figure 4.3: Land cover map of 2012 derived from Landsat 7 Enhanced Thematic Mapper (bands 4,3,2)

Table 4.4: Land cover classes in square kilometers for 1986, 2000 and 2012

Land cover classes	1986 Area in km^2	2000 Area in km^2	2012 Area in km^2
Deciduous forest/indigenous	76	44.2	67.9
Coniferous forest	120.6	117.0	109.2
Grassland	36.7	8.5	13.2
Bare ground	5.7	45.1	0.3
Wetland	14.1	0.1	5.1
Riverine vegetation	0.0	7.8	16.8
Crop land	31.9	62.4	72.5
Total	**285**	**285**	**285**

Table 4.4 shows the area covered by the various land uses/cover while Table 4.5 shows the various percentage land cover/use for 1986, 2000 and 2012. In the three years, forest had the highest percentage cover followed by crop land except for 1986 where grassland covered more area than cropland.

Table 4.5: Percentage land cover/ use for 1986, 2000 and 2012

Land cover classes	1986 January	2000 January	2012 January
Deciduous	26.67%	15.52%	23.8%
Coniferous	42.3%	41.04%	38.3%
Bare ground	2.01%	15.83%	0.1%
Grassland	12.87%	2.98%	4.6%
Wetland	4.96%	0.02%	1.8%
Ridge vegetation	0%	18.02%	5.9%
Crop land	11.19%	21.88%	25.4%

(Source: Author, 2015)

4.4 The impact of land use changes in Arror watershed on river flows using the SWAT model

From the GIS land use/cover analysis it was found that various changes had occurred within the study area as the classes representing the training sites change from one class to another or even show reduction in terms of area and percentage cover over the period. The change analysis was done using the year 1986 as the base year, and the year 2012 as the final year. It was found that major changes had occurred in the forest cover both the deciduous forest cover and coniferous forest over the period of twenty six years considered.

There was a decrease of 1.26% in the coniferous forest cover between the years 1986 to 2000 which is then followed with a decrease of 4.06% in the year 2012. Deciduous forest cover decreased with 11.15% between 1986 and 2000 and increased with 8.28% in 2012, this translates to 2.87% decrease for the 26 years' time period (Table 4.7).

Gradual increase trend is evident in the crop land cover due to increased agricultural activities mostly farming in the area of study; more demand for food due to population increase can be attributed to this gradual trend. Between the year 1986 and 2000 a total of 30.5 km^2 had been converted to crop land translating to 10.69% change, a further increase of 3.52% was realized in 2012. A decrease in wetland of 4.94% (14 km^2) from the year 1986 to 2000 is evident in the study area. There was a decrease of 9.86% in grassland in the period 1986-2000 and an increase of 1.62% in the period 2000 -2012.

4.4.1 Causes of changes in Arror River according to the residents of the catchment

As clearly depicted in the land use/cover analysis, there have been a lot of changes in Arror catchment. The respondents were asked about what they think could be causes of changes in the region and the main causes mentioned were; cutting of trees (58%), encroachment (51%), cultivation along the river banks (43%) and the least mentioned was overgrazing (20%) as shown in Figure 4.4. This explains the decrease of both deciduous and coniferous forests during the period 1986-2012.

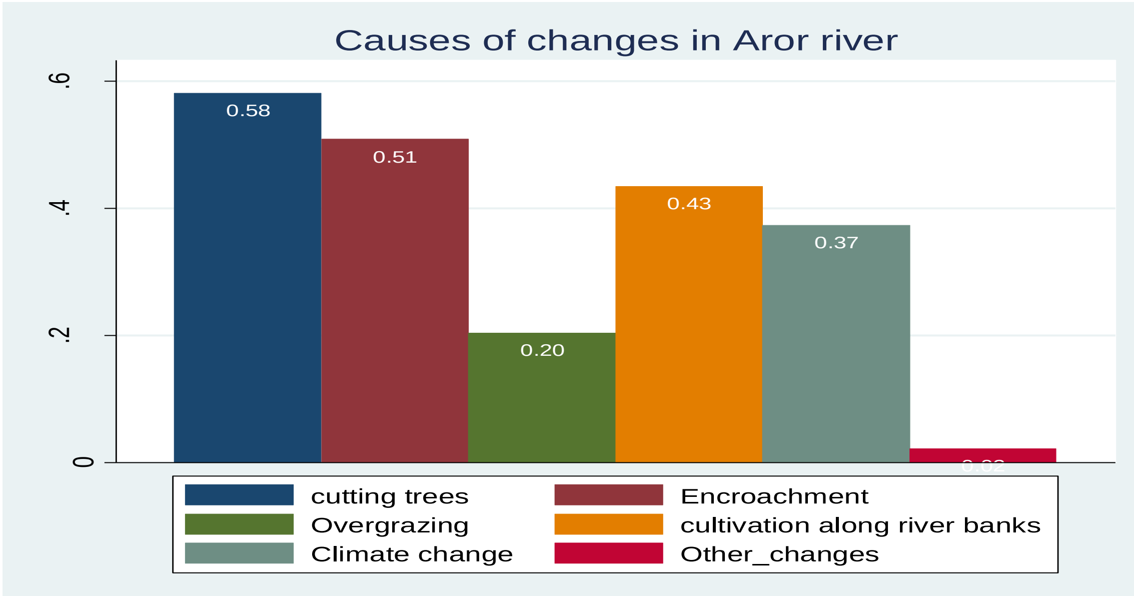

Figure 4.4: Main causes of changes in Arror River

SWAT model calibration results

The SWAT model was used to assess the impact of land use on Arror river discharge. The model had to be calibrated as illustrated in chapter 3 and the results are as shown in Figure 4.5, Table 4.6 and Appendix V

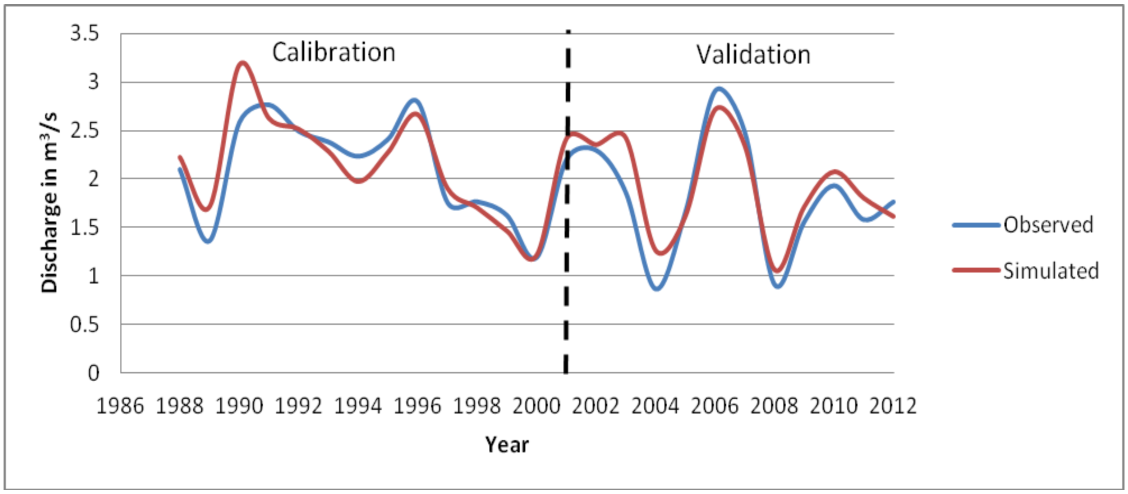

Figure 4.5: Annual observed vs. simulation discharge

Table 4.6: Results showing calibration and validation performance

Arror river outlet discharge

	Calibration	**Validation**
R^2	0.81	0.81
NSE	0.86	0.82

The results of the R^2 and the NSE above show that the model is not perfect but can provide a good estimate (Table 4.6). Having evaluated the model, it was then used to assess the impact of the changes in land use on the Arror river flows.

4.4.2 The impact of land use on stream flows of Arror River

Table 4.7: Percentage change in land use for the period 1986-2012

Land use	1986 – 2000(%)	2000- 2012(%)	1986-2012(%)
Deciduous	-11.15	8.28	-2.8
Coniferous	-1.26	-2.74	-4.0
Grassland	-9.89	1.64	-8.3
Agriculture	10.69	3.56	14.3
Bare ground	13.82	-15.72	-1.9
Wetland	-4.94	1.77	-3.2
Ridge/riverine	2.73	3.18	5.9

Table 4.7 above shows percentage changes in land cover in Arror catchment over 26 years period. This reveals the extent of changes between of 1986 - 2000, 2000 - 2012 and 1986 - 2012. In general, there is increase in the proportion of agricultural land over the years. This has been occasioned by the reduction of forest, grass and bare lands to provide space for farming. This can be attributed to the increase in population and subsequently the demand for food, leading to increased farming activities.

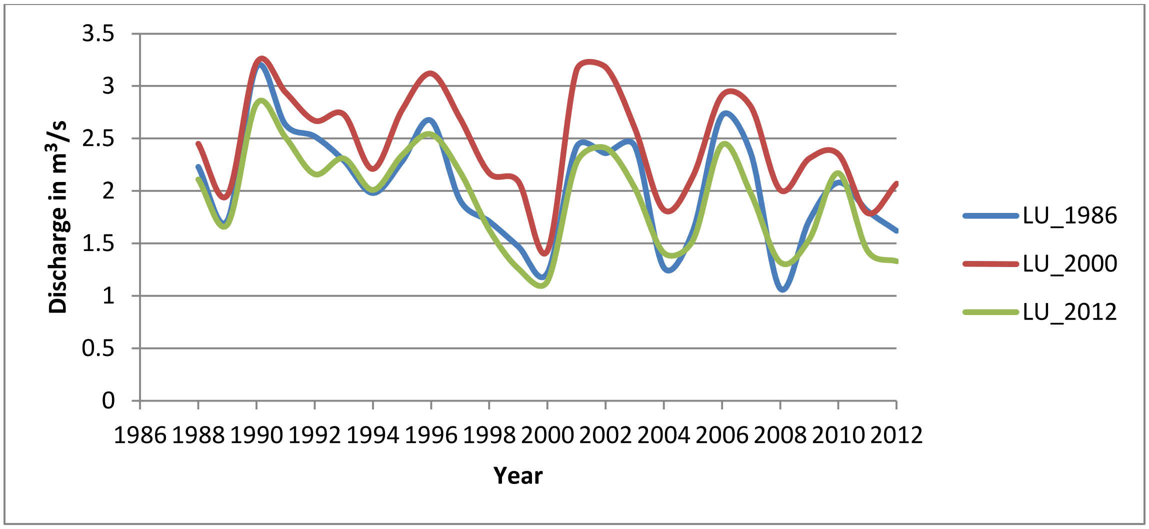

Figure 4.6: Simulated Arror River flows for 1986, 2000 and 2012

The change in land use, over a period of time, has had an impact on the hydrological processes in the catchment. This is confirmed and explained by the varying amount of water flow from the catchment in the 3 year regimes. With land use activities held constant over a period of time, the climate data applied yielded various results. The 1986 land use yielded an average of 2.04 m^3/s, 2000 yielded 2.46 m^3/s and 2012 yielded 1.94 m^3/s. The variation in flow is attributed to mainly land use changes. The increase of discharge flow in the year 2000 could be as a result of deforestation and rendering the land bare thus increasing runoff at critical areas of the catchment. From the results also it can be noted that the year 2000 posted high peaks and has the lowest forest cover (Figure 4.6; Appendix VI).

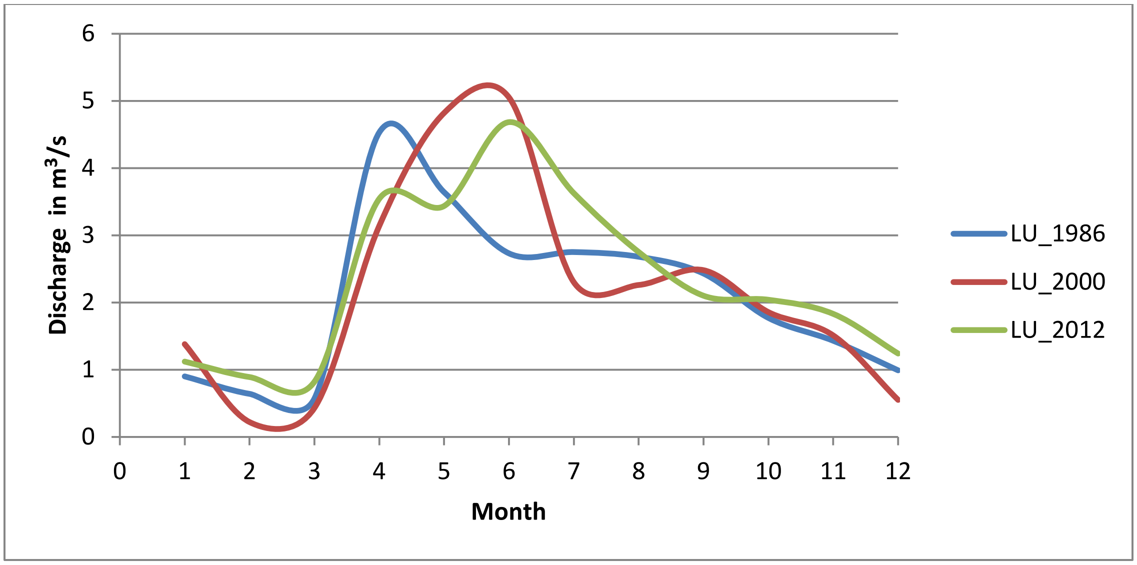

Figure 4.7: Average monthly flows for 3 regimes i.e. 1986, 2000 and 2012

The average monthly flows for the three regimes based on the actual land use and climate for those particular years are shown on Figure 4.7. The results show that the flows follow the same trend with the lowest flows at the beginning of the year, and the peak in the mid-year and lower towards the end of the year. It can be noted also that the peak has been shifting towards the right over time with 1986, 2000 and 2012 having their peaks in April, May and June, respectively. This shows that the seasons of the year have been changing and if the changes continue at the same rate there will be great alteration of the seasons in future. This can be attributed to changes in land use and land cover as well as climate change to some extent.

4.5 Assessment of water demand in Arror watershed using WEAP

The water demand was analysed in a Decision Support System (DSS) based on Water Evaluation and Planning System (WEAP). The WEAP model had to be calibrated and validated before any analysis was carried out.

4.5.1 Calibration and validation results of the WEAP model

The observed discharge for the period 1986 to 1999 were used to calibrate the model, and 2000 to 2012 for validation. The results presented in Figure 4.10 indicate that the model is able to predict the general trend of the catchment processes. However, this result was obtained after variation of land use factors that is, the Kc and Effective Precipitation.

The analysis was done using the data in Appendix VII and the results are as shown in Table 4.8 where the ME is -0.00, the MSE is 0.03 and the EF was found as 0.85. The ME, MSE and the EF indicate that the model is good. R-Squared is another statistical measure of how well a regression line approximates real data points; an R-squared of 1.0 (100%) indicates a perfect fit. Figures 4.8 and 4.9 show the goodness of fit and the R-squared values for calibration and validation, respectively and they indicate that the model is good and can be used to simulate the study area.

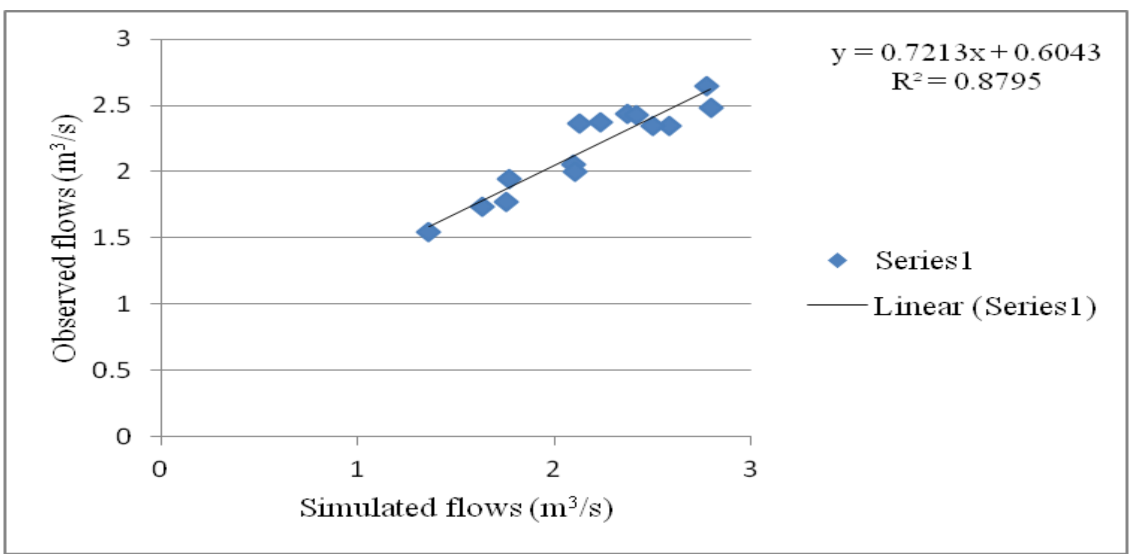

Figure 4.8: Goodness of fit for observed and simulated discharge (1986-1999)-Calibration

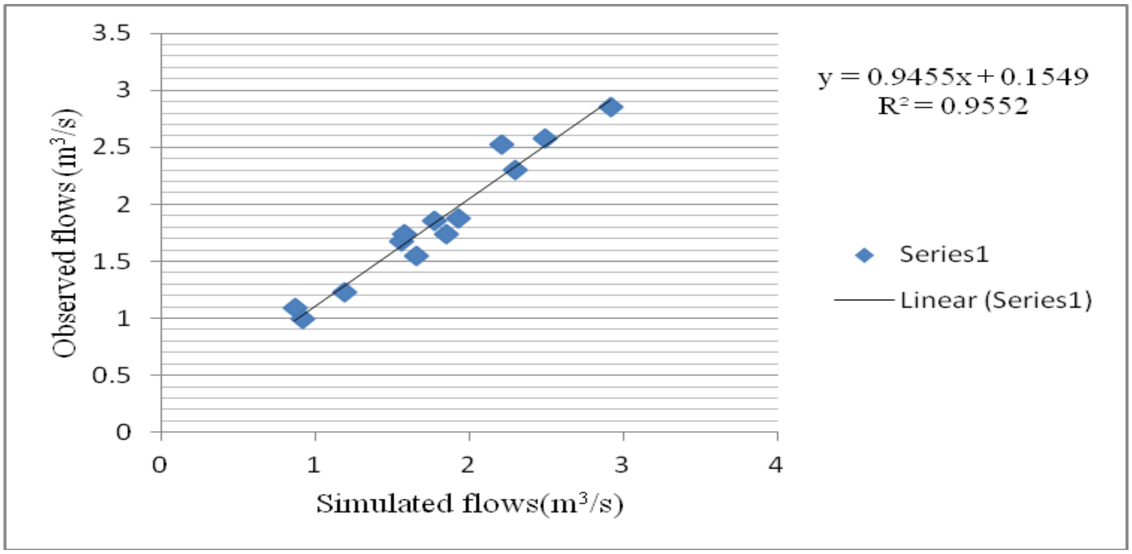

Figure 4.9: Goodness of fit for observed and simulated discharge (2000-2012)-validation

Table 4.8: Statistical analysis of the performance of river flows in Arror river

	ME (Fraction)	MSE (Fraction)	R^2 (Fraction)	NSE (Fraction)
Optimum	0.00	0.00	1.00	1.00
Calibration(1986-1999)	-0.00	0.03	0.88	0.85
Validation (2000-2012)	0.06	0.02	0.96	0.95
Range	≤ 0	≤ 0	$0 - 1$	$-\infty - 1$

ME: Mean error; MSE: Mean squared error; NSE: Nash-sutcliffe Model efficiency coefficient; R^2 goodness of fit.

In Figure 4.10, the time series shows the observed stream flows and the simulated stream flows of the reference scenario. The graph shows that the simulated flows follow the trend of the observed flows.

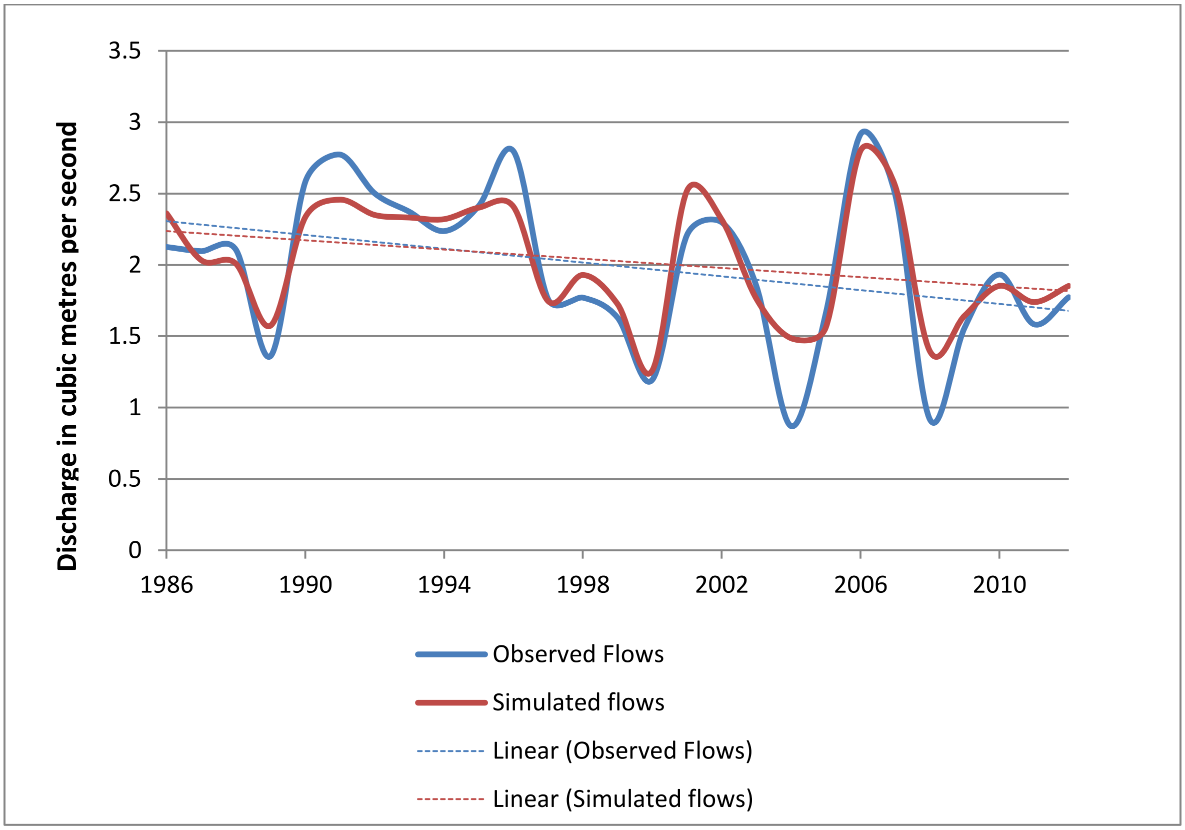

Figure 4.10: Mean annual discharge (1986-2012)

4.5.2 Scenario analysis

Scenario analysis enables the answering of 'what if' questions in a water system. The reference (business as usual scenario) is the base scenario that uses the actual data, to help in understanding the best estimates about the studied period. The objective of a reference scenario is to bring an understanding of the current trend and what could likely occur if current trend continued. Other scenarios are built on this reference scenario with variations on the demand or supply side.

(i) Reference Scenario

The Reference scenario is the scenario in which the current situation is extended to the 'future' (1987-2040). No major changes are imposed in this scenario. The current account year was 1986. A linear population increase was assumed based on the Central Bureau of Statistics reports (Republic of Kenya, 2010a). The model mimics reality over the period 1987 to 2040, given the constraints of simplification of the model and data limitations. This scenario was used to analyse the water allocations, the unmet demands and the demand coverage in Arror watershed.

a) Water allocation in the watershed

The demand sites that were considered were domestic, agriculture and livestock given that these are the major uses of water in the catchment. Agriculture and livestock keeping are the main economic activities in the study area. The upper and mid catchments depend mainly on rain fed agriculture while the lower catchment farmers depend on irrigation since rainfall there is quite erratic and scarce. In the whole catchment a large amount of water is utilized for agriculture followed by livestock and the least is domestic (Figure 4.11).

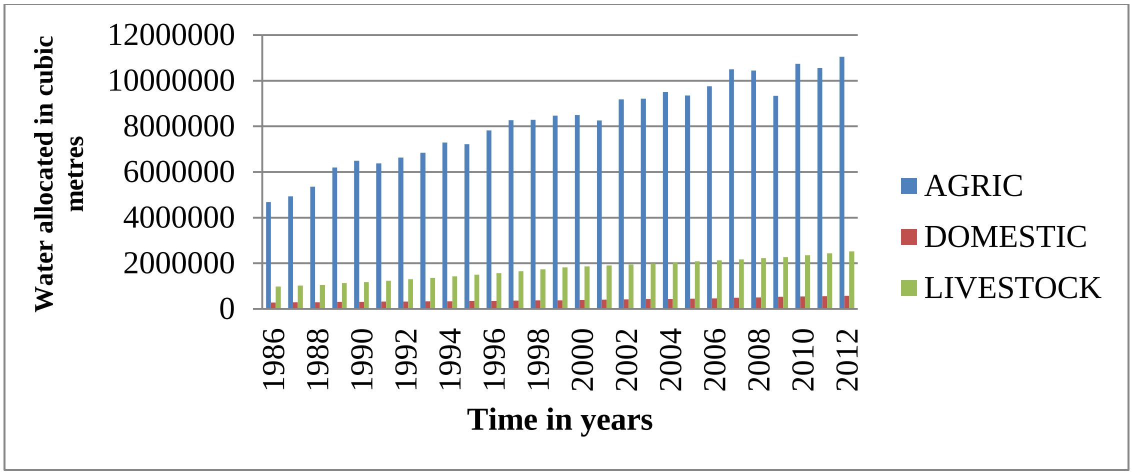

Figure 4.11: Annual total water allocation.

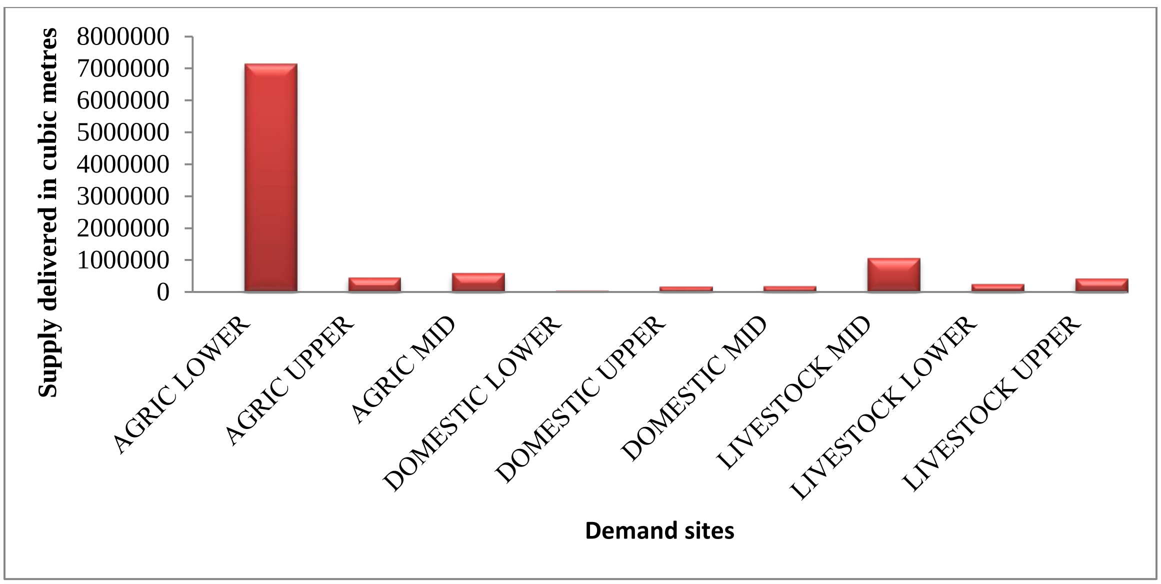

Figure 4.12: Average annual water allocation 1986-2012.

The mean annual water allocation over the period 1986-2012 showed that agricultre demand site in the lower catchment was allocated the highest amount of water (Figure 4.12 and Table 4.9). The total annual allocations also shows agriculture in the lower catchment taking the highest portion in all the 27 years (Figure 4.13).

Table 4.9: Average annual water allocation 1986-2012

Demand sites	Supply delivered in m^3
AGRIC LOWER	7154457
AGRIC UPPER	455810
AGRIC MID	583781
DOMESTIC LOWER	42225
DOMESTIC UPPER	177445
DOMESTIC MID	182048
LIVESTOCK MID	1064483
LIVESTOCK LOWER	254811
LIVESTOCK UPPER	418381

b) Demand coverage and unmet demand

The results for the reference scenario on the water demand and unmet demand are shown in Figures 4.13 to 4.21

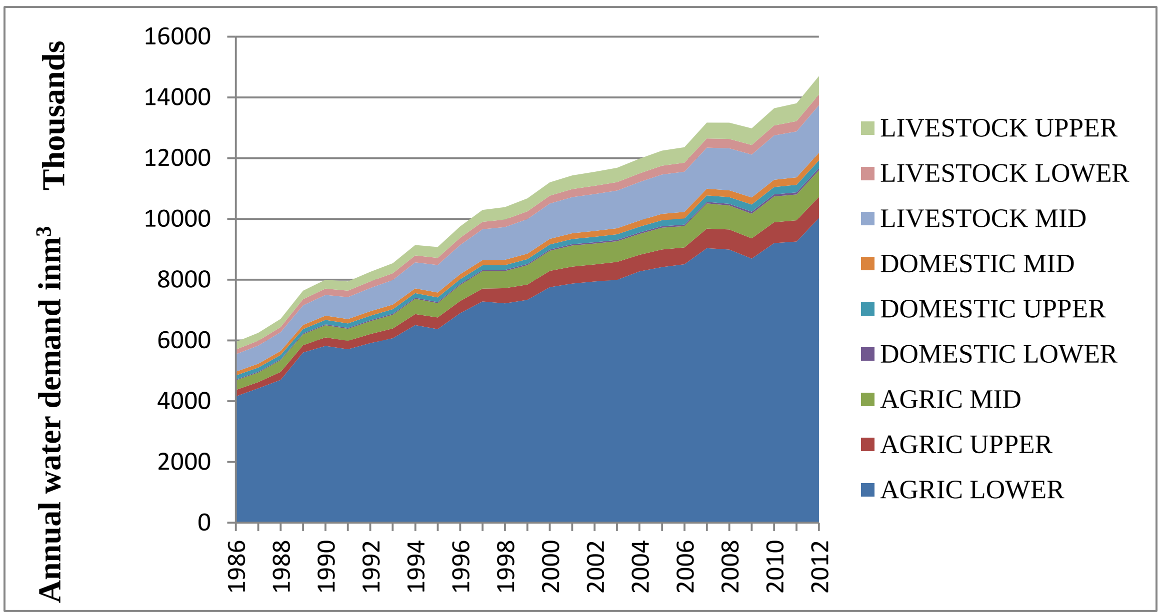

Figure 4.13: Reference Scenario1986 to 2012: Annual Water Demand

The annual water demands for the reference scenario (1986-2012) shows that the demand for water by the various uses in the three sub-catchments has been increasing steadily over time. For the upper and the lower sub-catchments the highest demand was for agriculture with a mean annual demand of 468,055 m^3 and 7,254,685 m^3 respectively while for the middle catchment livestock displayed the highest demand compared to the rest of the demand sites with annual mean of 1,064,483 m^3. Domestic demand was the lowest in all the three sub-catchments with a mean annual 177,445 m^3, 182, 048 m^3 and 42,225 m^3 for the upper, middle and lower sub-catchments, respectively (Figure 4.13).

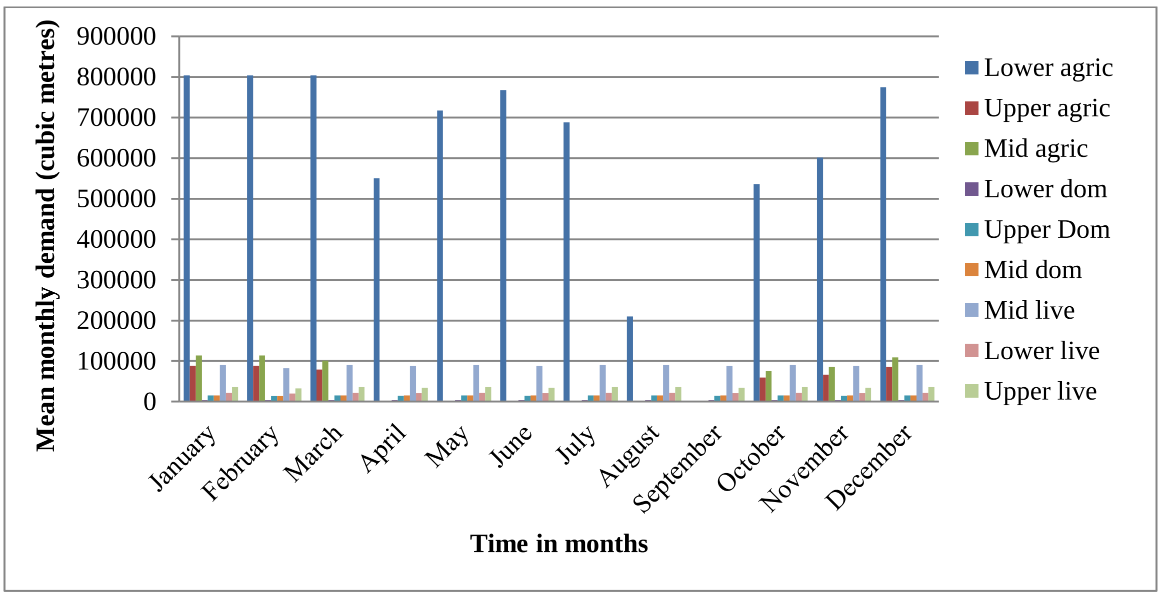

Figure 4.14: Reference scenario 1986-2012: Mean monthly water demand per sub-catchments

Figure 4.14 shows that the average monthly demand for agriculture for the lower sub-catchment was the highest in most months of the year as compared to other demand sites.

The lowest demand for the lower sub-catchment agriculture was posted in the months of August and September (209,975 m^3 and 104,345 m^3). The rest of the demand sites did not show substantial variation throughout the year.

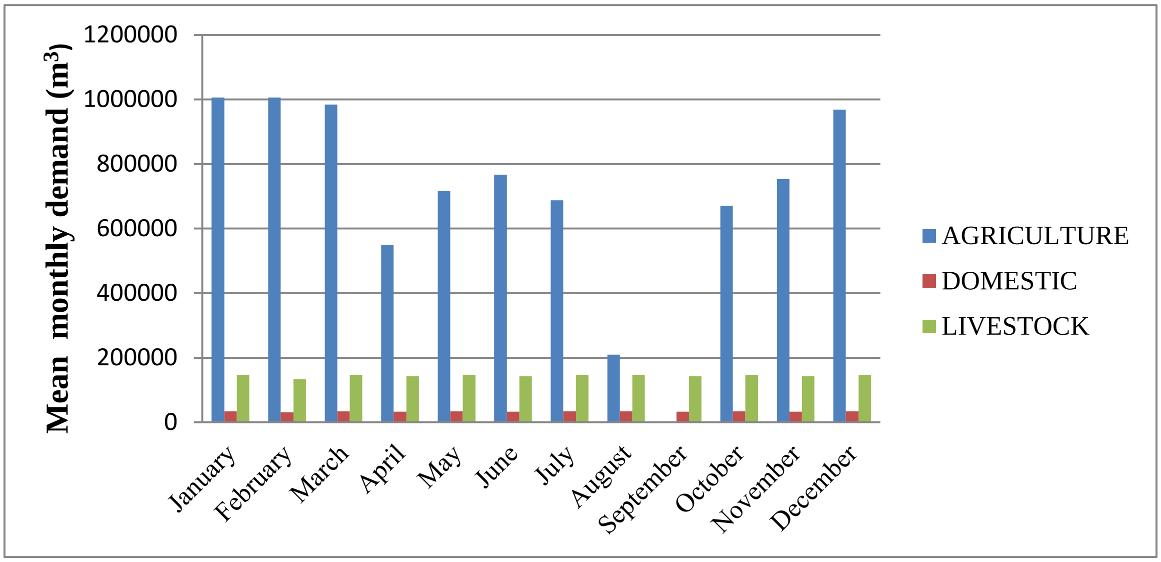

Figure 4.15: Reference scenario 1986-2012: Mean monthly water demand for the whole catchment

The average monthly demands for the entire catchment for the three major demand sites that is agriculture, livestock and domestic are shown on figure 4.15. The results show clearly that on average, agriculture is the main consumer of water throughout the year in Arror watershed with mean monthly demand of 604,557 m^3, 49,915 m^3 and 39,005 m^3 for the lower, middle and upper sub-catchment, respectively. It also shows that the highest demands for agriculture are in January, February, March and December which coincides with the dry season in the area.

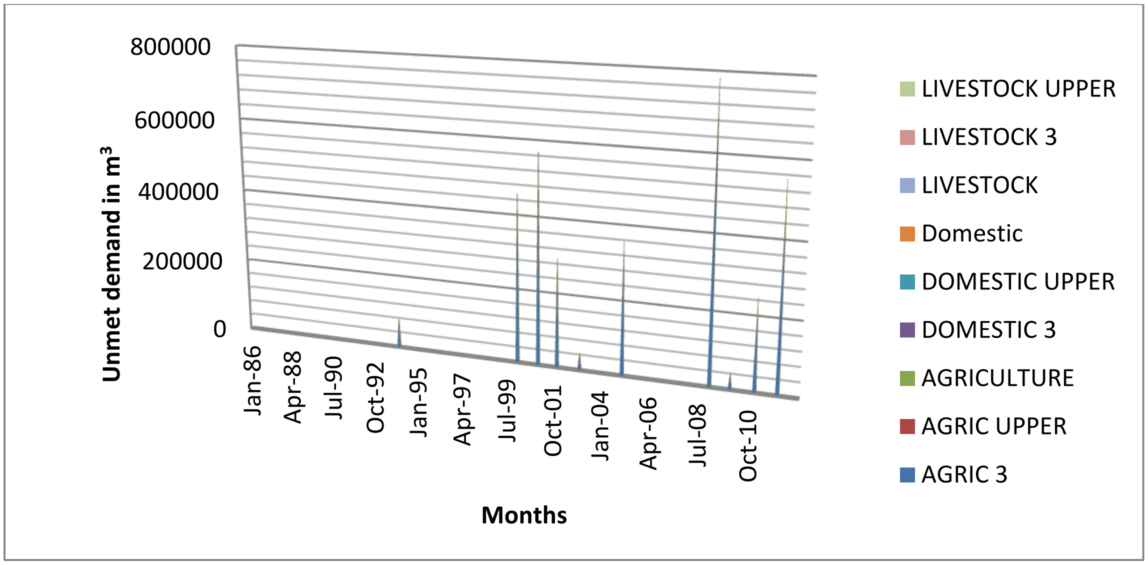

Figure 4.16: Reference Scenario 1986 to 2012: Monthly Unmet Water Demand

In order to understand the magnitude of water shortage in the catchment, the unmet demands for the various sites were determined. The results for the total monthly unmet demands for 1986-2012 show that agriculture in the three sub-catchment had some unmet demands in January 1994 (78,406 m^3), January 2000 (458,946 m^3), January 2001 (571,289 m^3), December 2001 (296,562 m^3), January 2003 (47,806 m^3), January 2005 (359,011m^3), January 2009 (784,765 m^3), December 2009 (46,539 m^3), January 2011 (250,855 m^3), January 2012 (553,218 m^3). The worst hit was agriculture demand in the lower sub-catchment with a mean monthly unmet demand of 8,352 m^3. The rest of the years had their demands met in all the sub-catchments throughout the year (Figure 4.16). The total unmet demand in the catchment in the period 1986-2012 (reference scenario) was 3,450,000 m^3.

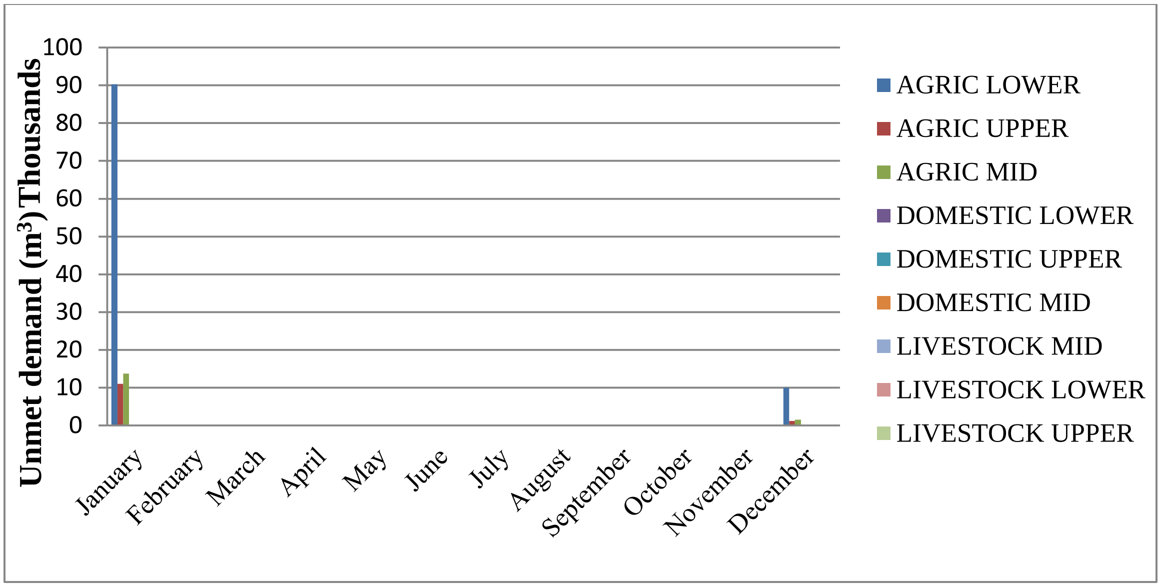

Figure 4.17: Reference scenario 1986-2012: Average monthly unmet demand

In the reference scenario (1986-2012), the highest mean monthly unmet demand is that of agriculture demand site in the downstream catchment in the month of January which is at 90,200 m^3 (Figure 4.19). In the month of January still there is unmet demand for the agriculture midstream and upstream catchments at 13,700 m^3 and 11,000 m^3 respectively. In December there is an average unmet demand of 9,900 m^3, 1,500 m^3 and 1,200 m^3 for the downstream, midstream and upstream respectively. The rest of the months from February to November have their supply requirements met fully (Figure 4.17).

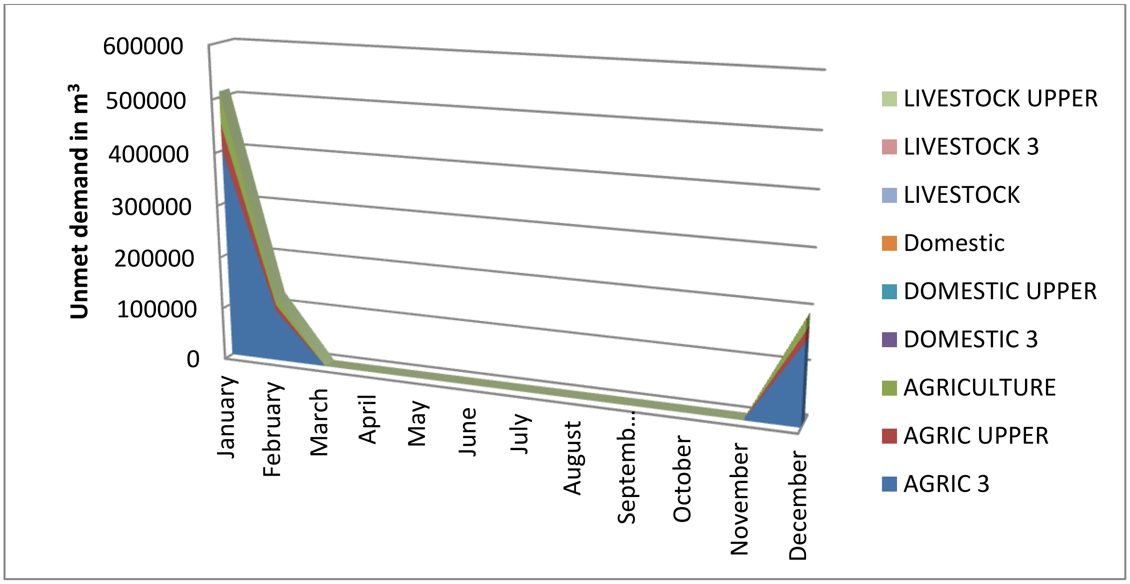

Figure 4.18: Reference scenario 1986 to 2040: Mean monthly unmet demand

When the reference scenario was extended to 2040, apart from January and December, February also had some unmet demand. In the same period the projected mean unmet demands for January increased to 401,000 m^3, 60,000 m^3 and 50,000 m^3 for the lower, middle and upper sub-catchments respectively. In December it was projected to increase to 152,000 m^3, 23,000 m^3 and 19,000 m^3 for the lower, middle and upper sub-catchments respectively. For February it was 97,000 m^3, 15,000 m^3 and 12,000 m^3 for the three sub-catchments in the same order as above (Figure 4.18).

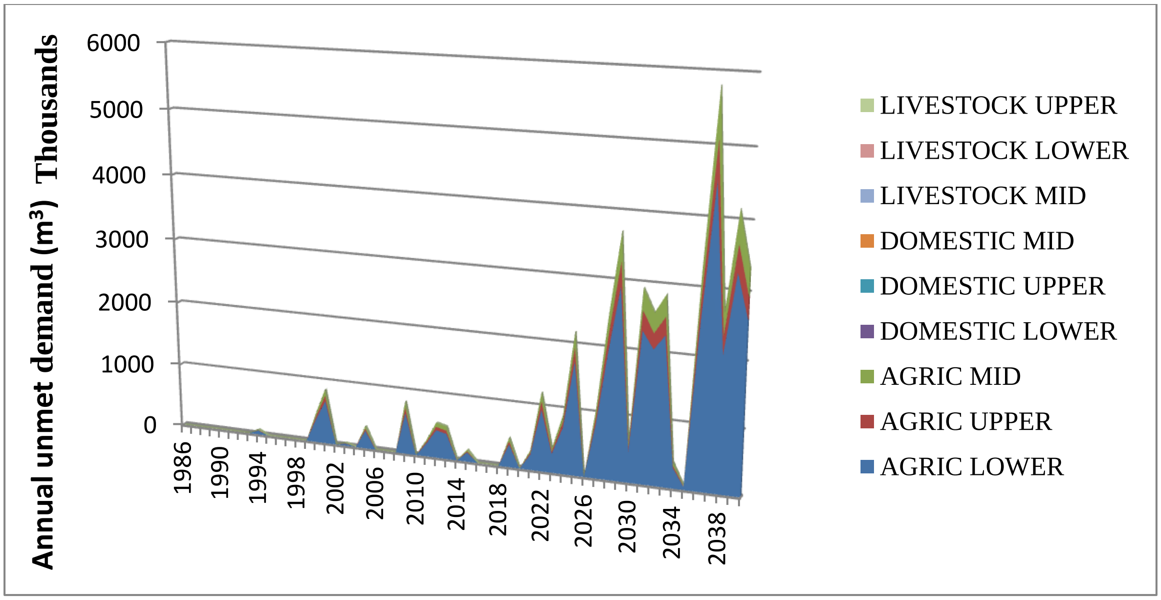

Figure 4.19: Reference scenario 1986 to 2040: Annual unmet demand

The total annual unmet water demand for the reference scenario extended to 2040 indicates that the demands for all sites in the whole catchment were satisfied in all the years before 1994. It shows that 1994 was the first year to experience some shortage ,then 2000, 2001 among others with 2037 expected to have the highest unmet demand of 5,813,000 m^3 (Figure 4.19).

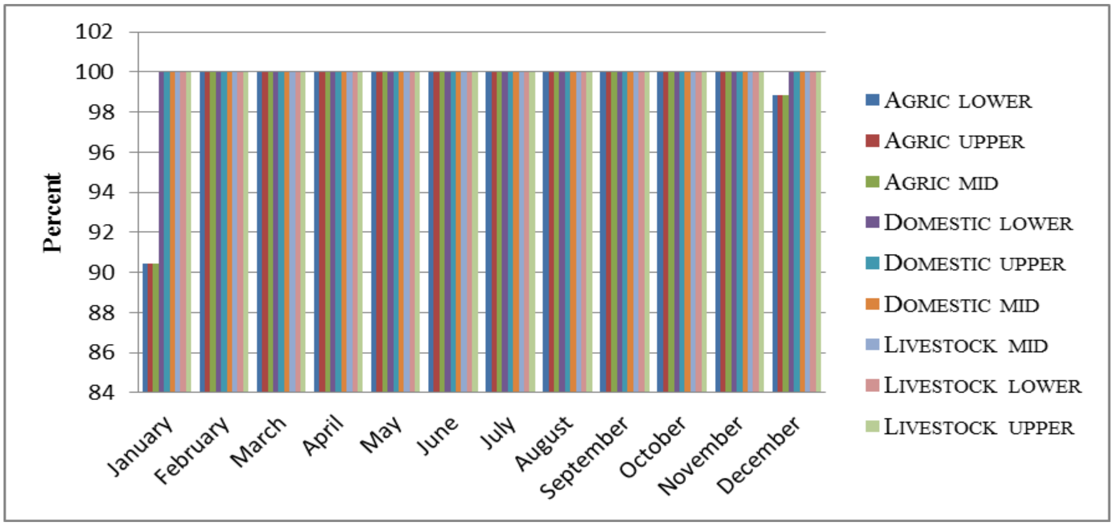

Figure 4.20: Reference Scenario 1986 to 2012: Mean Monthly Water Demand Coverage.

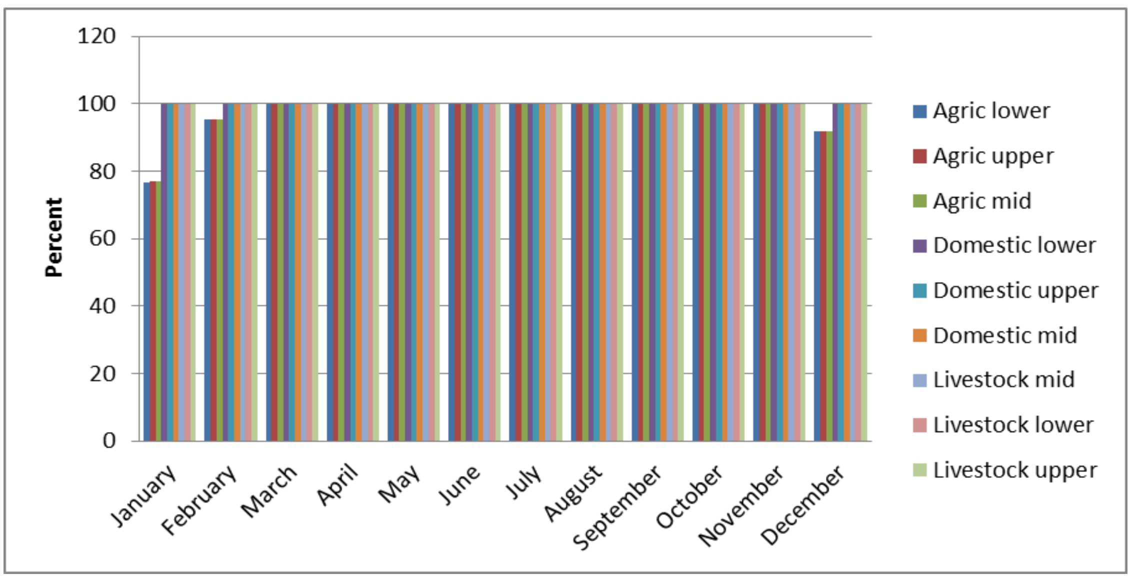

Figure 4.21: Reference Scenarios 1986 to 2040: Mean Monthly Water Demand Site Coverage

On average the demand site coverage (percentage requirement met) for the 1986-2012 period is 100% except for January and December where the coverage are 90% and 95% respectively for all the three agriculture demand sites (Figure 4.20). For the 1986-2040 period, the demand coverage is 100% for all demand sites for nine months that is from March to November. In January, February and December the agriculture demand coverage for the three sub-catchments are 77%, 95% and 92%, respectively whereas the rest of the demand sites are 100% each (Figure 4.21). The low demand coverage in these three months of the year can be attributed to the fact that most people in the catchment depend on river water and the river flows are quite low during these months given that they are the driest months of the year. During the rainy seasons the agriculture demand sites are fully covered since the rain water supplements the river water.

(ii) Other scenarios

Apart from the reference scenario, other scenarios were also considered so as to evaluate their impact on the water supply and demand in the catchment. All the scenarios were inherited from the current accounts scenario. These included:-

1. **Increased population growth from 2.7% in the reference scenario to 3.5% per annum from 2013 to 2040**

This scenario was used to model the impact of higher population growth rate on the water demand. This was meant to answer the question, what if population growth rate increased.

2. **Increased irrigated agriculture from a growth rate of 2.9% to 5% per annum**

This scenario was used to answer the question what if irrigated agriculture was increased at a higher rate than of the reference scenario.

3. **The water year method so as to factor in the historical climate change**

This scenario was used to simulate climate variation based on the historical trend. The water year method allows the use of historical data in a simplified form and to easily explore the effects of future changes in hydrological patterns. The water year method projects future inflows by varying the inflow data from the current accounts according to the water year sequence and definitions specified in the Hydrology section. Used to test a hypothetical event or set of events, or wish to approximate historic patterns.

4. Increased population combined with water year method

This scenario simulates the impact of increased population and hence higher demand combined with climate variation on the water resources in the catchment.

5. Reservoir added

This scenario was used to determine the possible impacts of construction of a reservoir on the water demands and stream flows in the catchment. It was also used to estimate the increase in irrigated agricultural area for a given reservoir capacity. River reservoir provides storage of river water, provide a source of water for demand sites and downstream requirements, and generate hydropower. The reservoir simulation in WEAP takes into account net evaporation on the reservoir, priorities of downstream requirements and for hydropower energy demands, and the reservoir's operating rules. The priority was set to 99 (the lowest possible priority), so that it will fill only after all other demands have been satisfied. There were three scenarios where one reservoir was introduced in the catchment but its capacity was varied (25, 50 and 100 million cubic metres). The purpose of the reservoir was limited to flow storage and flow regulation only. This is a scenario for water resource development.

6. Minimum flow requirement added

A minimum flow requirement is minimum monthly flow required along a river to meet water quality, fish and wildlife, navigation, recreation, downstream or other requirements. It is the minimum average monthly instream flow required for social or environmental purposes (SEI, 2005). The study used the Flow Duration Curve (FDCShift) in WEAP to estimate the minimum flow requirement of the river. The FDCShift function is used to estimate the recommended streamflow in a modified stream, by uniformly reducing (shifting) the natural (unregulated) flow duration curve by a fixed number of percentile places, and further disaggregating it into a complete time series of modified flows. This estimated time series represents the environmental flow requirement (in order to maintain the stream in a given ecological condition (environmental management class), and would typically be used to set the requirement for a flow requirement object. As an alternative to setting a flow requirement, a streamflow gauge object could be added to the river and its flow is then set using FDCShift. In this way, the streamflow simulated by WEAP could be compared to the FDCShifted flow representing an Environmental Management Class. There are six Environmental Management Classes; natural flow, slightly modified, moderately modified, largely modified, seriously modified and critically modified). The study utilized the natural flow which is a one shift step and represents minor modification of instream and riparian habitat. This scenario addressed the question; what if minimum flow requirement is introduced in the river?

7. Minimum flow requirement added under reservoir added

In this scenario the two scenarios were combined so as to simulate the impact on water quantity when both of them are introduced in the catchment. This is a scenario where a reservoir is constructed in the watershed and at the same time the minimum flow requirement is enforced.

8. Reservoir added under increased agriculture

Various capacities of reservoirs were simulated under increased agriculture. This is a scenario whereby a reservoir is constructed and the irrigated area is increased at a higher rate than it is on the reference scenario.

(iii) The impact of the various scenarios on water demand

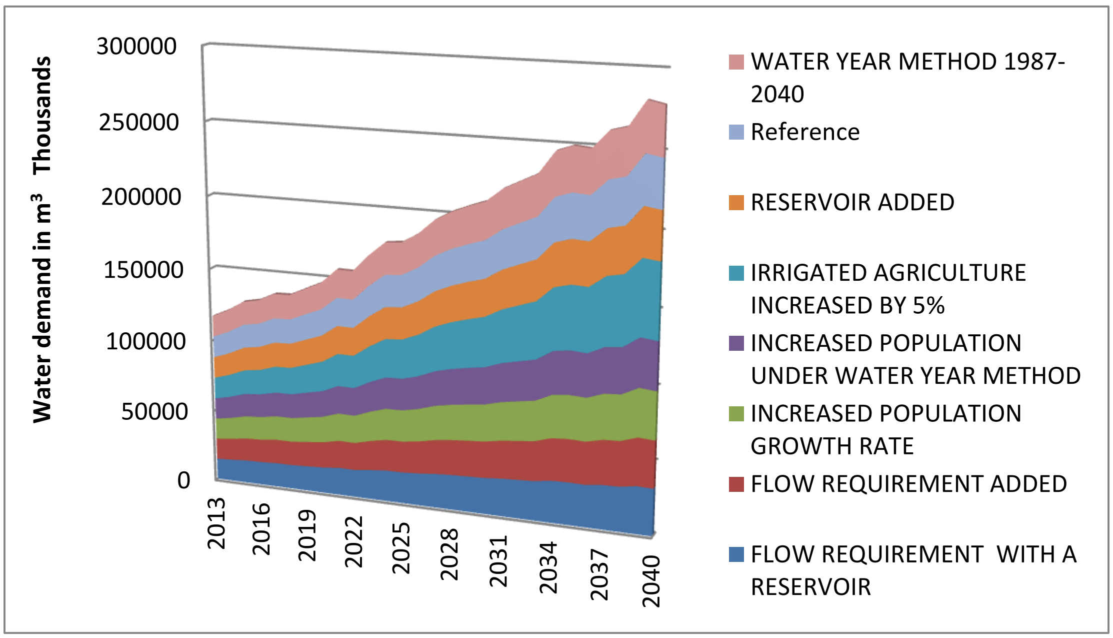

Figure 4.22: Annual water demand for all the scenarios 2013-2040

The result for the annual water demand shows that the demands in all scenarios increased steadily over time though the increased irrigated agriculture scenario increased at a higher rate than the rest of the scenarios. The 'higher population growth rate' and the' higher population growth rate with the water year method' scenarios posted slightly higher increase in demand than the other five scenarios. This shows that if irrigated agriculture is expanded in the study area there will be a significant impact on the water resources availability. If the supply is maintained at the same level then there will be a shortage (Figure 4.22).

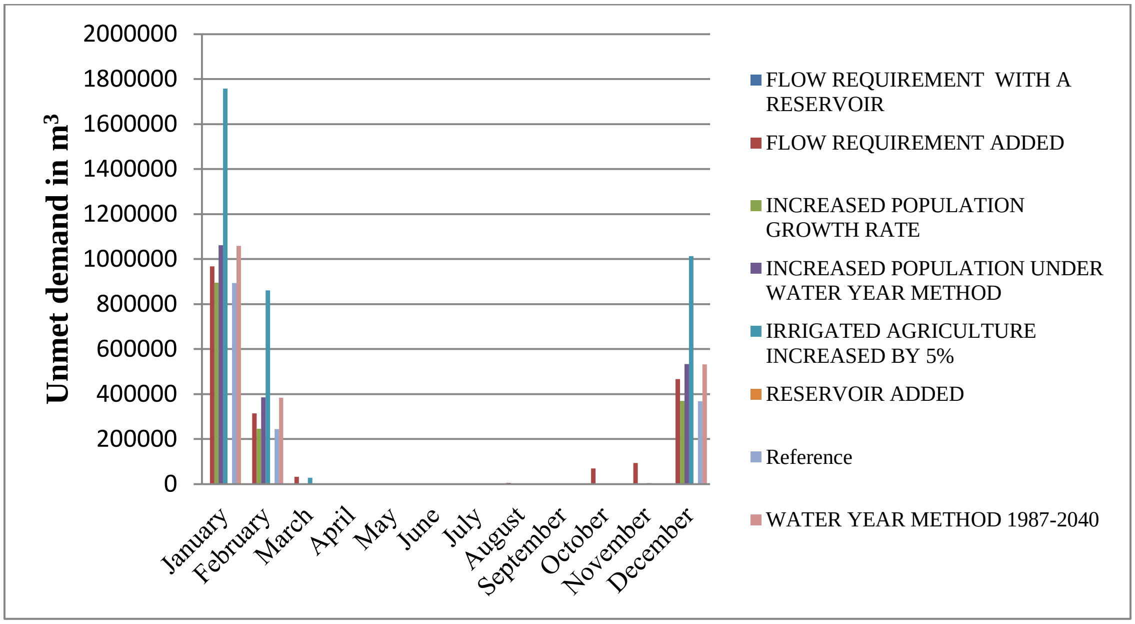

Figure 4.23: Mean monthly unmet demand in all demand sites for the eight scenarios: 2013-2040

On average, increased irrigated agriculture scenario shows highest unmet demands being severe in January, February and December. January has the highest unmet demand under seven out of the eight scenarios followed by February and December. The 'reservoir added' scenario is the only scenario without any unmet demands throughout the year. The 'flow requirement added' scenario had unmet water demands in more than half of the year (Figure 4.23).

On the varied reservoir capacities scenarios, the least storage capacity that will reduce the unmet demand is 15,000,000 m^3. When a reservoir is introduced in the catchment, water becomes adequate for all the demands. When agriculture is increased by 5%, the upper sub-catchment agriculture demand site is expected to have an average monthly unmet demand of 5,085 m^3 in January but for the rest of the months all demand sites are fully satisfied. On the reference scenario, there was a deficit of 510,000 m^3, 124,298 m^3 and 193654 m^3 for January, February and December respectively. The monthly unmet demand for the increased agriculture without a reservoir showed that there will be a mean monthly water shortage of 950,915 m^3, 438,318 m^3, 14,405 m^3, 2,351 m^3 and 521,895 m^3 for the months of January, February, March, November and December, respectively. On increasing the irrigated agricultural area in the lower catchment and leaving agricultural land in the other two sub-catchment to continue with the same trend as the reference scenario, unmet demands were realized in February (8,090 m^3) and March (45,739 m^3). After running several simulations, it was found that the minimum reservoir capacity that would ensure no water scarcities in the catchment would be 25 million m^3 but this would not allow for the expansion of the irrigated agricultural area. However, the most appropriate storage capacity for the reservoir would be 100 million m^3. With this reservoir constructed in the catchment, the farmers in the lower sub-catchment will be able to irrigate up to 150% of the current agricultural land comfortably without any shortages. With such increase in agricultural area it is expected that by 2040, the irrigated agriculture in the lower catchment will be 27% of the total area as compared to the current cover of less than 10%.

Table 4.10: Demand site coverage for the various scenarios: 2013 -2040

Demand Site Coverage (% of requirement met) (Percent)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
	All Demand Sites, Scenario: Reference, Monthly Average											
AGRIC LOWER	63.5	91.1	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	85.5
AGRIC UPPER	63.6	91.1	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	85.5
AGRIC MID	63.6	91.1	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	85.5
DOME LOWER	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
DOME UPPER	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
DOME MID	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
L.STOCK MID	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
L.STOCK LOW	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
L.STOCK UPPER	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
	Demand Site Coverage (% of requirement met) (Percent)											
	All Demand Sites, Scenario: INCREASED POPULATION GROWTH RATE, Monthly Average											
AGRIC LOWER	63.5	91.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	85.4
AGRIC UPPER	63.5	91.1	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	85.5
AGRIC MID	63.5	91.1	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	85.4
DOME LOWER	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
DOME UPPER	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
DOME MID	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
L.STOCK MID	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
L.STOCK LOW	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
L.STOCK UPPER	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
	All Demand Sites, Scenario: INCREASED POPULATION UNDER WATER YEAR METHOD, Monthly Average											
AGRIC LOWER	56.3	85.6	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	78.9
AGRIC UPPER	54.5	85.7	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	78.9
AGRIC MID	55.5	85.6	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	78.9
DOME LOWER	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
DOME UPPER	98.9	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
DOME MID	98.9	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
L.STOCK MID	98.8	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
L.STOCK LOW	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
L.STOCK UPPER	98.8	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
	All Demand Sites, Scenario: IRRIGATED AGRICULTURE INCREASED BY 5%, Monthly Average											
AGRIC LOWER	52.5	79.6	99.4	100.0	100.0	100.0	100.0	100.0	100.0	100.0	99.9	74.6
AGRIC UPPER	52.4	79.7	99.4	100.0	100.0	100.0	100.0	100.0	100.0	100.0	99.9	74.6
AGRIC MID	52.3	79.7	99.4	100.0	100.0	100.0	100.0	100.0	100.0	100.0	99.9	74.6
DOME LOWER	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
DOME UPPER	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
DOME MID	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
L.STOCK MID	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
L.STOCK LOW	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
L.STOCK UPPER	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

Table 4.10: Demand site coverage for the various scenarios: 2013 -2040 (Continued)

	All Demand Sites, Scenario: RESERVOIR ADDED, Monthly Average											
AGRIC LOWER	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
AGRIC UPPER	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
AGRIC MID	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
DOME LOWER	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
DOME UPPER	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
DOME MID	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
L.STOCK MID	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
L.STOCK LOW	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
L.STOCK UPPER	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
	All Demand Sites, Scenario: FLOW REQUIREMENT ADDED, Monthly Average											
AGRIC LOWER	67.35	94.41	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	86.62
AGRIC UPPER	11.03	54.44	84.96	100.0	100.0	100.0	100.0	100.0	100.0	58.987	50.0	30.70
AGRIC MID	67.40	91.44	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	86.65
DOME LOWER	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
DOME UPPER	61.20	81.18	96.97	99.55	100.0	100.0	100.0	95.75	97.38	90.16	81.89	72.95
DOME MID	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
L.STOCK MID	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
L.STOCK LOW	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
L.STOCK UPPER	61.15	87.15	96.96	99.55	100.0	100.0	100.0	95.73	97.36	90.13	81.85	72.911
	All Demand Sites, Scenario: FLOW REQUIREMENT WITH A RESERVOIR, Monthly Average											
AGRIC LOWER	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
AGRIC UPPER	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
AGRIC MID	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
DOME LOWER	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
DOME UPPER	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
DOME MID	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
L.STOCK MID	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
L.STOCK LOW	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
L.STOCK UPPER	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
	All Demand Sites, Scenario: WATER YEAR METHOD 1987-2040, Monthly Average											
AGRIC LOWER	56.4	85.7	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	79.0
AGRIC UPPER	54.7	85.7	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	79.0
AGRIC MID	55.6	85.7	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	79.0
DOME LOWER	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
DOME UPPER	99.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
DOME MID	99.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
L.STOCK MID	99.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
L.STOCK LOW	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
L.STOCK UPPER	99.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

(Source: Author, 2015

On demand site coverage as shown on Table 4.10, the best scenario that displays 100% coverage throughout the year on average is the reservoir added scenario. This is then followed by the 'reference' and the increased population growth rate' scenarios which have some slight drop in coverage for all the three agriculture demand sites in January, February and December. The 'irrigated agriculture increased' scenario had some deficit in the months of January, February, March, November and December for all the three agriculture demand sites. The 'water year method' scenario also had the same coverage as the 'reference' scenario except for January where the domestic and livestock demand sites for the upper and the middle sub-catchments had their demand coverage being slightly less than 100%. The 'increased population with water year method' scenario displayed the same results as the 'water year method'. The results for 'flow requirement added' as well as the 'flow requirement with a reservoir' scenarios show that apart from the shortages displayed by the reference scenario, domestic and livestock demand sites in the upper sub-catchment experienced some substantial shortages in most of the months of the year (Table 4.10).

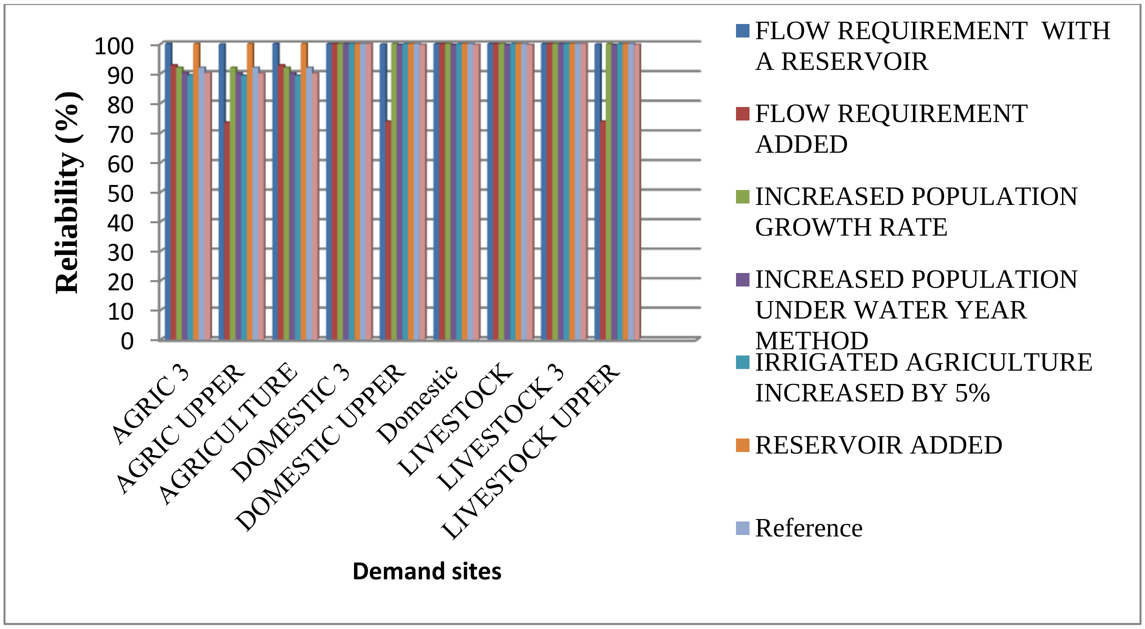

Figure 4.24: Demand reliability: 2013-2040

Reliability is the percentage of the time steps in which a demand site's demand was fully satisfied. On demand reliability, the results on Figure 4.24 show that all the domestic and livestock demand sites in the middle and lower sub-catchments were fully satisfied in all the scenarios over the 28 years (2013-2040). All the agriculture demand sites showed less than 100% in all the scenarios except for the 'reservoir added scenario'. The demand reliability in the 'reservoir added' and the 'flow requirement with a reservoir' scenarios was 100% for all the demand sites for the entire period. This means that all the demand sites were fully satisfied under these scenarios for the whole period. The 'flow requirement added' scenario in addition to the agriculture demand sites, showed the lowest demand reliability for domestic and livestock demand sites in the upper sub-catchment at 73.79%. This means that it is only during 73.79% of the entire period that the demand sites were fully satisfied.

4.6 Evaluation of sustainable management practices in Arror River watershed

The third objective was to evaluate the management practices for the sustainability of the watershed and the study therefore sought information from the respondents on both the traditional and contemporary practices they are applying, the challenges they are facing and probable solutions. The study then simulated some of the practices mentioned in SWAT and WEAP so as to evaluate their impacts on river discharge and water demand in the study area.

4.6.1 Traditional and contemporary watershed management and conservation practices in the study area

The results on the traditional and contemporary watershed management and conservation practices in the study area showed that the local communities in Arror watershed had traditional ways of managing their water catchments areas. Approximately 89% of the respondents reported prohibition of cutting of trees for firewood as traditional methods of watershed management practiced by the community; 71% reported having cultivation on river banks prohibited and 68% reported clan involvement in the management of forests (Table 4.11). According to the respondents each clan was assigned a forest in their jurisdiction to take care of and they were supposed to guard it against any intruder from other clans. They were also in charge of the enforcement of the laws that governed the forest protection and conservation. There were also taboos that were used to protect the forests and watersheds in the region for example; some areas of the forest were out of bounds, the use of some trees as firewood was prohibited.

Table 4.11: Traditional water resource and watershed management practices

Indicators	Number of times mentioned	Percentage
Cutting of trees prohibited	525	88.8
Felling of trees for firewood prohibited	524	88.7
Cultivation of riverbanks prohibited	420	70.7
Clan management of forests	402	67.7
Water Catchment areas out of bounds	397	67.2
Other clans not allowed to enter forests	363	61.1
Communal irrigation furrows developed	76	12.8

Note: Percentages do not add to 100% because respondents mentioned more than one concern.

Apart from the traditional water resource and watershed management practices mentioned above the respondents also reported the application of some of the modern management methods (Table 4.12). This was confirmed by the researcher through observation. Agro-forestry was the most popular method followed by terracing, rainwater harvesting and mulching in that order. It was also noticed that most residents had not embraced destocking and contour farming as some of the methods that could enhance watershed management.

Table 4.12: Contemporary water resource and watershed management practices

Management practices	Frequency	Percentage
Agro-forestry	407	67.5
Terracing	294	48.8
Rainwater harvesting	147	24.4
Mulching	123	20.4
Contour farming	29	4.8
Destocking	20	3.3

Note: Percentages do not add up to 100% because respondents mentioned more than one management practice**.**

4.6.2 Watershed and Water Resource Management issues in Arror watershed

Having looked at the watershed management practices in the study area, the study also sought to find out from the respondents the issues in watershed and water resource management. The respondents raised some of the issues as conflicts (caused by water and other resources distribution), famine, forest destruction, and reduction in water flows in Arror River (Plate 4.2).

Plate 4.2: Reduced flows of Arror River downstream

(Source: Author, 2015)

Over (70%) of the respondents indicated that major concerns limiting expansion of watershed management practices are encroachment at the highlands (74.6%), deforestation (71.0%), decreased water levels (69.9%) and cultivation along the river banks (61.8%), as shown on Table 4.13.

Table 4.13: Major concerns limiting expansion of watershed management practices

Watershed concern	Frequency	Percentage
Encroachment at the Highlands	443	74.6
Deforestation	422	71
Decreased water levels	415	69.9
Cultivation along the river banks	367	61.8
Population pressure	218	36.7
Pollution	197	33.2
Dam construction along watershed area	114	19.2

(Source: Author, 2015)

Note: Percentages do not add to 100% because respondents mentioned more than one concern.

There are indications of deforestation, cultivation and livestock keeping on the steep slopes, cleared riverine vegetation as depicted on plate 4.3.

Plate 4.3: Degradation in Arror watershed; conversion of forestland to grassland and cropland, cultivation and grazing on steep slopes and destruction of the riverine vegetation.

When asked to suggest the major mitigation measures for watershed and water resource management in the region, the majority of the respondents (92.9%) mentioned afforestation and conservation of forest areas (Table 4.14).

Table 4.14: Possible solutions to water resources and watershed management

Measures taken	Number of times mentioned	Percentage
Afforestation	552	92.9
Conservation of forest cover	551	92.8
Practice soil conservation measures	271	45.6
Local leaders empowerment	267	45
Enforcement of watershed management	225	37.9
Alternative income sources	179	30.2
Construction of dams	127	21.4
Coordination of water sharing	105	17.7
Government reward	104	17.5

Note: Percentages do not add to 100% because respondents mentioned more than one concern

4.6.3 The impact of soil conservation measures on Arror river discharge

The SWAT model was used to evaluate the impact of terracing and contour farming on water quantity. Terracing and contour planting were identified as probable measures in agricultural areas characterized by slopes as described in chapter three. In the model, the two conservation measures (terracing and contour farming) were introduced in the simulation and the purpose was to reduce runoff and the effects of erosion. This was done by assessing their impact on the water flows out of the catchment for the year 2012.

Terracing scenario was simulated in SWAT by adjusting both erosion and runoff parameters. The USLE practice (TERR_P) factor, the slope factor (TERR_SL) and curve number (TERR_CN) were adjusted to simulate the effect of terracing by providing values that would fit the particular soil properties and land slope. It was important to note that TERR_SL was set to a maximum of the distance between two terraces. Contour planting scenario was simulated in SWAT by altering curve number (CONT_CN) to account for increased surface storage and infiltration and the USLE Practice factor to account for decrease in erosion.

The two were applied to slopes between 2% and 10%. The results are as shown on Figure 4.25.

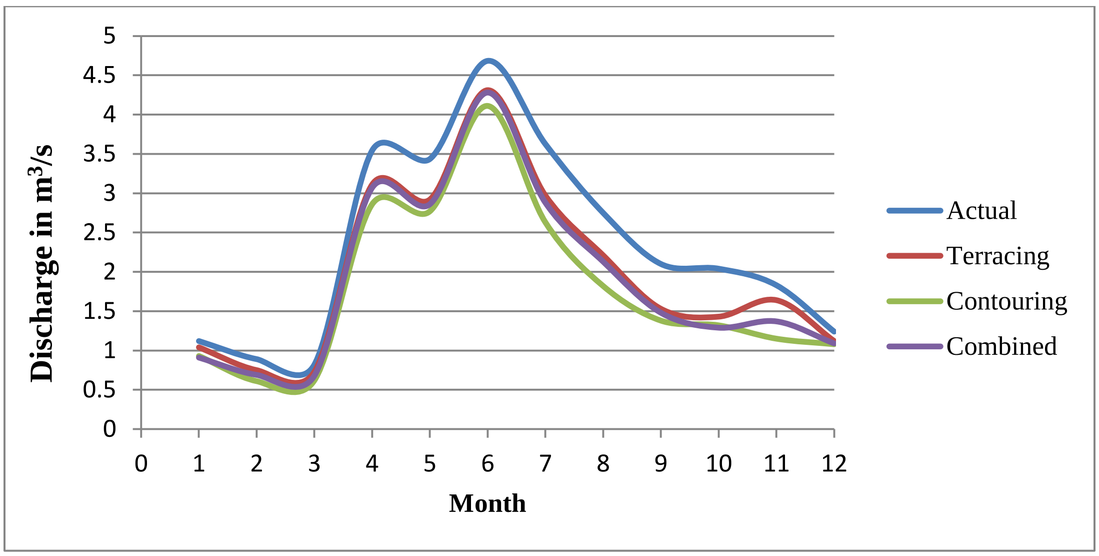

Figure 4.25: The stream flows of some management practices

Table 4.15: Comparison of annual mean discharge for the three scenarios

Scenario	Annual mean discharge m^3/s	% reduction	Total annual discharge m^3/s
Actual	2.34	-	28.076
Terracing	1.98	15.4	23.76
Contour planting	1.77	24.1	21.28
Combined	1.90	19.04	22.73

The impact of terracing over the 2012 period was analysed and revealed a decrease in the annual mean flow from 2.34 m^3/s to 1.98 m^3/s which is a reduction of 15.4% on the annual flows. The impact of contour planting over the 2012 period was analysed and revealed a decrease in the annual mean flow from 2.34 m^3/s to 1.77 m^3/s which is a reduction of 24.1% on the annual flows. A combined application of both terracing and contour planting was simulated to see the overall impact. It was done on a 50/50 ratio, which means half of the agricultural land on slope had terracing while the other half had contour planting. This scenario over the 2012 period was analysed and revealed a decrease in the annual mean flow from 2.34 m^3/s to 1.90 m^3/s signifying a reduction of 19.04% (Table 4.15). The minimum flows for actual, terracing, contouring and combined were 0.82 m^3/s, 0.73 m^3/s, 0.61 m^3/s and 0.68 m^3/s, respectively. The maximum flows were 4.68 m^3/s, 4.31 m^3/s, 4.11 m^3/s and 4.28 m^3/s in the same order as above.

As per the results of the simulation mentioned above, it is observed that application of contour planting yielded the highest reduction compared to terracing. To assess the impact of a combined application, both contour planting and terracing were applied, this resulted in reduction of flow higher than terracing and lower than contour planting. All the three scenarios yields less runoff than the actual and this implies higher water infiltration in the catchment. As per the simulation a scenario involving contour planting is the best management practice to consider when farming on the slopes since it reduces the flow out of the catchment significantly.

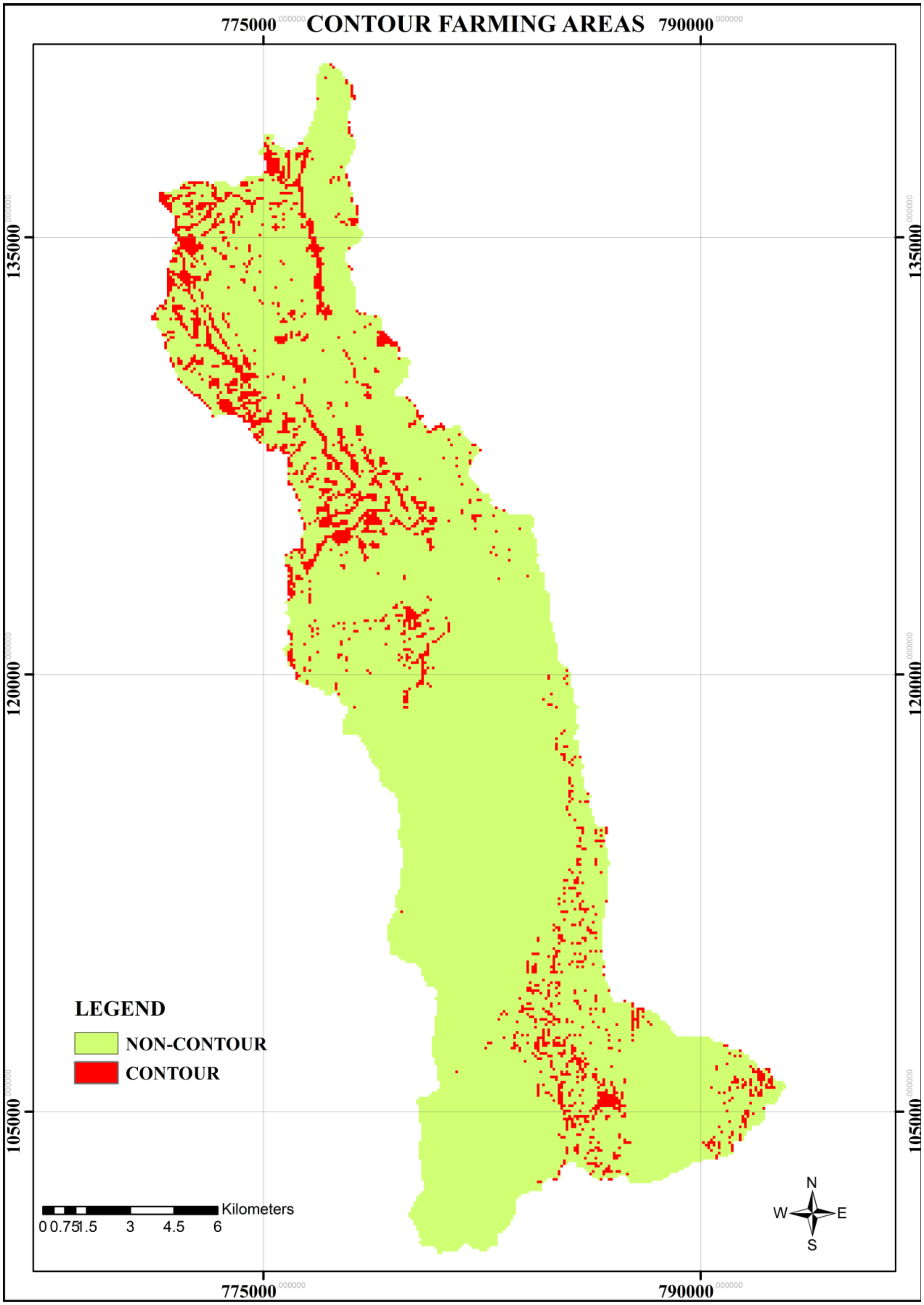

Figure 4.26: Areas suitable for contour farming

Figure 4.26 shows the areas that are suitable for contour farming in the watershed. These are the areas that are between 2% and 10% slope and are under crop land. The rest of the areas are either too steep for cultivation or have a slope that is less than 2% and thus do not require any conservation measure or are covered by another land use other than cropland. This was determined by performing a suitability analysis in ArcGIS.

4.6.4 The impact of the various scenarios on river flows in the WEAP model

Apart from assessing the impact of the various scenarios on water demand in the watershed, WEAP was also used to assess the impact of the various scenarios on the river flows. All these scenarios together with the simulations in SWAT were used to come up with some of the measures that can be put in place so as to enhance the sustainable management of Arror River watershed.

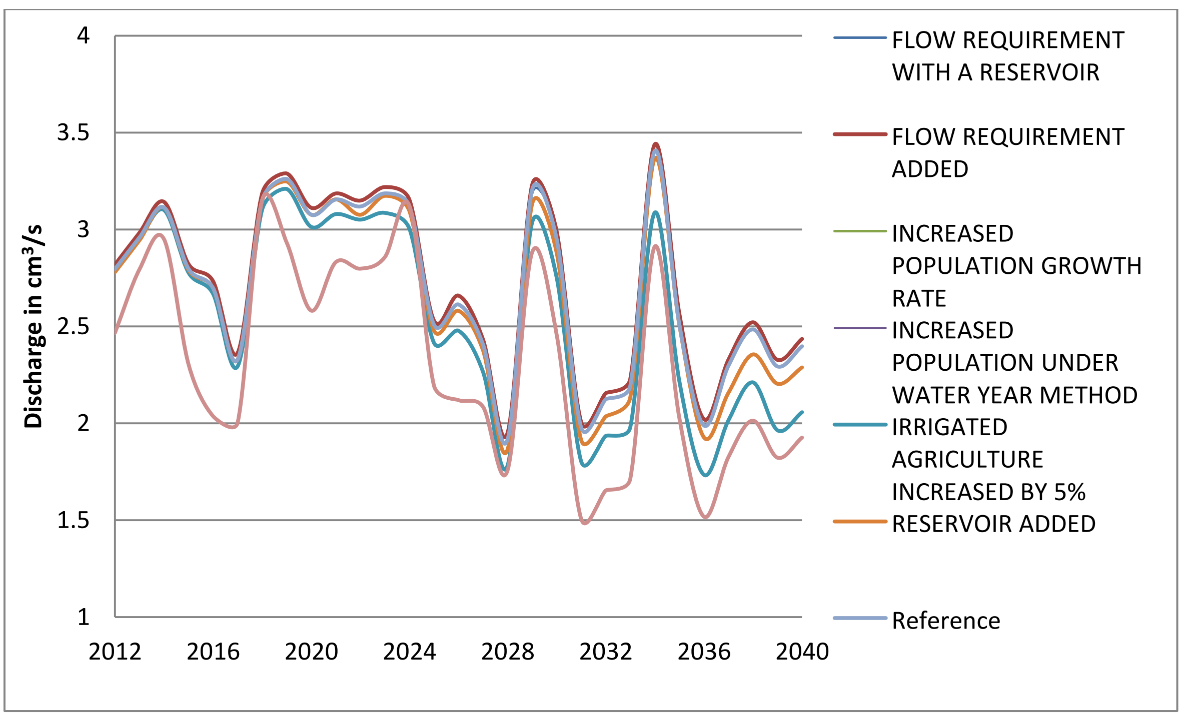

Figure 4.27: The mean annual flows for the eight scenarios (WEAP) for 2012-2040

Figure 4.27 shows that the 'flow requirement' scenario yieded the highest mean annual flows while the water year method yielded the lowest mean annual flows over the 28 years.

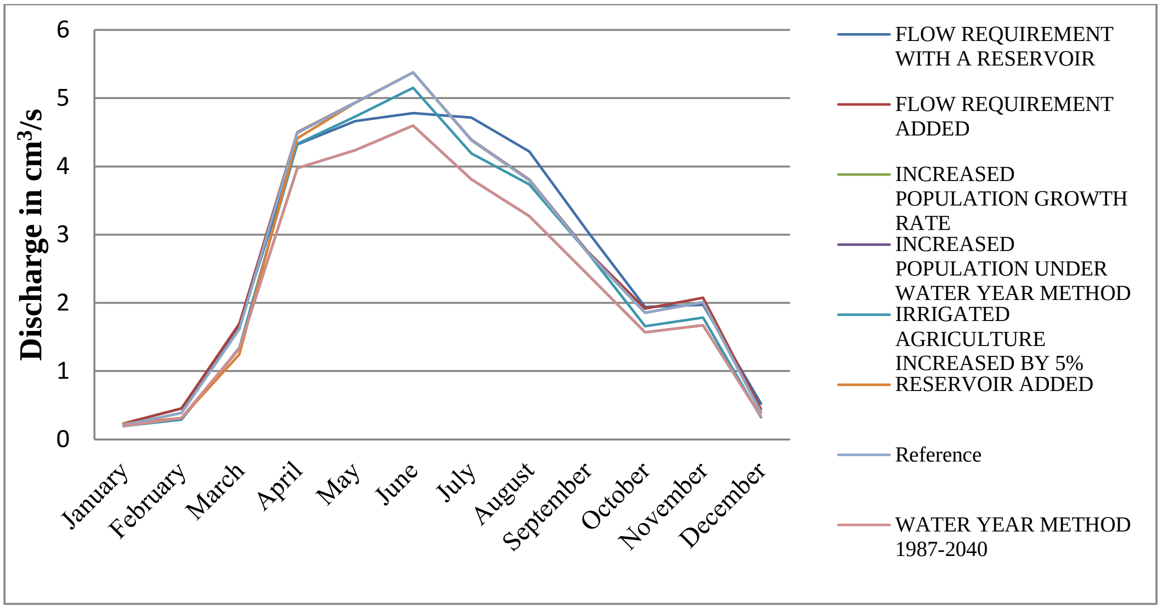

Figure 4.28: Mean monthly flows for all the scenarios 2013-2040

The mean monthly discharge for all the scenarios simulated in the study shows that the peak of the river flows is in June with January, February and December yielding the lowest amounts. The 'flow requirement added' scenario had the highest average flows from January to July where it was overtaken by the 'flow requirement with a reservoir' scenario for the rest of the year. The lowest average monthly flows were depicted by the 'water year method' and the 'increased population under water year method' scenarios in all the 12 months. The 'irrigated agriculture increased' was another scenario that yielded less average monthly flows than the 'reference' scenario. The 'reservoir added' scenario has its average monthly flows being less than reference scenario from January to October and equal to the 'reference' scenario from November to December thus reduced flows in most part of the year. The 'increased population growth rate' scenario yielded the same average monthly flows with the ‘reference’ scenario. On minimum mean monthly flows, the ‘flow requirement added’ scenario, posted the highest amount and had a smooth peak as compared to the rest of the scenarios (Figure 4.28).

Table 4.16: The outcome of the various scenarios in WEAP (Mean annual in Million Cubic Metres)

SCENARIO	RIVERFLOWS	SUPPLY	ANNUAL DEMAND	UNMET DEMAND
Reference	84.744	21.664	23.169	1.505
Increased agriculture (5%)	80.058	26.870	30.534	3.644
Increased population (3.5%)	84.719	21.777	23.288	1.511
Flow requirement	85.113	21.217	23.169	1.951
Dam construction	83.414	23.169	23.169	0.000
Water year method	72.970	21.194	23.169	1.975

Table 4.16 shows a summary of the major scenarios in WEAP. It is apparent that the ‘increased agriculture’ scenario posted the highest mean annual demand and thus the highest mean annual unmet demand. The second highest in terms of demand was the ‘increased agriculture’ scenario. On the unmet demand the second highest was the ‘water year method’ which is a scenario that puts into account the climatic variations and thus influencing the supply side of the water balance and given that the demand remains the

same then the unmet demand is increased. The third highest scenario for the unmet demand is the ‘flow requirement’ which ensures that there is a minimum amount of flows that should be retained in the river and hence reduces the supply of water in the watershed leading to increased shortage and thus higher unmet demand. The ‘dam construction’ scenario shows that there will be no unmet demand and this is because the dam will be able to collect and store water during the high rainfall seasons and this water will be used during the dry season and thus minimize the shortages in the watershed.

CHAPTER FIVE

DISCUSSION

5.1 Introduction

This chapter discusses the results based on the objectives of the study. It is presented in three parts. The first part is on the impact of land use changes in Arror watershed on river discharge using SWAT model; the second part is on the assessment of water demand using WEAP model and the last part is on the evaluation of watershed management practices for sustainability of water resources.

5.2 The impact of land use changes in Arror watershed on the river flows using SWAT model

The calibration and validation of the SWAT model showed that the model was not perfect but can provide a good estimate. The study results on the land use changes indicated that in general there was a reduction in the size of deciduous (2.8%) and coniferous forest (4%); grassland (8.3%) , bare ground (1.9%) and wetland (3.2%) over the 26 years. On the other hand, cropland increased by 14.3% over the same period. This indicates that most of the forest and grasslands were being converted into cropland and this was occasioned by population pressure and hence need for more food; and also insecurity downstream occasioned by cattle rustling and thus causing encroachment into the forested land upstream.

The change in land use, over a period of time, has had an impact on the hydrological processes in the catchment, this is confirmed and explained by the varying amount of water flow from the catchment in the 3 year regimes (1986, 2000 and 2012) as shown in chapter four. By using the same set of climate, soil and slope data and altering the land use the results varied proving that land use changes affect the river flows. As revealed by the results, the 1986 land use yielded an average of 2.04 m3/s, 2000 yielded 2.46 m^3/s while 2012 yielded 1.94 m^3/s. The variation in flow is attributed to mainly land use changes. The increase of discharge flow in the year 2000 could be as a result of deforestation and rendering the land bare thus increasing runoff from the catchment. The results of the analysis indicated that conversion of forests to agriculture and grassland in the basin headwaters reduced dry season flows and increased peak flows, leading to greater water scarcity at critical times of the year and exacerbating erosion on hill slopes. The findings also indicate that there has been a shift of the peaks over time which can be attributed to land use changes coupled with climate change. The results also revealed that the percentage forest cover has been changing over time with 1986 having 68.97%, 2000 had 56.56% and 2012, 62.61% of the total area of the catchment. The results show that the year 2000 had the highest runoff and the lowest minimum flows as discussed earlier. High runoff may cause disasters like floods downstream and landslides whereas minimum flows may cause drought during the dry season. Proper management of the catchment should therefore entail increase in forest cover which will in turn lead to higher minimum flows, lower peaks and thus water will be available at right quantity through the year. This in the long run minimizes the occurrence of the disasters mentioned above as well as increasing the infiltration of water into the soil hence boosting the base flow and conserving the soil. There is therefore need to improve the management of the watersheds so as to ensure environmentally sustainable flows.

These results concur with Muli (2007) who reported that a lot of deforestation had taken place in the catchment. The main factors that have contributed to deforestation in the catchment as outlined by MIDFAR (2005) were insecurity in Kerio Valley (includes downstream of Arror basin) that caused people to move from the valley to the escarpment where they experienced landslides forcing them to move into the Kipkunur and Embombut forest reserves; the issuing of grazing permits to families to graze in the forest glades back in 1914 and 1922; Dorobo clans in Marakwet have depended on gathering and hunting in the forest. Later on, they changed into farming and causing more pressure on land; soil infertility occasioned by poor land management on the settlement schemes near Kapyego location has resulted into soil infertility and consequently encroachment into the forest for fertile land. Public institutions have been established in the forest, for example 56 schools are located in forest area. There are also several shopping centres have also been established and are progressively expanding and encroaching into the forest land. Lastly, establishment of district headquarters in 1994 at Kapsowar town led into the proposal for forest excision at Chebara and Kapkoros forests (MDFAR, 2005). These changes have had an impact on the Arror river flows as exhibited in chapter four.

5.3 Assessment of the water demand in Arror River Watershed using WEAP model

The study results on the development of the DSS based on the WEAP indicated that the model is able to predict the general trend of the catchment processes. The time series showed the observed stream flows and the simulated stream flows of the reference scenario follow the same trend. The simulation of the various scenarios showed varied impact on water demand in the watershed as shown in chapter four. This DSS was able to predict the future water demands and shortages under various scenarios e.g. the increase in population, expansion in agriculture, some watershed management interventions put in place and the changes in climatic conditions based on historical trend. This is very useful information for watershed and water resource planners. With this the water resource planners and other stakeholders will be able to make informed decisions as they plan for water resources in the catchment.

These study findings are in agreement with findings by Sharifi (2003) who observed that WEAP incorporates water supply in the context of demand-side issues, water quality, and ecosystem preservation into a practical tool for water resources planning. WEAP is distinguished by its integrated approach to simulating water systems and by its policy orientation. Study results by Ritter (2006) agreed with these results that WEAP model can be used to predict the general trend of the catchment processes. Water balance is an accounting of the inputs and outputs of water. The analysis is done to account for all the water entering or leaving any hydrologic system. It can be determined by calculating the input and output and storage changes of water at the earth's surface. The amount supplied to a demand site is the sum of the inflows from its transmission links. Water demand analysis in WEAP is either by the disaggregated end-use based approach of calculating water requirements at each demand node or by the evapotranspiration-based irrigation demand in the physical hydrology module. Demand calculations for urban, rural, livestock and industrial entities are based on a disaggregated accounting for various measures of social and economic activity such as population served, livestock population and industrial production units. These are referred to as the Activity Levels. The Activity

Levels were multiplied by the water use rates of each activity defined as water use per unit of activity. Each Activity Level and water use rate was individually projected into the future using exponential growth rate function. WEAP calculates water mass balance for every node and link in the system on a monthly time step. Water is dispatched to meet in stream and consumptive requirements subject to demand priorities, supply preferences, mass balance and other constraints.

The various scenarios simulated in WEAP showed diverse impacts on water demand in the watershed. This agrees with the findings by Purkey and Huber-Lee, (2006) who noted that by simulation of water allocation, the elements that comprise the water demand-supply system and their spatial relationship are characterized for the catchment under consideration. WEAP also has the flexibility to accommodate the evolving needs of the user: e.g. availability of better information, changes in policy, planning requirements or local constraints and conditions.

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5.3.1 Allocation of current water resources and the extent, magnitude and duration of water shortage in the watershed

The study results on the allocation of water resources in the watershed indicated that Agriculture and livestock keeping are the main economic activities in the study area. The upper and mid catchments depend mainly on rain fed agriculture while the lower catchment farmers depend on irrigation since rainfall there is quite erratic and scarce. In the whole catchment a large percentage of water is utilized for agriculture followed by livestock and the least is domestic. The mean annual water allocation over the period

1986-2012 showed that agricultre demand site in the lower catchment was allocated the highest amount of water. The annual water demands for the period 1986 to 2012 in the reference scenario shows that the demand for water by the various uses in the three sub-catchments has been increasing steadily over time. For the upper and the lower sub-catchments the highest demand was for agriculture while for the middle catchment livestock displayed the highest demand compared to the rest of the demand sites. The results showed that on average, agriculture was the main consumer of water throughout the year in Arror watershed and that the highest demands in January, February, March and December which are the driest months of the year and hence evapotranspiration is at its peak. During this period also most farmers use water from the river for irrigation since precipitation is very low or missing completely. This conforms to earlier studies which concluded that in Africa, 88% of stored water is consumed by agriculture, mainly in irrigation. Domestic water consumption is very small (30 to 40 litres /day). It is anticipated that as Africa increasingly develops, the demand for water for food production and for domestic use, as well as for industrial development will also increase. The proportion of water used in industry is often seen as an indicator of economic development (United Nations Development Programme (UNDP), 1990).

The results for the total monthly unmet demands were that the worst hit was agriculture demand in the lower sub-catchment. This is due to low precipitation in the lower sub-catchment coupled with the fact that a lot of abstractions take place in the middle sub-catchment which reduces the amount of water that reaches downstream. This clearly illustrates the impact of the activities of the upstream users on the downstream dwellers.

The rest of the uses had their demands met in all the sub-catchments throughout the year except in the month of January where agriculture had some unmet demands in the entire catchment. This is because January is the driest month of the year in the catchment. On average, the highest mean monthly unmet demand was that of agriculture demand site in the downstream catchment in the month of January and this is attributed to low precipitation and high evapotranspiration.

When the reference scenario was extended to 2040, the results showed that the unmet demands increased with time and this can be attributed to increase in population which in turn leads to increased demand for food which calls for expansion of agriculture and increased number of livestock kept. This definitely will lead to more demand for water in terms of domestic, livestock and agriculture which is the highest consumer of water in the catchment. On the other hand there are issues of climate change and poor management of the catchment which may affect the supply side of the equation negatively. There are other issues like industrial development which will actually affect the demand of water but has not been considered in this study. With all these combined, it is expected that there will be an increase in demand and supply may reduce with time and thus water shortage in the catchment by the year 2040.

These study findings are in line with findings by Shim *et al.* (2002) who noted that DSS can be used in the allocation of water resources in a watershed. DSS in water resources is used to help decision-makers address management issues at every level and the allocation of water resources in the watershed. Highly involved and integrated DSS combine the technical, social, and economic issues at a watershed level incorporating many hydrologic processes into one system. With the emergence of GIS, water resource decision support systems shifted to integrating a spatial component into the generally accepted concepts of physical, environmental, economic, and social processes. As more strain is placed on river systems due to increased demand and industrial uses, coordinated activities are crucial to understanding the real impacts and developing a proactive plan for sustainability.

5.4 Evaluation of management practices for sustainable management of Arror River watershed

The SWAT and WEAP models were both used to analyse the impacts of some management practices so as to suggest those that would enhance the sustainable management of the watershed.

5.4.1 Watershed management and conservation practices

The study findings on the traditional and contemporary watershed management and conservation practices in the study area indicated that Arror watershed residents had their own traditional ways of managing their water catchments. Majority of the respondents reported prohibition of cutting of trees as traditional methods of watershed management practiced by the community. Each clan was assigned a forest in their jurisdiction to take care of and they were supposed to guard it against any intruder from other clans. They were also in charge of the enforcement of the laws that governed the forest protection and conservation.

The study results also indicated that apart from the traditional watershed management practices, the respondents also reported the application of some of the modern management methods. Agro-forestry was the most popular method followed by terracing, rainwater harvesting and mulching in that order. It was also noticed that most residents had not embraced destocking and contour farming as some of the methods that could enhance watershed management.

There is need therefore to integrate the traditional and the contemporary methods in the management of Arror watershed. The local institutions should be involved in the management and conservation of natural resources. Attention to management of watersheds is increasing across the developing world as soil erosion continues to degrade agricultural land, while dams, reservoirs and irrigation infrastructure continue to be clogged with sediment (Abdelsalam, 2008). The broader view through participatory management of watersheds is to capture dimensions and societal issues that are not normally included in a land use planning and management. These include causes of natural resource degradation and related land use activities. The importance of management of watersheds is therefore to ensure that use and modification of water resources, land based activities at catchments do not undermine the function of ecosystems and other resources. Participatory approach of water resource management is one of the principles of the Dublin convention which requires water development and management be based on involvement of all users, planners and policymakers at all levels. It further aims at managing the land and water resources of drainages in a manner that sustains adequate levels of water, soil and fibre production. To achieve proper management of the basin and its catchments, efforts are therefore required for regional coordination as well as planning at national and local levels. The stakeholders should be given opportunities to bring forward and jointly negotiate their interests, set priorities, evaluate opportunities, implement and monitor the outcomes.

The issues in watershed and water resource management in Arror watershed as raised by the respondents include conflicts (caused by water and other resources distribution), famine, forest destruction, and reduction in water flows in Arror River among others. Majority of the respondents indicated that major concerns limiting expansion of watershed management was deforestation. The respondents also indicated afforestation and conservation of forest cover as the major mitigation measures to watershed and water resource management problems in the study area.

These study findings agree with Lisa (2007) who found that inappropriate management of watersheds leads to a wide range of ecological and human changes in both upstream and downstream of a watershed. These may include destabilization of aquatic ecosystems, extinction of species and finally eutrophication due to nutrient and sediment load. Land degradation and soil erosion coupled with declining per capita availability of land and freshwater which are quite evident in the study area are posing serious threat to the watershed. To decrease the effects of degradation, it requires a process that promotes a coordinated development and management of water and land. Such a process is expected to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital eco-systems. Water resource management presents complex challenges since it is a common-pool resource that links multiple ecosystems and user groups. There has been a marked shift from traditional technical approach towards focusing water resource management on the watershed scale to account for these complexities. This shift has led to the emergence of watershed conservation groups and to the increased importance and recognition of participatory management of common-pool resources.

Perez & Tschinkel *(*2003) also noted that the stakeholders often belong to different social, ethnic groups, farming and pastoralists communities with diverse economic, social and political power but all of them derive different benefits from the watershed resources. Given such diversity, disagreements may become obvious since stakeholders may not share common vision in reaching consensus on implementation of policies and practices. This is evident in the study area where fights between pastoralists and farming communities have been reported. Hence the need for advocacy for an integrated water resource management that encourages public participation.

5.4.2 The potential of some watershed management practices in the study area

The study results on the demand reliability indicated that all the domestic and livestock demand sites in the middle and lower sub-catchments were fully satisfied in all the scenarios over the 28 years (2013-2040). The demand reliability in the 'reservoir added scenario' was 100% for all the demand sites for the entire period. This means that all the demand sites were fully satisfied under this scenario for the whole period. The 'flow requirement' added scenario on the other hand posted the lowest demand reliability for domestic and livestock demand site in the upper sub-catchment. This is because the minimum flow requirement was accorded the highest priority and so during the dry seasons the water was just enough to cover for the flow requirement and insufficient amounts were left for the other demands. The upper sub-catchment was highly affected because it had the highest livestock and human population. Therefore there is need to improve the management of the catchment so that the water quantity will increase hence satisfying the minimum flows and all the other demand sites as well.

The study findings showed that the 'flow requirement' scenario yieded the highest mean annual flows while the water year method yielded the lowest mean annual flows over the 28 years. The mean monthly discharge for all the scenarios simulated showed that the peak of the river flows occurred in June. The 'flow requirement added' scenario had the highest average flows from January to July where it was overtaken by the 'flow requirement with a reservoir' scenario in the remaining months of the year. This can be explained by the fact that the area experiences low rainfall in the earlier part of the year and therefore without the flow requirement introduced there will be less water retained in the river since it is scarce. Flow requirement usually ensures that there is a minimum flow retained in the river for ecological purpose and is normally given the highest priority so that it is satisfied before any other demand. It therefore guarantees river flows even during the driest seasons of the year. This is one of the management practices that should be employed in Arror catchment so as to ensure ecological sustainability. According to Acreman and Dunbar (2004), there is a growing demand worldwide to conserve or restore the ecological health and functioning of the rivers and their associated wetlands for the benefit of people and biodiversity. It is widely recognized that any artificial alteration to a river flow regime will change the river ecosystem. River managers need to be able to define the river environmental flow regime that will support the desired ecosystem and to quantify the ecological impacts of changes to the flow regime caused by artificial influences, such as abstractions and dam operations. There is no simple figure that can be given for the environmental flow requirements of river ecosystems. They are complex systems and knowledge is limited and much depends on social choice that determines the desired character of the river ecosystem under study. The challenge is to define the flow regime that best meets the objectives set, or makes the trade-off that the society finds most acceptable. A number of methods exist to achieve this together with broader decision making frameworks. There is no single method that is universally the best as each method has its merits and demerits depending on climatic regimes and different scales and each works at various level of detail. The methods and frameworks available demonstrate the desire to help improve and protect river ecosystems using the best knowledge with the involvement of local communities and other stakeholders.

The ‘irrigated agriculture increased’ scenario yielded less average monthly flows than the reference scenario. This is attributed to the fact that when agriculture is expanded the water requirement increases and thus less water available for run off. The ‘reservoir added’ scenario has its average monthly flows being less than reference scenario from January to October and equal to the ‘reference’ scenario in November and December thus reduced flows in the most part of the year. The ‘reservoir added’ scenario is the only scenario without any unmet demands throughout the year. The demand reliability in the 'reservoir added' scenario was 100% for all the demand sites for the entire period. This means that all the demand sites were fully satisfied under this scenario for the whole period. The best scenario that displays 100% coverage throughout the year on average is the reservoir added scenario. The 'flow requirement added' and 'flow requirement added with a reservoir' scenarios have unmet water demands in more than half of the year. This shows that if the environmental minimum flows were to be ensured in Arror River there will be increased shortage of water available for the various demands in the watershed. This means that there is great need to better manage the catchment so as to increase the water resource availability in the area and thus boost the water supply. With proper management there will be enough water for the sustenance of the ecosystem and for human use and all other organisms that depend on it.

The results further show that if a reservoir of 100 million m^3 is constructed in the area the water shortages that occur during some months of the year will be addressed and all the demand sites will be satisfied throughout the year. In addition, the reservoir will be able to supply adequate water for irrigating up to 150% of the current agricultural area in the lower catchment. This will indeed boost food supply, promote economic development and hence improve livelihoods in the watershed. The reservoir will also be used to supply piped water to the households in the region and this will improve clean water accessibility in that currently the residents have to walk for an average of 2.5 km (County Government of Elgeyo Marakwet, 2013) to fetch water from the river whose quality is not guaranteed.

These findings are in agreement with Eschenbach (2001) who found that a popular method for irrigating crops in Southern India is constructing a small scale reservoir across the slope of a valley. From the reservoir, water travels through many canals irrigating the bordering plots of agricultural land. The allocation of water depends on many factors such as hydrologic flow into the reservoir, types of crops being irrigated, area of agricultural land requiring water from each canal.

As per the results of the simulations in SWAT model, it was observed that application of contour farming yielded the highest run off reduction compared to terracing. To assess the impact of a combined application, both contour planting and terracing were applied, this resulted in reduction of flow higher than terracing and lower than contour farming. As per the simulation a scenario involving contour planting is the best management practice to consider when farming on the slopes since it reduces the flow of water out of the catchment significantly. Contour farming involves tilling and planting across the slope, following the contour of the land, as opposed to farming up and down hills. This creates small ridges that slow runoff water, and increases the rate of water infiltration, reduces the hazard of erosion, and redirects runoff from a path directly downslope to a path around the hill slope. It promotes better water quality by controlling sedimentation and runoff and the increased rate of water infiltration leads to conservation of soil moisture. Contour farming can reduce soil erosion by as much as 50% compared to farming up and down hills. Farming on the contour rather than up and down the slope reduces fuel consumption and is easier on equipment. It is suitable for slopes between 3% and 8% and hence suitable for the study area since most of the agricultural area has a slope of greater than 3%. Contour farming limits soil loss to about 18 t /ha/year as compared to 46 t/ha/year when using conventional tillage (FAO, 1993).

Another watershed management practice that was simulated in SWAT was terracing which involves the use of the topography of the land to slow water flow through a series of terraces. This manipulation of the water flow prevents it from gathering speed and washing soil away from farmlands. Terracing is the making or forming of a sloping land into a number of level flat areas resembling a series of steps. It promotes absorption of water by the soil and saves soil from erosion. Another positive effect is the decrease in surface runoff, and increase in groundwater recharge. However when the slope is steeper (>8%) terracing becomes expensive and less effective (UNDP, 1990). In summary, blue water flow and resources, in quantity and quality, are closely determined by the management practices of upstream land users.

5.4.3 The watershed management practices for Arror River watershed

The study findings show that the practices that can enhance sustainability in Arror watershed are the construction of a reservoir, enforcement of minimum flow requirement in Arror River, the use of contour farming in agricultural lands, agro forestry, conservation of the forest cover, application of more efficient irrigation methods, keeping an optimum size of stock, among others. The best watershed management practices should be those that are targeted at increasing productive transpiration, reducing soil surface evaporation, controlling runoff, reducing flood risk, encouraging infiltration and groundwater recharge.

The construction of a reservoir across the river will help in two ways; boost the water supply in the area and control soil erosion by river floods. A dam generally checks the speed of water and saves soil from erosion. Contour ploughing is usually done at right angles to hill and hence the ridges and furrows break the flow of water downhill. This prevents excessive soil loss as gullies are less likely to develop and also reduce run off and this increases the amount of water received by plants. The area under forests should be increased by afforestation and indiscriminate felling of trees should be stopped as more forest cover leads to low runoff and increased infiltration hence more water retained within the watershed in form of ground water and some find their way to the wetlands. This in the long run will reduce droughts and floods among other disasters in the area.

Overgrazing in forests and grasslands should be properly checked. Separate grazing grounds should be earmarked and fodder crops should be grown in large quantities to avoid free movement of animals in the fields as they loosen the soil by their hoofs which lead to soil erosion. All these management practices if put in place will boost the economy of the region by increasing the revenue from agriculture, livestock keeping and industry. In addition to this, there will be other benefits like increased blue water availability. The benefits of green water credits in rain fed areas for instance can be mainly attributed to the reduced loss in fertile soil through erosion, while additional benefits occur as more blue water becomes available and less siltation of the reservoirs takes place.

These findings are in agreement with Westphal *et al.* (2003) who observed that a basin-level perspective enables integration of downstream and upstream issues, quantity and quality, surface water and groundwater, and land use and water resources in a practical manner. In this study SWAT model was used to simulate the impact of land use changes on river flows and thereafter simulate the effects of some watershed management practices. The WEAP model on the other hand was used to assess the water demand which includes the allocations and shortages in the study area. Water resource systems are directly and indirectly affected by the interaction of numerous human related drivers of economic, social, and demographic functions, including climate change as an uncertain driver. These interactions of the various drivers are what are defined as the watershed dynamics in this study. Therefore the findings of this study together with the discussions will enhance the understanding of the stakeholders on their roles in water resource management. However, consultation with stakeholders on their needs and objectives is very crucial and should be a continuous process.

CHAPTER SIX

CONCLUSION AND RECOMMENDATIONS

6.1 Conclusion

Based on the findings and discussions above the following conclusions were drawn:-

The residents of the Arror watershed had their own traditional ways of managing their water catchments. They adopted measures such as prohibition of the cutting of trees and firewood as traditional methods of watershed management practiced by the community. Each clan was assigned a forest in their jurisdiction to take care of and they were supposed to guard it against any intruder from other clans. They were also in charge of the enforcement of the laws that governed the forest protection and conservation. The study also concluded that residents also applied the modern watershed management methods. Agro-forestry was the most popular method followed by terracing, rainwater harvesting and mulching in that order. It was also found that most residents had not embraced destocking and contour farming as some of the methods that could enhance watershed management. The study further concluded that there were issues in watershed and water resource management. Some of the issues were conflicts (caused by water and other resources distribution), famine, forest destruction, and reduction in water flows in Arror River among others.

There have been a lot of land use/cover changes in Arror catchment. The major changes have occurred in the forest cover both the deciduous forest cover and coniferous forest over the period of twenty six year temporal period change. Apart from forest there was an increase in the proportion of agricultural land over the years. The causes of changes in the region were cutting of trees and encroachment by agriculture and settlement which have been accelerated by population pressure. The change in land use, over a period of time, had an impact on the hydrological processes in the catchment as illustrated by the river flows. As more forestland is converted to crop land, the amount of runoff increase and thus the discharge during the rainy seasons and very low during the dry seasons.

Agriculture and livestock keeping are the main economic activities in the study area. The upper and mid catchments depend mainly on rain fed agriculture while the lower catchment farmers depend on irrigation since rainfall there is quite erratic and scarce. In the whole catchment a large percentage of water is utilised for agriculture followed by livestock and the least is domestic. The mean annual water allocation over the period 1986-2012 showed that agricultre demand site in the lower catchment was allocated the highest amount of water. For the upper and the lower sub-catchments the highest demand was for agriculture while for the middle catchment livestock displayed the highest demand compared to the rest of the demand sites. The study concluded that agriculture was the main consumer of water throughout the year in Arror watershed. It is quite apparent that water demand is increasing with time and by the year 2040 there will be higher water shortages in the catchment if appropriate measures are not put in place.

On total monthly unmet demands, agriculture demand in the lower sub-catchment was the most affected. On the demand reliability, the domestic and livestock demand sites in the middle and lower sub-catchments were fully satisfied in all the scenarios over the period 2013-2040. The demand reliability in the reservoir added scenario was 100% for all the demand sites for the entire period. The ‘flow requirement added scenario’ on the other hand posted the lowest demand reliability for domestic and livestock demand sites in the upper sub-catchment. In general the unmet demands are expected to go up while demand coverage is expected to decrease in future if the same trend continues.

When the minimum flow requirement is enforced there will be high flows while a variation in climate based on historical trends yields the lowest mean annual flows over the 28 years. This means that if the climate changes at the same rate, then the river flows will decrease at a higher rate. It can also be concluded that increased irrigation agriculture results in decreased avarege monthly flows.

Water resource systems are directly and indirectly affected by the interaction of numerous human related drivers of economic, social, and demographic functions, including climate change as an uncertain driver. Residents and water managers of the Arror watershed should understand how different drivers of change affect the hydrology and therefore affect the related water demands and functions by the inhabitants in the basin. Setting up a viable IWRM framework is necessary as a platform for adapting to changes where the adaptation responses to those changes can be prioritized. Reassessment of basin hydrology improves understanding of a changing water cycle and can be an opportunity to consider and address special drivers such as climate, land-use changes, and the agricultural footprint.

The watershed management practices that could enhance the sustainable management of Arror watershed are the construction of a reservoir with a storage capacity of 100 million m^3, enforcement of minimum flow requirement in Arror River, the use of contour farming in agricultural lands, agro forestry, conservation of the forest cover, application of more efficient irrigation methods and keeping of optimum livestock size.

In summary, degradation has occurred and has had an impact on the water quantity which in turn has caused high levels of unmet demands in the watershed. In addition to that, water demand is on the rise and has caused a decrease in water quantity and if proper management is not put in place water scarcity will be severe in the near future. This shows that watershed management dynamics have had an impact on the quantity of Arror River. There is therefore need for proper planning and management of the catchment so as to address the issues that have caused its degradation. Similarly, the water resources available in the watershed should be managed well and utilized more efficiently. This will in the long run lead to sustainable watershed management. However, it is worth noting that every river has its maximum capacity. Nevertheless, the rivers cannot exceed its carrying capacity despite improvement on watershed management and conservation. Thus, the main goal of watershed management is to achieve the optimum capacity of a river.

6.2 Recommendations

Based on the findings of the study and the conclusions made above, the following recommendations are made: -

i. The residents of Arror watershed should integrate both traditional and modern methods of water resource and watershed management practices.

ii. A reservoir whose main purpose will be irrigation and generation of hydroelectric power should be constructed in the watershed. This will ensure water availability throughout the year and in all parts of the watershed (upstream, mid-stream and downstream) and check soil erosion as well.

iii. The maintenance of minimum environmental flows in the Arror River should be observed. If the environmental minimum flows were to be ensured in Arror River the water shortages will be minimized in the watershed. This will lead to ecological sustenance of the river ecosystem.

iv. On soil conservation, the farmers should be encouraged to practice contour farming and terracing especially on steep slopes. This will help check the rate of runoff on the steep slopes hence reducing soil erosion. This in the long run will help in minimizing soil degradation, flooding and landslides during heavy rainfall seasons as well as sedimentation of the water bodies.

v. Excavation of dam, clearing of water ways as well as pruning of trees and excessive shrubs should be done between December and March since this is the dry season and thus the most appropriate time for such activities.

vi. Water harvesting should be done between April to October since this is the rainy season and if water is not collected and stored a lot of it will be lost through runoff and the area will experience high shortages during the dry season. The water harvested will then be utilized during the dry months.

vii. Agroforestry should be encouraged and trees planted especially during onset of the rainy season that is April and May.

viii. The importance of water should be recognized at the highest level of decision-making as well as at the watershed level. Food security, gender, health, environment, industry and many other objectives are closely related to sound water resources management. This recognition will help conserve waters at all catchment areas be it downstream, middle or upstream as well as prioritize water allocation to the various uses in a way that will ensure the satisfaction of the basic needs first.

6.3 Recommendations for Further Research

i. Based on the results of the study, it is quite apparent that the maintenance of environmental flows will help improve the management of water resources in the study area. It is therefore recommended that a study be carried out so as to establish the minimum environmental flows for Arror River as every catchment has unique characteristics that need to be considered when determining the levels.

ii. The results of the study indicated varied human activities within the Arror catchment and hence need for a further study to ascertain the effects of land use/land cover on the water quality of Arror River.

iii. As shown by the results of this study, a reservoir should be constructed in the watershed. An assessment of the catchment should therefore be carried out with a view of identifying the best location, its capacity and other parameters required as well as its prospects for hydroelectric power production.

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APPENDICES

APPENDIX I: QUESTIONNAIRE

Catherine Chebet of Moi University is conducting this interview for purpose of research. The information provided will be used to analyse the impacts of alternative watershed management practices on water quantity in Arror River, Marakwet district. The information obtained will be kept strictly confidential and used solely for the purpose of thesis writing. Your co-operation and contributions is highly appreciated.

Date----------------------------------- Site -------------------------------------

1. Respondent's sex
   a) Female b) Male

2. Age (in years) -----------

3. Occupation
   a) Farmer b) Civil servant
   c) Teacher c) Any other specify ---

4. What is your level of education?
   1. Primary level 2. Secondary level
   3. Tertiary level 4. University
   5. Never went to school

5. What is the land tenure?
   a) Communal land ownership b) individual land ownership

6. What is the size of your land?
   a) Less than 1 acre b) 1 acre to 1.5 acres
   c) 1.5 to 2 acres d) Greater than 2 acres
7. What is the size of your household? --

8. How much water do you use per day in the household? ---------------------

9. If a farmer in 3 above, which type of farming?
   a) Arable farming b) Livestock keeping

10. What crops do you plant in your farm?
    a) Maize b) Beans
    c) Millet d) any other specify------------------------

11. What is the main purpose of your farming?
    a) Subsistence b) Commercial

c) Both

12. Based on water sources what type of arable farming do you practice?
    a) Irrigated agriculture b) Rain fed agriculture

13. If irrigated agriculture, what is the source of the water?
    a) River b) well
    c) Dam d) Any other specify ---------------------

14. How much area is cultivated? (in acres)
    a) Rain fed agriculture ----------------- b) Irrigated agriculture---------------

15. Which crops are under irrigation?

16. Is the water enough for your irrigation throughout the year?
    a) Yes b) No
17. If no during which months of the year is the water not enough?-----------------
18. If livestock, which ones?
    a) Cattle b) goats
    c) Sheep d) All the above
    e) Any other specify------------------------------
19. What is the size of your stock? -------------------------
20. How many times do you water your animals per day? ----------------
21. Is the available water enough for your stock?
    a) Yes b) No
22. If no, is the problem seasonal or throughout the year?
    a) Seasonal b) Throughout the year
23. If 'a' in 18 above when and for how long? --
24. If 'no' in 17 above, then what measures have you put in place so as ease this problem?
    (i)--
    (ii) --
    (iii) ---
    (iv) ---

25. What traditional methods were used by the community in the past to manage water resources in the study area?
    (i)--
    (ii) --
    (iii) ---
    (iv) ---
26. What water resource management practices do you apply in your farm if any?
    (i)--
    (ii) --
    (iii) ---
    (iv) ---

27. In your own opinion what are the water resource concerns in the region?
    (i)---
    (ii) ---
    (iii) --
    (iv) --

28. For the concerns raised in 23 above what do you think should be done so as to curb these issues?
    (i)---
    (ii) ---
    (iii) --
    (iv) --

29. Are there any conflicts between you and your neighbours?
    a) Yes b) No

30. If yes in 25 above, what do you think are the causes?
    (i)---
    (ii) ---
    (iii) --
    (iv) --

31. In your own opinion, what can be done so as to reduce such conflicts?
    (i)---
    (ii) ---
    (iii) --
    (iv) --

32. What do you think about the utilization of water in the watershed?
    a) It is being underutilized b) Utilized efficiently
    c) Over utilized

33. If 'a' in 28 above, what can be done so as to ensure that water is utilized efficiently in the watershed?
    (i)---
    (ii) ---
    (iii) --
    (iv) --

34. Do you at any given season experience famine in the region?
    a) Yes b) No

35. If yes in 30 above, suggest the measures that can be put in place so as to eradicate this phenomenon
    (i)---

(ii) --
(iii) --
(iv) --

36. Are you aware of any policies, legislation and institutions that are concerned with water resource management practices?
    a) Yes b) No
37. If 'yes' in 32 above, name them
    (i)--
    (ii) --
    (iii) --
    (iv) --

38. What are the impacts of the policies, legislation and institutions in 33 above on existing water management practices?
    (i)--
    (ii) --
    (iii) --
    (iv) --

APPENDIX II: POPULATION OF ARROR WATERSHED 1986-2012

YEAR		POPN	
	Lower catchment	MID CATCHMENT	UPPER CATCHMENT
1986	2863	13458	14473
1987	2960	13916	14965
1988	3061	14389	15473
1989	3165	14878	15727
1990	3256	15310	15903
1991	3351	15754	16080
1992	3448	16211	16260
1993	3548	16681	16441
1994	3651	17164	16625
1995	3757	17662	16811
1996	3866	18174	16998
1997	3978	18701	17188
1998	4093	19244	17380
1999	4212	19647	17574
2000	4362	20160	18201
2001	4518	20686	18851
2002	4679	21226	19524
2003	4846	21781	20221
2004	5019	22349	20943
2005	5199	22933	21691
2006	5384	23531	22465
2007	5576	24146	23267
2008	5776	24776	24098
2009	7292	25423	25903
2010	7489	26109	26602
2011	7691	26814	27321
2012	7899	27538	28058

Source: Republic of Kenya Population census of 1979, 1989, 1999 and 2009

APPENDIX III: ARROR WATERSHED LIVESTOCK POPULATION 1986 TO 2012

		LOWER CATCHMENT				MIDDLE CATCHMENT				UPPER CATCHMENT		
YEAR	CAT	DONK	GOAT	SHEEP	CAT	DONK	GOAT	SHEEP	CAT	DONK	GOAT	SHEEP
1986	4504	88	17662	3621	16252	2322	6332	54876	8047	635	2036	11745
1987	4678	92	18346	3761	16881	2412	6577	57000	8358	660	2115	12200
1988	4859	95	19056	3906	17534	2505	6831	59206	8681	685	2197	12671
1989	5947	117	23320	4781	18213	2602	7096	61497	9017	712	2282	13162
1990	6079	119	23838	4887	19280	2754	7512	65102	9381	746	2348	13756
1991	6214	122	24367	4995	20410	2916	7952	68918	9765	782	2417	14385
1992	6352	125	24908	5106	21607	3087	8418	72958	10169	821	2488	15052
1993	6493	127	25461	5220	22873	3268	8912	77235	10596	861	2561	15759
1994	6637	130	26026	5335	24214	3459	9434	81762	11046	905	2637	16510
1995	6784	133	26604	5454	25634	3662	9987	86555	11522	951	2715	17306
1996	6935	136	27195	5575	27136	3877	10573	91629	12024	1001	2796	18153
1997	7089	139	27799	5699	28727	4104	11192	97000	12555	1053	2879	19052
1998	7246	142	28416	5825	30411	4344	11848	102687	13118	1109	2966	20009
1999	7407	145	29047	5955	32194	4599	12543	108706	13713	1169	3055	21028
2000	7571	148	29692	6087	32891	4699	12815	111060	14055	1198	3131	21551
2001	7740	152	30351	6222	33603	4800	13092	113465	14405	1228	3210	22088
2002	7911	155	31025	6360	34331	4904	13376	115923	14765	1258	3290	22638
2003	8087	159	31714	6501	35074	5011	13665	118433	15133	1290	3373	23201
2004	8267	162	32418	6646	35834	5119	13961	120998	15510	1322	3458	23779
2005	8450	166	33138	6793	36610	5230	14264	123619	15897	1354	3544	24371
2006	8638	169	33874	6944	37403	5343	14573	126296	16294	1388	3633	24978
2007	8830	173	34626	7098	38213	5459	14888	129031	16701	1423	3724	25600
2008	9026	177	35394	7256	39041	5577	15211	131826	17117	1458	3818	26238
2009	9226	181	36180	7417	39886	5698	15540	134680	17544	1494	3913	26891
2010	9549	187	37447	7677	41282	5897	16084	139394	18158	1547	4050	27832
2011	9883	194	38757	7945	42727	6104	16647	144273	18794	1601	4192	28807
2012	10229	201	40114	8223	44222	6317	17230	149323	19452	1657	4339	29815

Source: Republic of Kenya Population census of 1979, 1989, 1999 and 2009

APPENDIX IV: AREA UNDER IRRIGATION IN ARROR WATERSHED

YEAR	LOWER CATC (M^2)	MID CATCHM (M^2)	UPPER C (M^2)
1986	2517605	441179	280730
1987	2615036	458252	291594
1988	2716238	475986	302878
1989	3324042	494407	314599
1990	3397846	523389	339078
1991	3473288	554070	365514
1992	3550406	586550	394068
1993	3629235	620934	424908
1994	3709815	657333	458221
1995	3792184	695865	494207
1996	3876382	736657	533080
1997	3962449	779840	575076
1998	4050428	825554	620446
1999	4140359	873948	669463
2000	4232288	892874	685982
2001	4326257	912211	702912
2002	4422313	931967	720260
2003	4520502	952150	738036
2004	4620870	972771	756251
2005	4723468	993838	774915
2006	4828343	1015362	794040
2007	4935546	1037352	813637
2008	5045130	1059818	833717
2009	5157147	1082770	854294
2010	5337648	1120667	884194
2011	5524465	1159890	915141
2012	5717821	1200487	947171

Source: Field survey

APPENDIX V: ANNUAL OBSERVED AND SWAT SIMULATED DATA

YEAR	OBSERVED	SIMULATED
1986	2.12	2.19
1987	2.09	1.93
1988	2.10	2.23
1989	1.36	1.72
1990	2.58	3.18
1991	2.76	2.63
1992	2.49	2.52
1993	2.38	2.29
1994	2.23	1.98
1995	2.41	2.28
1996	2.79	2.67
1997	1.76	1.91
1998	1.76	1.71
1999	1.62	1.47
2000	1.19	1.22
2001	2.20	2.42
2002	2.29	2.36
2003	1.86	2.43
2004	0.87	1.27
2005	1.65	1.62
2006	2.90	2.72
2007	2.48	2.35
2008	0.91	1.07
2009	1.56	1.72
2010	1.93	2.08
2011	1.58	1.81
2012	1.76	1.62

APPENDIX VI: SIMULATED ARROR RIVER FLOWS FOR 1986, 2000 AND 2012 LAND USES

	LU_1986	LU_2000	LU_2012
1986	2.12	2.22	1.89
1987	2.21	2.31	1.96
1988	2.23	2.45	2.11
1989	1.72	1.96	1.68
1990	3.18	3.22	2.83
1991	2.63	2.94	2.51
1992	2.52	2.67	2.16
1993	2.29	2.73	2.31
1994	1.98	2.21	2.01
1995	2.28	2.77	2.34
1996	2.67	3.12	2.54
1997	1.91	2.69	2.18
1998	1.71	2.17	1.63
1999	1.47	2.09	1.26
2000	1.22	1.43	1.14
2001	2.42	3.15	2.27
2002	2.36	3.18	2.41
2003	2.43	2.60	2.03
2004	1.27	1.82	1.41
2005	1.62	2.14	1.53
2006	2.72	2.91	2.44
2007	2.35	2.80	1.97
2008	1.07	2.01	1.32
2009	1.72	2.31	1.54
2010	2.08	2.35	2.17
2011	1.81	1.79	1.43
2012	1.62	2.07	1.33

APPENDIX VII: OBSERVED AND WEAP SIMULATED DATA

Year	Observed	Simulated
1986	2.13	2.36
1987	2.10	2.03
1988	2.11	2.01
1989	1.36	1.57
1990	2.58	2.33
1991	2.77	2.46
1992	2.50	2.35
1993	2.37	2.33
1994	2.24	2.32
1995	2.41	2.40
1996	2.80	2.41
1997	1.76	1.75
1998	1.77	1.93
1999	1.63	1.73
2000	1.19	1.26
2001	2.21	2.52
2002	2.30	2.32
2003	1.85	1.76
2004	0.87	1.49
2005	1.66	1.56
2006	2.92	2.80
2007	2.49	2.55
2008	0.92	1.40
2009	1.56	1.64
2010	1.93	1.85
2011	1.58	1.74
2012	1.77	1.85