# DROUGHT POLICY DEVELOPMENT AND ASSESSMENT IN EAST AFRICA USING HYDROLOGIC AND SYSTEM DYNAMICS MODELING

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# ABSTRACT

Gies, Lauren, M.S., Purdue University, August 2013. Drought Policy Development and Assessment in East Africa Using Hydrologic and System Dynamics Modeling.
Major Professor: Venkatesh Merwade

Drought is a natural disaster that affects millions of people across the globe. Lack of rainfall reduces crop yields and livestock productivity and in turn, food availability and income. In developing countries, these effects are even more detrimental. As droughts become more frequent, adaptation is a fundamental concern for countries and their policy makers. Hydrologic and system dynamics models were developed for a region in East Africa, focused on the Horn of Africa (i.e. a region bordering Kenya, Somalia, and Ethiopia), an area well-known for frequent droughts due to unpredictable rainfall and high temperatures. The models simulate the interdependencies between water availability, land degradation, food availability, socio-economic welfare and the impact new adaptation policies can have on the region over a 10 year simulation. It was found that a combination of increased hydraulic infrastructure and innovative agricultural practice policy can reduce domestic water deficits by 54-100% while increasing the income per capita up to 285% over the 10 years. By innovatively combining hydrologic and system dynamics modeling, realistic simulation of the effects water scarcity has on natural systems can be observed. Implementation of policies within the model aids the selection process by evaluating multiple options, quantifying the effectiveness the policies have on individual stakeholder livelihood, and analyzing the overall outcome to ensure equitable costs and benefits.

# CHAPTER 1 INTRODUCTION

Natural disasters occur throughout the world, often with no warning. They can cause millions of dollars in economic losses and have a drastic effect on the lives of those affected. In developing areas, these disasters frequently result in a population that struggles to support itself, requiring outside assistance to get through this period of uncertainty. When disaster hits a large enough area, this outside relief cannot reach or support the entire population effected and the disaster can lead to catastrophic consequences: famine, displacement, and death. A prime example of such a disaster is drought.

For hundreds of years, semi-arid and arid lands have dealt with frequent and uncertain droughts. The shortage in water supply often leads to a lasting effect on the population. People's livelihoods are threatened or even diminished completely, leaving behind a weakened, deteriorating society that can barely recover. In 1992/1993, Southern Africa suffered through widespread drought. Specifically, over 40% of Namibia's population was affected by food shortages and the cost of relief was over $60 million US dollars (Sweet, 2008). No famine deaths were reported in this region during the drought, as a result of over five million metric tons of relief food supplied by international donors (Callihan et al, 1994). Dependence on outside aid is not a viable solution to avoid potentially catastrophic outcomes; policymakers strive to implement innovative and supportive strategies to reduce these effects. Ideally, proper drought adaptation measures would results in a resilient population, sustaining themselves through times of drought by means of adaptive measures and a reliable infrastructure. Resilient meaning the population would recover from the effects of drought quickly. In order to do this, policymakers need to understand the different systems affected by drought and which adaptation policies will most efficiently alleviate the detrimental consequences of a water shortage.

## 1.1 Previous Studies

Drought adaptation has been studied extensively. Previous studies have focused on drought and the specific effects that individual systems face due to limited water availability. Because drought is a reoccurring phenomenon and the regions affected by drought are vast, understanding the complex systems and their involvement with drought is essential to determine beneficial policies.

### 1.1.1. Drought and Natural Systems

Drought also has an effect on the natural environment and causes ecological changes. A study done by Moore et al (2012) concluded that food security and crop yield in general, is very vulnerable to climate change mainly due to the corresponding effects on land use and land cover change. They noted that land use and land cover change is a primary driver of food production risk and drought negatively effects land productivity. They also note that there will be impacts on other human systems such as water availability and livestock health, but do not directly include these systems in their analysis.

Each system responds to drought and water shortages differently and has the potential to affect other systems indirectly. There is a strong correlation between rainfall variability and livestock dynamics; it has been shown that in times of drought, calving rates and animal mortality rates will be affected. Angassa and Oba (2007) studied these effects on both communal and range management cattle systems in southern Ethiopia and found that there is not a significant benefit with range operated systems over traditional pastoral management, but there is a significant correlation between rainfall variability and breeding females and immature animals. They made policy suggestions based on their findings to improve livestock management, such as improved market access through transport subsidies and a drought insurance system for pastoralists, but they did not model the benefits or potential effects these policies may produce.

Livestock dynamics in relation to drought and recovery has also been studied extensively by McCabe (1987) in relation to nomadic, pastoral Kenya. He details the specific stresses that pastoral livestock keepers face in relation to drought in hopes of implementing changes that promote resilience during extended dry periods. Through a study period of five years, McCabe monitored the livestock mortality and recovery of a pastoral region that experienced two droughts. Though this brought a greater understanding of increased livestock mortality due to drought and the corresponding recovery period for pastoralist herds, the policy options to help mitigate these effects were not explored.

Additionally, there has been a study done on rain variability and the effect on livestock production and mixed farming to determine the effect on land change and land use alteration in an effort to establish best management practices (Biazin and Geert, 2013). The study concludes that the transition from traditional pastoralism to a crop-livestock mixed farming system is a better way to cope with drought as this allows a more diversified source of income. This paper monitors and observes these agricultural trends and relationships between drought and land-use practices, although it does not model the direct relationship or alternative solutions to maximize benefits.

There have even been studies done on the correlation between food, resilience, and drought adaptation (Rockström, 2003). Understanding the link between food security and rainwater management is essential for the many regions that rely on rain fed agriculture. Rockström also addresses the importance of land degradation in relation to food security. Natural resources are becoming more vulnerable to extreme weather due to poor management and population growth. This paper also evaluates multiple policies that aim to strengthen the resilience of the populations effected through techniques like water harvesting, conservation farming, and improved water management. The connections between these systems are clearly explained, but the impact that possible adaptation policies can have on said systems are not quantified in any way.

### 1.1.2. Modeling Natural Systems Using System Dynamics

These studies effectively present the relationship between drought and affected systems, but they do not model the interaction between them. A methodology that is increasingly being used to simulate complex relationships is system dynamics modeling approach. Systems dynamics modeling can successfully reveal the complex relationship between different systems. In the case of drought, system dynamics has the potential to show the effect new adaptation policy options may have on the overall livelihood of a region. This modeling helps to understand complex relationships and potentially exposes unforeseen interdependencies between systems.

Saysel, Barlas, and Yenigün (2002) used a system dynamics approach in order to model the relationships involved with agricultural development. Although independent of extreme climate effects, they were able to show the correlation between land degradation and overall production based on water availability, population, energy and market behavior. With their system dynamics model, they were able to introduce new policy options that would improve and increase long-term environmental sustainability.

System dynamics has also been used by Bontkes (1993) to study and model rural development in southern Sudan. The goal of the modeling was to determine the best way to improve living conditions for the rural population in Sudan who were poor and relied on agriculture and animal husbandry to survive. This study focused on four interacting sectors: population, food consumption, crop production (sorghum), and livestock production. The model goal was to increase food security and living conditions for the population. Though the model was able to link these sectors well, the study concluded that the policy options explored did not produce substantial benefits and he suggests that expanding the analysis to the dynamics of the larger system would improve the decisions regarding selection of beneficial intervention.

## 1.2. Knowledge Gap

System dynamics methodology has been shown to be a powerful tool for modeling systems and policies, but it has not been used in conjunction with hydrologic modeling in order to simulate drought and adaptation policies. Many previous studies note the critical connections between drought, water availability, and their contingent systems; however, none of the studies have successfully combined all the systems related to drought in order to gain a complete understanding of the interdependencies between them in relation to the livelihood of the population. It is important to recognize these associations when implementing drought adaptation policy in order to maximize the effectiveness and extent of relief. Additionally, although many of these studies suggest possible adaptation strategies, they do not model nor attempt to quantify the potential affects the policies may have. This is a critical step in assessing the impact and potential success a policy holds.

## 1.3. Research Objective

The hydrologic and system dynamics modeling presented in this paper, seek to understand the effects of drought due to limited water availability and explore possible methods to alleviate or improve these undesirable consequences. The modeling will focus on water availability, land change, livestock production, agricultural production, and social welfare. A simplified framework of the system dynamics relationships is shown in Figure 1.1.

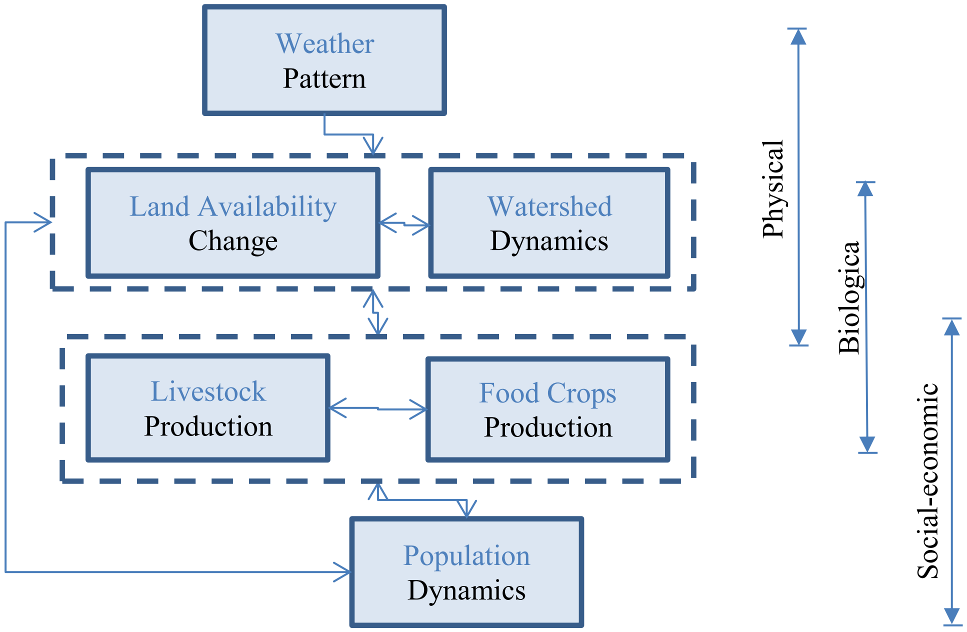


Figure 1.1: Interdependent systems affected by drought (Agusdinata, 2012)

The objective of this study is to create a system dynamics framework for policymakers that will help in the understanding of interdependencies across multiple systems affected by drought: physically, biologically, and socio-economically. Hydrologic modeling can simulate the water cycle for a given region using climate and geological data. Using water availability data from the hydrologic model, system dynamics modeling can be used to show different effects and interdependencies due to water availability and scarcity over time. Additionally, the systems dynamic model has the ability to incorporate new adaptation measures and compare the impacts between scenarios in order to measure improvements or breakdowns within the systems. Many of the of the systems effected by drought have been studied, but they have not been modeled and simulated in order to introduce and evaluate mitigation policies that may drastically improve the well-being of the populations suffering through drought. By understanding these complex relationships and evaluating different scenarios for drought adaptation, the system dynamics modeling can be a powerful tool for policymakers when they are selecting the best solution or combination of solutions for drought adaptation.

# CHAPTER 2 BACKGROUND

The simple definition of drought is a period of water shortage. If this period is lengthy, the shortage in water supply will have a trickledown effect on many other aspects of society. The severity of the drought and its effects will depend on a number of factors: the duration of the water shortage, the degree of soil moisture deficiency, and the size of extent of the affected area.

From a meteorological point of view, drought is seen as a departure from normal rainfall for a region (Wilhite, 2005). This will affect the hydrological elements in the region because reduced rainfall leads to reduced surface runoff. Subsurface water resources can also become depleted during prolonged periods of drought. Dependence on groundwater will increase during dry periods and sources will become strained after prolonged periods of drought. The lack of available water will begin to gradually affect other aspects of society. Agricultural drought will be experienced as soil moisture is diminished, resulting in crops losses. Additionally, natural shrubbery will begin to exhibit the effects of soil moisture depletion, reducing the available grazing land for pastoralists and their livestock. With a limited water supply, the health and quality of livestock will begin to suffer, diminishing their value. This will affect market prices and corresponding income due to livestock sales. All of these results will affect the local population. They will be competing for water use, struggling to support their crops and livestock, a key source of income, and may eventually be displaced from their land in search of opportunity.

## 2.1. Study Area

Over the past few decades, the Horn of Africa has been struck by multiple droughts, leaving a majority of the population in a food crisis. They have become dependent on outside aid to sustain their populations. Over $1 billion (US) in aid has been committed to this region in response to the effects of drought and more is needed (IFRC, 2011). Additionally, Somalia has been under political turmoil and civil war, resulting in a large migratory refugee population spilling in to Ethiopia and Kenya. Because drought is an expected occurrence for this region, proactive drought adaptation policies need to be implemented in order to ease the effects of drought and sustain a resilient population.

The hydrologic and systems dynamic modeling will be focused on this region in East Africa known for its arid climate. It is part of the Juba River Basin and encompasses parts of Southern Ethiopia, Eastern Kenya and Southern Somalia. The study area is centered on the Mandera Triangle in the Horn of Africa as seen in Figure 2.1. The modeled watershed has an area of approximately 537,023 sq. km, extending from 36.2 to 45.0 east latitude and 7.5 north longitude to -2.5 south longitude. The watershed for this region is broken up into 11 subwatersheds and covers roughly 203,260 sq. km of Kenya, 170,008 sq. km of Somalia, and 163,755 sq. km of Ethiopia. The outlet of the basin is the culmination of the Juba and Shabelle Rivers, located in southern Somalia and discharges into the Indian Ocean.

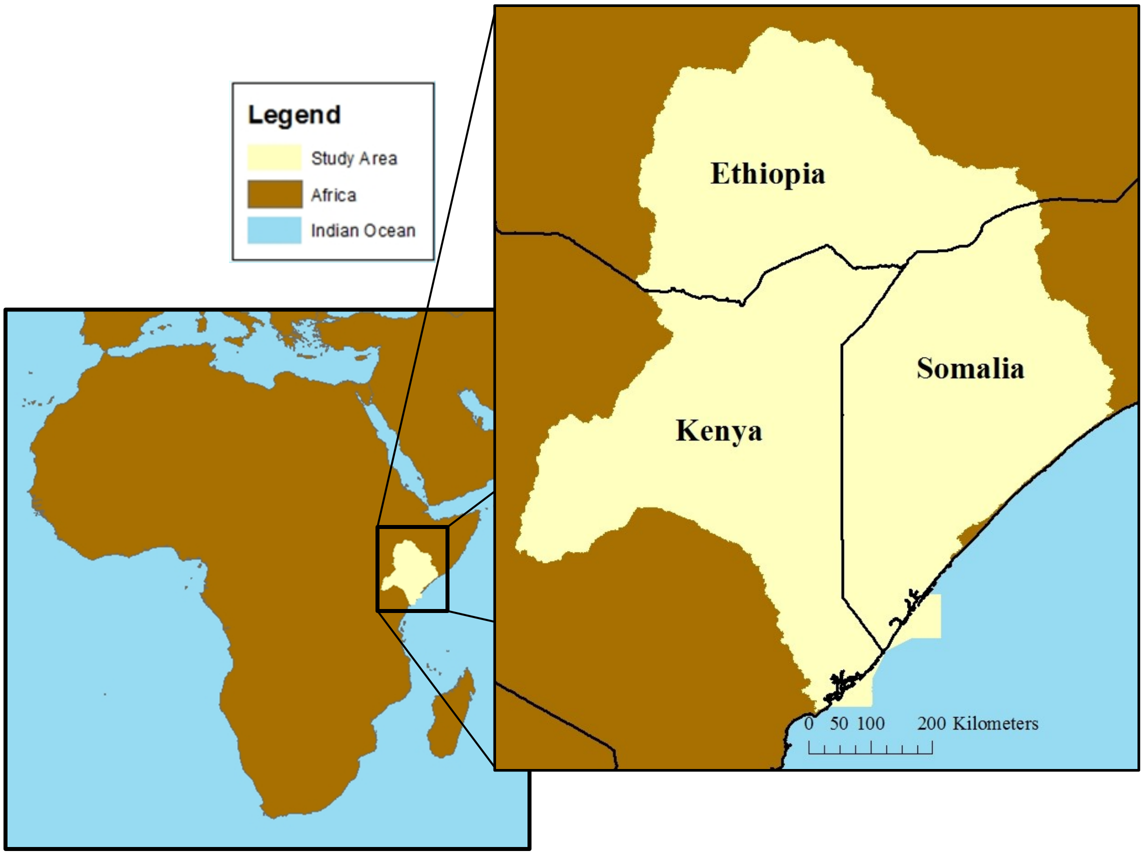


Figure 2.1: Study area for hydrologic and system dynamics modeling

The region is known for its arid climate and primarily depends on two rainy seasons: long rains from March to June known as Gu and short rains from October to November called Deyr (Frenken, 2005). This rainfall pattern is illustrated in Figure 2.2 along with monthly rainfall averages for the three regions within the study area using the National Centers for Environmental Prediction (NCEP) Climate Forecast System Reanalysis (CFSR) data. Average rainfall for the region varies from 200-600 mm a year and is often unreliable (Nicholson, 1996). This region is mainly pastoral and depends on communal rangeland for their livestock to graze. There are also rain-fed agricultural regions within the study area and agro-pastoralists whose livelihood depends on agriculture and livestock. Pastoralists in this region are not a homogeneous group; they vary on their dependence to livestock, their level of mobility, their ethnically, and by many other factors (REGLAP, 2010).

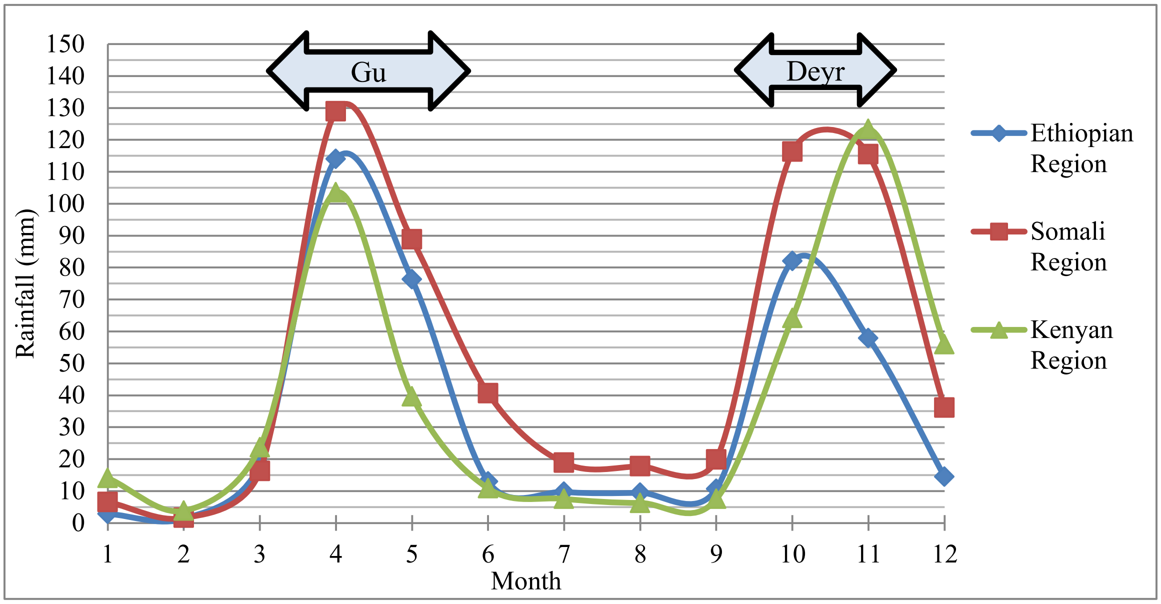


Figure 2.2: Monthly average rainfall for the regions within the study area

## 2.2. Effects of Drought

Unreliable rainfall and an arid climate make water availability a focal concern for Eastern Africa; limited water availability causes multiple breakdowns to a sustainable way of life. This region relies heavily on rainfall to supply water in regards to all aspects of life: domestic and agricultural. When this water supply is reduced because of drought, all facets of life begin to suffer.

### 2.2.1. Land Alteration

Land use and cover, especially agricultural crops, are affected by the amount of rainfall received as well as the total population using the land. Often land change or land degradation is associated with human alteration and expanding populations. However, it has been found that environmental change can occur with no population change at all (Reid, 2000). While it has been observed that semi-arid lands that are kept free from human impacts do not undergo degradation or desertification, this study region is influenced by pastoral communities and their livestock (Lehouerou, 1996). East African grazing lands are often at risk of degradation due to high stocking rates of livestock, erosion, and impaired rainfall infiltration (Prins, 1989). When drought occurs, livestock have to travel further for forage and water.

Drought is a normal feature for arid climates and its effects are usually temporary; thus, it affects production but not productivity in the long-term (Lehouerou, 1996). The Horn of Africa practices dry land agriculture, relying solely on rainfall to water their crops; thus, yields are directly correlated to annual rainfall.

### 2.2.2. Livestock Consequences

The Horn of Africa has a large pastoral presence accounting for approximately 37-87% of total household income and encompassing much of the region's widespread grazing land (Solomon, 2003). In order to survive during the bimodal rainfall seasons, pastoralists move their herds throughout the year to find available sources of water and forage. During a drought, herds must travel further to access a limited water supply. The carrying capacity of the grazing land is closely linked to the total sustainable livestock population; however, pastoralists tend to overlook this concept of carrying capacity and overexploit communal land (Lehouerou, 1996). Drought conditions also affect the calving and mortality rates of livestock. Mortality rates increase during times of drought for both mature and immature animals, while calving rates significantly decrease during drought, quickly depleting overall herd size (McCabe, 1987).

### 2.2.3. Socioeconomic Factor

The ecological effects of drought eventually begin to impact society and their livelihood. First, there are the market effects on agriculture: both crops and livestock. Second, the lasting effect of drought may force people to migrate in search of opportunity. And finally, there is the necessity to fund mitigation options to reduce these expected drought conditions which of often costly.

Approximately 80% of the population in the Horn of Africa relies on livestock and agriculture sales as a primary source of food and income (FAO, 2013). Drought is a productivity shock for this region. Unlike grain prices that will typically rise, livestock prices do not stabilize pastoralist incomes in the face of one of these shocks as animal quality will be highly variable; livestock prices and mortality rates are negatively correlated (Barrett, 2001). This means that during a drought, livestock have higher mortality rates due to less water and forage availability and also sell for less at market. It has been observed that in good rainfall years, prices will be high and fairly stable, but during a period of drought they are low and volatile. The instability of income during drought, coupled with lower land productivity and overall low water availability can lead to population migration. Based on the severity of the drought and the corresponding effects on livelihood, this migration may be a choice or forced; households will be looking for supplementary income for sustenance or searching for any opportunity available (Meze-Hausken, 2000). The only way to avoid these effects is to invest in mitigation techniques and infrastructure that enable a more resilient population. Unfortunately, the average income in the study region is very low and these improvement options are very costly. Thus, most of the population does not have the extra capital necessary to implement adaptation techniques and must rely on government or other outside assistance.

## 2.3. Drought Adaptation

Drought is a naturally occurring phenomenon, and it is known that droughts will sporadically but consistently occur within the study region. The issue of drought adaptation in relation to resilience building is integral in understanding the link between crop failure and famine (Rockstrom, 2003). It has been observed that a short dry spell will affect ecological systems differently than a prolonged drought, but some negative outcomes are avoidable through better management practices, innovation, and improved infrastructure.

The key for policy makers is to be proactive rather than reactive in their policy implementation (Wilhite, 2005). It will be more cost-effective and result in a population that is self-reliant and can recover quickly. This requires an integrated system that understands the connection between society and the environment. The policies applied should be able to absorb an outside disturbance and maintain a satisfactory outcome (Rockström, 2003). With systems dynamics, policymakers can learn and adapt different strategies to develop the most beneficial and effective policies. In the case of drought, policies implemented should be aimed to improve livelihood resilience during periods of water shortage. One way this can be achieved is through additional hydraulic infrastructure, built to increase the capacity of total water availability. Additionally, vulnerabilities can be reduced by introducing new innovative agricultural modifications as an alternative to traditional rain fed agriculture to diversify income and produce crops that are not solely dependent on rainfall.

# CHAPTER 3 MODELING DROUGHT AND ITS EFFECTS

Drought has various effects across multiple systems. This paper focuses on watershed dynamics and water availability, population dynamics, livestock and crop production, land alteration, and social welfare. The hydrological modeling was done through the Soil and Water Assessment Tool (SWAT) program to determine the water availability throughout the region. This data was then introduced into the system dynamics modeling software, Vensim (http://vensim.com/), to monitor existing conditions and introduce new policy options.

## 3.1. System Dynamics Approach

System dynamics modeling simulates interdependent dynamic systems in order to determine how they are affecting each other over time. The system dynamics model consists of stocks (or levels) which accumulate and recall values over time, flows (or rates) that affect them, and other variables that can affect stocks and flows. The system dynamics modeling reveals cause-effect polarity and feedback loops between system variables and factors. These feedback loops determine how systems influence one another.

### 3.1.1. System Dynamics for East Africa

A system dynamics model is used to assess the impact of drought adaptation policies on human population and their livelihood within the study region. Using the hydrologic model results as water availability input, other systems were built and linked based on their known interdependencies using literature and available data as a foundation. A simplified version of the systems dynamics model is displayed in Figure 3.1 which highlights the five systems being investigated: water availability, land dynamics and crop production, population dynamics, livestock production, and socio-economic welfare.

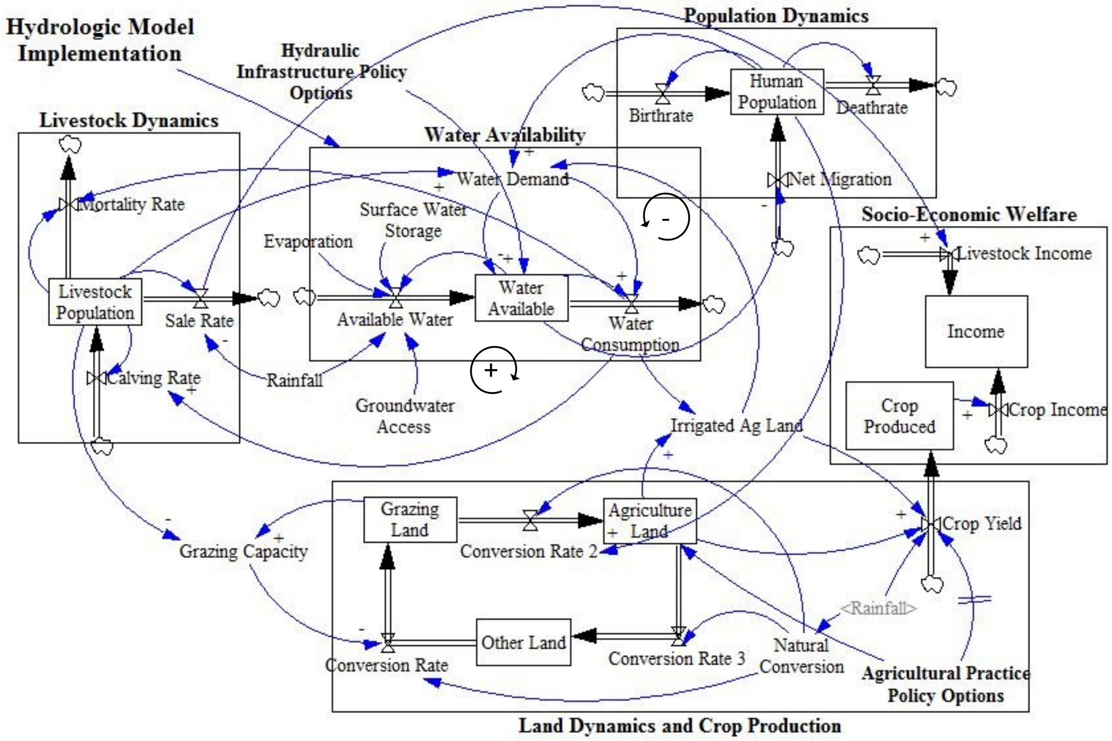


Figure 3.1: System dynamic framework for linking the systems affected by drought

For this model, a stock can be seen as “Livestock Population” which increase and decreases based on the rates in and out, or “Calving” and “Mortality” rates. A negative feedback loop is shown between the population dynamics and water availability. As the population grows, so does the water demand; this reduces the total volume of water available, reducing consumption available for the population. This will increase migration out, decreasing the population.

Conversely, a positive feedback loop is shown between the livestock dynamics and water availability. Increased water consumption will increase the calving rate. This will lead to a larger livestock population, a larger water demand, and larger water consumption.

## 3.2. Hydrologic Model – Watershed Dynamics

The Soil and Water Assessment Tool (SWAT) is a physical based watershed model developed for the United States Department of Agriculture (USDA) Agricultural Research Service to simulate the water cycle and the effects of various land management practices (http://swat.tamu.edu/). The model requires weather data, soil properties, topography, and land use data for the area of interest and simulates long term water balance within a watershed (Neitsch, 2011). This model was used to simulate the watershed dynamics and determine water availability for the study area.

The model defines a watershed based on topographic input and a user defined threshold. The watershed is further broken up into smaller subwatersheds (or subbasins). Based on soil and land use data, these subbasins are divided up into single or multiple hydrological response units (HRUs). An HRU is a grouped land area within a subbasin that is distinguished by a unique land cover, soil, and management combination. The model simulates the responses of each individual HRU and then aggregates the results to the subwatershed level along with the associated reach through the stream network.

SWAT follows the water balance equation in order to track water movement throughout the basin. This cycle is broken up into two phases. The first is the land phase that controls the amount of water that reaches the main channel in each subbasin. It is based on the following equation (Neitsch et al, 2011):

$$SW_t = SW_0 + \sum_{i=1}^{t}\left(R_{day} - Q_{surf} - E_a - w_{seep} - Q_{gw}\right) \qquad (1)$$

Where $SW_t$ is the final soil water content, $SW_0$ is the initial soil water content on day i, t is the time (days), $R_{day}$ is the amount of precipitation on day i, $Q_{surf}$ is the amount of surface runoff on day i, $E_a$ is the amount of evapotranspiration on day i, $w_{seep}$ is the amount of water entering the vadose zone from the soil profile on day i, and $Q_{gw}$ is the amount of return flow on day i.

The second is the routing phase that follows the movement of water through the stream network and to the watershed outlet. Once the main channel water loadings are determined, the water is routed through the stream network of the watershed using the Muskingum routing method. It also takes into account losses due to evaporation and transmission through the channel bed.

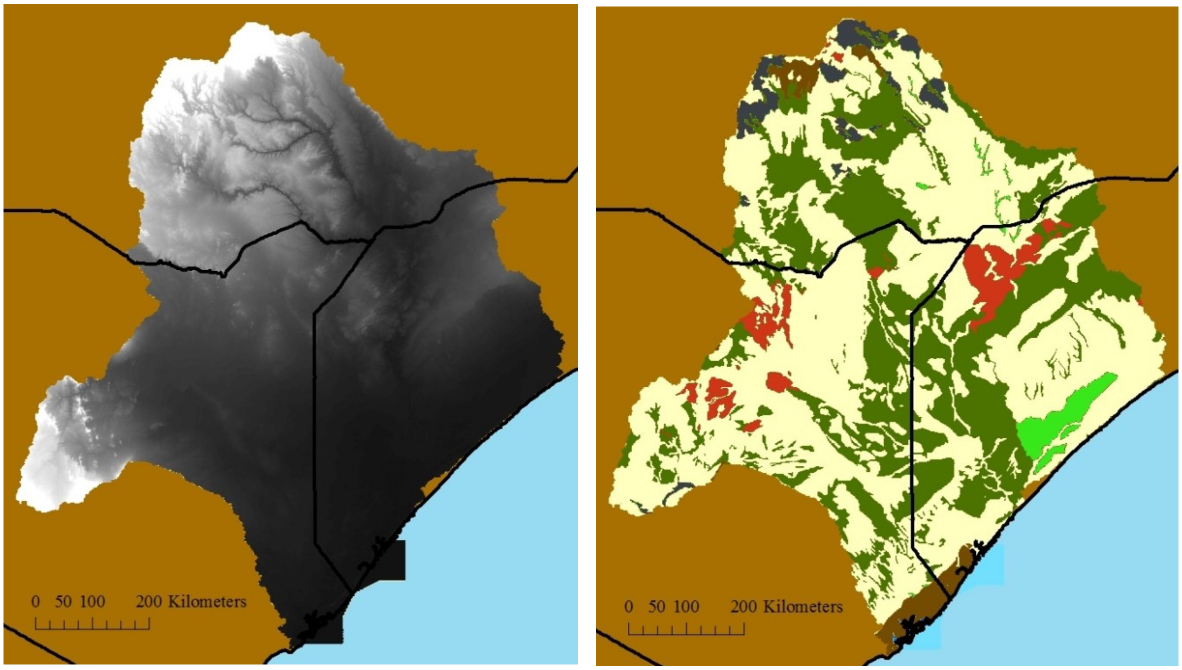
For the purposes of this study, SWAT was used to simulate the water cycle the region of interest in East Africa and select inflow/outflow data was extracted for use in the systems dynamic model. Specifically, the total water each basin received, the subbasin outflows or discharge (as a measure of harvestable water), the groundwater flow (to replicate shallow aquifer availability), and the percolation rates (to simulate aquifer recharge). The value of percolation over an extended period of time is comparable to the groundwater recharge rate (Neitsch et al, 2011).

### 3.2.1. Hydrologic Model Input Data

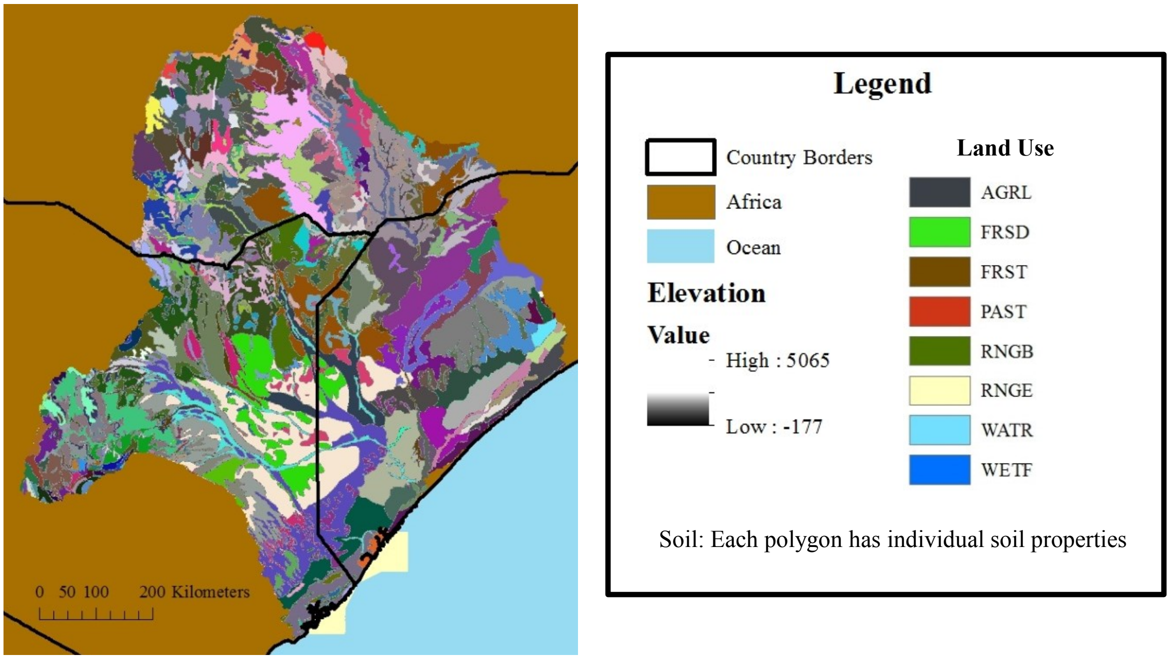
Topographic data used for the region came from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model (GDEM), which is a product of the Ministry of Economy, Trade, and Industry (METI) of Japan and the United States National Aeronautics and Space Administration (NASA) (http://asterweb.jpl.nasa.gov/gdem.asp). The DEM has a resolution of 30 m by 30 m and is available in 1x1 degree tiles. The raster was projected to WGS1984 UTM Zone 37S. The DEM was processed in SWAT using 5% of the study area as a threshold to delineate the watershed. This elevation raster can be seen in Figure 3.2a.

Land use data was taken from the Food and Agriculture (FAO) Soil and Terrain (SOTER) Database of East Africa. The vegetation fields were used as the land use classifications to be input for SWAT. These categories were reclassified to correlate with the predetermined SWAT land use categories as seen in Figure 3.2b.

The soil data was also taken from the FAO Soil and Terrain Database of East Africa although the format was altered and appended to the SWAT user soils database. In order to make this data compatible with SWAT, soil properties of the SOTER dominant soils were used for each polygon in the region as seen in Figure 3.2c. Additionally, pedotransfer functions were used to find missing soil parameters needed for the SWAT model based on soil textural data from the SOTER database (Saxton, 2006). Land use and soil conversion data are provided in Appendix A.



a) Elevation Data b) Land Use Data



c) Soil Data

Figure 3.2: SWAT input data for study area

Because the watershed is located outside of the United States, a custom weather database was created for the basin. This was done using the SWAT weather generator (http://swat.tamu.edu/). The generator calculates weather station statistics needed to create user weather station files for SWAT. This data was downloaded from the National Climatic Data Center Global Summary of the Day (GSOD) for 12 weather stations in or surrounding the watershed. This provided daily dew point temperature, precipitation, maximum and minimum daily temperatures, and daily wind speed for a period of 20 years (1990-2010). The generator also requires daily solar radiation data that was obtained from NASA Surface meteorology and Solar Energy for each station and for the same time period. Finally, the generator requires a half hour rainfall value which was estimated using the monthly precipitation (JRC-IPSC, 2009).

For model simulation, daily weather data for the region was used for the period of 2000-2010. It was readily available for SWAT via Texas A&M University's online global weather database (globalweather.tamu.edu). This data is formatted to be directly used in SWAT and contains daily precipitation, maximum and minimum temperature, wind speed, relative humidity, and solar radiation.

### 3.2.2. Hydrologic Model Results

The SWAT model monitored the entire water cycle over the region for the period of January 1, 2000 - December 31, 2010 on a monthly time step. The year 2000 was taken to be a "warm-up" year and was not used in the system dynamic modeling. Actual long term monthly discharge data from the region was obtained from the FAO SWALIM Project Report W-13 (Basnyat and Gadain, 2009). Though the Somali gauging stations are not located at the SWAT subbasin outlets or for the same time period, the flows are comparable in magnitude and overall annual discharge patterns for the gauged regions based on historical maximum, minimum, and average discharges (Figure 3.3). The output from the model was given for 46 subbasins within the region which was reduced to 11 subbasins for simplification when converted to the dynamic model as seen in Figure 3.4. Each subbasin had individual output; the variables applied from SWAT for each subbasin were total water in, outflow (stream discharge), percolation, shallow groundwater flow, and rainfall.

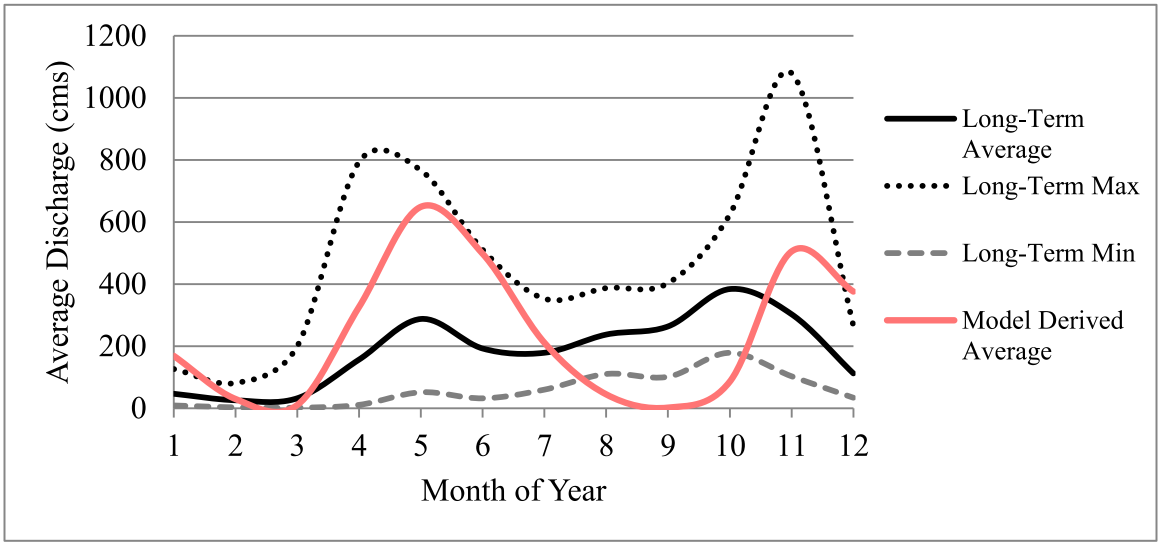


Figure 3.3: Discharge comparison for SWAT and Somali gauge data

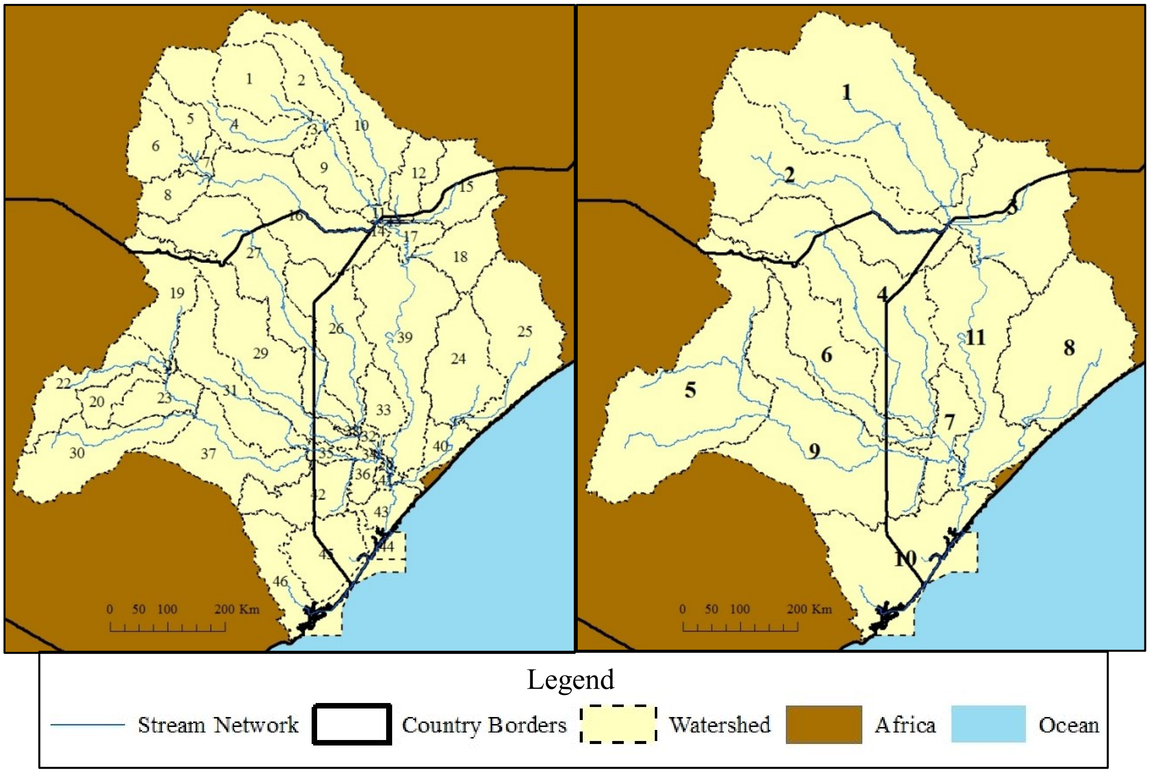


Figure 3.4: Final SWAT watershed model to be incorporated into system dynamics model

## 3.3. Elements of System Dynamics Model

In order to model the complex interdependencies between water availability, land degradation, livestock and agriculture production, and socioeconomic impacts, the system dynamics modeling program Vensim was used. The model contains over 1300 dynamic variables representing different environmental and economic systems within this East African region. Drought has a strong effect on water availability which is directly related to land, livestock, and population dynamics. The resulting socio-economic welfare is measured based on the effected systems.

The model was run on a monthly time step for a period of 10 years (2001-2010). The SWAT model result variables listed in the previous section were used as input for water availability. Depending on different characteristics of each subbasin, such as existing hydraulic infrastructure and land cover, stock and flow dynamics were established between the different features affected by drought. The descriptions of the model components and their development are discussed below.

### 3.3.1. Water Availability

The dynamic model consists of 11 subbasins connected via the stream network defined in SWAT. A simplified framework of the system dynamic watershed system is shown in Figure 3.5. Each subbasin has its own monthly rainfall, inflow, outflow, shallow aquifer flow, and percolation value. Additionally, each subbasin’s percolation values are combined based on the limited aquifer data of the region (Puri, 2009) and approximate overlays based on individual subbasin topographic delineation.

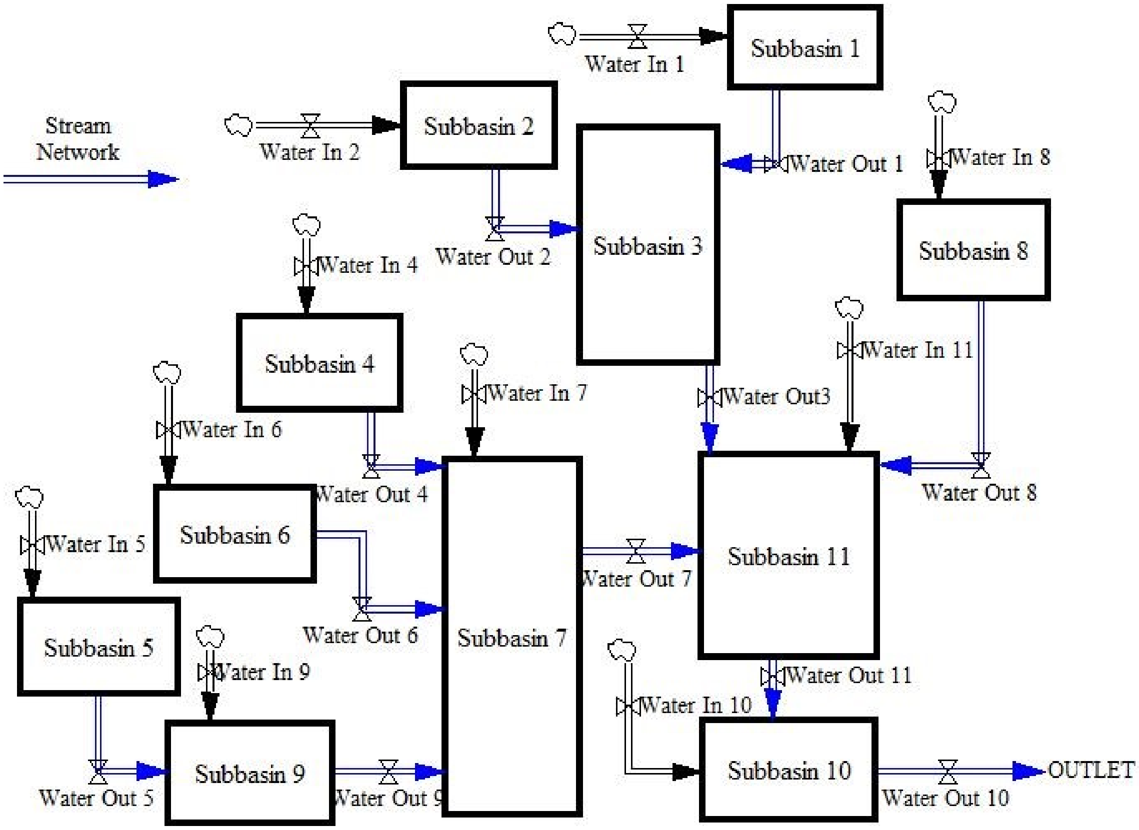


Figure 3.5: Framework of watershed dynamics implemented in system dynamics model

Groundwater data for the region is severely lacking in terms of quantifying and specifically locating aquifers in the region. The largest aquifer in the region is the Ogaden-Juba Aquifer that covers parts of Ethiopia, Kenya, and Somalia (Puri, 2009). It is a multilayered aquifer and has an extent of approximately 1 million square kilometers. Based roughly on maps and the SWAT model, subbasins 1, 2, and 3 cover this area and their percolation values all converge into “Aquifer 1” in the dynamic model. Another trans-boundary aquifer in the region is the Merti Aquifer that crosses the Kenya-Somalia border. Roughly, this aquifer is covered by subbasins 4, 6, 7, 8, and 11 and is represented by “Aquifer 2” in the dynamic model. Finally, it was assumed that the other subbasins shared aquifers within their country boundaries. Thus subbasins 5 and 9 share “Aquifer 3” which is contained within the Kenyan borders. Finally, subbasin 10 is allocated its own aquifer, “Aquifer 4” as it is on the coast and is fairly evenly split between Kenya and Somalia.

These are rough assumptions made due to the fact that hydrogeography data for the region is severely lacking. An aquifer cannot be classified by political or topographical boundaries (in terms of defining a watershed) and often vary sporadically in terms of depth and size. It has been estimated that Africa as a whole has between 0.36 -1.75 million km$^3$ of groundwater storage (MacDonald, 2012). Groundwater storage can be estimated through saturated thickness and effective porosity of an aquifer although none of this data is readily available for the Horn of Africa. Based on maps depicting groundwater storage and subbasin area, estimations of aquifer volume were approximated (MacDonald et al, 2012). Not all of this ground water is accessible; the volume of water that can be extracted via pumping is often much less. The term specific yield represents the drainable porosity of an unconfined aquifer, and can be estimated as approximately half of the measured porosity. Further investigation of the region needs to be done in order to obtain a more accurate calculation of quantifying aquifer boundaries and capacities.

The total water availability for each subbasin can be accessed from surface runoff and storage or subsurface pumping. For each subbasin, data for existing infrastructure was found via the FAO Geonetwork. Specifically, a dataset entitled “VMAP0 Surface Water Feature Point Reference” which contains a GIS shapefile with hydraulic infrastructure data such as existing wells, dams, waterholes, etc. with their location. The location of these water sources in relation to the study area can be seen in Figure 3.6. Additionally, each type of infrastructure was given an estimated capacity value based on volume or rate of extraction found in literature (Ruotsalainen, 1994; Mati et al, 2005; Basnyat, 2007). Table 3.1 summarizes these assumptions. It is possible that the region contains more undocumented water sources that were not included in the FAO database. For the purpose of this study, only these known sources were taken into account and all were assumed to be fully functioning.

Additionally, the river itself can serve as a water source when streamflow is present. It was determined that approximately 12% of total streamflow can be extracted and counted for consumptive purposes. This was based on a 5 km buffer region surrounding the rivers in relation to the area of the total study area (Figure 3.6). The distance of 5 km was chosen because it is considered the daily maximum distance a human can travel to retrieve water, making the trip 10 km in total (Mati et al, 2005). These sources of water determine the maximum volume of water available for the region that can be allocated among agricultural, livestock, and domestic demands.

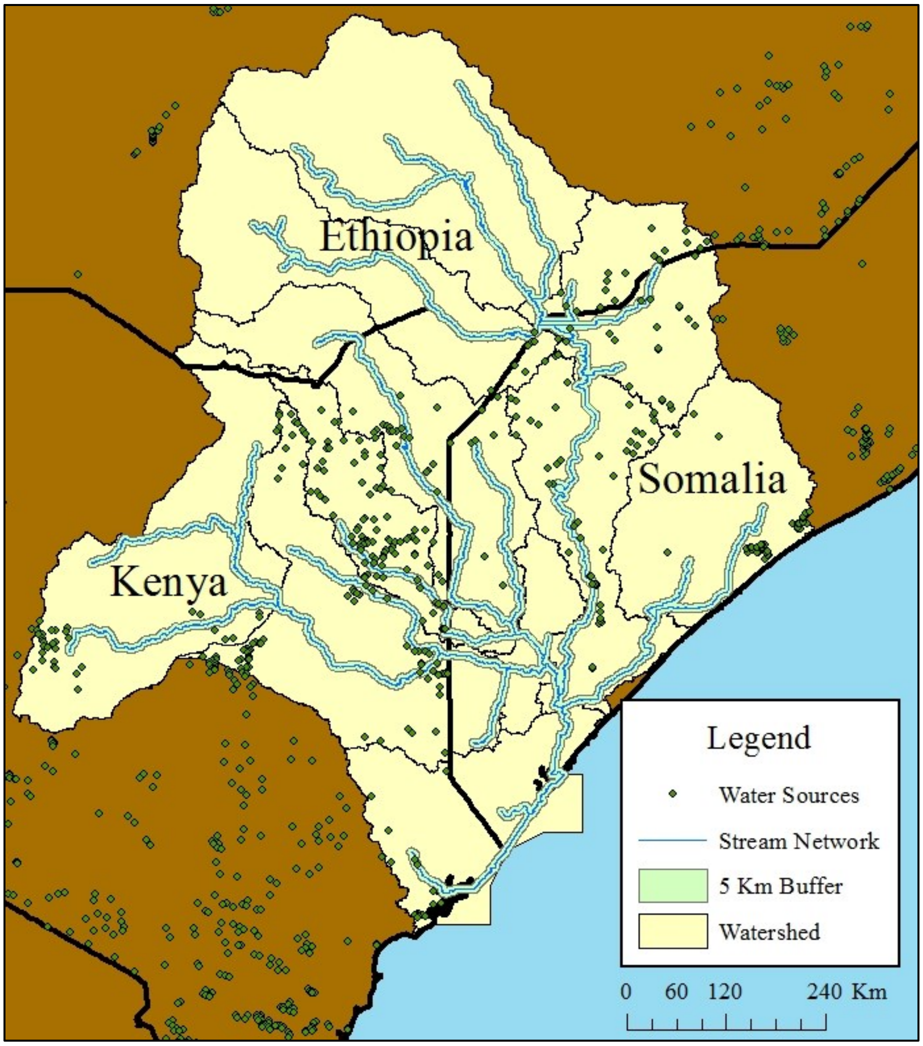


Figure 3.6: Study Area with distribution of known water sources

Table 3.1: Capacity of hydraulic infrastructure in study region

| Hydraulic Infrastructure | Capacity |
|---|---|
| Shallow Wells | 75 $m^3$/day |
| Boreholes | 15 $m^3$/hr |
| Dams | 50,000 $m^3$ |
| Ponds | 20,000 $m^3$ |
| Tank | 100 $m^3$ |

### 3.3.2 Land Dynamics and Crop Production

Regional land use data was taken from the FAO Soil and Terrain Database of East Africa. The FAO categorizations were reclassified into 6 different land types: rich agricultural land, poor agricultural land, rich grazing land, poor grazing land, degraded land, and conservation land based on land use and soil properties. The model was derived under the assumption that land can change between the six different types over time based on both natural conditions and human interaction. Figure 3.7 shows the basic structure for each subbasin and the corresponding channels through which land can be altered, improved, or degraded. Using data derived from the relationship between rainfall and normalized difference vegetation index (NDVI), land expansion and contraction was quantified. A “Drate” is a degradation rate corresponding to a period of contraction and an “Irate” is an improvement rate corresponding to a period of expansion (Bai and Dent, 2006). The relationship between NDVI and the actual area of expansion or contraction was estimated based on a rain-greenness ratio proxy for each land type (Davenport and Nicholson, 1993). This ratio estimates the percentage of land change that could occur for each different land type based on the change in NDVI. Appendix B highlights the equations used to quantify land change.

Human induced land use change was also taken into account through the “Human Intervention” rates. The model simulates human based land use change differently because it is a non-natural alteration. Land can be turned into agricultural land from the conservation and grazing land that is located within a 25 $km^2$ radius of human settlements (Figure 3.10). Based on historical data, the rate at which grazing land and conservation land was converted into agricultural land was taken to be approximately 0.5% a year, and the rate of change for conservation land to grazing land was taken to be a maximum of 2% a year (Olsen et al, 2004). This maximum percentage fluctuated based on the strain on the land due to livestock grazing. An increase in grazing would occur if the land is overstocked and a decrease in grazing land would occur when the land is under stocked and there is no immediate need for expansion. The grazing land was used as a variable associated with livestock population. A carrying capacity relationship was developed between total area of grazing land and livestock population to observe stocking rates to determine if the land was over or under stocked. This correlation is discussed in detail in section 3.3.4 Livestock Production.

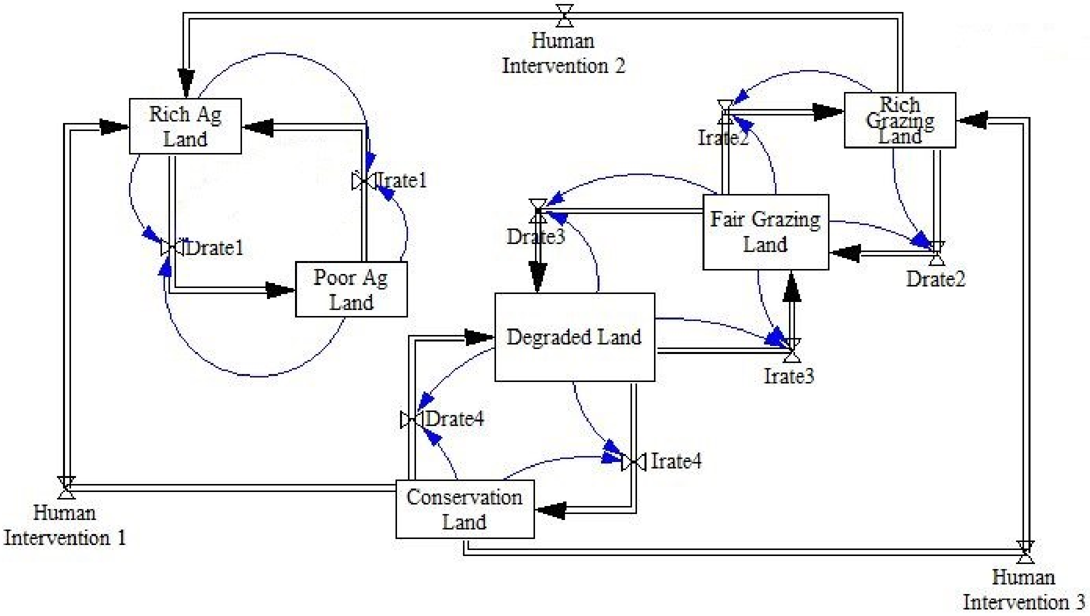


Figure 3.7: Land change dynamics structure for each subbasin

For the agricultural land, three staple food crops for the region were used to estimate yields, corresponding income, and food availability. Crops were produced only on “Rich Agricultural Land”. Settled population is also a potential limiting factor for the cultivable land; the region consists of small holder farmers with the average farm size of two hectares (ha) and a household of seven people to maintain the fields (USAID, 2011). A rough estimate of each region’s population whose livelihood depended on cropping or agro-pastoralism was determined to estimate the maximum cultivable agricultural land. The minimum between this value and total available agricultural land was used to determine overall crop production. The crops produced were maize (corn), dry beans, and sorghum, each crop representing 40%, 20%, and 40% of the total cultivated land, respectively. From literature, a relationship between yield and rainfall was found for each crop and are shown below with Y representing the yield in tons/hectare and X is annual precipitation in millimeters (mm) (Hollinger and Changnon, 1993; Padilla-Ramirez et al, 2004; Rowhani, 2011). The maize yield was determined from data found in the United States; this equation was altered to represent knowledge of the East African region, where maize yields are roughly 7-9 times smaller (Wani et al, 2009).

$$\text{Maize: } Y = 6.7761+0.0085(X) \tag{2}$$

$$\text{Dry Bean: } Y = 0.00389(X) - 0.13765 \tag{3}$$

$$\text{Sorghum: } Y = 1.27 + 0.002(X) \tag{4}$$

Because there are two rainy seasons within this region, there are also two agricultural growing seasons; however, these yield equations are modeled on an annual time step. Because growing, planting, and yields are not constant throughout the year, one annual yield value was estimated instead of monthly yields. This annual yield value was taken at the end of each 12 months (December of each year simulated).

### 3.3.3. Population Dynamics

Population data was available for each country separately through the CIA World Factbook (2013). The regional populations were estimated based on smaller province population data within the study area. Each country has a regional population stock with a constant annual birthrate and death rate that remain static through the duration of the model simulation. Fertility and mortality were not linked to the water availability because it has been found that famine and food storage do not have a direct effect on mortality (Seaman, 1993). People tend to cope differently when enduring severe situations; some may leave in hopes of finding relief while others may stay and adjust to the limited resources available.

Additionally, another source of population change comes from. As stated above, when the population becomes stressed, some individuals will seek relief by migrating to nearby areas. Many of these people are circulatory migrants who leave for a period shorter than 6 months and return with economic aid earned elsewhere (Findley, 1994). Others may leave indefinitely in search of a more secure region. In the systems dynamics model, migration was possible between all three regions, but does not occur outside of the study region boundaries. Migration is a choice; the population may choose to migrate if the benefits of moving outweigh the cost of staying. For this model, the migration was environmentally based, depending on water availability (Reuveny, 2007). As see in Figure 3.8, migration has a range of drivers based on environmental conditions (Meze-Hausken, 2000). When a region is stressed and the water demand far outweighs the supply, some of the population will choose to migrate. Similarly, when the land cannot produce adequate fodder or crops, people will either choose or be forced to migrate.

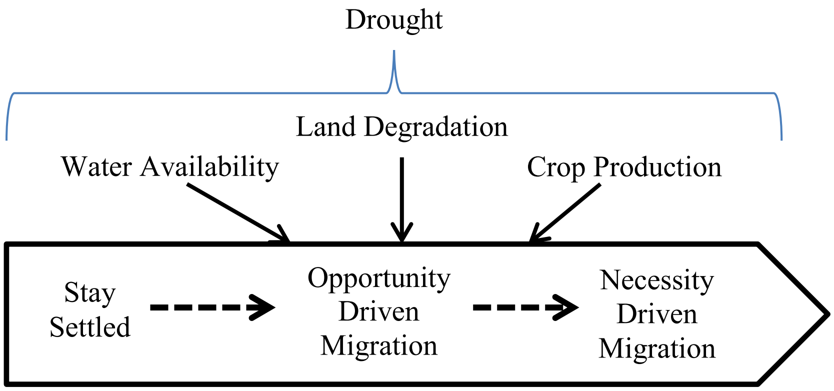


Figure 3.8: Environmental factors that determine migration

The domestic water demands were established based on the total regional populations. From literature, it was found that 15 liters per capita per day is the minimum domestic requirement for humans (0.45 $m^3$/month) (Mati, 2005). This domestic requirement includes consumption for drinking, hygienic use, and cooking (Thompson et al, 2003). The domestic water supply comes primarily from subsurface sources like boreholes, as this water usually has a higher water quality. However, during water scarce times, domestic consumptions can also come from surface water reserves.

### 3.3.4. Livestock Production

The Horn of Africa is a highly pastoral region. For the system dynamics model, three different varieties of livestock were considered for each of the three countries within the study area: cattle, camels, and small stock consisting of goats and sheep. These species were chosen because they are the main productive livestock kept in the region of study (Simpkin, 2005). The regional livestock populations for each country were determined using census data by type and district (Kenya Open Data Project; FSAU-FAO, 1999; Central Statistical Agency of Ethiopia, 2006). Additionally, mortality rates, calving rates, and immature animal survival rates for each animal type were determined from literature (Oba, 2001; Baumann, 1992; McCabe, 1987). These previous studies relate the effects of drought to livestock mortality. Using this data, a correlation between present and normalized rainfall was determined. These rates increase or decrease accordingly throughout the simulation period for each species of animal in relation to rainfall and water availability. It should also be noted that calving rates are not directly affected by current rainfall; these rates are not affected until much later and were determined from rainfall at previous time steps. Figure 3.9 shows the system dynamics structure for the livestock model.

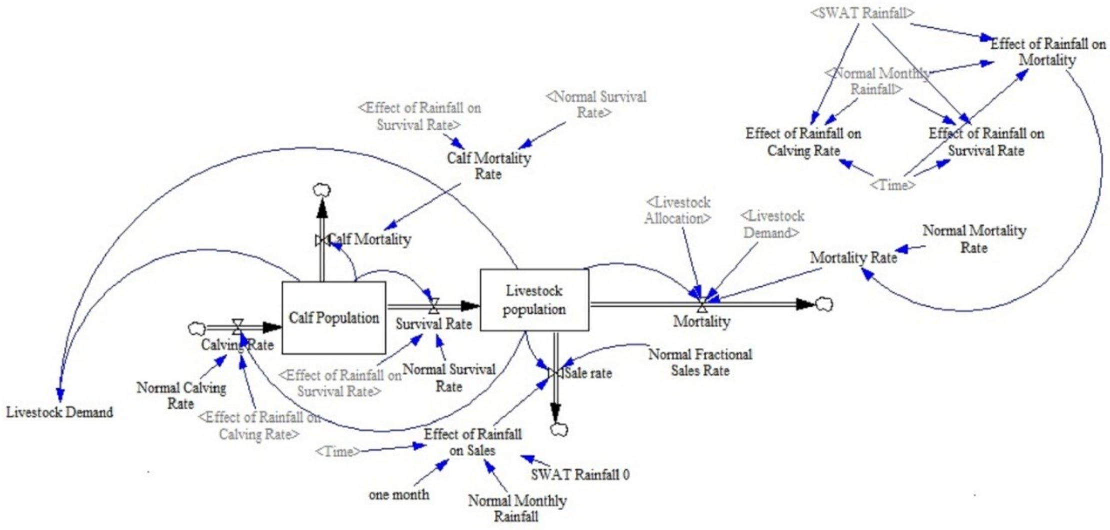


Figure 3.9: System dynamics livestock configuration

Each type of livestock contributed to an overall livestock water demand. This value was determined by literature based on the average daily water consumptions for each species of animal (Table 3.2)(Lindqvist, 2005; Mati, 2005). This water demand can come from either surface water or ground water sources; if the total demand exceeds the volume of water that is available and allocated, then the mortality of the cattle population will increase due to the water supply being inadequate for the total livestock population.

The sustainability of the livestock population was also taken into account through the relationship between total livestock population and available grazing land. Each livestock population was converted to tropical livestock units (TLU, 1 TLU = ruminant of 250 kg live weight) based on livestock conversion factors for pastoral systems in Table 3.3 (Kassam, 1991). Stocking ratios were determined following the procedure by Mulindwa et al. (2009) documented in their modeling of pasture production and estimation of carrying capacity. Monthly forage was determine using the concept of rain use efficiency (RUE, kg dry matter/ha/mm/year) and monthly rainfall; the RUE value was taken to be 6 based on long-term annual averages for the region (Bai and Dent, 2006). Finally, a monthly carrying capacity was determined using an average daily intake requirement of 2.5% of body weight per TLU, the monthly available forage, and a proper use factor. The proper use factor is the percentage of land usable while still leaving a sustainable, untarnished grass cover behind. For the rich grazing land, this value was taken to be 50%, and for fair grazing land the value was taken to be 30% (Kavana et al, 2005; Guevara, 1996). Variability in carrying capacity is much more prominent within a year due to dry and wet seasons rather than between years. This relationship will show when overstocking is occurring and land will be stressed and also if the system is sustainable. It will also help determine if land will be converted to grazing land.

Table 3.2: Livestock water requirements

| **Animal Type** | **Average Water Requirement** | |
|---|---|---|
| | Liters/day | $m^3$/month |
| Cattle | 14 | 0.42 |
| Camel | 25 | 0.75 |
| Small Stock (Goats/Sheep) | 3.5 | 0.105 |

Table 3.3: TLU conversion factors

| **Animal** | **TLU Conversion** |
|---|---|
| Cattle in Herd | 0.7 |
| Sheep/Goat | 0.09 |
| Camel | 1.25 |

### 3.3.5. Socio-Economic Welfare

Market dynamics are highly volatile and can be affected by many factors. The main source of income for this region comes through the livestock and rain fed agriculture sector. The data for the livestock market is based on the volume of animals being sold and the market price which they are selling for, both of which are effected by drought. On average, a household in this region needs approximately $7 per month, or $84 a year to supply their regular needs such as consumption good and seasonal needs like school fees (Barrett, 2006).

Historical livestock market data for Ethiopia and Kenya is available through the Livestock Information System for Ethiopia and Kenya, respectively. Both pricing and volume data for the 4 different animals are available. Using this data, along with historical rainfall data, a relationship between monthly price and monthly rainfall was created. There are many factors that go into determining market price volatility, but for this model, rainfall was taken to be the main component in determining price fluctuations. Regardless of rainfall, prices have steadily increased over the period of simulation, but it is also evident that prices will increase during prolonged dry periods (Barrett, 2001). Camel prices are the least affected by drought, dropping up to 12% in price, while cattle prices are most affected and can lose up to 50% of their value during drought. Sheep and goats can see between 10-30% of a price drop during drought (Barrett, 2003). A steady increase for each animal type for price was taken from the livestock market data and input into the system dynamics model. In order to illustrate the effect rainfall has, a variable called “Effect of Rainfall on Price” was created. Based on deviation from a long-term monthly average rainfall value for each region, the price will either decrease during dry periods or increase during normal or wet periods. A three month delay between the effect of rainfall variation and actual price change was also implemented.

Similarly, the volume of animals sold will fluctuate between wet and dry periods. Pastoralists tend to sell animals when there is a financial need, not to accumulate wealth or take advantage of high market prices (Barrett, 2006). This correlates to a higher volume of sales during drier periods when there is often an immediate need for money due to increases in grain prices. Conversely, there is often a decrease in the volume of sales during wet periods as pastoralists restock their herds (Bailey, 1999). Again, a variable was created to show the effect of deviations from long-term average rainfall to show this relationship between low rainfalls and an increase in the volume of sales.

Livestock market data for Somalia is unavailable; however, many of the livestock in Somalia are sold at Kenyan markets based on pastoral migration patterns to markets in the region (Farmer, 2012). Thus, the historical Kenyan market data was also used as a baseline for Somalia.

The income from rain fed agricultural was also taken into account for the socioeconomic analysis. Based on historical producer prices for each of the three crops being modeled (maize, dry beans, and sorghum), pricing trends were recognized from the FAOstat database. Like livestock pricing, rainfall was taken to be the main influence in price fluctuations as that determines the crop yield experienced. When crop yields are good, the prices tend to slump and conversely when crops fail, the prices soar (Olsson, 1993). Crop yield was determined annually, thus income generated from crop sales was also obtained annually.

The total annual income for each country within the study area from agriculture and livestock was then divided by the respective population livelihoods to illustrate a quasi-annual income per capita. The historical market data is shown in Appendix C.

### 3.4. Application of Drought Adaptation Policy

The drought adaptation policies explored within the systems dynamics model were chosen based on this study area. They include constructing new hydraulic infrastructure that would increase the overall volume of water availability within the region and also implementing innovative agricultural methods that can increase productivity and resiliency during water scarcity. Community involvement is very important when implementing a mitigation policy.

Communities will need to operate and repair the infrastructure themselves, so a good understanding of the technology being applied is necessary in order to maintain and fully take advantage of the benefits.

### 3.4.1. Hydraulic Policy

Drought adaptation through hydraulic policies involves building new infrastructure to increase water storage and availability. Because the majority of rainwater is lost to runoff or evaporation, storage facilities would be a way to harvest the water when it is available and store it for use during drier periods.

The first hydraulic structure suggested for implementation is a sand dam. A sand dam is a small dam that is built into the riverbed of a seasonal sand river; it is essential that it be a sand riverbed that is underlain with impervious bedrock (SASOL, 2009). The dam increases the natural storage capacity of the riverbed aquifer during storm events. Depending on the quality of the sand, 25-40% of the volume of the saturated sand will be extractable water. During drier seasons, water can be removed from the subsurface reserve through shallow wells or springs. If the dam is built under appropriate conditions, it can provide water throughout the dry season. Because the water is being stored within the sand, water quality is improved due to natural filtration and evaporation is less of a factor because the water is not open to the surface. For implementation into the model, the average water capacity of a sand dam was taken to be 100,000 $m^3$ at a cost of approximately $80,000 USD for construction (Stern, 2011; RELMA in ICRAF & UNEP, 2005). Dam construction requires a great deal of community involvement and much of the labor can be done through the local population. However, because these dams must be along a sand river, they cannot be implemented everywhere.

The second hydraulic policy to be utilized is the concept of rain water harvesting (RWH) through two methods. The first is rooftop RWH that is stored in tanks. This method involves harvesting rainwater that lands on impervious surfaces, such as household rooftops, and storing this water in tanks for later use. It allows communities to manage their own water supply and is applicable for settlements where impervious rooftops exist. For model implementation, an average tank size of 100 $m^3$ was used at an approximate cost of $1,000-2,000 a tank depending on the materials used (Van Waes, 2007). The implementation of this policy was decided based on known settlements from Settlement Mapping from the Socioeconomic Data and Applications Center (SEDAC) dataset GRUMPv1 that locates settlements with a population greater than 1,000 people as seen in Figure 3.10 (CIESIN, 2011). It is assumed that the rainwater collected will be the direct result of runoff from an impervious surface. In the systems dynamic model, the water availability of the harvesting tanks is a function of settlement area and rainfall. The second type of RWH structure considered was a pond or pan. A pond or pan is an excavated water storage structure that catches and stores surface runoff, usually located at the low point of a catchment area. There are various names associated with this structure, but essentially all describe the same thing; a pond is often associated with farmers while pans are associated with herders. Excavated ponds can range in size from 200 $m^3$ up to 50,000 $m^3$ providing water for individual households up to an entire community. For the model, an estimated average pond size of 20,000 $m^3$ was assumed at a cost of approximately $40,000 to construct (Lindqvist, 2005; AFDB, 2008).

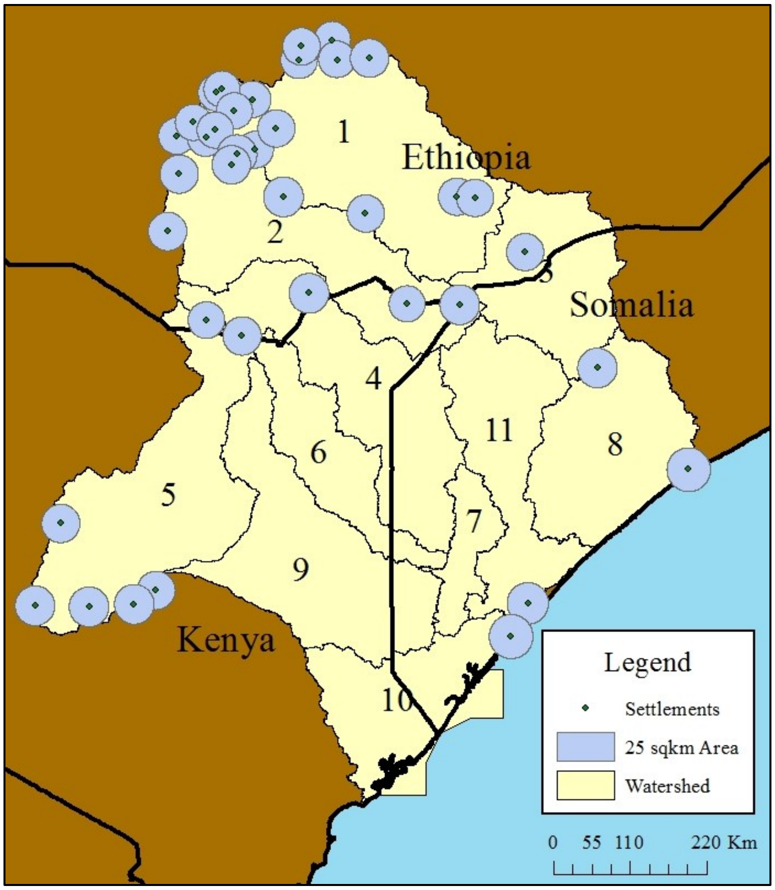


Figure 3.10: Settlements within the study area where rooftop RWH would be applicable

Finally, the last hydraulic infrastructure policy was the introduction of new wells within the region. Two types of wells were considered: shallow wells and deep wells. Shallow wells are most often hand-dug and provide a low-cost, low-technology solution for water availability for suitable areas (Collins, 2000). Shallow wells tap into shallow unconfined aquifers as a source of water and usually range from 6 m – 25 m in depth. They can supply up to 75 $m^3$/day of water and cost in the range of \$400 - \$1,200 (US) to build (Abbott, 2013). Because shallow wells extract water from shallow aquifers, during drier periods it is possible for these aquifers to dry up and the wells can become unproductive. Deep wells, or boreholes, on the other hand require high technical skills and knowledge of the subsurface hydrogeography. Deep wells are usually drilled to depths ranging from 25 m - 100 m and extract water from confined aquifers. These wells are less vulnerable to contamination and to drought because they utilize deep, confined aquifers; if properly sited, they are capable of producing large water yields (Soulsby, 2010). These wells can produce yields of around 3-30 $m^3$/hr of water but at a high cost of approximately $15,000 (US) per well. It should also be noted that although, boreholes are a very reliable source of water, they tend to encourage settlement in the area. Because the region is highly pastoral, this could lead to immense natural resource deterioration (Abikar, 2013).

From this data, the capacity and associated cost of the hydraulic policy options were estimated and shown in Table 3.4. These are the values used in modeling each specific infrastructure type. Realistically, these capacities will vary (both lower and higher) throughout the region, but these values were taken as an estimated standard for each infrastructure.

Table 3.4: Hydraulic infrastructure capacities and associated investment costs

| **Infrastructure Type** | **Capacity** | **Cost** |
|---|---|---|
| Sand Dams | 100,000 $m^3$ | $80,000 |
| RWH Tanks | 100 $m^3$ | $1,500 |
| Ponds | 20,000 $m^3$ | $40,000 |
| Shallow Wells | 2,250 $m^3$/month | $800 |
| Boreholes | 10,800 $m^3$/month | $15,000 |

### 3.4.2. Agricultural Policy

The goal of the adaptation policies is to make the population more resilient and self-sustaining during droughts. Agriculturally, this translates to being self-sufficient through dry periods when crop yields are known to suffer. Two agricultural policy implementations aim to accomplish this in the systems dynamics modeling for the study region. The first is introducing agroforestry into land management. Agroforestry is a land-use system where trees or shrubs are grown with traditional agricultural crops or pastures. Implementing agroforestry can reduce the vulnerability farmers experience for a number of reasons. First, trees have a deeper root zone which allows them to reach lower soil moisture and nutrients. Also, the tree fallow can provide nutrients for the crops below. The trees can also help decrease runoff and increase soil cover that leads to higher infiltration and water retention which is advantageous in low rainfall years. Finally, these trees can also produce an additional crop yield, supplying a new source of income and diversifying farmers' products, making them more resilient to changing conditions (Verchot et al, 2007). The initial cost of agroforestry is relatively low; it requires approximately $80 per hectare for the plants, plus a onetime cost of $10 for fertilizer (Franzel et al, 2002; Kandji et al, 2006). With this system implemented, farmers can expect up to twice the normal yields for crops during good rain years. However, lower yields may occur during water stressed years as the crops will be competing with trees for nutrients (FAO, 2002; Sanchez, 2002). Once implemented and fully mature, the farmer's overall income will increase by approximately $360 per hectare based solely on the agroforestry tree products (Verchot et al, 2007). This increase in income due to crop yield improvement and tree products will be gradual over the first 10 years, as it takes 2-5 years for trees to mature (Sanchez, 1995).

The second agricultural policy chosen for the region was drip irrigation. Drip irrigation is one of the most water efficient methods of irrigating crops. The system is comprised of a tank of water connected to hoses or plastic pipes that are laid on the ground along field crops. Small holes within the hose or pipes allow a small amount of water to drip out and wet the root zone of the plant (RCDC, 2008). Because the water is being released slowly and directly at the plant's root zone, losses due to runoff, percolation, and evaporation are kept to a minimum and water use is approximately 90-95% efficient (Sijali, 2001). For large areas, drip irrigation ranges in cost from $5,000 to $10,000 per hectare; however, for smaller plots of land, the cost is approximately $300 to cover 500 m$^2$ of cultivated area. The equipment itself has a lifespan of approximately 5 years and requires annual maintenance to make sure it is operating properly (Keller, 2001). Additionally, the crops are no longer solely dependent on rainwater, so there is now a water requirement of approximately 4-6 mm/day (approximately 12,000 $m^3$ of water per $km^2$ of land per month) for the crops when rainfall alone cannot provide an adequate water supply (Belder et al., 2007). This new agricultural water demand will be competing with domestic and livestock water demands. The benefits of drip irrigation are seen immediately; it has been observed that consistent drip irrigation can increase the yield of crops up to 4 times more than normal, rain fed yields. The actual yield will depend on the volume and consistency of water being used for irrigation (Pathak et al., 2009). This irrigation also creates an agricultural system semi-independent of the rain seasons. With an adequate water supply, it may also be possible to introduce an additional growing season, increasing annual yields by 50%. Drip irrigation will also allow farmers to produce higher income crops to improve their agricultural revenue. Drip irrigation can be explored on a large scale (fully implemented across all agricultural land) and small scale, where households utilize drip irrigation over a smaller plot of their land (500 $m^2$) and produce cash crops such as tomatoes, cabbage, or onions that can increase their household income by $320 per plot (with sufficient watering)(Keller, 2001). These two methods were used in the system dynamics model with the previously established expected rain fed yields found in section 3.3.2. Although this technology has the potential to significantly increase agricultural production, it also requires proper instruction by the farmers in order to be implemented and maintained effectively.

The summary of the agricultural policies is shown in Table 3.5. It shows the initial investment costs, potential yields, and additional outcomes.

Table 3.5: Agricultural policy benefits and associated investment costs

| **Agricultural Policy** | **Initial Costs** | **Expected Crop Yields**** | **Additional effects** |
|---|---|---|---|
| Agroforestry* | \$80 /ha for trees<br>\$10/ha for fertilizer | Up to 2-3x greater | Tree product income<br>Up to \$360/ha |
| Drip Irrigation | | | |
| Large Scale | \$7,500 /ha | Up to 4x greater | Water demand<br>12,000 $m^3$/month/$km^2$ |
| Small Scale | \$300 (500 $m^2$ plot) | Normal crops<br>(no effected) | Cash crop income<br>Up to \$320/plot |

*overtime as trees mature (5-10 years until fully mature)

**varies based on rainfall (agroforestry) or available water for irrigation (drip)

# CHAPTER 4 RESULTS AND ANALYSIS

## 4.1. Verification of System Dynamics Model

For this model to be considered beneficial for policymakers, validity tests were used to build confidence and credibility into the relationships and interdependencies developed between systems. Although there is no universal framework for validating system dynamics models, there are tests in literature that can increase the credibility of a model (Qudrat-Ullah, 2010). Ensuring the legitimacy of the model's behavior is the most important way to validate a system dynamics model. This verification should focus on pattern prediction versus point prediction because the overall behavior between all systems is being analyzed, not just extrapolations. For this model, three different validation tests were used: structural assessment, dimensional consistency, and extreme conditions examination.

### 4.1.1. Structural Assessment Test

A structural assessment of the model was done to ensure that the system dynamics was consistent with the knowledge available for the real system. This test aims to confirm that the decisions within the model are realistic and follow all basic physical laws such as the conservation of matter and energy (Sterman, 2000). This requires ensuring stocks cannot become negative. For example populations or available water supply cannot physically drop below zero. Additionally, some rates should never be negative such as mortality rates or income rates. These variables and their corresponding assessments are shown in Table 4.1. For this analysis, each variable was run over the baseline 10 year simulation period and the results were observed. Direct inspection of each equation was done to certify that basic physical realities were not being overlooked or violated.

Table 4.1: Structural assessment of system dynamics variables

| System | Variable | Assessment |
|---|---|---|
| Hydrologic | Storage Rates<br>Outflow<br>Evaporation<br>Pumping Rates<br>Percolation | Cannot be negative, flows are strictly outflows from subbasin |
| | Available Surface Water<br>Water Storage<br>Aquifer | Stocks cannot become negative, water supply has a minimum value of 0 |
| | Allocated Water | Total water allocation can never exceed total water available |
| Population | Birthrate<br>Deathrate | Rates cannot be negative, population only increased by birth and only decreased by death |
| | Regional Population | Stock of population cannot become negative |
| Economic | Sales Rate of animals | Rate cannot be negative, sales only decrease herd size |
| | Income rate | Rate cannot be negative, if no sales then rate will be 0 |
| | Harvest and Yield Rate | Rate cannot be negative, only positive harvest and yields |
| | Crop Stocks | Cannot have a negative supply of crops, minimum value of 0 |
| Livestock | Calving Rate<br>Mortality Rate<br>Survival Rate | Rates cannot be negative, minimum values of 0 |
| | Livestock populations | Stock of population cannot become negative |
| Land Dynamics | Land Categories | Stock of lands cannot become negative, minimum value of 0 |
| | Improvement/Degradation Rates | Cannot be negative, land is either shrunk through degradation, or expanded through improvement |

### 4.1.2. Dimensional Consistency Test

One of the most basic tests for systems dynamic modeling is examining dimensional consistency. This requires specifying and checking units of measure for each variable being used to ensure there are no basic flaws in the understanding of the structure or decision process within the model (Sterman, 2000). This model was run on a monthly time step, so all rates needed to indicate this. However, some of the agricultural variables were determined annually; these variables were calculated once every 12 months. Many of the variables that were created to show the effect of rainfall on a specific rate were dimensionless; thus, these were inspected directly to ensure they were simply used as scaling, multiplicative factors and did not alter the dimensional structure of the model. A summary of the variable types and their corresponding units of measure are in Table 4.2.

Table 4.2: Units of measurements used in system dynamics model

| System | Variable | Units of Measure |
|---|---|---|
| Hydrologic | Rates | $m^3$ water/month |
| | Stocks | $m^3$ water |
| | Water Demands/Storage | $m^3$ water |
| | Rainfall | mm |
| Livestock | Rates | Animals/month, |
| | Stocks | Animals |
| | Normal Monthly Rainfall | mm |
| | Conversions | dollars/animal |
| | | TLU/animal (based on breed) |
| | | $m^3$ water/animal |
| Population | Rates | People/month |
| | Population | People |
| | Conversions | $m^3$ water/person |
| Land Dynamics | Rates | $km^2$/month |
| | Stocks | $km^2$ |
| | Conversions | kg forage/month/ha |
| | | 0.01 $km^2$/ha |
| | | ha/TLU |
| Crop Production | Rates | tons/month |
| | Stocks | tons |
| | Conversions | Tons/kcal |
| | | kcal/person |
| | | dollars/ton |
| Economic | Rates | dollars/month |
| | Stocks | dollars |
| | Conversions | dollars/year |
| | | dollars/person |

### 4.1.3. Extreme Conditions Test

Extreme conditions are used to test the robustness of a model. When extreme scenario inputs or policies are inflicted on the system, it should react in a realistic manner (Sterman, 2000). For this model, that would mean water supplies should never drop below zero, even when demands may be larger than availability. Also, populations may never fall below zero in the most destitute conditions. Conversely, when ecological elements are thriving, like an abundance of water, the result would be a growing population. This testing can be done in two ways: direct inspection of equations and through simulation.

For this model, simulations using different extreme values were used to test how the system would react. The first extreme condition was changing the available stored volume of water to an unrealistically large number. With this, the expectation of the model would be to allocate the necessary volume of water to each demand, resulting in a steady increase in the populations of livestock. Figure 4.1 shows the original subbasin livestock results for the entire study area (as shown through TLUs) compared to the extreme water availability scenario. The expected result is confirmed. Additionally, the reverse scenario was implemented through an extreme water scarcity condition; the expected result for almost no water availability would be an immediate and constant decline in livestock populations. Figure 4.2 also shows the results of this water deprived condition from the model and again, it verifies the expectations. There is a constant growth when an unlimited water source is available and an exponential decay associated with extreme water scarcity.

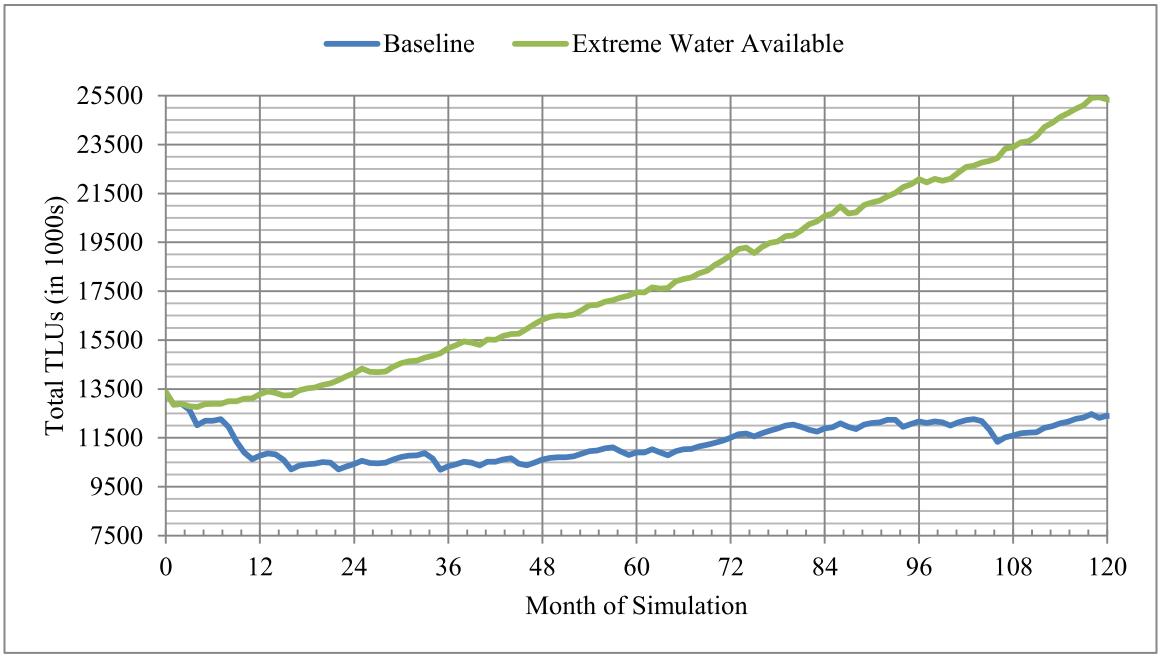


Figure 4.1: Results of livestock population stocks from extreme water availability

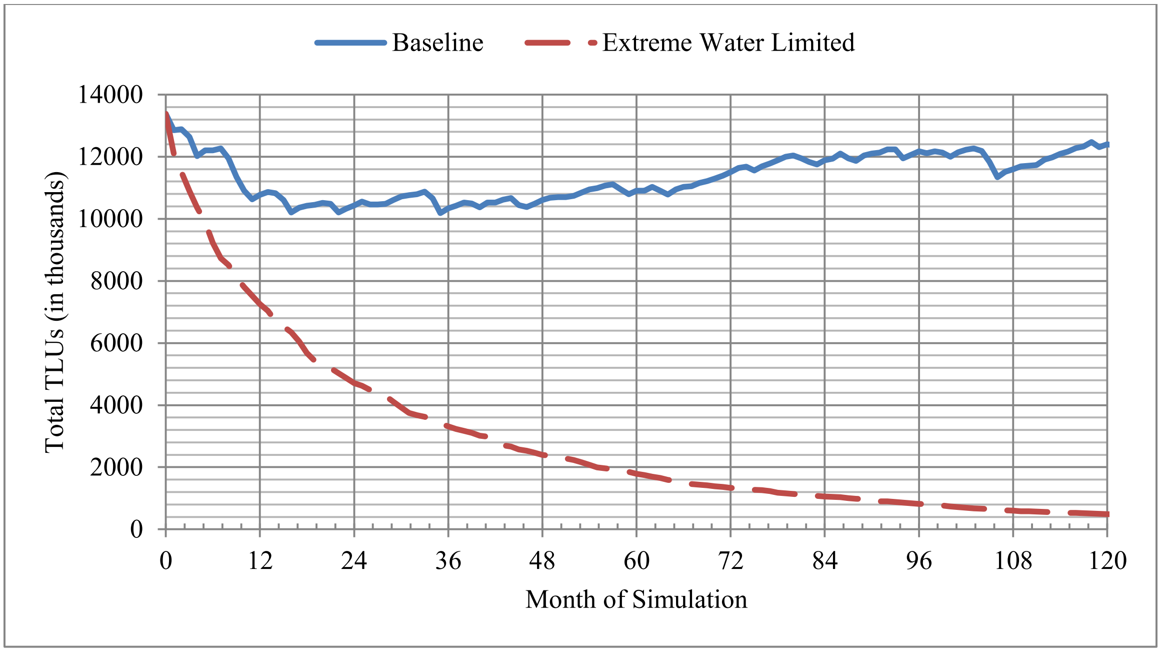


Figure 4.2: Results of livestock population stocks from extreme water scarcity

## 4.2. Policy Application and Outcomes

The main variables that were used as indicators of overall livelihood were water availability and water demand (a deficit during dry periods can be determined from these values), livestock populations, income based on livestock sales and crop sales, and percentage of diet fulfilled by crop yields in this region. The water demands and supply are processed on a monthly time-step and normalized based on the current population per region. This indicates how much water is available per person in relation to the basic human requirements of 15 liters/day (0.45 $m^3$/month). An overall water deficit can be determined based on the difference between available water supply and water demand.

Additionally, the regional income based on livestock is modeled on a monthly time-step, while the crop sales are on an annual time-step because crop yields are calculated annually. The income due to crops makes the assumption that all crops are sold for income, or it is a maximized approximation. Like water availability, this overall income can be estimated into a per capita income based on regional populations and livelihoods. Finally, the caloric fulfillment per person is based solely on crop production within each region. It is determined based on the caloric production of each crop from the total yield and the regional population's human required caloric intake (2100 kcal per day per person) (Latham, 1997). This result is given as an annual percentage of required caloric intake per person that is fulfilled based on the three crop yields. Imported foods and diet fulfillment from livestock products like milk were not factored into the caloric availability. Again, this is a maximized value where all crops grown in the region are also consumed in the region.

## 4.3. Baseline Simulation

The baseline simulation was run over a 10 year period using weather data via SWAT (2001-2010) with no policies implemented to monitor the existing water availability and corresponding effects. The annual rainfall used in the SWAT model can be seen in Figure 4.3 for the simulation period for each region within the study area.

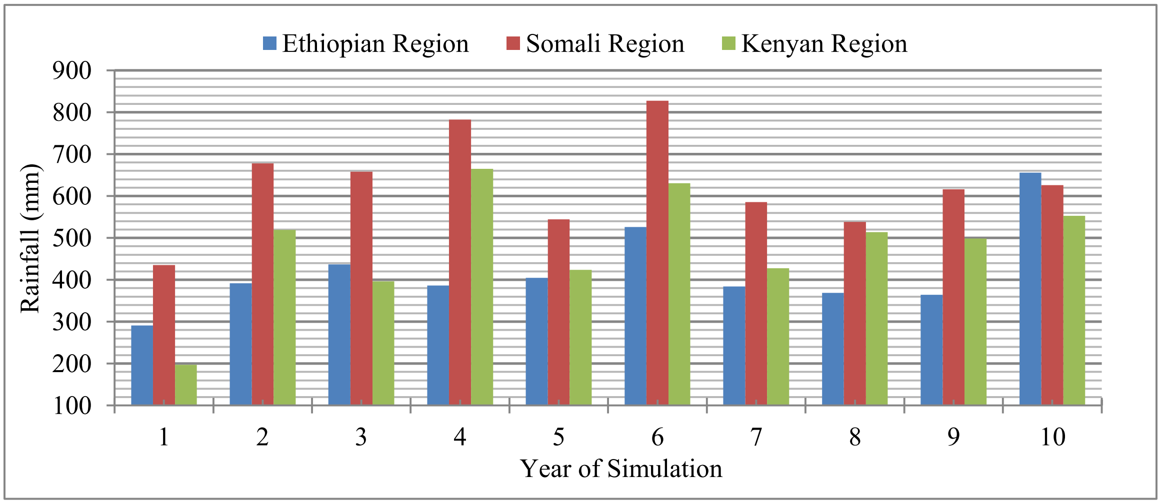


Figure 4.3: Annual rainfall for regions within study area for duration of model simulation

### 4.3.1. Water Availability

The results from the baseline simulation for each country within the study region are shown separately. Figures 4.4, 4.5, and 4.6 show the number and magnitude of water deficits the Ethiopian, Somali, and Kenyan regions experience, respectively, as well as the volume of water available per capita compared to the basic human required 0.45 m³/month/person over the 10 year simulation. These water deficit results are also summarized in Table 4.3. Somalia has the least number of water deficits; this corresponds to consistently higher rainfall over the 10 years compared to the Ethiopian and Kenyan regions. Ethiopia has the most deficits and also experienced the lowest rainfalls. Additionally, Ethiopia has the fewest known water sources. Kenya experiences fewer deficits than Ethiopia; however, the deficits have a larger magnitude. This is due to Kenya having the largest livestock population resulting in the highest overall water demand between the regions.

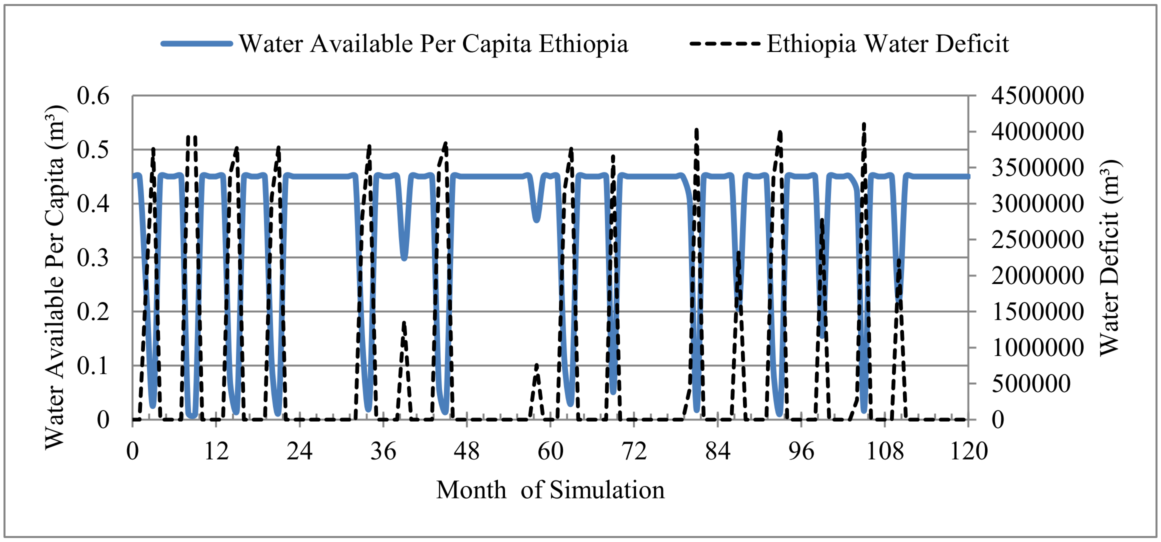


Figure 4.4: Water deficit and water availability per capita for Ethiopian region

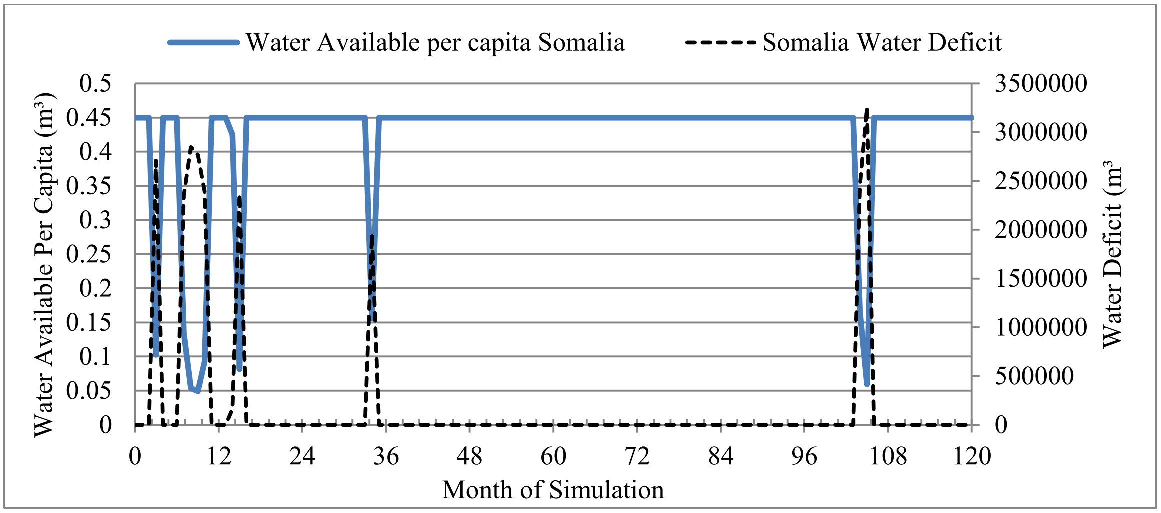


Figure 4.5: Water deficit and water availability per capita for Somali region

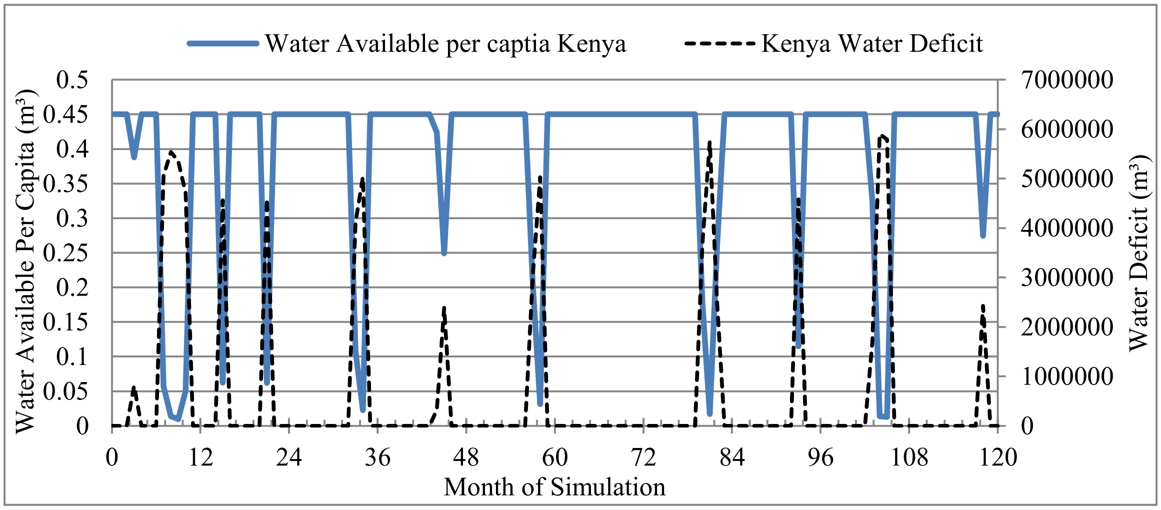


Figure 4.6: Water deficit and water availability per capita for Kenyan region

Table 4.3: Baseline simulation monthly water deficit results

| | **Ethiopia** | **Somalia** | **Kenya** |
|---|---|---|---|
| Number of Months with Deficits | 26 | 10 | 21 |
| < 1,000,000 m³ | 3 | 1 | 2 |
| 1,000,001 - 2,000,000 m³ | 2 | 1 | 1 |
| 2,000,001 - 3,000,000 m³ | 4 | 7 | 3 |
| 3,000,001 - 4,000,000 m³ | 14 | 1 | 2 |
| > 4,000,000 m³ | 3 | 0 | 13 |

### 4.3.2. Crop Production and Food Availability

The baseline results for crop production were analyzed for each country within the study area. Crop production was modeled based on the available agricultural land; it was assumed that the cultivated agricutural land in each region was allocated in the following manner: 40% for maize, 20% for dry beans, and 40% for sorghum. The associated yield of each crop was determined based on the annual rainfall for each region (Section 3.3.2.) and the corresponding annual yields for each region are shown in Figures 4.10, 4.11, and 4.12.

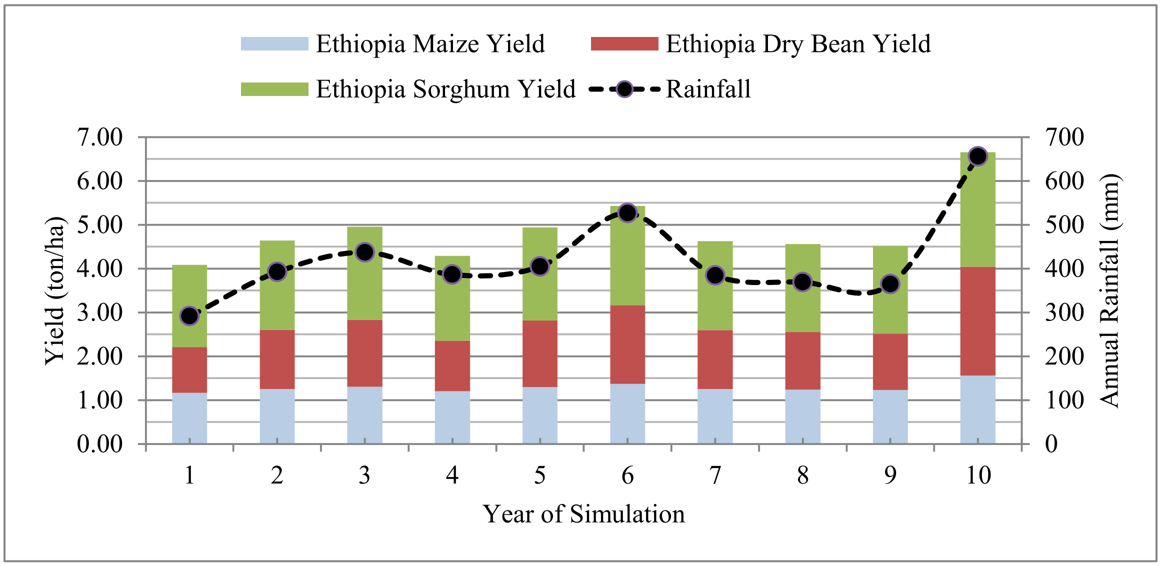


Figure 4.7: Ethiopian region crop yield in relation to annual rainfall

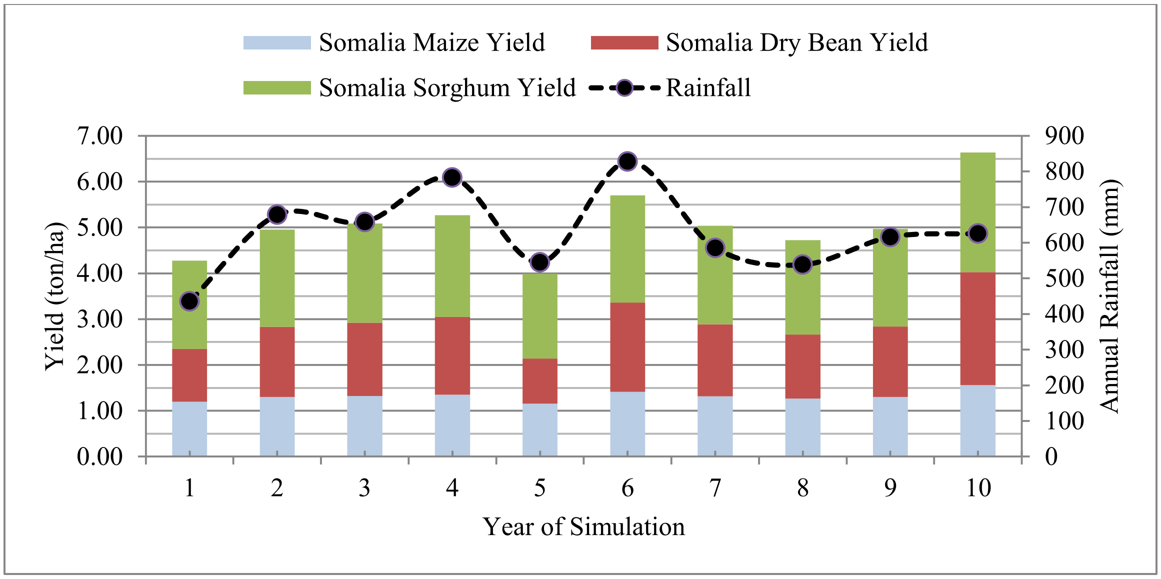


Figure 4.8: Somali region crop yield in relation to annual rainfall

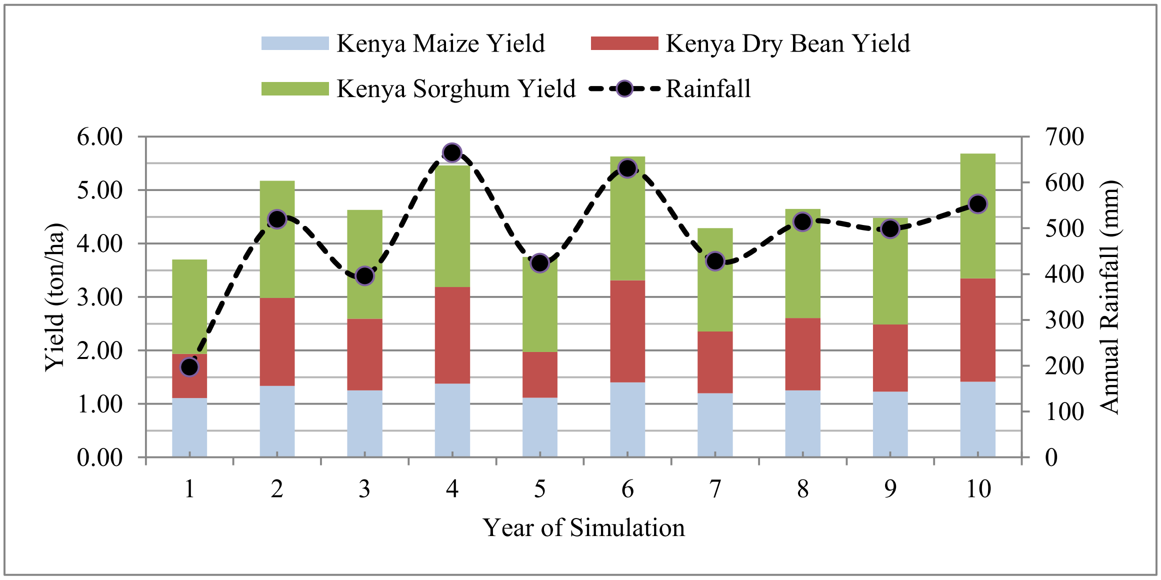


Figure 4.9: Kenyan region crop yield in relation to annual rainfall

Based on the recommended human caloric intake of 2100 kcal per person per day, the total regional population, and the total caloric availability from crop yields, the percentage of diet fulfilled annually from crops grown within the region was determined and can be seen in Figure 4.13 (Benson, 2004). This analysis assumes that all crop yields are consumed by each respective regional population. In actuality, farmers are most likely to keep their crops for their own consumption and sell excess stock for additional income.

Ethiopia has the largest fulfillment because the region has the most agricultural land to produce crops, while Somalia has the smallest agricultural land cultivated, yielding the smallest calorie fulfillment. None of these countries produce enough crops to sustain the entire population. Thus, households will need to either rely on other sources of nourishment through livestock products (milk, meat, etc.) or by importing their food, which are not incorporated in this model.

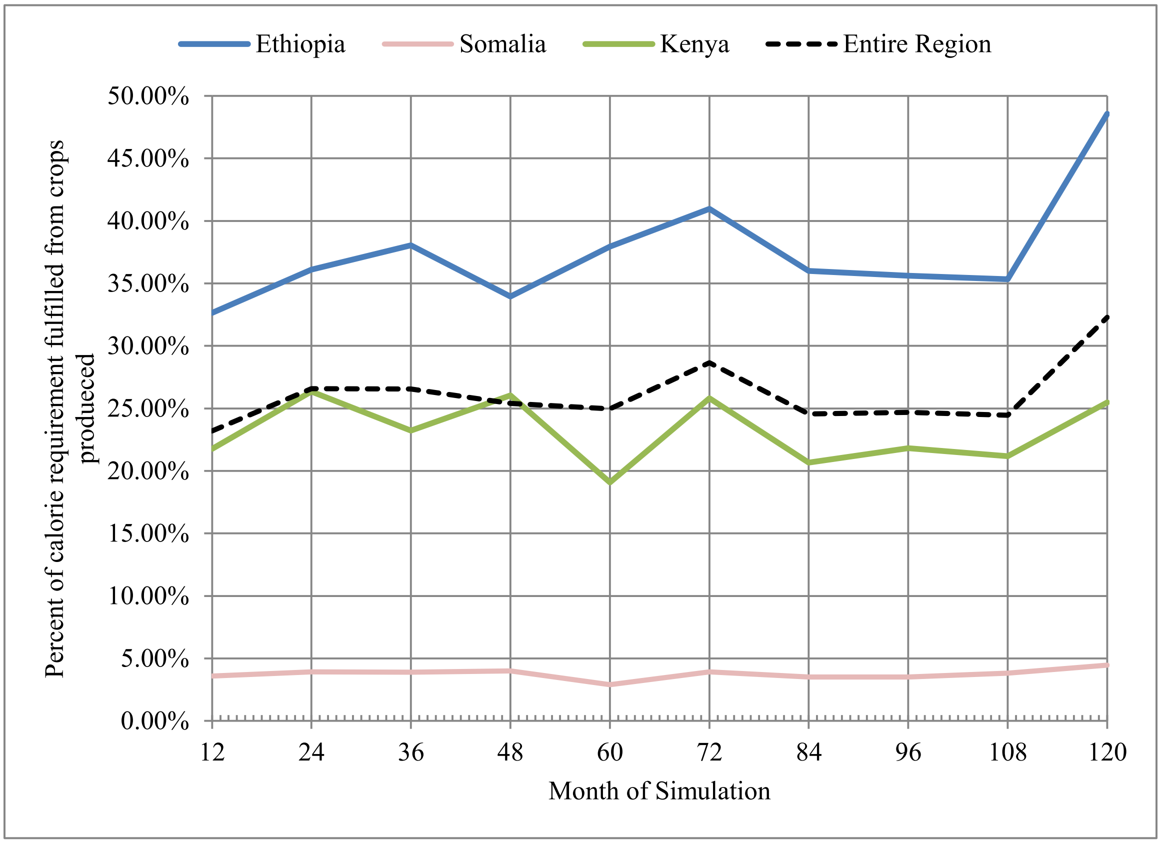


Figure 4.10: Percent of human caloric intake fulfilled by regional crop yield annually

### 4.3.3. Livelihood Analysis

The regional income per capita was calculated on an annual basis. The crop yield was determined on an annual basis and the income was determined under the assumption that all crop yield was sold; thus, the income due to crops is a maximum possible value.  The livestock income was initially calculated on a monthly time-step, but summed over 12 months to get the annual income.

Livelihood data from the Famine Early Warnings System Network (FEWS NET) was used to determine a rough estimate distinguishing the pastoral, agro-pastoral, and settled farming populations in each region (www.fews.net). Using the average herd size and farm size for each livelihood group, the income from livestock, farming, or a combination of both were estimated for each community based on the model's annual income results.

Figures 4.7, 4.8, and 4.9 show the baseline scenario incomes for agro-pastoralists, pastoralists, and farmers in USD for each of the 3 regions. These incomes would fluctuate up or down depending on the social standing of each household. The income for all livelihoods were averaged and compared to the Gross National Income (GNI) per capita for each country for the period of 2001-2010 the regional income is compared as a percentage of the respective country's GNI (United Nations, 2012).  The study region has low development indicators and an extremely high incidence of poverty (Gomes, 2006).  Because the GNI values are given for the country as a whole, these values are expected to be higher than the overall GNI of each particular country's sub-region of interest. Each region has a slightly different livelihood depending on crop production, livestock sales, and various other means of income. This could be waged labor, casual labor, self-employment, sales of milk, and social support which are not included or quantified in this model.

Each country has a slightly different economic trend. Ethiopia has the most agricultural land of all of regions, and the profit associated with farming is highest in this region. While there is a large Ethiopian livestock population, there is also a large pastoralist population, so the income per pastoralist household would not be as high as the farming households. Conversely, Somalia has the smallest area of agricultural land resulting in a low farming income, while the income from livestock is much more prominent. Kenya is the most well-mixed of the three regions, containing a large livestock population and a fairly large area of agricultural land. All regional incomes have an increasing economic trend.

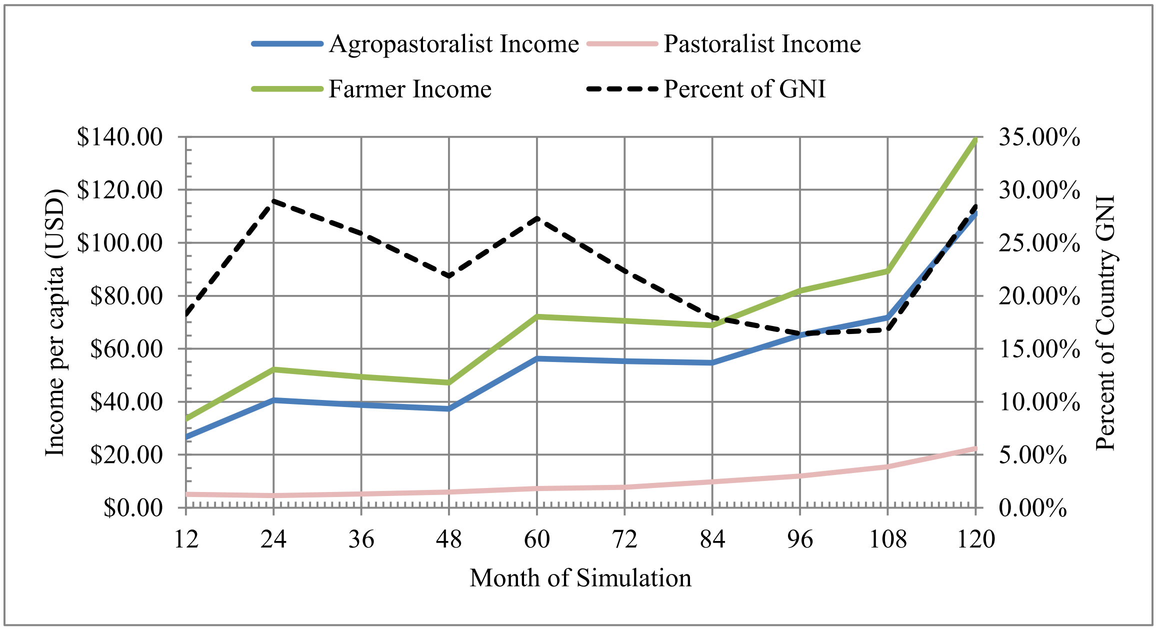


Figure 4.11: Ethiopian region income per capita

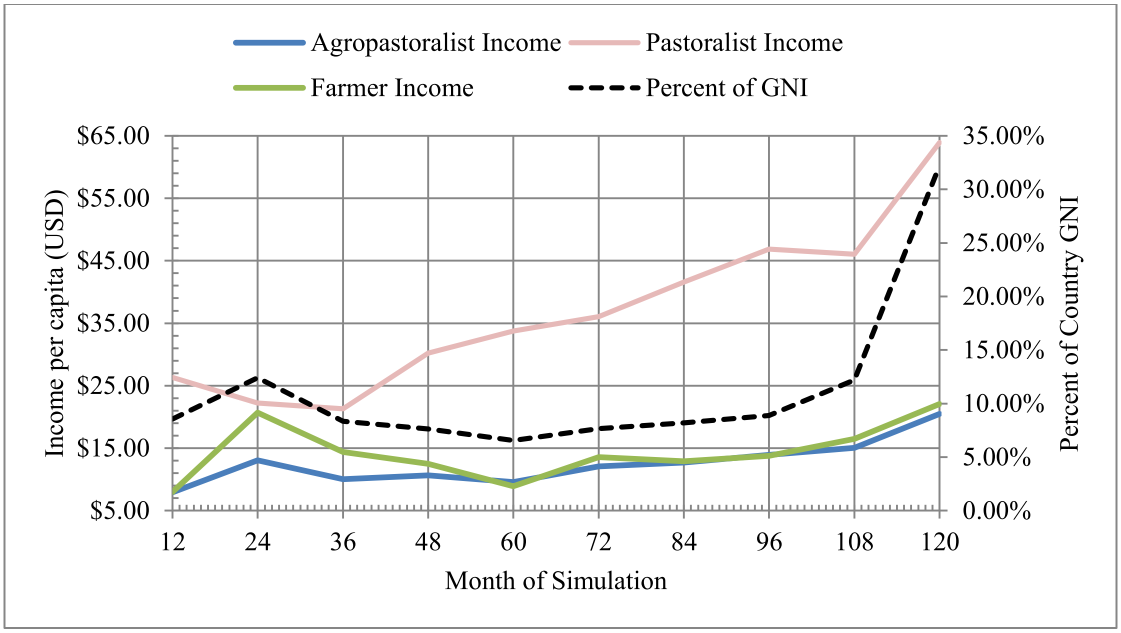


Figure 4.12: Somali region income per capita

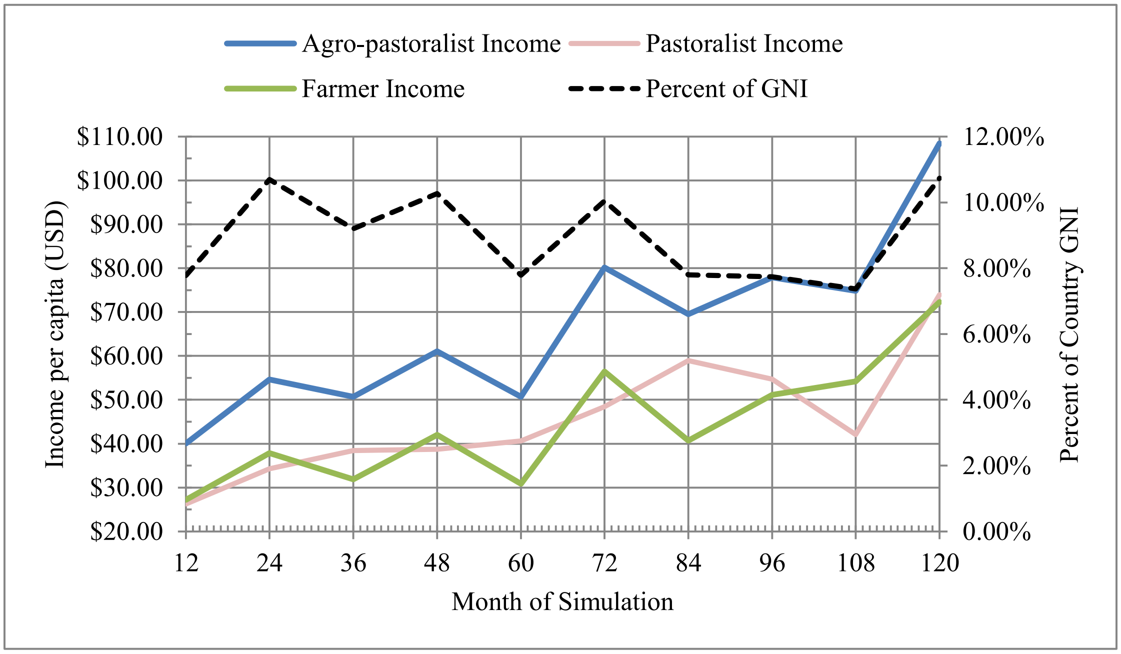


Figure 4.13: Kenyan region income per capita

## 4.4. Policy 1 – Increased Hydraulic Infrastructure

The first policy implementation was proposed to improve the overall water availability. This requires adding new hydraulic infrastructure that would act as a source of water in order to meet demands and reduce deficits in each region. Five different types of hydraulic infrastructure were implemented to diminish the shortages based on the total number and magnitudes of the water deficits in each region (Table 4.6). The quantity of each infrastructure added was based on the capacity of water each can potentially add to reduce the deficits of 4,000,000 $m^3$, 3,000,000 $m^3$, and 5,000,000 $m^3$ for the Ethiopian, Somali, and Kenyan regions, respectively (as estimated in Table 3.4). Each different type of hydraulic infrastructure was introduced and tested separately in the model. The infrastructure was added to the 11 subbasins based on the area within each country's region. The exception was the rainwater harvesting tanks; they rely on impervious surfaces to catch water runoff, so their allocation was based off of the location of settlements within the country.

Once the model was run with each improved individual hydraulic infrastructure improvement, the same baseline variables were examined at to determine the effectiveness at reducing both the frequency and magnitude of water deficits and the effects on other systems.

### 4.4.1. Water Availability

First, the water deficits were compared to verify that the infrastructure reduced the magnitude or eliminated the water shortages. The results for each region and infrastructure type are shown in Table 4.4, 4.5, and 4.6. The "baseline" corresponds to the initial simulation of the model with known water sources; each additional column is the simulation under the added infrastructure. Each region has similar results, and it is noticeable that with the new infrastructure, the magnitude of the deficits is reduced. The most successful infrastructure is the wells which reduce the number of total as well as the overall magnitude of deficits. Ponds and sand dams reduce the magnitude of the water deficits, but are not as successful at eliminating them completely. Finally, the RWH tanks are the least successful; they do not add enough water to the system to change the baseline deficits.

Each region experiences similar results with each respective type of infrastructure. Although it appears the total number of water deficits have not been decreased, with the added hydraulic infrastructure, the magnitudes of the water deficits are significantly decreased. The exception to this is the RWH tanks which do not have a substantial effect on reducing water deficits.

Table 4.4: Months with water deficits in Ethiopia under various hydraulic infrastructures

| **Water Deficit** | **Baseline** | **Sand Dam** | **RWH Tanks** | **Ponds** | **Shallow Wells** | **Boreholes** |
|---|---|---|---|---|---|---|
| Number of months with deficits | 26 | 23 | 26 | 17 | 15 | 15 |
| < 1,000,000 $m^3$ | 3 | 2 | 3 | 6 | 9 | 9 |
| 1,000,001 - 2,000,000 $m^3$ | 2 | 5 | 2 | 0 | 5 | 5 |
| 2,000,001 - 3,000,000 $m^3$ | 4 | 14 | 4 | 2 | 1 | 4 |
| 3,000,001 - 4,000,000 $m^3$ | 14 | 2 | 14 | 6 | 0 | 0 |
| > 4,000,000 $m^3$ | 3 | 0 | 3 | 3 | 0 | 0 |

Table 4.5: Months with water deficits in Somalia under various hydraulic infrastructures

| **Water Deficit** | **Baseline** | **Sand Dams** | **RWH tanks** | **Ponds** | **Shallow Wells** | **Boreholes** |
|---|---|---|---|---|---|---|
| Number of months with deficits | 10 | 9 | 10 | 9 | 7 | 2 |
| < 1,000,000 $m^3$ | 1 | 1 | 1 | 4 | 3 | 1 |
| 1,000,001 - 2,000,000 $m^3$ | 1 | 5 | 1 | 1 | 4 | 1 |
| 2,000,001 - 3,000,000 $m^3$ | 7 | 3 | 7 | 3 | 0 | 0 |
| 3,000,001 - 4,000,000 $m^3$ | 1 | 0 | 1 | 1 | 0 | 0 |
| > 4,000,000 $m^3$ | 0 | 0 | 0 | 0 | 0 | 0 |

Table 4.6: Months with water deficits in Kenya under various hydraulic infrastructures

| **Water Deficit** | **Baseline** | **Sand Dams** | **RWH tanks** | **Ponds** | **Shallow Wells** | **Boreholes** |
|---|---|---|---|---|---|---|
| Number of months with Deficits | 21 | 19 | 21 | 17 | 16 | 12 |
| < 1,000,000 m³ | 2 | 2 | 2 | 3 | 3 | 6 |
| 1,000,001 - 2,000,000 m³ | 1 | 3 | 1 | 1 | 4 | 4 |
| 2,000,001 - 3,000,000 m³ | 3 | 2 | 3 | 1 | 2 | 2 |
| 3,000,001 - 4,000,000 m³ | 2 | 5 | 2 | 4 | 2 | 0 |
| > 4,000,000 m³ | 13 | 7 | 13 | 8 | 5 | 0 |

It was determined that all of the RWH tanks were not being utilized based on surface water availability levels throughout the period of simulation. This was due to the vast quantity added but limited number of settlements with impervious surfaces to collect water from. Based on the actual storage capacity during the simulation period, the number of RWH tanks successfully employed was determined and this value was used to analyze the cost effectiveness for the infrastructure. Also, some of the infrastructure does not consistently function at full capacity. Many areas in Africa are known for failing wells and boreholes. This can be due to a number of reasons: lack of water, limited hydro-geographical knowledge, poor engineering, inadequate maintenance, etc. (MacDonald et al, 2001). For this region, boreholes are known to have a 38% failure rate (Harvey, 2004). Additionally, shallow wells cannot produce their expected yield year round, as shallow ground water supplies fluctuate during dry and wet seasons.

From this new deficit data, the cumulative water supply added during baseline deficits was taken as the net water gain (in m³) for each hydraulic infrastructure applied. This is considered the total volume of water the infrastructure has supplied during a known water scarcity and is shown in Figure 4.14 for each region and infrastructure type. Because Somalia has the least deficits and the lowest magnitudes, the total water added in smaller for this country. Overall, boreholes and shallow wells add the most water during deficit periods followed by sand dams and ponds. The RWH tanks add the least water; they have the smallest capacity and are limited to where they can be effective due to the requirement of settlements with impervious runoff area.

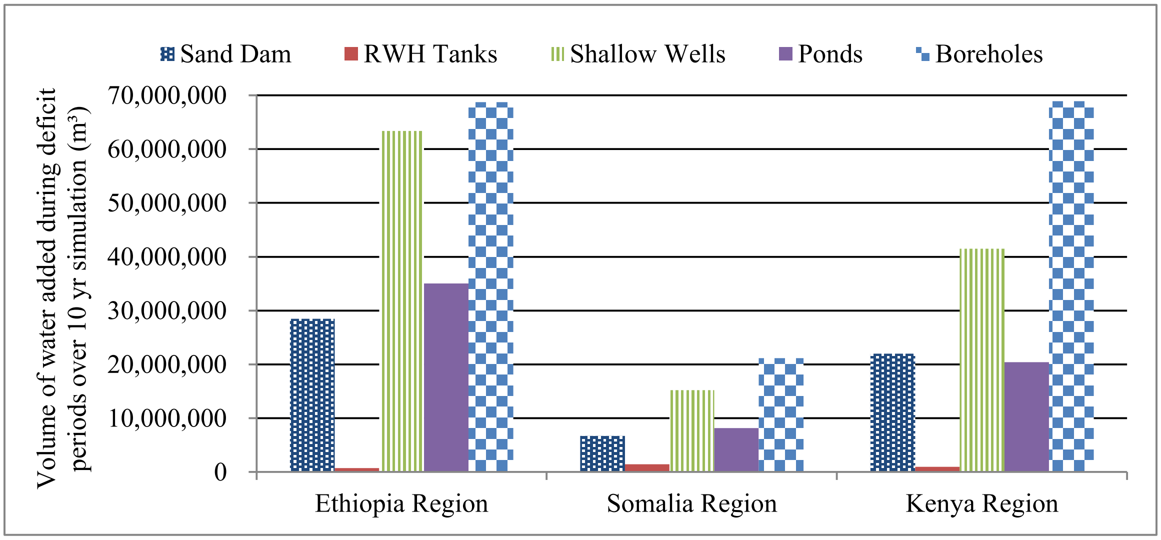


Figure 4.14: Water added during baseline deficits with respective hydraulic infrastructure

This net gain was then divided by the initial investment costs of each respective infrastructure to determine a cost per gained cubic meter of water. These results are shown for each region in Figure 4.15. Boreholes are the most reliable source of water because the water comes from deep aquifers that are not immediately affected by drought. Although they have a high initial investment cost, they provide a large amount of water and have a low cost per cubic meter of water added during deficits for each region. The three countries follow a similar result in cost per cubic meter added for each respective infrastructure, but Kenya is slightly different due to the RWH tanks. The RWH tanks are much more economic in Kenya than in the other two countries because Kenya has the lowest number of tanks successfully employed.

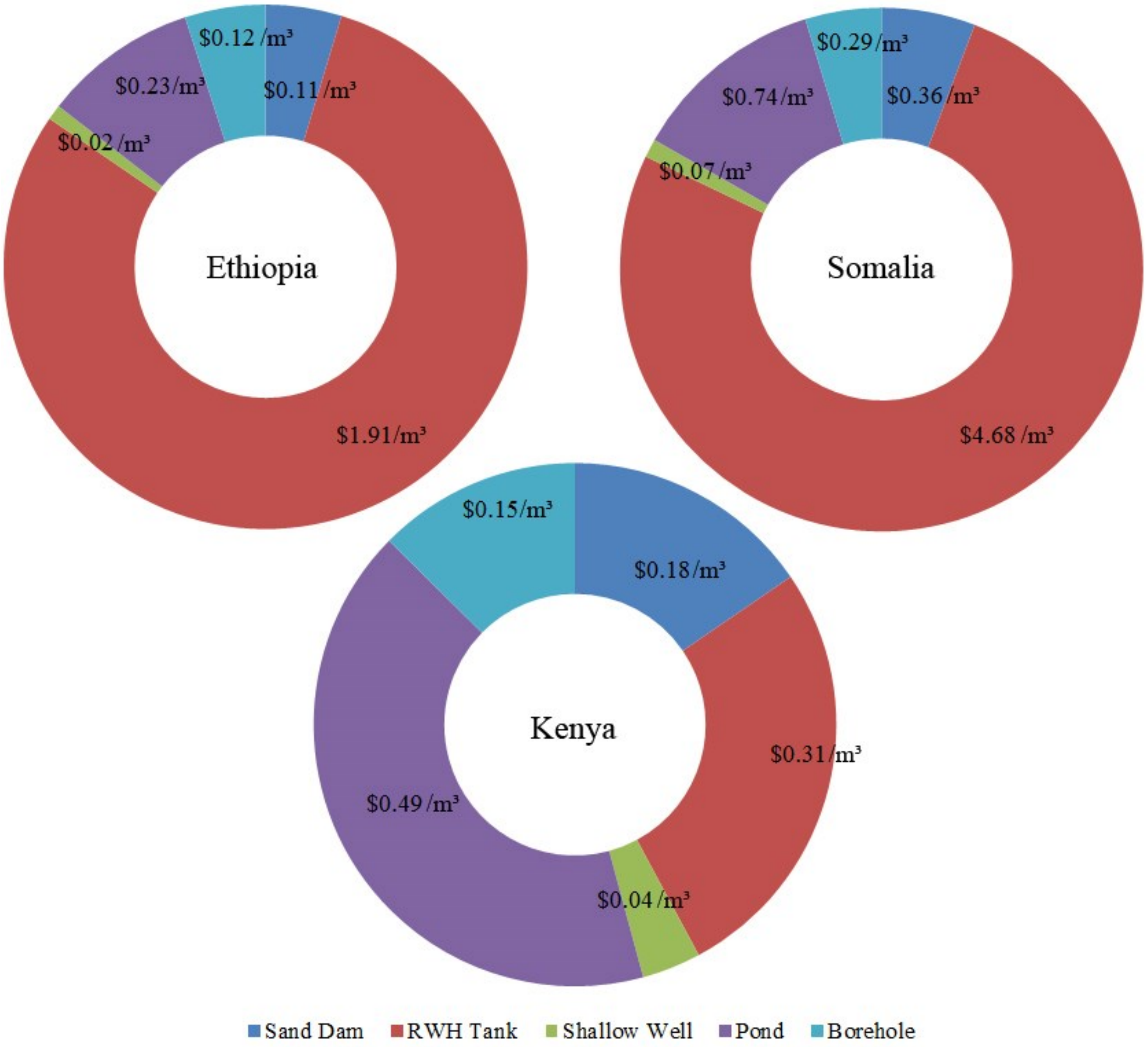


Figure 4.15: Cost per cubic meter water added during deficits from new hydraulic infrastructure

Although the hydraulic infrastructures help reduce the magnitude of water deficits, none of them successfully prevent the deficits from occurring completely. For all three regions, shallow wells and boreholes are the most cost effective infrastructure over the 10 year period (assuming they are implemented in a well suited location), but there are still deficits occurring over extended dry periods.

### 4.4.2. Crop Production and Food Availability

The agriculture in this region relies on rainfall to water crops; thus, there was no change in the crop yields based on increased hydraulic infrastructure.

### 4.4.3. Livelihood Analysis

Analysis on individual livelihood was also compared between the baseline scenario and each hydraulic infrastructure implementation. The total income for the entire 10 year period was calculated for each of the 3 livelihood classifications and then compared to the baseline scenario. Table 4.7 summarizes the total income and corresponding percent increase or decrease from the baseline.

Table 4.7: Effect hydraulic infrastructure has on individual livelihood income

| Ethiopia | | | Somalia | | | Kenya | | |
|---|---|---|---|---|---|---|---|---|
| AP* | Pastoral | Farmer | AP | Pastoral | Farmer | AP | Pastoral | Farmer |
| Baseline | | | | | | | | |
| **$558** | **$95** | **$704** | **$125** | **$368** | **$143** | **$668** | **$456** | **$444** |
| Sand Dams | | | | | | | | |
| $562 | $107 | $705 | $130 | $396 | $143 | $708 | $510 | $458 |
| 0.8% | 13.0% | 0.1% | 3.5% | 7.6% | -0.2% | 6.0% | 11.9% | 3.1% |
| RWH Tanks | | | | | | | | |
| $558 | $97 | $704 | $123 | $354 | $143 | $669 | $457 | $444 |
| 0.1% | 2.0% | 0.0% | -1.9% | -3.9% | -0.1% | 0.1% | 0.2% | 0.0% |
| Shallow Wells | | | | | | | | |
| $577 | $153 | $705 | $143 | $477 | $143 | $755 | $580 | $471 |
| 3.5% | 61.4% | 0.2% | 14.0% | 30.0% | -0.4% | 13.1% | 27.1% | 6.0% |
| Ponds | | | | | | | | |
| $570 | $132 | $704 | $136 | $431 | $143 | $720 | $536 | $457 |
| 2.2% | 38.5% | 0.1% | 8.1% | 17.1% | -0.2% | 7.8% | 17.5% | 2.9% |
| Boreholes | | | | | | | | |
| $581 | $169 | $705 | $168 | $629 | $142 | $798 | $676 | $467 |
| 4.3% | 77.8% | 0.1% | 33.6% | 70.8% | -0.7% | 19.4% | 48.0% | 5.1% |

*AP = Agro-pastoralist

From this table, the pastoralists are the main beneficiaries from the increase water availability as the increase in their total income is the most significant. More water available for animals during times of deficit result in lower mortality rates and higher overall livestock populations for both pastoral and agro-pastoral households. Farmers will also benefit from an increased water supply domestically, but because this region depends on rain fed agriculture, improving water availability alone would not affect the overall crop production or resulting income. Thus, there were no major changes in yields, caloric availability, or total crop income. The only variation to these values would come from slight changes in human migration due to changes in water availability.

## 4.5. Policy 2 – Improved Agricultural Practice

The second type of policy explored was intended to improve the farmer livelihood and overall crop production within the study area. There were 2 different innovative techniques implemented into the model: drip irrigation and agroforestry.

For the implementation, it was assumed that all cultivated agricultural land would employ each respective technique. There is an initial investment cost associated with an area of land being converted for each agricultural practice (Table 3.5). Based on the total area of agricultural land being improved, a cost of implementation was found. For agroforestry, the cost associated is the labor to convert land and the price of the trees themselves. Agroforestry does not have any type of irrigation techniques associated with it, so there is no added agricultural water demand to the system; however, it takes time for the trees to mature and results will take longer to develop. Conversely, drip irrigation requires a specific volume of water per area of cultivated land. For drip irrigation, a new water demand is introduced to the system that competes with domestic and livestock demands, but the increase in crop yields will be evident as soon as the new technology is installed. When analyzing the results of the drip irrigation, the water supply must also be examined because there will likely be more water scarcity under the new water scarcity because of the added irrigation demand.

### 4.5.1. Water Availability

For the drip irrigation, when looking at the water supply versus demand, the previous deficits are now larger in magnitude and more often because of the new agricultural water demand (approximately 12,000 $m^3$ a month per $km^2$ during dry periods). These demands will result in more water deficits during the 10 year period due to the increased demands. The added water demands are shown in Figure 4.22. The Ethiopian region contains the largest amount of agricultural land followed by Kenya, and the demands resemble this. The troughs in the graph correspond to periods where rainfall alone will satisfy the irrigation demands. The added irrigation demand is in the hundreds of millions of cubic meters of water, which previously was zero. The new agricultural water demands are much larger than the existing baseline water demands (domestic and livestock); drip irrigation over large areas would create an intense competition with domestic and livestock water suffering larger and more frequent deficits. Ethiopia has the largest water demand because it contains the largest agricultural land area; Somalia adds the smallest water demand because it holds the smallest agricultural land area. Agroforestry does not add any additional water demands to the system.

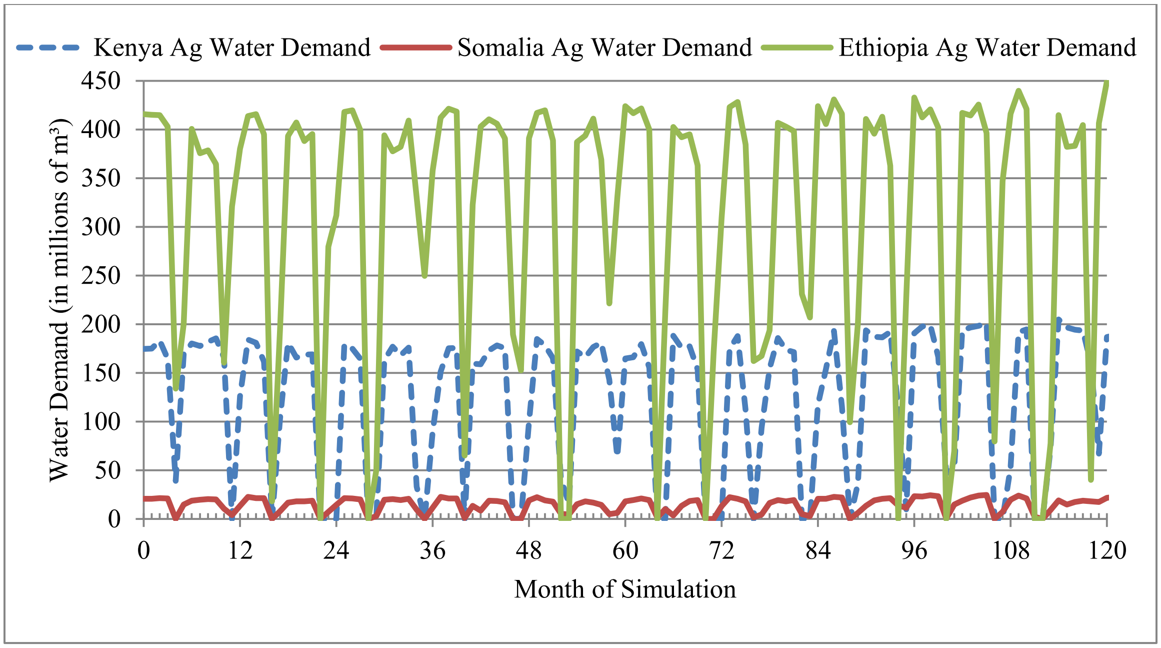


Figure 4.16: Regional agricultural water demands under drip irrigation agricultural practice

### 4.5.2. Crop Production and Food Availability

The annual yields for each crop and agricultural practice are show in Figures 4.16, 4.17, and 4.18 for Ethiopia, Somalia, and Kenya, respectively. Both the drip irrigation and agroforestry provide higher yields over the 10 year period. Drip irrigation consistently has a higher yield in the range of 1 to 2 times greater than the baseline scenario. On the other hand, the increase in yield through agroforestry is more gradual and is maximized at the end of the 10 year period. Agroforestry shows lower than baseline yields in the first few years of simulation when the trees are not yet productive and are competing with crops for nutrients and water. After 2-3 years, the trees are reaching maturation and providing benefits to the crops like water storage in soil and fallow to fertilize the crops.

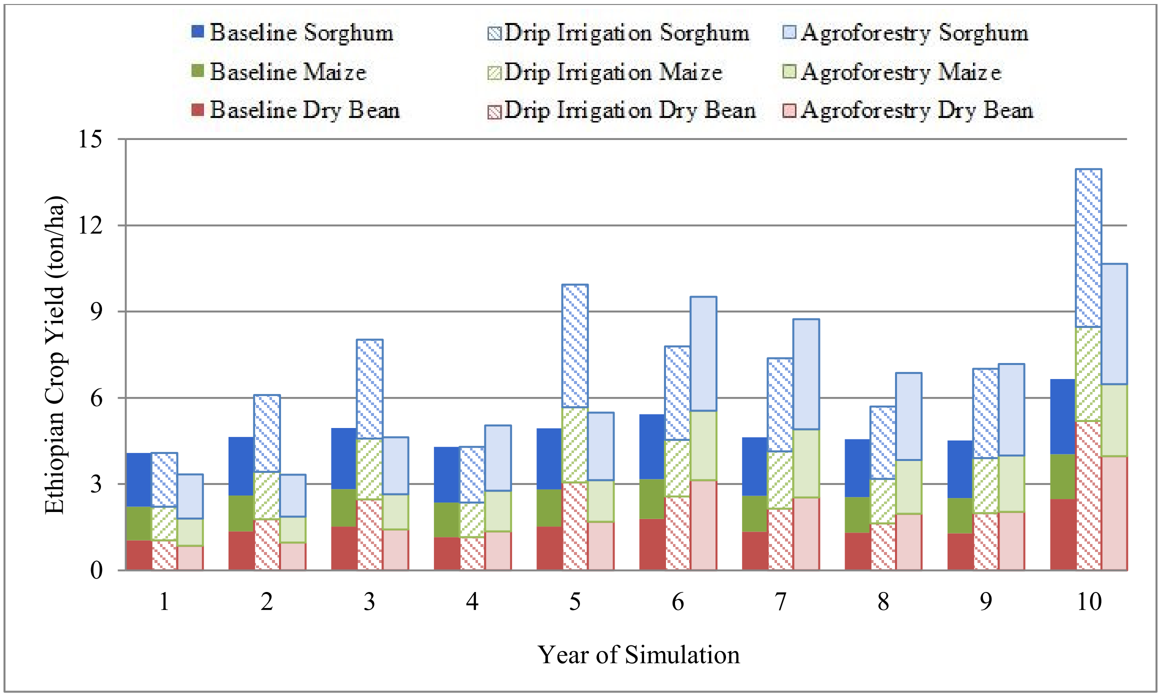


Figure 4.17: Agricultural improvement effect on Ethiopian region crop yields

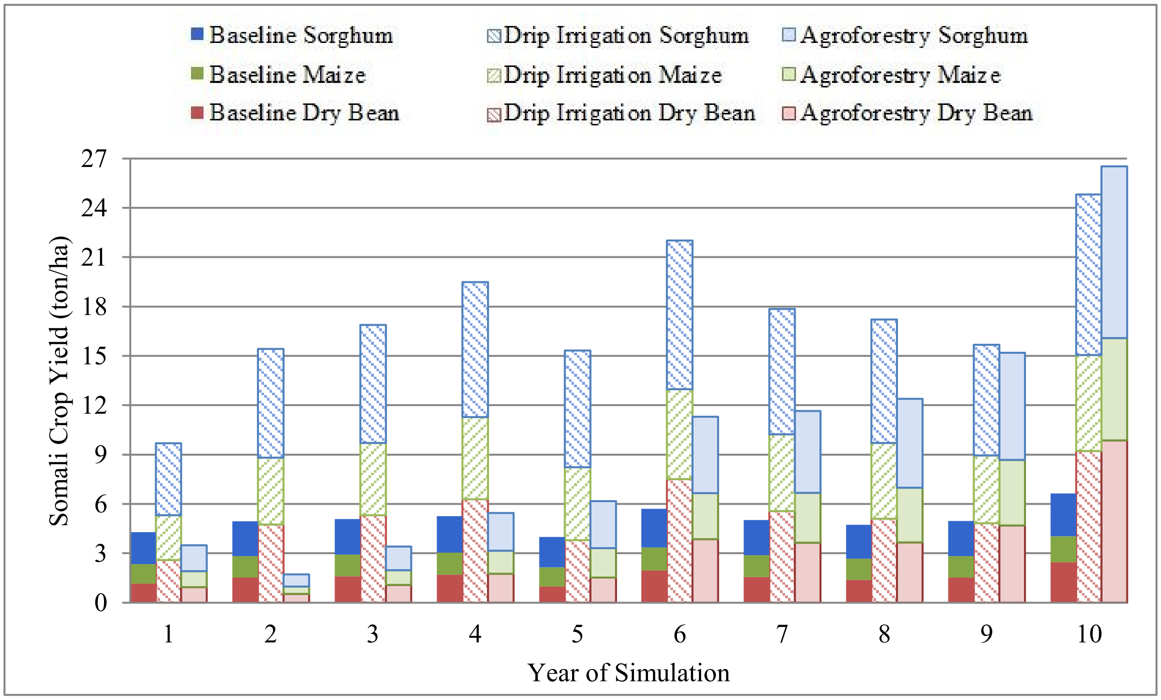


Figure 4.18: Agricultural improvement effect on Somali region crop yields

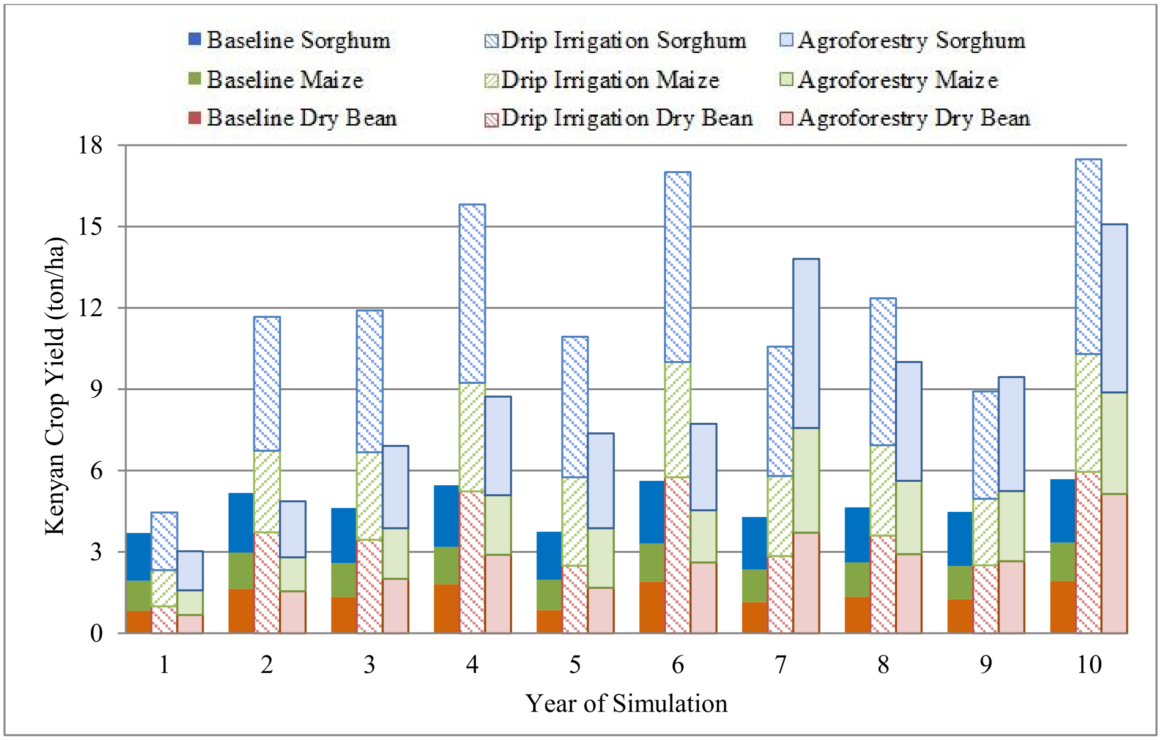


Figure 4.19: Agricultural improvement effect on Kenyan region crop yields

The impact on the regional livelihood can also be observed through the change in available food for the population. Like the baseline scenario, the total caloric availability was determined based on crop yield and calorie content for each region. Dividing that value by the average annual population and recommended human caloric intake (2100 kcal/day), an estimate for the percentage of the regional population's diet that can be sustained through the local agricultural practice was determined. Again, these results were compared to the baseline simulation. Figures 4.19, 4.20, and 4.21 show the change in percentage of population caloric fulfillment from the baseline scenario each year for drip irrigation and agroforestry for Ethiopian, Somali, and Kenyan agricultural practice, respectively. The yields are still a function of rainfall, which explains the fluctuations of caloric fulfillment throughout the simulation.

For the drip irrigation, if there is not ample water supply, the crops will simply have the same yields as rain fed conditions. Because the Ethiopian region has the lowest rainfall for this period and the most water deficits, drip irrigation is the least effective for this country. The Somali region had the highest rainfall and lowest deficits during the simulation period and has the most consistent increase in yields under drip irrigation.

For all three regions, there is a decrease in caloric fulfillment under agroforestry during the first few years due to the trees growing and competing with crops for water and nutrients. After this growing period, the trees provide soil stability, water retention, and tree fallow to fertilize the land, resulting in higher yields and a higher percentage of caloric supply from crop production.

Overall, Somalia has the lowest increase in caloric fulfillment from both agricultural practices. This is because the Somali region has the smallest area of agricultural land. Even with improvement, the agriculture being produced is not enough to sustain the population for the whole Somali region.

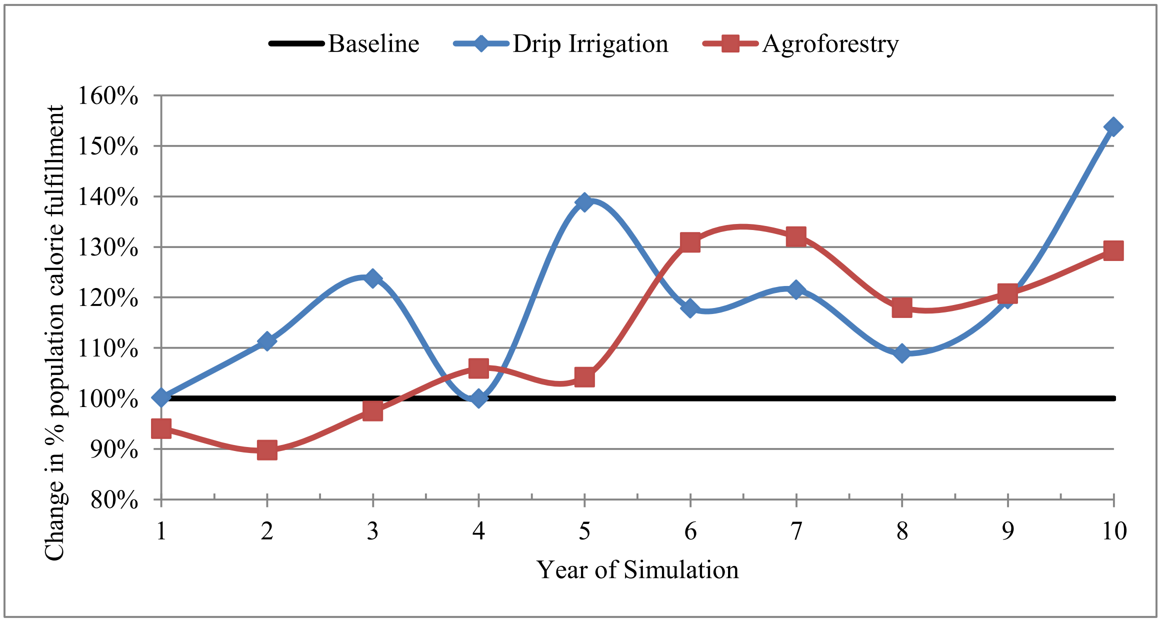


Figure 4.20: Change in percent of Ethiopian region caloric supply due to agricultural practice

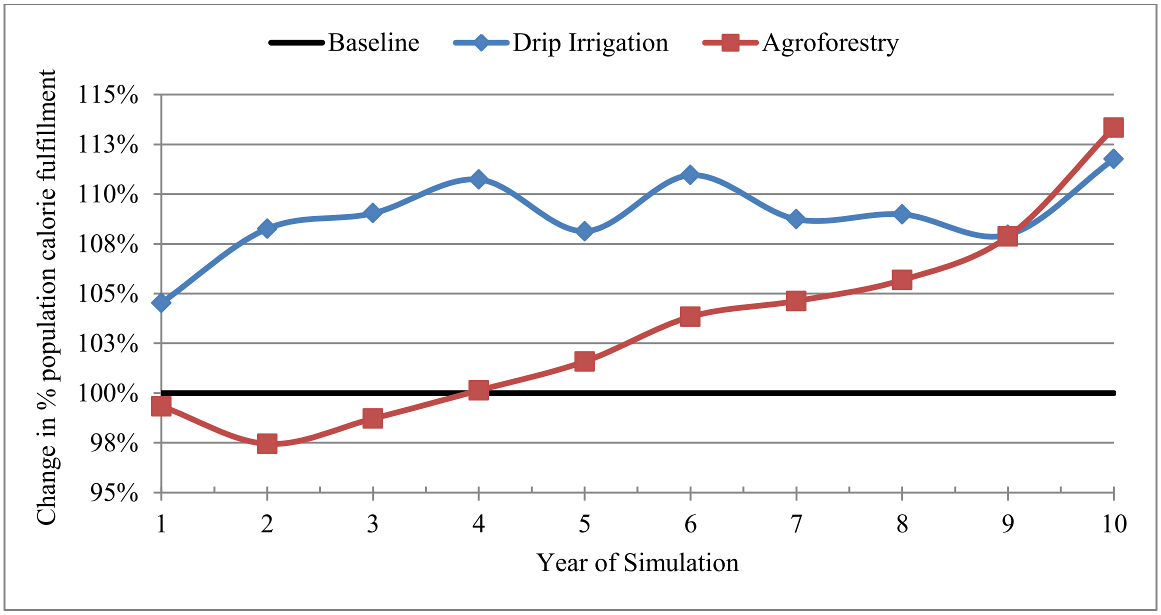


Figure 4.21: Change in percent of Somali region caloric supply due to agricultural practice

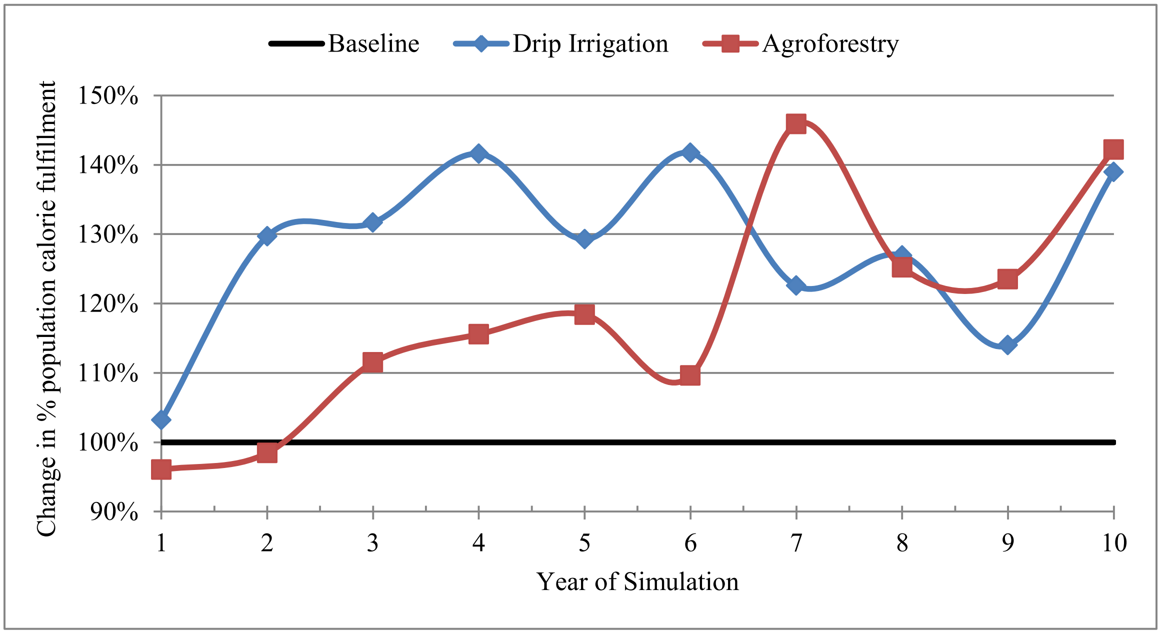


Figure 4.22: Change in percent of Kenyan region caloric supply due to agricultural practice

### 4.5.3. Livelihood Analysis

Analysis on individual livelihood was also compared between the baseline scenario and each agricultural practice implementation. Like before, the total income for the entire 10 year period for each of the three livelihood classifications were calculated and then compared to the baseline scenario. Table 4.8 summarizes the total income and corresponding percent increase or decrease from the baseline for the 10 year simulation.

Table 4.8: Effect agricultural practice has on individual livelihood

| Ethiopia | | | Somalia | | | Kenya | | |
|---|---|---|---|---|---|---|---|---|
| AP* | Pastoral | Farmer | AP | Pastoral | Farmer | AP | Pastoral | Farmer |
| Baseline | | | | | | | | |
| **$558** | **$95** | **$704** | **$125** | **$368** | **$143** | **$668** | **$456** | **$444** |
| Drip Irrigation | | | | | | | | |
| $842 | $24 | $1,112 | $257 | $214 | $487 | $1,087 | $177 | $1,001 |
| 51.0% | -74.3% | 58.0% | 104.8% | -41.9% | 240.1% | 62.8% | -61.3% | 125.2% |
| Agroforestry | | | | | | | | |
| $661 | $95 | $842 | $208 | $368 | $324 | $1,240 | $456 | $1,017 |
| 18.6% | 0.0% | 19.7% | 65.8% | 0.0% | 126.4% | 85.7% | 0.0% | 128.8% |

*AP = Agro-pastoralist

The beneficiaries from the agricultural policy are the farmers and agro-pastoralists. In the case of drip irrigation, the pastoralists have a severely negative outcome from this policy. Due to the high irrigation water demand, the water availability for livestock is diminished and the dry periods will result in higher mortality rates. This results in lower incomes and livelihoods for the pastoralists. Because agroforestry does not add a new water demand on the system, pastoralists are not affected.

Both measures increase the overall yield of staple crops for the region, but it is necessary to examine how profitable the practice is for farmers to determine if they should invest and adopt the new method. To do this, an initial investment cost was determined based on the area of agricultural land and the average cost for implementing each type of agricultural practice (Table 3.5). The cost for drip irrigation was doubled, because the lifetime of the system is approximately five years (implemented at year 0 and year 5). For the entire 10 year period, the total increase in crop income (from maize, dry bean, and sorghum) was then found along with the additional income for tree products for agroforestry. Based on the annual cash flows and initial investment cost, the net present value (NPV) of the total increase in income was determined (Beaves, 1993). A discount rate of 10% was used in this calculation based on historical interest rates from the Central Bank of Kenya (www.centralbank.go.ke). The results are in Table 4.9. This only displays the added income from agriculture over the 10 year period of study. Pastoralists do not benefit from drip irrigation; the income from livestock sales will decrease under this policy while it remains unaffected by the agroforestry.

Table 4.9: Regional profitability of agricultural systems over 10 year simulation

| | **Ethiopia** | **Somalia** | **Kenya** |
|---|---|---|---|
| **Drip Irrigation** | | | |
| Area of Ag Land (ha) | 357,743 | 18,700 | 157,772 |
| Initial Investment cost ($/ha) | $15,000 | $15,000 | $15,000 |
| Total Investment | $5,366,155,500 | $280,501,200 | $2,366,587,500 |
| Increase in Income From Crops* | $655,974,500 | $328,658,610 | $1,512,947,500 |
| *NPV Profit* | -$3,652,253,130 | -$37,037,190 | -$1,000,294,720 |
| *NPV profit (per ha)* | -$10,210 | -$1,980 | -$6,340 |
| **Agroforestry** | | | |
| Area of Ag Land (ha) | 396,618 | 18,700 | 157,772 |
| Initial Investment cost ($/ha) | $90 | $90 | $90 |
| Total Investment Cost | $35,695,620 | $1,683,010 | $14,199,530 |
| Increase in Income From Crops* | $337,812,200 | $183,718,670 | $1,270,943,800 |
| Income From Tree Products* | $891,278,340 | $41,313,270 | $348,089,710 |
| *NPV profit* | $76,324,920 | $68,691,680 | $545,603,610 |
| *NPV profit (per ha)* | $190 | $3,670 | $3,460 |

*over 10 years

From this analysis, Agroforestry is successful at returning a profit for the farmer investing. Because drip irrigation has such a high initial investment cost, when applying it to such a large area, the resulting income due to increased yield of the staple crops is not enough to justify the high cost of implementation. In all regions, there is no positive return. Additionally, the increase in water demand that drip irrigation adds is immense and creates a negative effect on the pastoral population as livestock income decreases.

### 4.5.4. Small-Holder Drip Irrigation

Implementing drip irrigation across all agricultural land is not a feasible option; however, implementing smaller plots of drip irrigation per household could be a more practicable solution. Smallholder drip irrigation systems have the ability to grow cash crops that sell at a higher value and the small plots significantly decrease the demand of water.

To implement smallholder drip irrigation in the model, 500 $m^2$ plots were implemented in each household based on the regional population, household size, and available agricultural land. This will reduce the amount of land being used for traditional crops (maize, dry bean, and sorghum) so the total yields and income from these crops will be slightly lower. However, the plots of drip irrigated cash crops will provide an additional increased income. The same analysis was done to determine the main beneficiaries (Table 4.10) and the net present value (NPV) of crop profits and expenditures based on the cash flows (Table 4.11) over the 10 year period (using 10% as the rate of return).

Table 4.10: Effect small-holder drip irrigation has on individual livelihood

| Ethiopia | | | Somalia | | | Kenya | | |
|---|---|---|---|---|---|---|---|---|
| AP | Pastoral | Farmer | AP | Pastoral | Farmer | AP | Pastoral | Farmer |
| Baseline | | | | | | | | |
| **$558** | **$95** | **$704** | **$125** | **$368** | **$143** | **$668** | **$456** | **$444** |
| Small-scale Drip Irrigation | | | | | | | | |
| $694 | $63 | $899 | $261 | $300 | $464 | $843 | $379 | $658 |
| 24.5% | -34.3% | 27.8% | 107.7% | -18.4% | 223.8% | 26.3% | -17.0% | 48.0% |

Table 4.11: Regional profitability of smallholder drip irrigation over 10 year simulation

| | **Ethiopia** | **Somalia** | **Kenya** |
|---|---|---|---|
| **Smallholder Drip Irrigation** | | | |
| Area of Ag Land (ha) | 9739 | 5752 | 10377 |
| Initial Investment cost ($/ha) | $12,000.00 | $12,000.00 | $12,000.00 |
| Total Investment Cost | $116,871,530 | $69,033,460 | $124,533,730 |
| Decrease in Income From Staple Crops* | -$71,922,900 | -$41,210,200 | -$63,228,300 |
| Income From Cash Crops* | $463,314,100 | $335,259,300 | $554,129,400 |
| *NPV profit* | $128,822,330 | $107,047,290 | $173,124,080 |
| *NPV profit (per ha)* | $13,230 | $18,610 | $16,680 |

*over 10 years

Although based on the NPV profit for the farmers over the 10 year period is positive, there is still a negative effect on pastoralists because the drip irrigation still increases water demand. As a result, income due to livestock would suffer. However, with smaller plots, Figure 4.23 shows the small-holder water demand will result in a more reasonable added water demand compared to full implementation of drip irrigation on all agricultural land (Figure 4.22). The small scale drip water demand is magnitudes smaller. Again, Ethiopia has the largest demand and Somalia has the smallest demand corresponding to the total area that implementing the irrigation. Although farmers are giving up some of their agricultural land that was previously harvesting maize, dry beans, and sorghum, the profits from the cash crops more than make up for any economic losses. The cash crops can also be used as a source of food for their own families.

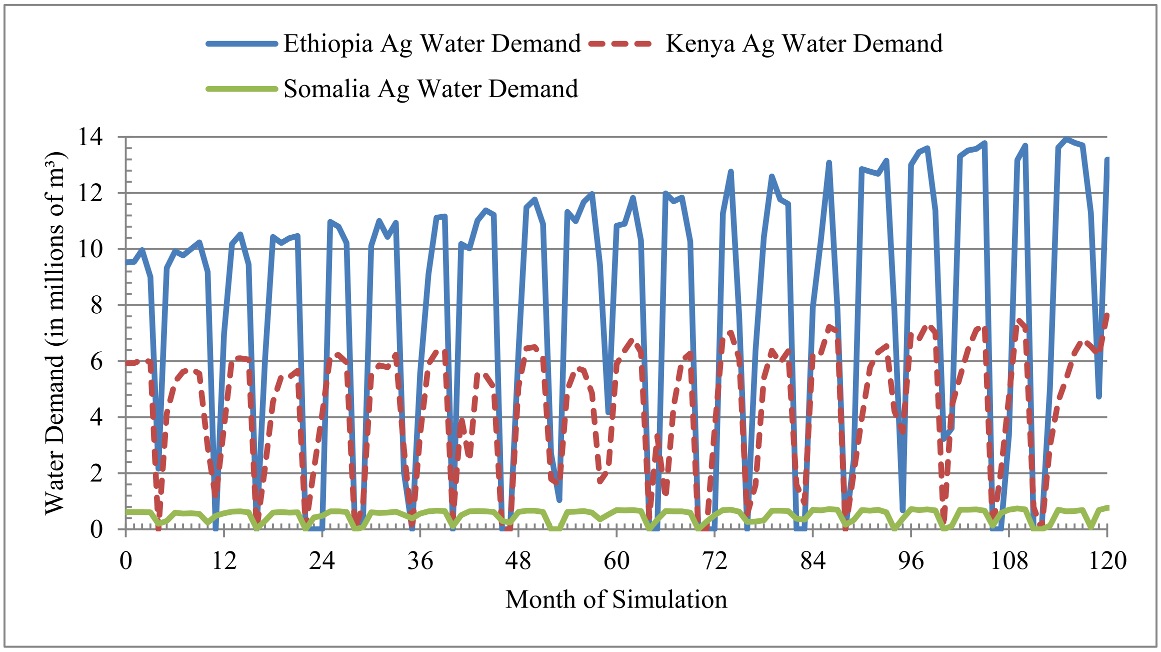


Figure 4.23: Regional agricultural water demands under smallholder drip irrigation

## 4.6. Policy 3 – Combined Hydraulic Infrastructure and Agricultural Practice Improvement

The last policy option explored was a combination of the improved hydraulic infrastructure and the agricultural practices to improve the livelihood of all groups: agro-pastoral, pastoral, and farmers. Based on the model results for the hydraulic infrastructure, it was determined that the RWH tanks did not efficiently supply water to the population. RWH tanks are more appropriate at the single household scale domestic needs. Because this model focuses on the larger, regional scale and include livestock and agricultural demands, their impact is not as visible as a large pond or sand dam that provides water at a community scale. Thus, for the combined policy, RWH tanks were not considered.

The hydraulic infrastructure was separated between surface water storage and ground water access; each responsible for half of the initial deficit reduction volume of water. A combination of surface water storage infrastructure and ground water infrastructure were determined for each region based on their cost benefit analysis from policy 1 (Section 4.2.1.). The infrastructure added to each region is summarized in Table 4.12. The agricultural policy was applied using both agroforestry and small-holder drip irrigation. Agricultural policy is much more expensive to implement across large areas of land. For the combined policy, 2% of households implemented a 500 $m^2$ plot of drip irrigated land used for cash crops and 10% of the remaining agricultural land applied agroforestry. This produces a new water demand due to irrigated plots, income due to cash crops and tree products, and both agroforestry aided crops and natural rained crops.

Table 4.12: Hydraulic infrastructure and agricultural policy implemented in combined model

| | **Ethiopia** | **Somalia** | **Kenya** |
|---|---|---|---|
| Hydraulic Infrastructure (units added) | | | |
| Sand Dams | 14 | 11 | 19 |
| Shallow Wells | 747 | 540 | 900 |
| Ponds | 33 | 25 | 34 |
| Boreholes | 30 | 27 | 44 |
| Agricultural Practice Implemented (ha) | | | |
| Drip Irrigated Land | 201 | 115 | 190 |
| Agroforestry Land | 40,731 | 1,859 | 15,758 |

### 4.6.1. Water Availability

Drip irrigation adds an additional demand on the water supply, to water the cash crops when rain water is not sufficient. Figure 4.24 shows this added water demand for each region based on the total area of land employing drip irrigation. In the baseline scenario, there was no agricultural water demand because all of the crops were rain fed. Ethiopia and Kenya have the largest demands because they have a larger total agricultural area with drip irrigation.

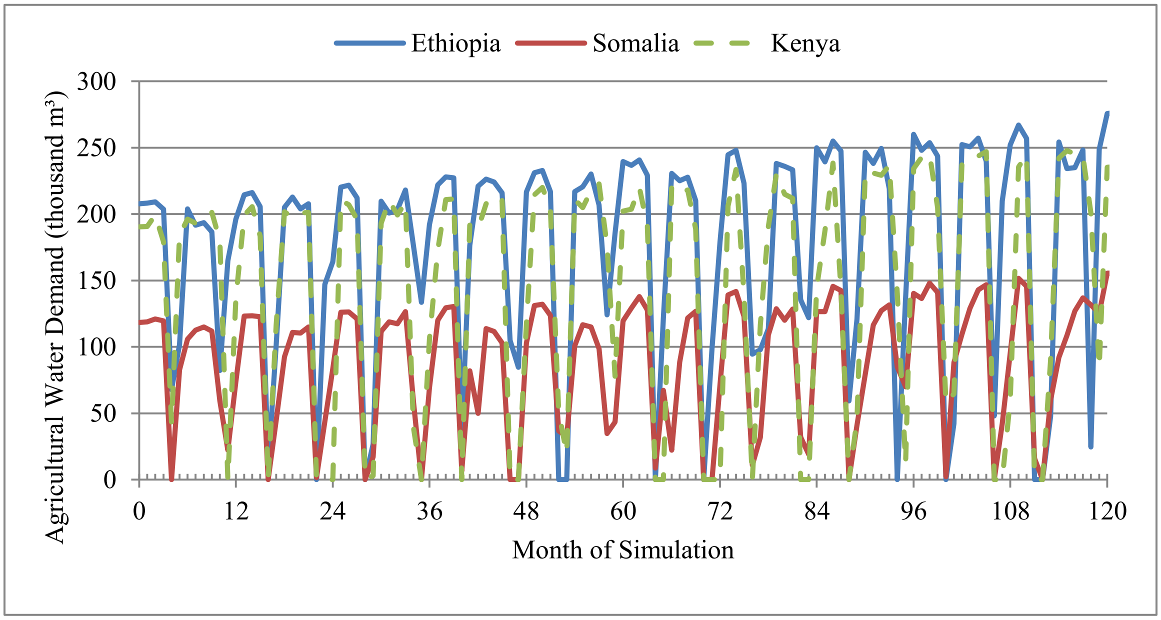


Figure 4.24: Agricultural water demand added by drip irrigated land

With no additional hydraulic infrastructure, this demand would create more competition for water and larger deficits for domestic and livestock consumption. However, with the combined policy, the additional hydraulic infrastructure reduces this consequence. Based on the minimum human water consumption requirements (0.45 $m^3$/month), a comparison between the baseline and combined policy models show that even with the added agricultural water demand, the overall water availability is still higher with the added infrastructure and drip irrigation (Figures 4.25, 4.26, and 4.27). Ethiopia has the most agricultural land and lowest rainfall for the simulation period; the country had the most water deficits during the baseline simulation, but the domestic deficits are significantly reduced with the combined policy. Similarly, with the combined policy, Somalia and Kenya almost entirely irradiate domestic water deficits. Thus, the added water demand from drip irrigation in conjunction with increased hydraulic infrastructure has an overall positive effect on water supply.

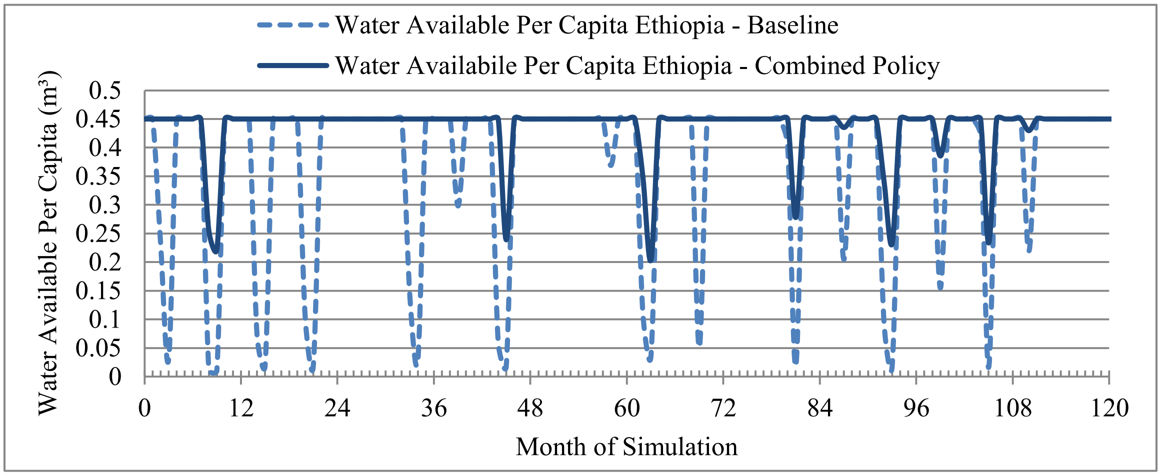


Figure 4.25: Comparison of minimum human water requirement availability - Ethiopia

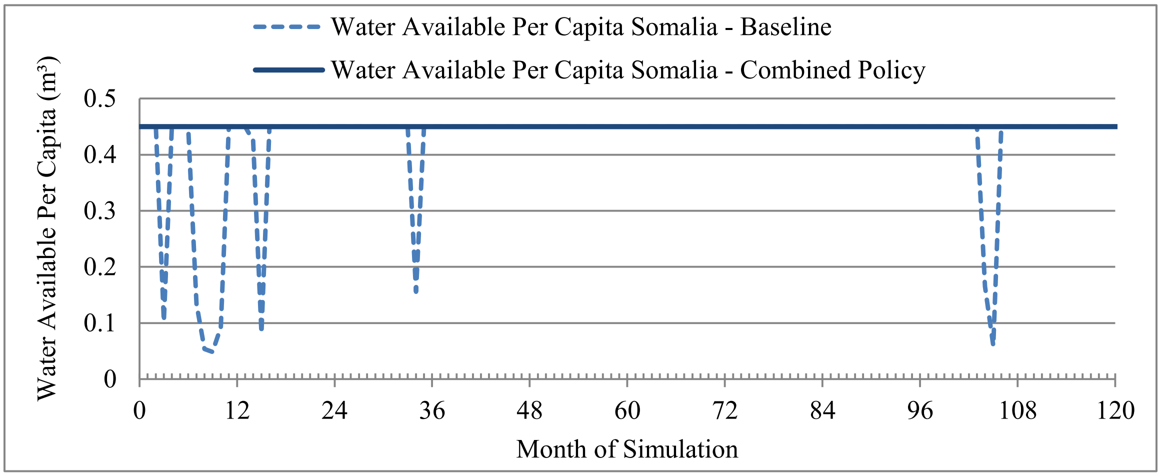


Figure 4.26: Comparison of minimum human water requirement availability - Somalia

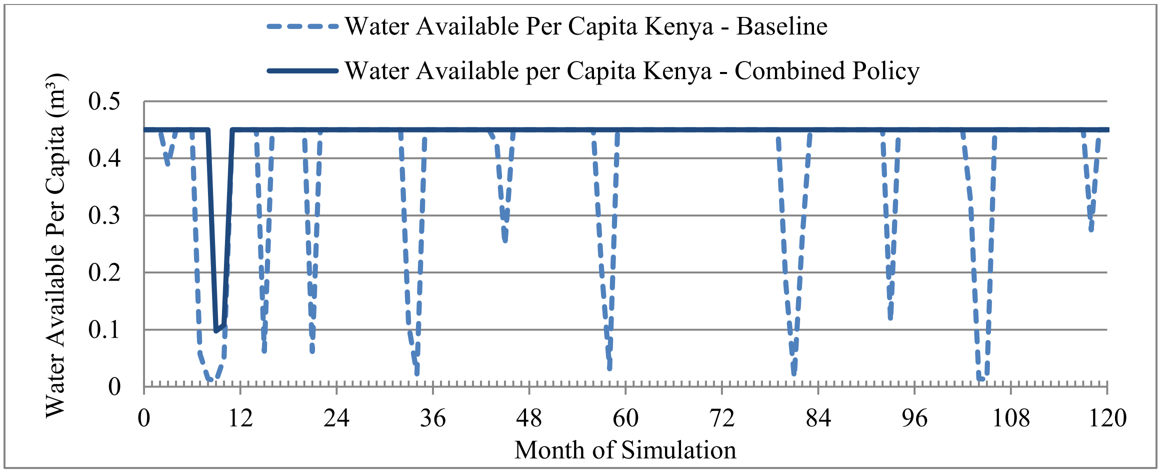


Figure 4.27: Comparison of minimum human water requirement availability – Kenya

### 4.6.2. Crop Production and Food Availability

Although small sections of agricultural land are partitioned off for cash crops, over the 10 year simulation, the total yield of staple crops increases due to the agroforestry. As seen in Figure 4.28, the first 2 years of simulation have lower diet fulfillment from staple crops. This is due to less land being used for staple crop production and the competition between the crops and maturing trees. After year 3 there is a steady increase the percent of diet fulfillment. Somalia has the least growth because it also has the least available agricultural land. There are still fluctuations over the 10 year simulation because the crops are still dependent on rainfall which varies over the 10 years. Kenya's annual rainfall is larger than Ethiopia's rainfall over the simulation period, which is why the diet fulfillment for Kenya is higher.

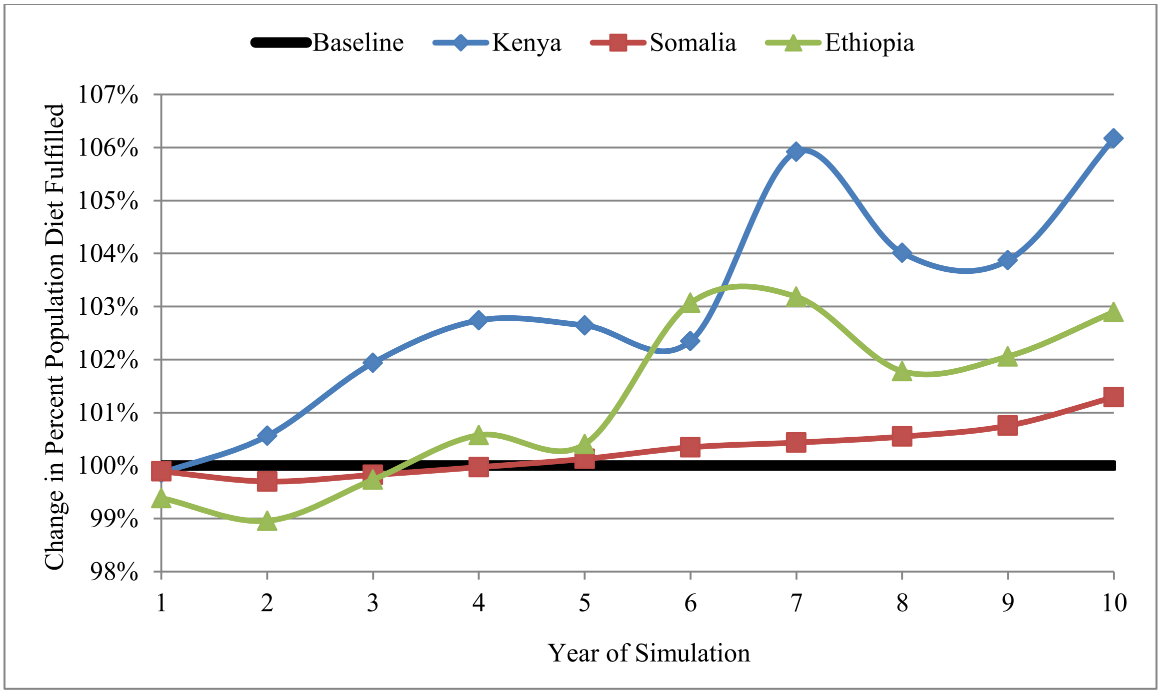


Figure 4.28: Change in percent of caloric supply due to combined policy

### 4.6.3. Livelihood Analysis

Income analysis was done to determine the beneficiaries of the combined policy implementation. The results were again, compared to the baseline income over the 10 year period for each livelihood group in each region. The combined policy results are shown in Table 4.13. Each group benefits from the implementation of the hydraulic and agricultural policies; farmers benefiting the most (under the assumption they sell all their crops for profit). Additionally, the pastoralists still benefit from the increased water availability for their livestock, as the mortality rates decline and overall populations increase (Figure 4.29).

Table 4.13: Effect of agricultural and hydraulic infrastructure policy on individual livelihood

| Ethiopia | | | Somalia | | | Kenya | | |
|---|---|---|---|---|---|---|---|---|
| AP | Pastoral | Farmer | AP | Pastoral | Farmer | AP | Pastoral | Farmer |
| Baseline | | | | | | | | |
| **$558** | **$95** | **$704** | **$125** | **$368** | **$143** | **$668** | **$456** | **$444** |
| Combined Agricultural and Hydraulic Infrastructure | | | | | | | | |
| $812 | $126 | $1,029 | $326 | $456 | $551 | $1,083 | $548 | $814 |
| 45.6% | 32.7% | 46.3% | 159.8% | 23.9% | 285.1% | 62.1% | 20.2% | 83.2% |

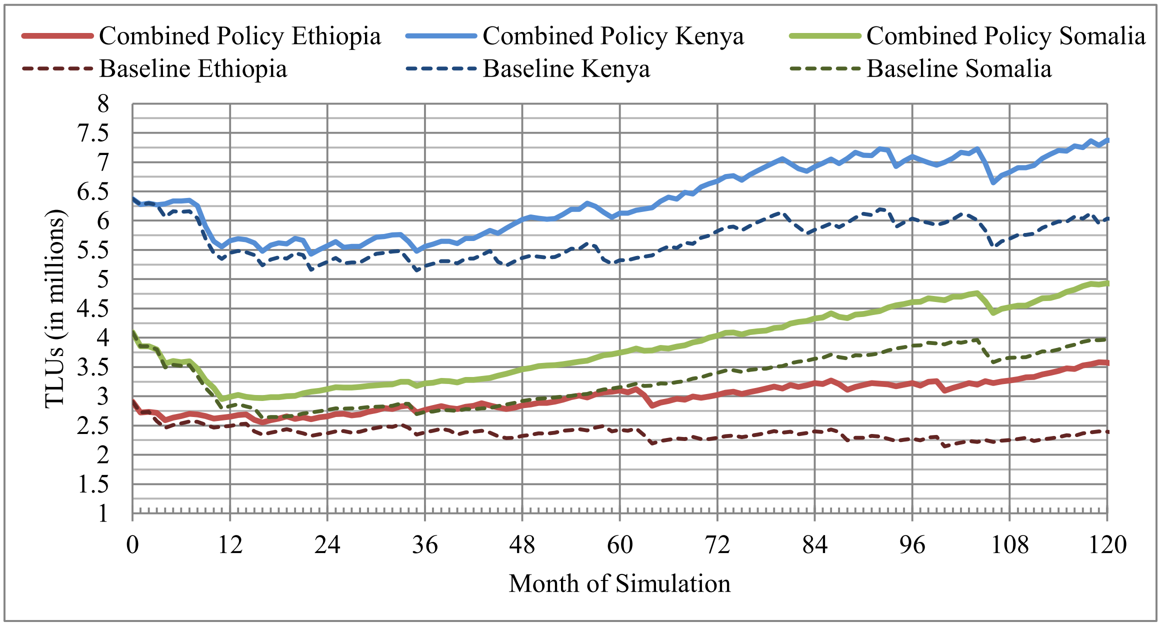


Figure 4.29: Comparison of tropical livestock units (TLUs) with policy implementation

Finally, the costs to implement these policies were analyzed in Table 4.14. Over the 10 year period, there are increased profits for all sources of income when compared to the baseline simulation. For the first few years, the staple crops do not produce as high of yields, but as the trees mature in the agroforestry agricultural land, yields do increase above baseline harvests. After the 10 year period, the total net present value (NPV) profit based on initial investment costs (with drip irrigation occurring at year 0 and year 5) and the resulting profit cash flows (net change in income from the baseline scenario for each year of simulation) it is evident that the combination policy results in a positive annualized return on investment (ROI). Moreover, the increased income extends across all livelihoods (crops and livestock) and would benefit the entire population.

Table 4.14: Cost and profits from combined policy model over 10 year simulation

| | Ethiopia | Somalia | Kenya |
|---|---|---|---|
| Sand Dams | $1,120,000 | $880,000 | $1,520,000 |
| Shallow Wells | $597,600 | $432,000 | $720,000 |
| Ponds | $1,320,000 | $1,000,000 | $1,360,000 |
| Boreholes | $450,000 | $405,000 | $660,000 |
| Drip Irrigated Land** (ha) | $2,413,270 | $1,379,340 | $2,275,4230 |
| Agroforestry Land (ha) | $3,665,760 | $167,270 | $1,418,250 |
| Total Policy Costs | -$9,566,630 | -$4,263,610 | -$7,953,670 |
| Income Gained - Agroforestry | $53,105,970 | $4,105,030 | $34,765,770 |
| Income Gained - Cash Crops | $618,409,900 | $363,457,800 | $576,834,700 |
| Income Gained - Livestock | $128,225,900 | $115,775,100 | $140,118,000 |
| Income Gained - Staple Crops | $117,855,830 | $13,315,280 | $91,013,030 |
| *NPV Profit* | $456,170,430 | $254,040,340 | $424,247,790 |
| *Annualized Return on Investment* | 477% | 596% | 533% |

** (drip irrigation has a 5 year lifespan)

### 4.7. Summary of Results

An increase in water availability will result in a direct increase in pastoral income; water availability for livestock will result in lower mortality during dry spells. Agricultural policy will positively affect farmers and agro-pastoralists; however, if an increased water demand is added due to irrigation, livestock and human water availability will suffer. The agricultural policies explored create a more drought resilient livelihood for crop production and overall sources of income for farmers and agro-pastoralists. After the application of the 3 different policy options, the combination of additional hydraulic infrastructure and initiating new agricultural practices in conjunction had the most favorable outcome for the entire population.

Figure 4.30 shows an illustration of costs and benefits among the different livelihood groups under the combined hydraulic and agricultural policies (Agustinata, 2013). The financial gain is determined from Table 4.13. Over 100% improvement was considered very significant, 50-100% improvement was considered significant, 0-50% improvement was indirectly significant, and if the livelihood group wasn't affected, it was considered insignificant. The other categories were given the distinction based on the reliance on water availability (livestock, irrigation), improvement to other aspects of income (land improvement, food availability, diversified income), and potential conflicts (water, land, etc.). Minor benefits and costs correspond to various non-measurable factors like overall well-being or comfort (overall water availability, effect on way of life, etc.).

| | Ethiopia | | | Somalia | | | Kenya | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | AP | P | F | AP | P | F | AP | P | F | |
| Benefits | ☾ | ☾ | ☾ | ● | ☾ | ● | ◖ | ☾ | ◖ | Financial Gains |
| | ◖ | ☾ | ◖ | ◖ | ◖ | ● | ◖ | ☾ | ◖ | Increased Food Availability |
| | ☾ | ○ | ◖ | ◖ | ○ | ◖ | ☾ | ○ | ◖ | Improved Land |
| | ☾ | ☾ | ☾ | ☾ | ☾ | ☾ | ☾ | ☾ | ☾ | Other Minor Benefits |
| Costs | ● | ◖ | ● | ● | ◖ | ● | ● | ◖ | ● | Financial Burden |
| | ☾ | ◖ | ☾ | ☾ | ◖ | ☾ | ☾ | ◖ | ☾ | Competition for Resources |
| | ○ | ☾ | ○ | ○ | ☾ | ○ | ○ | ☾ | ○ | Other Minor Costs |

● = Very Significant
◖ = Significant
☾ = Indirectly Significant
○ = Insignificant

AP = Agro-pastoralist
P = Pastoralist
F = Farmer

Figure 4.30: Distribution of costs and benefits among livelihoods for combined policies options

Using visual, qualitative analysis of the costs and benefits associated with the policy implementation reveals potential tensions between groups. For the combined policy, pastoralists have higher costs versus benefits. If all livelihoods were to split the policy costs equally, pastoralists could argue that their benefits are not equitable compared to the farming sector. Additionally, the analysis can highlight other areas of interest for policy implementation. Competition over resources is a high cost for pastoralists who depend on communal resources; exploring range management policies may alleviate this potential outcome.

From this illustration of costs and benefits, it is clear that all livelihoods experience a high financial burden from the policy implementations. Because the region is extremely impoverished, it would be almost impossible for the communities to fund these improvements themselves. The region would need the support of government funding or outside aid in order to reap the benefits of the improved water availability and agricultural production. The economic analysis done in section 4.6.3. based on initial investment costs and estimated increase in income, is useful information for these investors. The ROI is a tool the donors can use to evaluate the impact their money and corresponding policies can have on the region affected.

# CHAPTER 5 CONCLUSION

Drought adaptation is a key area of interest for many policymakers as droughts have become more frequent and outside aid is often the only source of relief. Adaptation techniques must focus on preventing the detrimental effects of drought rather than reacting to them. Policymakers want to ensure the policies they implement are the most effective and beneficial for the entire population of a particular region of interest. Hydrologic and system dynamics modeling allows policymakers to explore policy options through model simulation to tailor adaptation techniques to specific regions. The modeling will demonstrate the effect and change a new policy can generate to improve overall livelihood.

System dynamics modeling establishes a pattern of behavior between the natural systems being demonstrated. It is important to focus on the patterns and overall changes between the baseline scenario and policy implemented scenarios rather than the actual values being generated. The goal of the model is to understand the effect a policy will have on the system, negative or positive. Through system dynamics and hydrologic modeling, the effects of different policies were explored and analyzed for an East African region known to be chronically effected by drought. For the study area, this modeling highlights the relationships between water availability, livestock and crop production, and the socio-economic effects on the people within the region. An understanding of these complex relationships is essential when determining strategies to alleviate potential undesirable consequences due to water shortages. The hydrologic model effectively determines water availability for the region based on historical weather data. Through literature and system dynamics modeling, it is possible to explore alternative policy options that could potentially lessen the effects of drought within the region and improve the overall livelihood of the population. Based on the three policies explored, it was found that a combination of hydraulic infrastructure to improve water availability and introducing new agricultural practice to increase crop production would be the most beneficial for all livelihood categories within the study region in East Africa. The increased water availability reduced domestic water shortages by 54%, 90%, and 100% in the Ethiopian, Kenyan, and Somali regions respectively. The livelihoods of all populations within the region were also improved over the 10 year simulation; farmers benefiting the most from the policy implementation with a 46%-285% increase in income over the 10 years.

Through hydrologic modeling, the water availability can be estimated for a region of interest. Having reliable and up-to-date soil and land use data is essential for accurate results; however, for regions with documented stream flow and discharge data, a hydrologic model can be calibrated to better represent the measured values. For the SWAT model of East Africa, the output results were agreeable for the region based on limited historical data. Determining water availability is crucial when studying drought adaptation, and understanding the effect that limited water availability has on the livelihood and welfare of a region is vital for determining what adaptation techniques will be beneficial.

The study region in the Horn of Africa was considered because it is known for frequent droughts and dependence on outside aid. Adaptation techniques explored (increased hydraulic infrastructure and improved agricultural practice) were chosen as they aim to establish a more self-reliant, resilient population. A simulation under existing conditions enables a baseline outcome; when implementing policies, a comparison between the new results and the baseline will determine the policy's success or failure.

For the study region in East Africa, it was determined that the livelihood of pastoralists, agro-pastoralists, and farmers would all benefit from the combined implementation of increased hydraulic infrastructure to improve water availability and the implementation of innovative agricultural practice that would increase staple crop yields and diversity farm income. Both of these policies alleviate the stress caused during drought. The hydraulic infrastructure increases water storage during dry spells and introduces more groundwater extraction which is a more resistant source of water during drought, but would not directly benefit the livelihood of farmers. The agroforestry improves the soil moisture and quality for the crops growing nearby, increases yields and introduces another source of income from the tree products themselves without negatively affecting pastoralists. Additionally, the drip irrigation provides a more drought resistant food source and allows for more profitable crops to be grown; although when applied on a large scale or without increased hydraulic infrastructure, the irrigation reduces pastoralist livelihood due to competition for water. Overall, these policies implemented in conjunction, improve the livelihood for the entire population.

These results were based on many assumptions using limited available data pertaining to the study region. To confirm credibility of the results and the system dynamics model, further investigation of current water resources and agricultural practices within the region should be completed. More detailed data collection of current hydraulic infrastructure, including their capacities, would ensure baseline water availability is accurate. Additionally, hydrogeographical exploration would verify shallow well and deep well potential. Knowing aquifer capacity, depth, and location are essential for siting successful wells. Finally, more accurate agricultural yield estimations should be studied based on specific practices in the study region. Rainfall variability will affect various processes within crop production differently; the timing of water shortages between planting, growing, and harvesting will have differing effects on the overall crop yields.

Determining crop production in relationship to rainfall on a monthly or weekly timescale will improve the estimated yields and overall food availability.

This model effectively shows the power of system dynamics modeling in relationship to policy development. By understanding the different systems and the way they interact with one another, it is possible to determine how effective policies are and which will produce the most beneficial outcome. It allows for experimentation of policy development by observing the prospective outcome of policies: the scale of the policies (extent), the target of the policies (specific livelihood improvement), or a combination.

System dynamics modeling allows for endless approaches to evaluate and develop policies. Combined with hydrologic modeling, policy exploration within Eastern Africa indicated the effects of drought can be reduced and overall livelihoods can be improved. This modeling can be tailored to any region and investigate various other policies.

## 5.1. Future Investigations

System dynamics modeling approach opens the doors for future research and expands investigation involving policy development. There are other policies that can be explored and implemented into the system dynamics model to analyze the effects and major beneficiaries to maximize the overall gain. It is possible to introduce new crops that may fare higher yields under water stress or introduce imported food as an option to sustain caloric requirements. Also, natural resource management policy can also be explored to reduce potential conflict and ensure shared resources are not depleted.

Many assumptions were made based on literature due to lack of credible, up-to-date data for this region. With more reliable data in regards to available hydraulic infrastructure its functional capacity, more detailed agricultural and livestock practice data, and the specific location of these sources and practices, the system dynamics model can produce an even more realistic investigation of the implementation and outcome of new policies. With the specific location of water sources, their capacities, and settlements, the system dynamics modeling can be simulated on a smaller, community scale. This will be beneficial for policy development that is more focused on the well-being of a specific population.

Stochastic elements can also be introduced into the system dynamics model. Specifically, an area for further investigation is introducing climate forecasting into the hydrologic and system dynamics models. The effects of climate change are potentially severe for semi-arid and arid regions with more sporadic rainfall and higher temperatures. This would allow for more extreme weather scenarios to be explored and test the robustness and effectiveness of policies through these new, potential conditions.

Finally, the implementation of agent-based gaming within the system dynamics models should be explored. This would allow actors to portray each livelihood group and make decisions based off their personal interests, allowing the model to generate the corresponding outcome. Actors would introduce a more realistic conflict of interests between livelihood groups and allow for negotiation and compromise between parties.

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# APPENDICES

# Appendix A –SWAT Input Parameters

Tables A.1 was used to reclassify FAO Soil and Terrain Database of East Africa data to SWAT predetermined land use values. Tables A.2 and A.3 were used in conjunction with the Soil and Water Characteristic model to find missing soil parameters needed for the newly generated soil database. All other soil values were found following the guidelines in the SWAT2009 Input/Output File Documentation available at swat.tamu.edu/documentation/.

Table A.1: Reclassification of SOTER Land Classifications into SWAT Land Cover

| FAO Symbol | Land Classification | SWAT Symbol | Land Cover |
|---|---|---|---|
| A | alpine vegetation | PAST | Pasture |
| B | bushland | RNGB | Range - brush |
| BC | bushland/cultivation | RNGB | Range - brush |
| BCG | bushland/cultivation/grassland | RNGE | Range - grasses |
| BCW | bushland/exposed surface, bare | RNGB | Range - brush |
| BE | bushland/exposed surface, bare/grassland | RNGE | Range - grasses |
| BEG | bushland/forest | RNGB | Range - brush |
| BF | bushland/forest/grassland | RNGB | Range - brush |
| BFG | bushland/grassland | RNGE | Range - grasses |
| BG | bushland/grassland/woodland | RNGE | Range - grasses |
| BGW | Bushland/grassland/woodland | RNGE | Range - grasses |
| BGWd | bushland/grassland/woodland dense | RNGE | Range - grasses |
| BS | bushland/ swamp vegetation | RNGB | Range - brush |
| BW | bushland/woodland | RNGE | Range - grasses |
| Bd | bushland dense | RNGB | Range - brush |
| BdB | bushland dense/bushland | RNGB | Range - brush |
| BdBG | bushland dense/bushland/ grassland | RNGB | Range - brush |
| BdC | bushland dense/cultivation | RNGB | Range - brush |
| BdE | bushland dense/exposed surface, bare | RNGB | Range - brush |
| BdW | bushland dense/ woodland | RNGB | Range - brush |
| C | cultivation | AGRL | Agricultural land - generic |
| CF | cultivation/forest | AGRL | Agricultural land - generic |
| CFG | cultivation/forest/grassland | AGRL | Agricultural land - generic |
| CG | cultivation/grassland | AGRL | Agricultural land - generic |
| CGF | cultivation/grassland/forest | AGRL | Agricultural land - generic |

Table A.1 (cont.)

| FAO Symbol | Land Classification | SWAT Symbol | Land Cover |
|---|---|---|---|
| CGW | cultivation/grassland/woodland | AGRL | Agricultural land - generic |
| CS | cultivation/swamp vegetation | AGRL | Agricultural land - generic |
| E | exposed surface, bare | PAST | Pasture |
| EG | exposed surface, bare/grassland | RNGE | Range - grasses |
| EGW | exposed surface, bare/grassland/woodland | RNGE | Range - grasses |
| EW | exposed surface, bare/woodland | RNGB | Range - brush |
| F | forest | FRST | Forest - mixed |
| FG | forest/grassland | FRST | Forest - mixed |
| FGW | forest/grassland/woodland | FRST | Forest - mixed |
| FM | forest/mangrove | FRST | Forest - mixed |
| FW | forest/woodland | FRST | Forest - mixed |
| G | grassland | RNGE | Range - grasses |
| GS | grassland/swamp vegetation | WETN | Wetlands - nonforested |
| GW | grassland/woodland | RNGE | Range - grasses |
| M | mangrove | WETF | Wetlands - forested |
| S | swamp vegetation | WETL | Wetlands - mixed |
| W | woodland | FRSD | Forest - deciduous |
| Wa | water | WATR | Water |
| Wd | woodland dense | FRSD | Forest - deciduous |
| X | complex mixture | RNGE | Range - grasses |

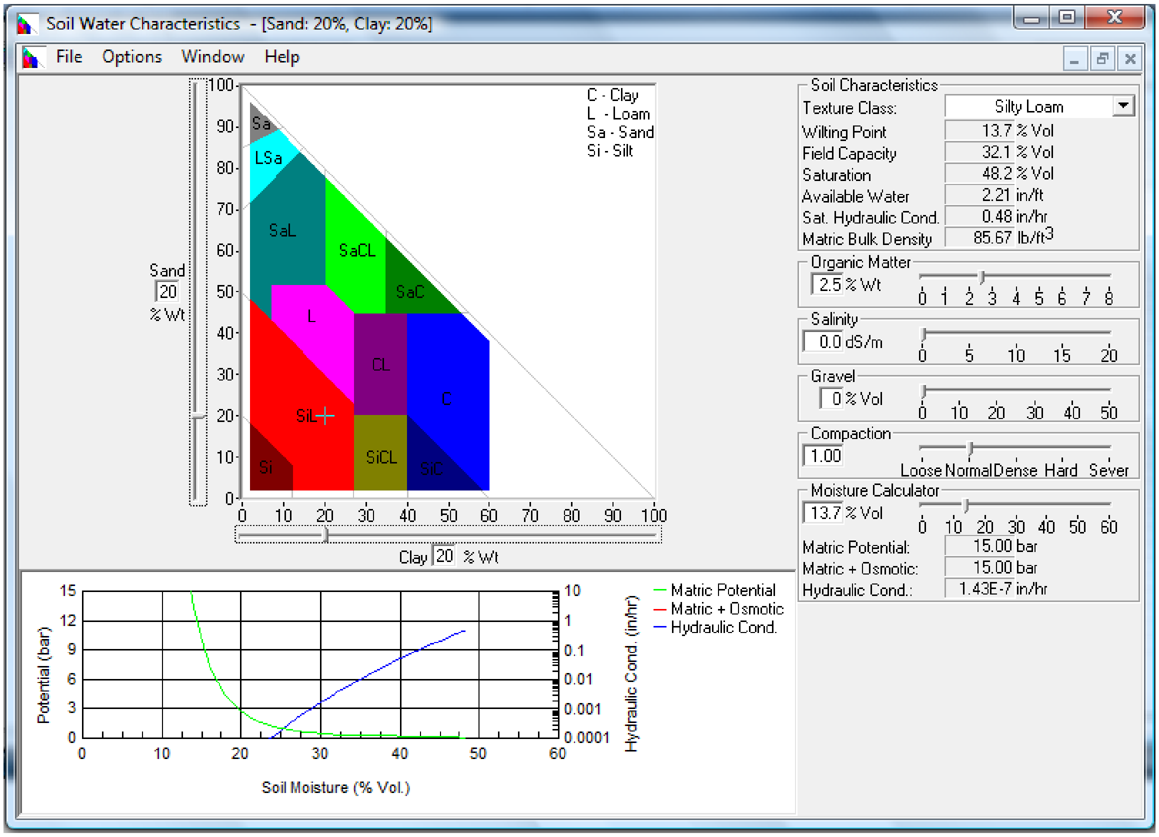
Table A.2: SOTER soil textural data used in SPAW

| FAO – Texture Classification | % Clay | % Sand | % Silt |
|---|---|---|---|
| C – Clay | 50 | 30 | 20 |
| CL- Clay Loam | 34 | 33 | 33 |
| L – Loam | 18 | 42 | 40 |
| LS – Loamy Sand | 6 | 82 | 12 |
| Sa- Sand | 5 | 92 | 3 |
| SC- Sandy Clay | 42 | 52 | 6 |
| SCL – Sandy Clay Loam | 28 | 60 | 12 |
| SL- Sandy Loam | 10 | 65 | 25 |
| Si - Silt | 6 | 7 | 87 |
| SiC – Silty Clay | 47 | 7 | 46 |
| SiCL – Silty Clay Loam | 34 | 10 | 56 |
| SiL – Silty Loam | 20 | 20 | 60 |

Table A.3: SOTER Organic Matter data used in SPAW

| FAO – Organic Matter Classification | Organic Carbon in % weight | OC % used in SPAW |
|---|---|---|
| A | 0 - 0.6% | 0.3% |
| AB | 0 – 2% | 1% |
| B | 0.6 - 2% | 1.3% |
| C | 2 - 3% | 2.5% |
| D | 3 - 8% | 5.5% |
| E | 8+% | 8% |
| MISSING DATA | N/A | 0.1% |

Missing soil parameters were found using the Soil Water Characteristic model developed by Dr. Keith E. Saxton through the United States Department of Agriculture (USDA) using FAO SOTER data. These missing parameters were available water, saturated hydraulic conductivity, and bulk density.



Sand 20 % Wt

Clay 20 % Wt

Texture Class: Silty Loam

Wilting Point 13.7 % Vol

Field Capacity 32.1 % Vol

Saturation 48.2 % Vol

Available Water 2.21 in/ft

Sat. Hydraulic Cond. 0.48 in/hr

Matric Bulk Density 85.67 lb/ft$^3$

Organic Matter 2.5 % Wt

Salinity 0.0 dS/m

Gravel 0 % Vol

Compaction 1.00

Moisture Calculator 13.7 % Vol

Matric Potential: 15.00 bar

Matric + Osmotic: 15.00 bar

Hydraulic Cond.: 1.43E-7 in/hr

Figure A.1: Soil water characteristic model graphical input screen used to find soil parameters

# Appendix B – Land Dynamics Quantification

Normalize difference vegetation index (NDVI) values were found using the following equation (Bai and Dent, 2006):

$$NDVI = 6.465 \times 10^{-10}(R)^3 - 0.3819 \times 10^{-6}(R)^2 + 7.780 \times 10^{-3}(R) - 0.6 \qquad \text{B.1}$$

Where R is the monthly rainfall in millimeters, and if the NDVI value is negative, the model assumes a value of zero. The relationship between land cover and NDVI was determined using the following equation:

$$Landcover = -4.337 - 3.733(NDVI) + 161.968(NDVI)^2 \qquad \text{B.2}$$

The change in land cover was taken to be the different between equation B.2 at time (t) and time (t-1). Based on this change in land cover, the Rain Greeness Ratio (RGR) was used as a proxy for land types to determine the measure of change within each category (Davenport and Nicholson, 1993).

Table B.1: RGR values used in determining land change

| **Land Type** | **RGR Value** |
|---|---|
| Ag Land | 5.5 |
| Grassland | 3.7 |
| Conservation | 2 |
| Degraded | 3.9 |

# Appendix C: Historical Market Data

Historical livestock and crop market data were used to determine the relationship between price, rainfall, and time and incorporated into the system dynamics model. Below are the historical livestock data from the Livestock Information System of Kenya and Ethiopia (monthly) and the crop market data (annually) from the FAOStat database (http://faostat.fao.org). All currency is in USD. There is no historical data was available for Somalia.

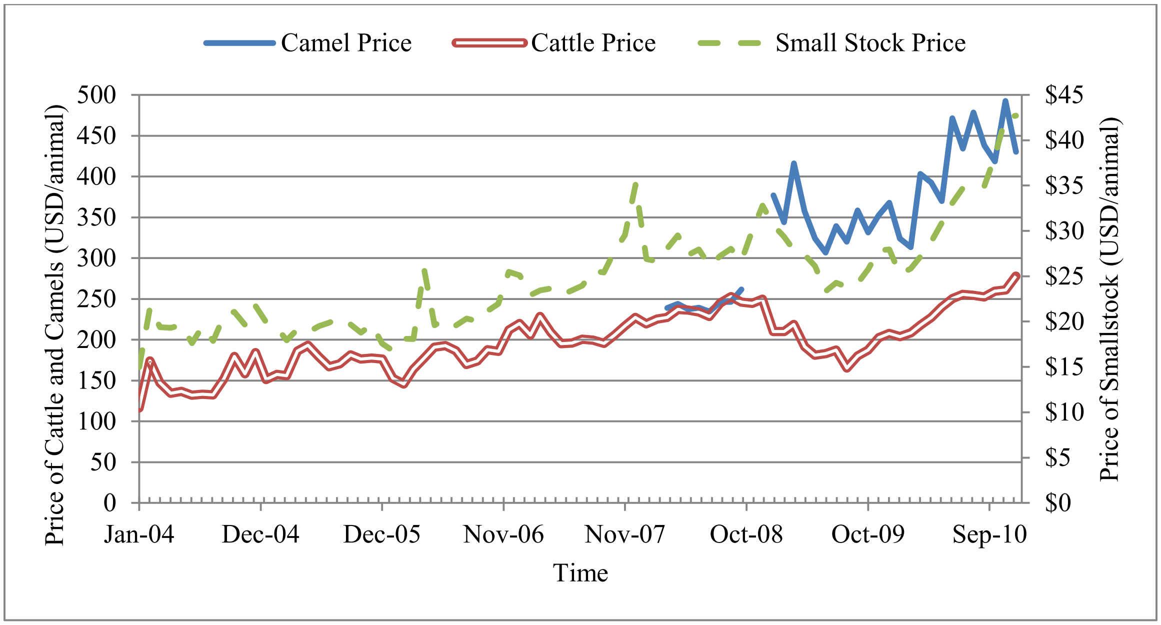


Figure C.1: Historical livestock market data for Kenya

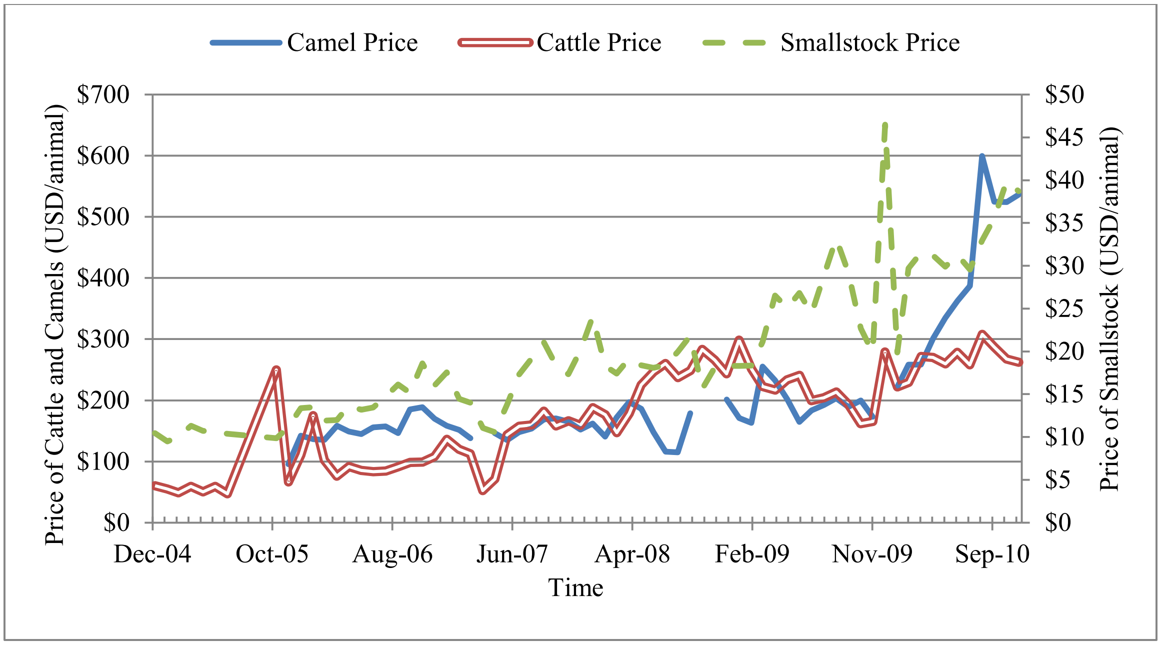


Figure C.2: Historical livestock market data for Ethiopia

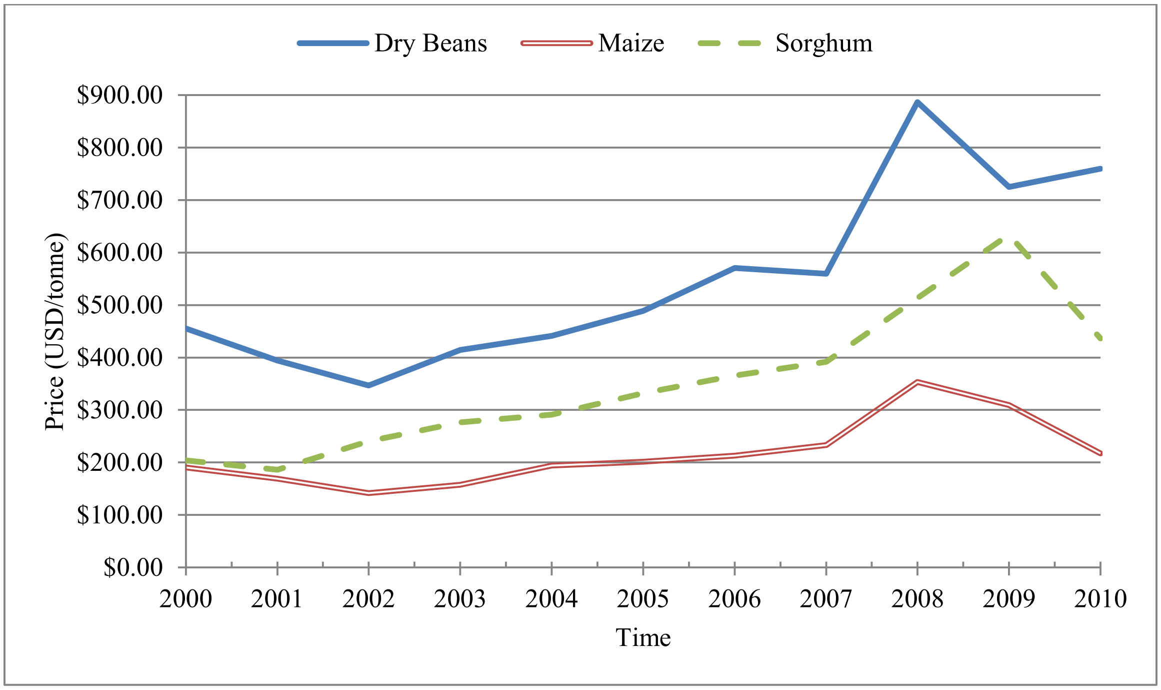


Figure C.3: Historical crop market data for Kenya

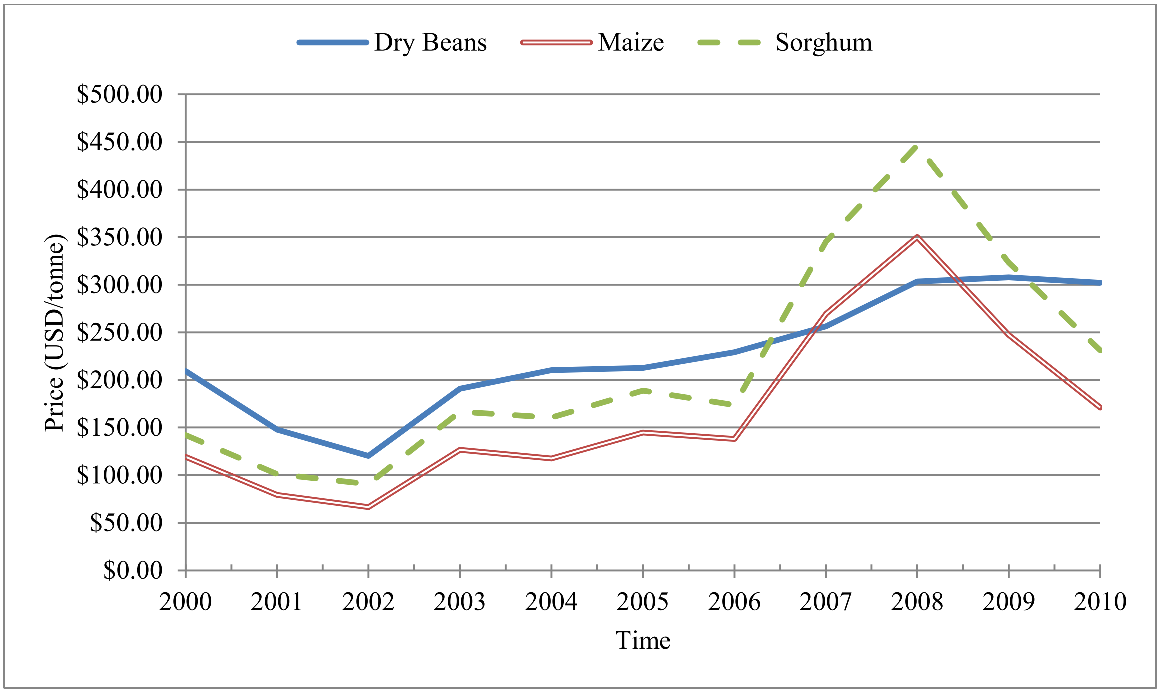


Figure C.4: Historical crop market data for Ethiopia

# Appendix D: Livelihood and Economic Assessment

The income analysis for each region's population was determined based on their reliance on crops and/or livestock. Each region's livelihoods were determined based on Famine Early Warnings System Network (FEWS NET) data for each country. Tables D.1-D.3 summarize the livelihood classifications.

Table D.1: Ethiopia livelihood distribution

| | **% Population** | **% Livestock** | **% Farmland** |
|---|---:|---:|---:|
| Agro-Pastoralists | 40.00% | 20.00% | 75.00% |
| Pastoralists | 50.00% | 80.00% | 0.00% |
| Farmers | 10.00% | 0.00% | 25.00% |

Table D.2: Somalia livelihood distribution

| | **% Population** | **% Livestock** | **% Farmland** |
|---|---:|---:|---:|
| Agro-Pastoralists | 50.15% | 17.67% | 66.21% |
| Pastoralists | 38.18% | 82.33% | 0.00% |
| Farmers | 11.67% | 0.00% | 33.79% |

Table D.3: Kenya livelihood distribution

| | **% Population** | **% Livestock** | **% Farmland** |
|---|---:|---:|---:|
| Agro-Pastoralists | 35.00% | 30.00% | 58.33% |
| Pastoralists | 40.00% | 70.00% | 0.00% |
| Farmers | 25.00% | 0.00% | 41.67% |

The profitability of the agricultural and combined policies was determined by calculating the net present value (NPV) of the investment cost and profits over the 10 year simulation using the following equation (Beaves, 1993):

$$NPV = \sum_{t=0}^{n} \frac{a_t}{(1+k)^t} \tag{D.1}$$

Where $a_t$ is the net cashflow at time $t$ and $k$ is the rate of return (10% was used for analysis). The initial investment cost is taken at year 0 and the net income between the policy scenario and baseline scenario is taken at years 1 through 10. The return on investment (ROI) was determined below:

$$ROI\ (\%) = \frac{Net\ Profit}{Investment} x\ 100 = \frac{NPV\ Profit}{Investment} x\ 100 \tag{D.2}$$

$$Annualized\ ROI = \frac{ROI}{Investment\ Term} \tag{D.3}$$