Spatial and Temporal Allocation of Water and Land Resources for Optimal Cereal Production in Kenya

by

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B.S. Environmental Engineering
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ABSTRACT

As the population of the world increases, food security becomes a more pressing issue. This is especially true for Kenya. The country's population is increasing at a very fast rate and food production has not been able to keep up with the increasing population. This analysis assesses Kenya's ability to feed its own people by modelling the potential for increasing the production of cereals, specifically maize, wheat and rice, which together amount to approximately half the calories in the average Kenyan diet.

To determine the spatial and temporal allocation of land and water resources for the optimal calories produced by maize, wheat and rice two optimization models were used. The first optimization is a least squared estimation used to calibrate the model and reproduce current conditions. The second optimization maximizes total calories produced for wheat, maize and rice, while being constrained by a water balance and land availability given soil suitability for each crop.

The results of this analysis reveal that Kenya has a very large potential to increase its cereal production mainly on the western and southern part of the country. Approximately half the water for these crops comes from irrigation. As production increases, the flow in the river decreases, and groundwater use increase. The conclusion of this paper is that Kenya has the potential to increase its calorie production of cereals by at least a factor of 5.

Key words: Kenya, cereal production, food security
Thesis Supervisor: Dennis McLaughlin
Title: H.M. King Bhumibol Professor of Civil and Environmental Engineering

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List of Acronyms and Abbreviations

DEM – Digital Elevation Model

DRT – Dominant River Tracing

FAO – Food and Agricultural Organization of the United Nations

FAOSTAT – Statistics Division of FAO

GAEZ – Global Agro-ecological Zones

GAMS – General Algebraic Modeling System

GIS – Geographic Information Systems (ArcMap software issued by ESRI)

KARI – Kenya Agricultural Research Institute

KWSCRP – Kenya Water Security and Climate Resilience Program

NCDC – National Climatic Data Center

NOAA – National Oceanic and Atmospheric Administration

TRIP – Total Runoff Integrated Pathways

UN – United Nations

UNEP – United Nations Environment Programme

UNESCO – United Nations Educational, Scientific and Cultural Organization

UNWWAP – United Nations World Water Assessment Programme

USAID – United States Agency for International Development

WFP – World Food Programme

List of units and symbols

Units

mm	millimeters	MCM	million cubic meters
km	kilometers	kcal	kilocalories
ha	hectares	kg	kilogram

Definition of sets

p	pixel	{1-759}
t	month	{1-12}
c	crop	{maize, wheat, rice}
s	soil grade	{1-5}

List of symbols

Area(p)	Area of pixel p	[km^2]
LS	least squares variable	[-]
T_Cal	Total Calories	[kcal / year]
Crop_Cal(c)	Calories for crop c	[kcal / kg]
Y_max(c)	Attainable yield	[ton / ha]
Y_per(s,c)	Percent of attainable yield for crop c on soil grade s	[-]
K(c)	crop factor for crop c	[-]
ET_0(p,t)	reference evapotranspiration for pixel p for month t	[mm / year]
ET_{meas} (p,t)	measured evapotranspiration at pixel p for month t	[km^3 / month]
ET_{est} (p,t)	estimated evapotranspiration at pixel p for month t	[km^3 / month]
ET_{crop} (c,p,t)	estimated crop evapotranspiration at pixel p for month t for crop c	[km^3 / month]

ET_N(p,t)	Non-crop evapotranspiration at pixel p for month t	[km^3 / month]
e_non(p,t)	Nominal non-crop evapotranspiration at pixel p for month t	[mm / month]
P_{meas} (p,t)	measured precipitation at pixel p for month t	[km^3 / month]
P_{est} (p,t)	estimated precipitation at pixel p for month t	[km^3 / month]
ΔS(p,t)	estimated change in storage at pixel p for month t	[km^3 / month]
A	flow direction matrix	
Q(p,t)	estimated pixel outflow from pixel p for month t	[km^3 / month]
f(c,p,t)	fraction of pixel p planted by crop c in month t	[-]
f(s,c,p,t)	fraction of pixel p planted by crop c on soil grade s in month t	[-]
f_max(s,c,p)	maximum allowed fraction of pixel p planted by crop c on grade s	[-]
f_N_min(p)	minimum allowed non-crop fraction of pixel p	[-]
f_overlap_MR	overlap fraction between maize and rice	[-]
f_overlap_MW	overlap fraction between maize and wheat	[-]
f_overlap_MR	overlap fraction between wheat and rice	[-]
f_overlap_MW	overlap fraction between maize ,wheat and rice	[-]

Chapter 1 – Introduction

1.1 Motivation

1.1.1 Food Security

Food security is an issue that has been at the top of the global agenda, quite literally. The first goal on the list of the Millennium Development Goals, as developed by the leaders of 189 countries at the United Nations, is to eradicate extreme poverty and hunger (UN 2008). Specifically, the goal with regards to food security is to halve, between 1990 and 2015, the proportion of people who suffer from hunger (UN 2008). The Food and Agricultural Organization of the United Nations (FAO) estimates that 805 million people across the world were chronically undernourished between 2012 and 2014 (FAO et al. 2014). The same organization – FAO – has launched the Special Programme for Food Security to help feed these people by focusing on agriculture and agricultural technology (FAO 1996). In addition, in 2012, UN Secretary-General Ban Ki-moon publicized his own personal vision of ending hunger by developing the Zero Hunger Challenge (UN). The World Food Programme has also joined the fight against hunger by combatting malnutrition through nutrition support, school meals and helping poor farmers (WFP 2015).

Even though so many actions to defeat hunger are being taken, the question of whether we can feed the world's growing population remains. Some believe that civilization will collapse due to world hunger (Schade and Pimentel 2009; Ehrlich and Ehlich 2013). Others are more optimistic and believe that the increasing population of the planet can be fed (Godfrey et. al 2010; McLaughlin and Kinzelbach 2015; Foley et. al 2011). However, optimists and pessimists agree on what thing: we need to take action now if we are to secure food for the future. Increasing agricultural productivity and providing access to markets and inputs is part of the solution (FAO 2014). Closing the yield gap and increasing production limits will also contribute to this fight (Godfrey et. al 2010; McLaughlin and Kinzelbach 2015; Foley et. al 2011). Actions can also be taken on the consumer side to achieve food security, such as reducing waste and changing diets (Foley et. al 2011). In addition, for these efforts to be truly sustainable conserving resources and protecting the environment also need to be integrated with the supply chain of food production and consumption (Ehrlich and Ehlich 2013; Godfrey et. al 2010).

Land and water lie at the heart of the food security issue since they are the ones that produce our food. This paper focuses on land and water resources allocation in an attempt to determine Kenya's potential to increase its food production.

1.1.2 The case of Kenya

Kenya is located at the Eastern shore of Africa. It borders Tanzania in the south, Uganda in the west, South Sudan in the North-West, Ethiopia in the North, and Somalia in the East. It has one of the biggest economies in East Africa, was recently classified as a lower middle income country since and its GDP has grown at an average of 6% per year between 2010 and 2013 (World Bank 2015). Its economy comprises primarily of services (53%), followed by agriculture (29.3%) and finally industry (17.7%) (CIA).

Even though the economy and life quality have been improving recently, food security is still an issue in Kenya. In 2010, almost a quarter of population of Kenya was undernourished (World Bank 2015). In addition, in 2009 approximately 17% of children under 5 were malnourished (World Bank 2015). The average caloric intake for people in Kenya in 2010 was 2160 kcal/capita/day (FAOSTAT 2015B), barely above the recommended minimum of 2,100 kcal per day (Gibson 2012).

In 2013, Kenya's population was 44.35 million people (World Bank 2015) and has been growing at average rate of 3.1% per year since the 1980's (United Nations 2012). According to the United Nations the population is expect to double by the year 2050. The figure below shows the expected population under different scenarios. Even in a low fertility scenario, the Population is expected to reach 100 million by 2065.

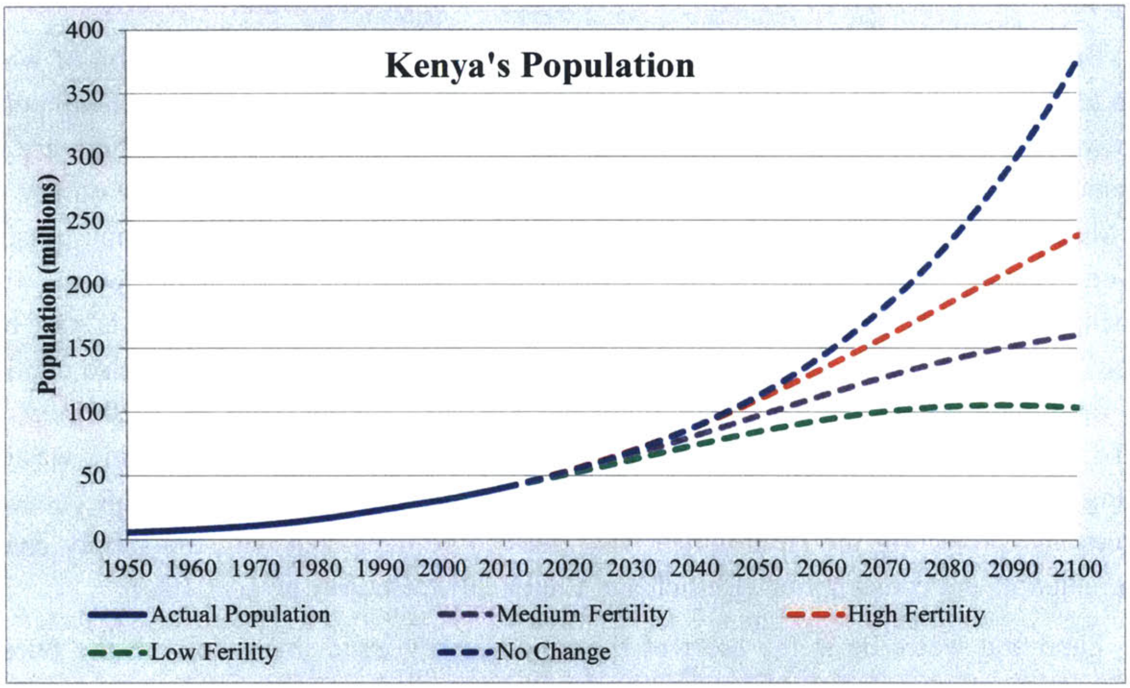


Figure 1. 1: Kenya's Population 1950 to 2100 (projected)
(source: United Nations 2012)

To feed its growing population, Kenya has been increasing its food production at an average rate of 2.8% per year since the 1980's (FAOSTAT 2015B). However, food imports have been increasing at a much faster rate – an average of 25.3% per year (FAOSTAT 2015B). Since the 1980's food production has doubled while imports have increased by at least a factor of four (FAOSTAT 2015B). The figure below shows the trends in food production and imports since the 1960's.

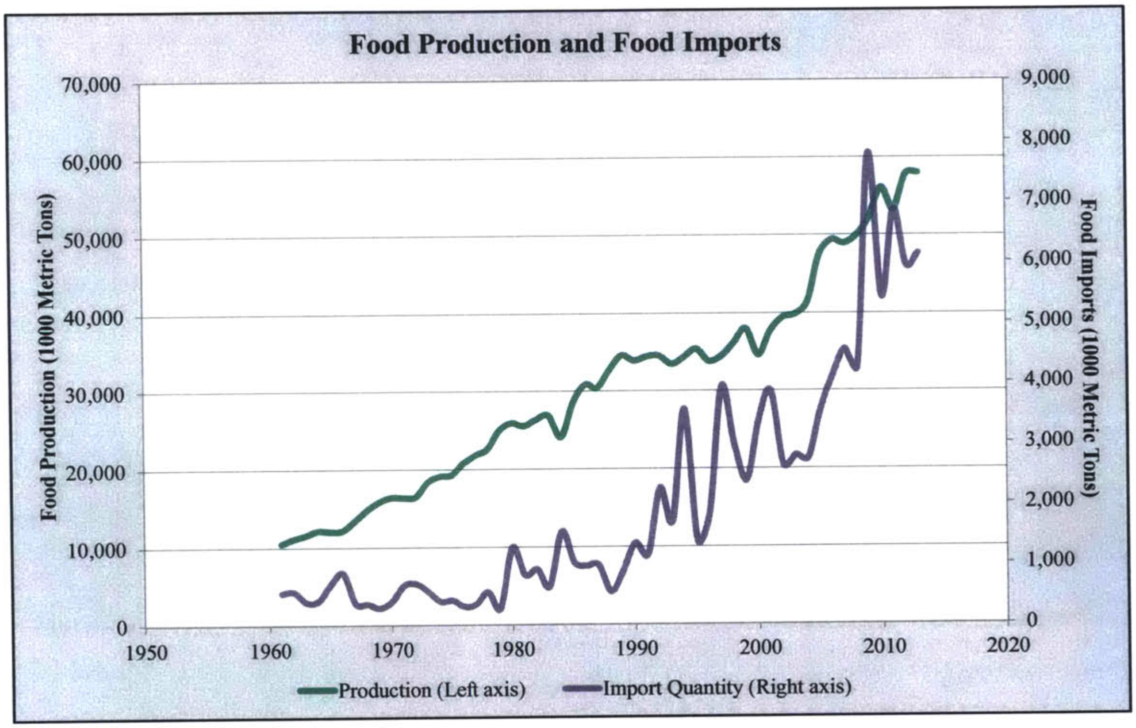


Figure 1.2: Food Production and Food imports in Kenya over time
(Source: FAOSTAT 2015B)

Even though imports have been increasing to supplement production, this presents a potential problem given the poverty in the country. In 2005, 45% of the population was living below the national poverty with rural poverty at 49% and urban poverty at 34% (World Bank 2015). Given the rural population prevalence and the high poverty rates, imports may not be the solution to self-sufficiency.

Food security is "a situation in which all people, at all times, have physical, social and economic access to sufficient, safe and nutritious food which meets their dietary needs and food preferences for an active and healthy life" (KARI, 2012). Currently, Kenya is not able to meet its food needs as a vast proportion of its population is undernourished. The increasing population in Kenya is putting pressure on the country's production, which has been supplemented by imports. However, imports are not accessible and affordable to all. All these factors constitute the motivation to study food security in Kenya.

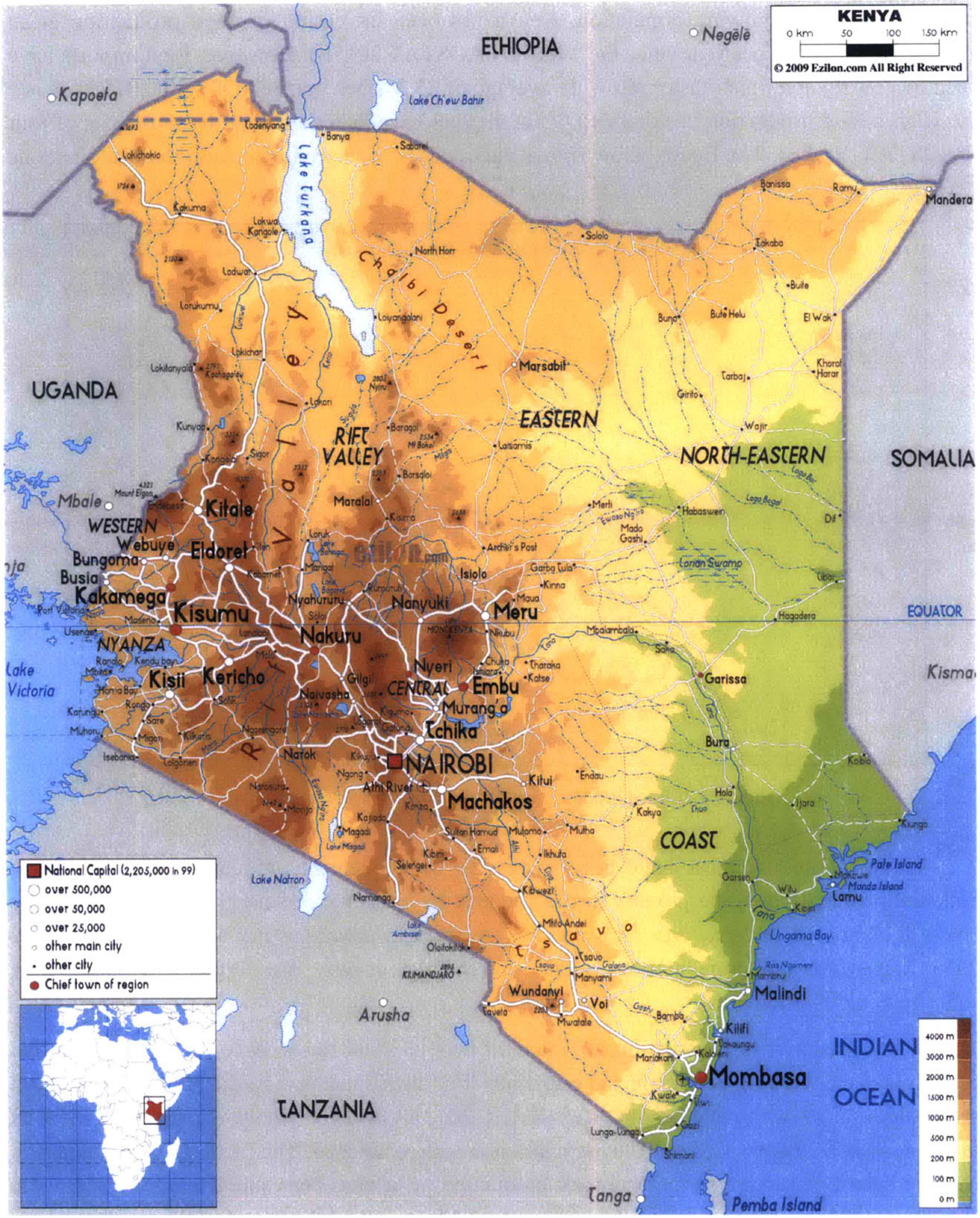


Figure 1.3: Map of Kenya
(Source: Ezilon 2009)

1.2 Objective

This thesis examines the issue of food security in Kenya. The crops that were examined in this analysis were maize, wheat and rice, as they play a vital role in the Kenyan diet and make up most of the cereal consumption. To determine the potential for increasing production two factors were examined: land suitability and water availability. The former was investigated through a spatial analysis, while the latter was studied for its spatial and temporal elements. The question this thesis answers is: Which parts of the country are suitable for production of maize, wheat and rice, given land suitability and water availability?

1.3 Thesis Organization

This thesis is organized in several different chapters. This chapter presents a brief overview of the issue and defines the research objective.

The second chapter reviews the context in which this research question is posed. Specifically, it briefly reviews Kenya's history and its role in setting up the agricultural scene in Kenya today. In addition, it provides some details about the country as a whole and its development goals. The chapter also discusses the agricultural sector in Kenya, with a focus on production and irrigation. The last section of this chapter reviews water in Kenya.

Chapter 3 describes the methodology used to answer the research questioned posed. The first part of the chapter briefly reviews the methodology to introduce the reader to the processes used. Then, the water allocation modelling used is discussed. The following section summarizes the approach used to determine land suitability. Sections 3.4 and 3.5 present in detail the optimization models used to determine the allocation of land and water resources for the optimal food production of cereals in Kenya. The last part of this chapter outlines the scenarios considered to test the sensitivity of the model.

The fourth chapter presents the results for each of the four scenarios considered. The results for each scenario are discussed in chapter 5.

Chapter 6 is the conclusion of this thesis. It summarizes the findings and discusses their implications concisely. In addition, the limitations of this approach as well as recommendation for further research are presented.

Please note that this analysis was conducted in cooperation with Wenjia Wang. Her primary focus was the evaluation of land suitability. This author focused primarily on the water allocation. This author conducted the analysis that integrates the main two elements: water and land. As such, the evaluation of the land is summarized in this thesis; for more details please see Wang 2015.

Chapter 2 – Context

2.1 Kenya's History

2.1.1 A brief overview

Kenya is located on the Eastern coast of Africa, and due to its proximity to the Arab peninsula is has had trading relations with Arab peninsula since the 1st century AD (Kenya, Embassy of the Republic of Kenya in Japan). Between 1498 and the end of the 19th century, it was under the influence of different nations [ibid], but also traded with Europe by receiving imports (Ochieng' and Maxon 1992). Between 1895 and 1920, the country was part of the British East African Protectorate, during which the construction of a railway between Mombasa and Lake Victoria began. In 1920, Kenya became a colony, and that is when British increased their involvement in the Kenya government. Between 1920 and independence, settlers owned a significant amount of land, which was used to cultivate tea and coffee employing locals for manual labor (Ochieng' and Maxon 1992). In 1963, Kenya became independent after the Kenya African National Union party won the majority in parliament [History World]. The following, the official name of the country became Republic of Kenya, and in 2010 it issued a new constitution, which separated the judiciary and legislative powers, under a presidential representative democracy (Denmark in Kenya).

2.1.2 Kenya's past and its effects on Agriculture

The construction of the railway through Rift Valley connected the agricultural land with the sea. This created an opportunity for Kenya's agriculture to grow through exports. Actually, the development of the railway demanded exports in order to produce revenues (Pereira 1997). As a result foreign farmers were invited to cultivate the land since the traditional agriculture of local tribes was primarily for subsistence purposes (Pereira 1997). The settlers took advantage of the high rain in the Rift Valley area to grow profitable crops such as coffee, tea and pyrethrum by establishing plantations (Ochieng' and Maxon 1992). It was during those times that the first agricultural schemes were established, leading to land consolidation and water resources development (Cone and Lipscomb 1972).

At the same time, most Kenyan farmers were using traditional farming techniques to provide for themselves, which led, at least to some extent, to soil degradation (Pereira 1997). However, in 1955 the Swynnerton Plan, named after the British Director of Agriculture, was introduced. Under this plan Kenyan families were given access to farms that they could use to grow cash crops (Swainson 1980). In addition, the farmers would receive support from the European and African staff in the form of training (Thurston 1987). The Swynnerton Plan is considered a success as it allowed small farmer to access commercial agriculture; however, the land tenure individualization is considered uneven (Lando and Bujra 2009).

Kenya's agricultural history and colonial influences set the foundations for two pillars of modern agriculture in Kenya: private large scale farms and small-holder farming. In addition, it established Kenya as a major exporter of cash crops, primarily tea and coffee. At the same time, other small-holder farmers grew for their own subsistence.

2.2 Kenya Today

In 2013, Kenya's population was 44.35 million people (World Bank 2015). Currently, 25% of Kenya's population is urban and since the mid-1990's the urbanization rate has been higher than 4% (World Bank 2015). The main cities in the country are Nairobi (3.77 million), and Mombassa (1.1 million) (CIA). The following table summarizes some key indicators about life quality in Kenya.

Indicator	Units	2000	2010
GDP per capita	*2013 US $*	406	978
Life Expectancy	*year*	53	60
Literacy	*% adults (over 15 years) total*	82	72*
Fertility	*births per woman*	5	4.6
Infant Mortality	*per 1000 births*	68.6	52
Malnutrion	*% prevalence in children under 5*	17.5	16.4**
Undernourishment	*% of population*	31.9	24.7

Table 2.1: Indicators about Life Quality in Kenya (World Bank 2015)
** 2007; ** 2009*

This table shows that in general life quality in Kenya has been increasing over the past decade (with the exception of literacy). Undernourishment and malnutrition, however, remain relatively high. The following section discusses the composition of the Kenyan diet to further understand the issue of nutrition in Kenya.

2.2.2 The Kenyan Diet

In 2010, the average Kenyan was supplied with 2,165 kcal/day, down from 2,376 kcal/day in 1978, but up from 1,898 kcal/day in 1993 (FAOSTAT 2015b). A breakdown of the calories they consumed in 2010 is shown in Figure 2.1. As the figure shows, the main component of the Kenyan diet is cereals. Other important components of the Kenyan diet are starchy roots, sugar, pulses, vegetables oils and milk. Since cereals are the biggest contributor of calories, their breakdown is shown in Figure 2.2. Maize is the most consumed crop in the Kenyan diet and accounts for approximately a third of the total calories consumed on a daily basis (671kcal/day). Wheat and rice are also important contributing 255kcal/day and 98kcal/day respectively.

Of the starchy roots, the most significant one is potatoes (93kcal). Kenyans also consume a lot of cassava (45kcal/day) and sweet potatoes (44kcal/day). In the pulses category, the highest calorie contributor is beans (115kcal/day). Lastly, palm oil is consumed at a rate of 113kcal/day.

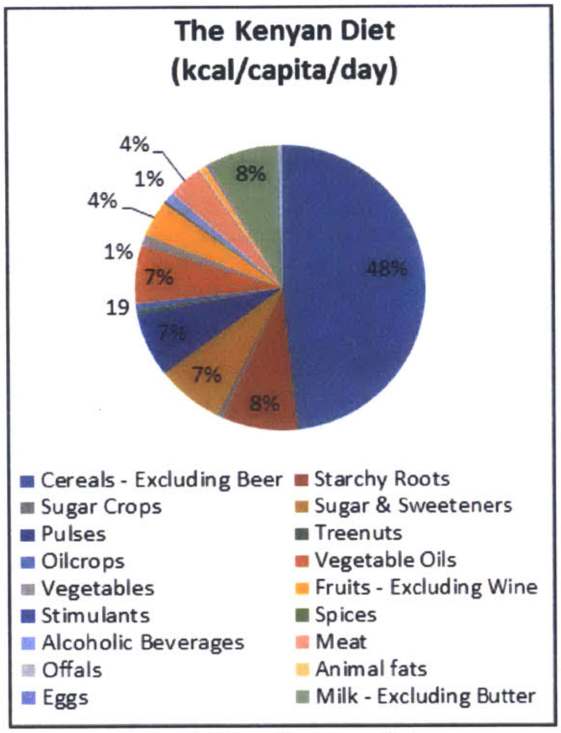


Figure 2.1 The Kenyan Diet

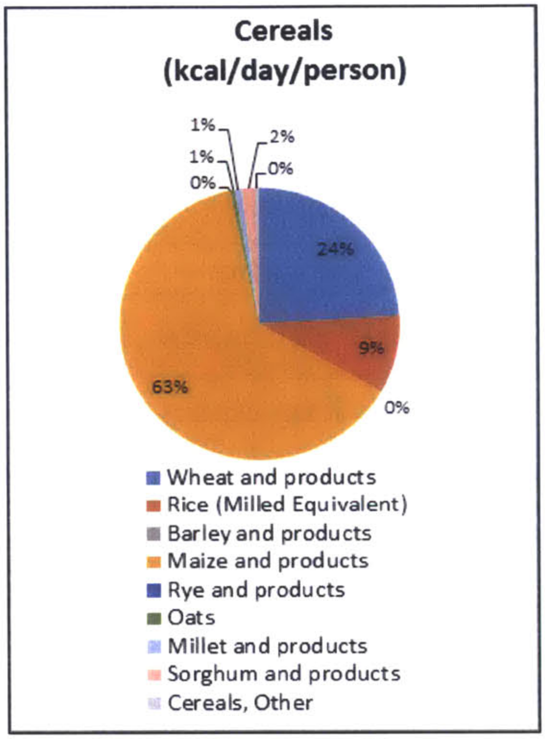


Figure 2.2: Breakdown of Cereals

Source: FAOSTAT 2015b

In addition to calories, one also needs to look at protein and fat consumption in order to better understand the composition of a diet. In 2010, the supply of protein and fat to each person in the country was 63.7 grams per day 48.8 grams per day respectively (FAOSTAT 2015b). According to the FAO, the average recommended consumption for protein and fat are 56 and 56.5 g/day respectively (Gibson 2012). Therefore, it appears that the current amount of food provided is sufficient in terms of protein, but not sufficient in terms of fat. A breakdown of the sources of protein and fat is shown in Figure 2.3.

It is clear that cereals contribute the most in terms of protein (28.1 g/day) but not that much in terms of fat (8.7 g/day). As with total calories, milk is an important source in the Kenyan diet. Even though meat does not contribute much in terms of calories, it is an important source of protein (6.4 g/day) and fat (6 g/day), most of which comes from beef.

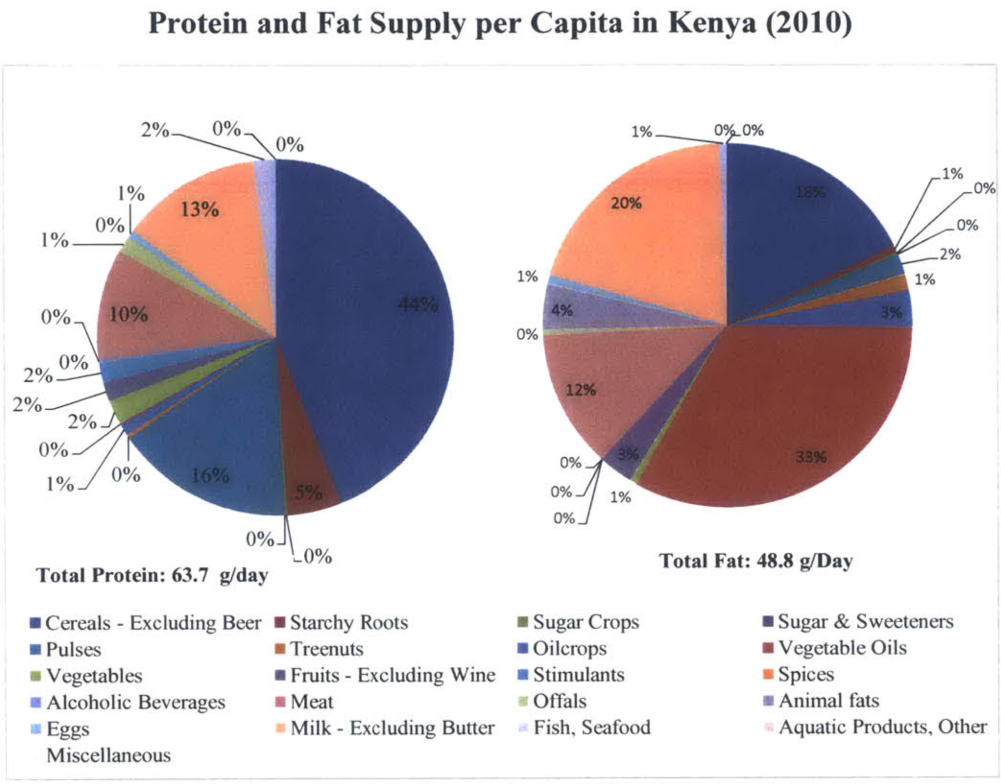


Figure 2.3: Protein and Fat Supply per Capita (2010) (FAOSTAT 2015b)

2.2.2 Kenyan Vision 2030

In 2007, the Government of Kenya created the *Kenya Vision 2030*, "the country's new development blueprint covering 2008 to 2030" (Government of the Republic of Kenya 2007). The Government aims to transform Kenya into "A Globally Competitive and Prosperous Nation with high quality of life by the year 2030" (Ndung'u, Thugge, and Otiento, n.d.). This vision is based on three pillars: economic, social and political; under each pillar policies for each sector are recommended in order to achieve the broader goal of development.

Under this mandate, the Kenyan agricultural sector is expected to be transformed to become "innovative, commercially-oriented and modern farm and livestock sector" (Republic of Kenya and Office of the Prime Minister, n.d.). This is to be achieved through five policies (Ndung'u, Thugge, and Otiento, n.d.):

- Institutional Reform
- Increased Productivity of crops and livestock
- Transform Land Use Structure
- Prepare New Cultivation Lands
- Increase Access to Markets

As with agriculture, Kenya also envisions to address the water sector through Vision 2030. Here the goal is to ensure "water and sanitation availability and access for all" (Government of the Republic of Kenya 2007). The government has identified the fact that the growth of population and the economy will put pressure on existing resources and will focus on improving there five key areas (Ndung'u, Thugge, and Otiento, n.d.):

- Resource Management
- Water Storage and Harvesting
- Water Supply
- Sanitation
- Irrigation and Drainage

In the context of this thesis, this is important as it shows that the government has identified that agriculture and water are sectors that need attention and improvement.

2.3 Kenya's Agriculture

Agriculture is a significant component of the Kenyan economy. Almost half the land of the country is in allocated to agriculture, and 60% of the population is employed by the sector (World Bank 2015). In fact, in 2010 it contributed approximately 30% of the country's GDP and 10% of the countries raw material exports (World Bank 2015). Even though agriculture is such a significant component of the Kenyan economy and Kenya is a relatively arid country, only 3.5% of the agricultural land is irrigated (World Bank 2015).

2.3.1 A brief overview

The agricultural sector in Kenya can be categorized into four different sub-sectors: industrial, horticulture, food crops and livestock and fish. A summary of the characteristics and activities of each sector is shown below.

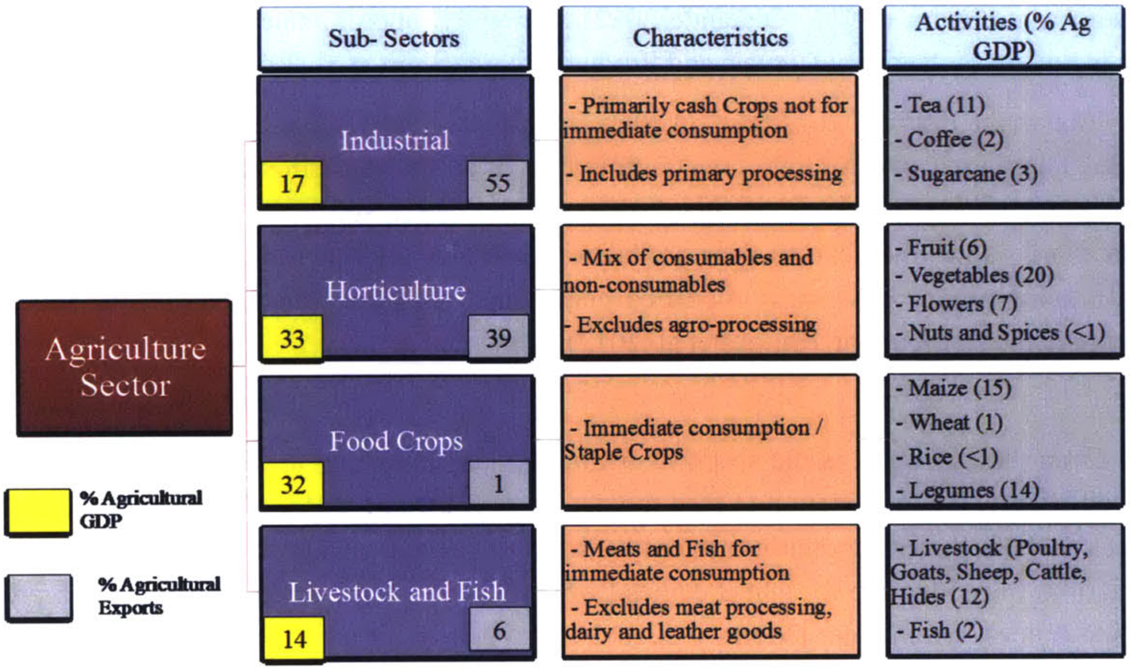


Figure 2.4: A summary of the Agricultural Sector in Kenya

(Republic of Kenya)

Horticulture contributes the most to the country's agricultural GDP (32%), followed by food crops (32%). Even though the industrial sector contributes less than the above to the agricultural GDP (17%), it contributes the most to exports (55%), primarily through the sale of tea and coffee in global markets. Horticulture is also very important in terms of agricultural exports (39%), primarily through the sale of fruits, vegetables and flowers globally.

2.3.2 Characteristics of production of some key crops

2.3.2.1 Staple Foods

Maize

Maize is the most produced staple crop in Kenya. In 2013, Kenya produced 3.4 million metric tons of maize (FAOSTAT 2015b). Overall Kenya is almost self-sufficient in terms of Maize. In times when not enough maize is produced, it is imported – duty free – from Uganda and Tanzania (Short et. al 2012).

Approximately 3.5 million small-scale farmers are involved in maize production accounting for approximately 75% of production (Nyoro 2002). The remaining production comes from large-scale farming which employs 1000 people (Nyoro 2002). The average yield for maize across the country is 1.66 tons/ha (Republic of Kenya). The yield of maize in Kenya is one of the lowest in the region: South Africa, Malawi and Zambia all higher yield than Kenya (Olwande 2012). The technical efficiency of small-holder famers is very low – at an average of 49% with a minimum of 7% (Olwande 2012). Currently, approximately 25% of the Maize in Kenya is bought by National Cereals and Produce Board (Short et al. 2012).

The main limiting constraint in increasing maize production is the lack of access to fertilizer (Gitonga 2014). Another constraint is lack of access to pesticides which is exacerbated by the presence of *Stringa* (Ndwiga 2013). Furthermore, soil acidification is a common phenomenon, due to the year-on-year production of Maize (Gitonga 2014). Lastly, Kenya has banned the imports of genetically modified maize since they are concerned that the seeds may contaminate their production (Snipes et al. 2012).

Wheat

Even though wheat is the second most important staple crop in the Kenyan diet, and it is produced locally, it is not enough to feed the people of Kenya. In 2013, 453 thousand metric tons of maize were produced accounting for only a third of the total consumption (FAOSTAT 2015b). The majority of production for wheat comes from middle and large-scale farmers, which produce in a capital intensive manner (Monroy et. al 2013). As a result the yield for wheat is relatively high in Kenya at an average of 2.2 tons/ha (Republic of Kenya).

Even though wheat production has high yields, Kenya has not been able to increase its wheat production to keep up with the increase in population (Ariga et. al 2010). In addition, even though Kenya has the potential to increase its wheat production in terms of soil quality, it fails primarily due to inability to adapt its management strategies not only in terms of fertilizer and capital, but also in terms of seeds (Mahagayu et. al 2007; Gamba et. al, 2003). Lastly, the tariff for wheat imports has been decreasing over time, and is expected to decrease even further (Monroy et. al 2013). This stands to affect wheat production in Kenya as local farmers will have to compete with international prices.

Rice

Rice is the third most important staple food in the Kenyan diet. In 2013, 98 thousand metric tons of rice were produced: 17% of the total food production (FAOSTAT 2015b). The remaining rice was imported. Consumption of rice in Kenya has been increasing very fast at an average rate of 16% per year since 2000 and in total up 300% from 2000 (FAOSTAT 2015b). However, production has not been able to keep up with this increase: it has been increasing at an average of 14% per year since 2000, but in total has "only" increased by 180% since 2000 (FAOSTAT 2015b).

Rice in Kenya is cultivated under two schemes: the government-owned rice fields and individually owned farms. The government-owned rice fields are operated by the National Irrigation Board (NIB), which – as the name suggests – are irrigated, while the individually owned farms grow rice under rain-fed conditions. There are different measurements with regards to the proportion of production coming from these schemes; however, the agreement is that the NIB is responsible for at least 80% of the rice production (Onyango 2014).

There are a lot of limitations to increasing rice production in Kenya, the primary one being the requirement for irrigation since rainfall is erratic (NIB 2014). This is often costly as it requires investment in capital. That said, there is very high potential for increasing rice production in Kenya (540,000 ha of irrigated land and 1M ha of rain-fed land) (Onyango 2014). The government has identified this potential and is working on increasing rice production by introducing policies such as: technical training, credit support and infrastructure development (Republic of Kenya). Lastly, there are incentives for farmers to increase rice production since there is a 35% import tariff on rice (Short et al. 2012).

2.3.2.2 Industrial Crops

Tea

Kenya is Africa's largest tea producer, and the world's second largest tea exporter [FAO]; in 2013 it produced 432 thousand metric tons of tea. Tea is grown in two types of farms: large plantations owned by companies, which employ approximately 150,000 workers, and smallholder farmers, which employ approximately 600,000 people and produce 60% of the total tea [USDA]. Tea in Kenya is grown under rain-fed conditions, and thus is heavily depended on weather conditions (Cheserek 2013). This is a risk that Kenyan farmers face, as droughts are recurring in certain parts of Kenya. Other challenges tea growers face are volatile prices, pressures to increase wages, and increasing cost of production (Gesimba et. al, 2005).

Sugarcane

Sugarcane is, and has been, the most produced crop in Kenya. In 2013, Kenya produced 5.9 million tons of sugarcane – a 50% increase from 2000 (FAOSTAT 2015b). The majority of sugarcane (consistently more than 80% of it) is used in food processing (FAOSTAT 2015b), which is done in Kenya's 11 mills (Monroy et. al 2013). Sugarcane is primarily produced by small-holder farmers; it is estimated that 250,000 farmers produce 92% of the total output (Monroy et. al 2013). It is also estimated that 25% of the population depends, either directly or indirectly on the industry (ibid). In addition, sugarcane covers three times more land than any other cash crop in Kenya (Waswa et. al 2014).

Sugarcane is primarily grown in Western Kenya, where the sugar belts are located. These regions are appropriate for growing sugarcane because of their temperature, rainfall and soil quality. In 2008, the average sugarcane yield was 70 tons crushed per hectare, down from 73 tons per hectare in 2004 (Ministry of Agriculture 2009). The industry is highly protected by import tariffs which, has led to large inefficiencies in the field (Monroy et. al). In 2009, the ministry of agriculture set a vision to become "a world-class multi-product sugarcane industry" (Ministry of Agriculture 2009). To that end, the ministry set goals to increase efficiency in harvesting, transport and processing (ibid).

2.3.2.3 Horticulture

Flowers

Kenya's cultivates flowers for the purpose of exporting them and has almost a third of the flower market share in the EU (Kenya Flower Council 2015). It is estimated that 500,000 people are dependent on floriculture, 90,000 of which are farm workers (Kenya Flower Council 2015).

The export of flowers is very vulnerable to changes in economic factors: the strength of the euro/dollar, prices of oil and economic conditions of the importing country (Rikken 2011). However, there is a lot of room for improvement in the Dutch-Kenyan supply chain that will allow Kenya to trade more efficiently with its biggest partner (Hortiwise, 2012).

Fruits and Vegetables

In 2013, 2.4 million tons of vegetables and 2.9 million tons of fruits, of which 102 and 260 thousand tons were exported primarily to the developed world (FAOSTAT 2015b). Since 2000, the production of fruits and vegetables has been increasing at an average rate of 5% per year and 81% in total, while exports have been increasing by 12% on average and a total of 161% over the same period (FAOSTAT 2015b). The main vegetables grown in Kenya are French beans, cauliflower and cabbage, while the main fruits fall in the citrus, deciduous and tropical fruits categories.

Horticulture in Kenya is deemed a success story for the region of Sub-Saharan Africa (English et. al, 2004; Minot et. al, 2004). It is characterized as such, not only because production has significantly increased over the past years, but also because small farmers have played an important role in this development (Minot et. al, 2004). Even though the working conditions in the sector are not perfect, people employed are better off than their peers (English et. al, 2004).

This is especially true for women who are heavily involved in the process and earn a wage (Dolan et. al). Furthermore, the involvement of the government in this sector has been limited, which can be considered as a factor contributing to this success (English et. al, 2004; Minot et. al, 2004). In addition, the increased tourism in Kenya has led to an increased demand of these products domestically as well (Minot et. al, 2004).

Given that horticulture in Kenya is deemed as such a success the threats are not discussed. The main threat potentially comes from the increasing standards posed by European markets. In order to adjust, Kenyan farmers need to invest in capital and fertilizers. However, the literature suggests that this should not be deemed as a setback; rather if farmers adapt they can increase their incomes and be better off (Jaffe et. al, 2005; Asfaw et. al, 2007)

2.3.3 Water in Agriculture

As previously mentioned, only 3.5% of the area of the country is irrigated. However, Kenya has a very large irrigation potential (see table below); Kenya could increase its irrigated area by at least a factor of 5.

Basin	Irrigation Area	
	ha	
	Developed (2006)	Potential
Lake Victoria	10,827	200,000
Tana River	68,678	205,000
Athi	10,818	40,000
Ewaso Ng'iro	10,000	30,000
Rift Valley	5,477	64,000
TOTAL	105,800	539,000

Table 2. 2: Kenya, Irrigation Area Developed and Potential [UNWWAP, 2006]

The majority of irrigated schemes are owned by smallholder farms, (48,000 ha; 46%), followed by private ownership – usually companies (43,000 ha; 42%), and last is the government (12,000 ha; 12%) (AQUASTAT 2005). In addition, most of the irrigation is done with sprinklers (60%), the second best is surface irrigation (38%), and last is localized irrigation (2%). Even though the irrigation on the fields is relatively efficient, the water conveyance canal systems are very inefficient, with a 30% efficiency (UNWWAP 2006).

The main irrigated crops in the country are rice, coffee, tea, sugarcane, pineapple and flowers. These 5 together amount for 35% of the total irrigated area. The irrigated area occupied by each crop is represented in the figure below. Coffee is the crop with the highest irrigation area (14,500 ha), followed by rice (13,200 ha). Actually, these two crops combined account for 40%

of the blue water consumption in the whole country, blue water being irrigation water, amounting to 86MCM/year (Mekonnen and Hoekstra 2011).

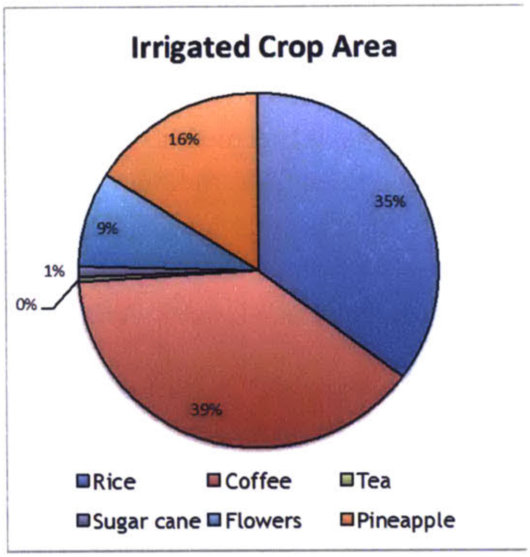


Figure 2.5: Irrigated Area by crop (AQUASTAT)

2.3.4 The Role of Trade and Aid

2.3.1.1 Imports

In recent years, as the population of Kenya has been increasing, imports have been increasing as well. In 2010, total food imports contributed approximately 12% to total food consumption (FAOSTAT 2015a). The figure below shows the breakdown of imports for Kenya for the year 2010.

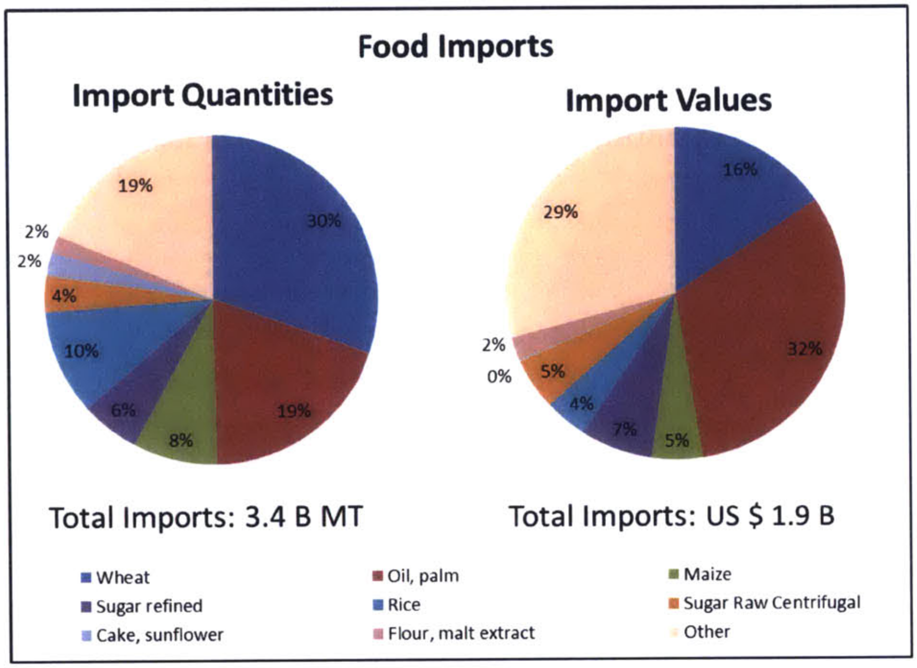


Figure 2.6: Kenya's Food Imports (2010)
Source: FAOSTAT 2015a

The figure above shows that wheat is the most imported crop, followed by palm oil and rice. Furthermore, maize is also imported even though it is the most produced staple food in Kenya.

In 2010, around 880 thousand metric tons of wheat were imported – almost double the amount produced, and almost all of it was used for food consumption. Most of the wheat imported comes from Ukraine (40%), while a lot of it also comes from Russia (30%) and the US (10%), at an average price of US $292/ton. In the same year, around 230 thousand metric tons of wheat were imported, which consisted of approximately 75% of total rice consumption. Most of the rice was imported from Pakistan (83%), with Vietnam and Tanzania contributing 8% and 6% respectively, at an average price of US $370/ton. Even though maize is one of the most produced crops in Kenya, 69 thousand metric tons of it were imported to Kenya in 2010. This amount is insignificant when compared to the supply (~2%), but significant enough in terms of volume of imports.

These three crops are the most important staple foods in the Kenya diet. When the country is not able to produce enough to feed its people it imports wheat and rice from large scale producing countries. The case for maize is different due to the import tariffs set in place; as a result, Kenya imports maize from its neighboring countries.

2.3.1.2 Exports

Agriculture is a very significant component of the Kenyan economy as it contributes with production not only for domestic consumption but also exports. A breakdown of food exports – and flowers - in terms of both quantity and value is shown below.

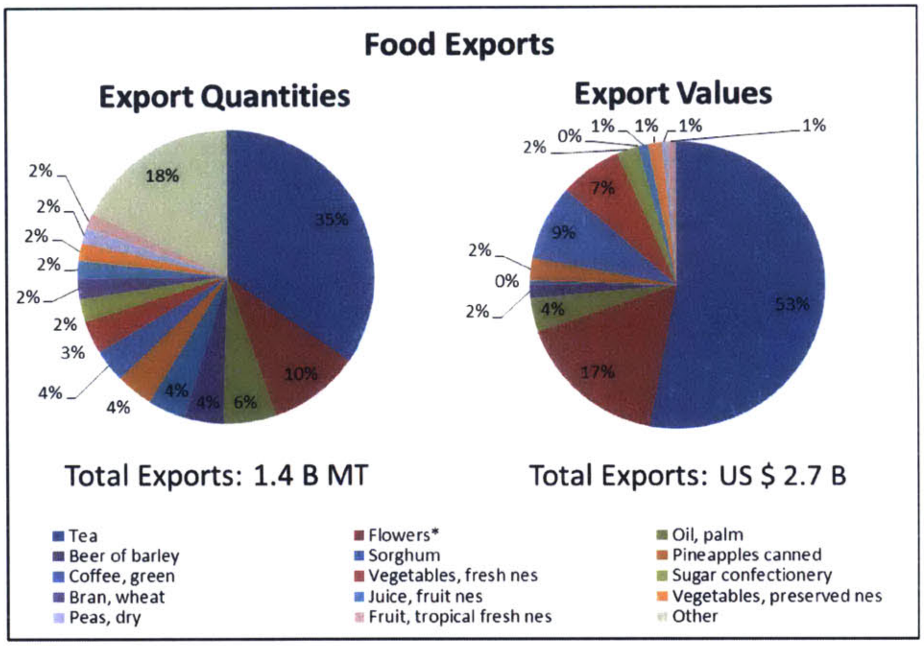


Figure 2.7: Kenya's Food Exports (2010)
Sources: FAOSTAT 2015a; Kenya Flower Council

As we can see tea is Kenya's major export not only in terms of quantity, but also value. Even though flowers are not a food they are considered here since they are grown on agricultural land, and thus there exists a tradeoff between growing flowers for exports and growing food for the local population. They are the second most important agricultural export in Kenya. Other important food exports are coffee, pineapples, fresh vegetables and fresh fruits.

2.3.1.3 Aid

Kenya receives three types of food aid: Emergency, Programme, and Project. Emergency Food Aid is given on a short-term basis to victims of natural or man-made disasters; Programme Food Aid is a form of non-targeted government-to-government aid sold in an open market; Project Aid is given via grants for a targeted purpose (WFP 2015). The majority of Kenya's aid comes from Emergency Aid in years of low precipitation. The figure below shows the variation of food aid over time for all three types in total actual tons of food.

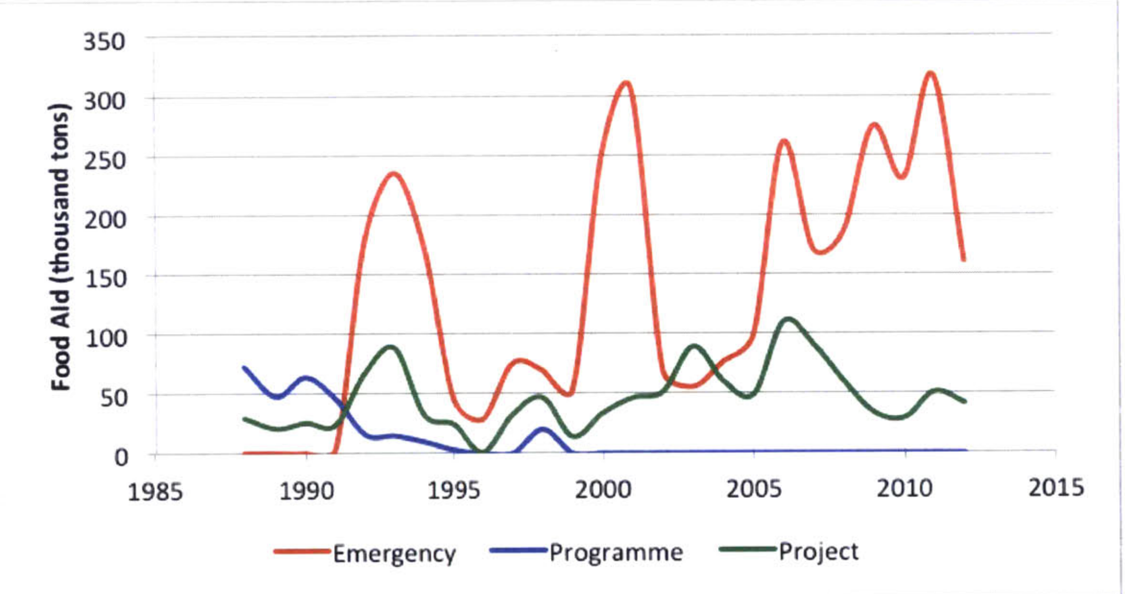


Figure 2.8: Food Aid for Kenya
Source: [WFP]

In the recent past, 2001 was the year with the highest emergency aid. This was the case because that year precipitation was extremely low (average of 465mm with some places receiving as little as 40mm). In that year Kenya received 350 thousand tons of actual food from a variety of different countries. The figures below show the donor countries and the types of food received. Most of the food aid came from the United States (77%) and the most prevalent commodity type was maize. In the case of 2001, maize production took a small hit; however, maize consumption remained approximately the same, suggesting that aid was used to supplement the Kenyan diet.

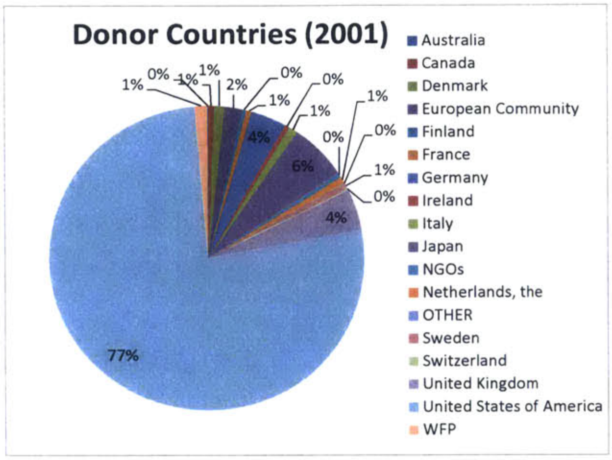


Figure 2.9: Food Aid Donor Countries to Kenya (2001)

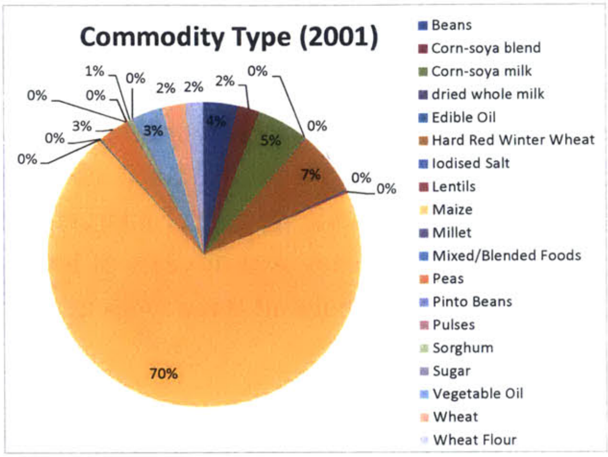


Figure 2.10: Food Aid Commodity Type to Kenya (2001)

Source: [WFP]

In 2001 Kenya received the most aid it has ever received. That amount of aid corresponded to 2.3% of the total food consumed in Kenya that year. Actually, food aid has never amounted for more than 3% of the total food consumed in that year, and on average is 1.1% of total consumption. In addition, food aid does not appear to be highly correlated with production, but rather with the precipitation of the previous year. Therefore, food aid does not seem to affect the amount of production and thus the argument that giving a country aid will decrease the amount of food produced does not hold for the case of Kenya. This is consistent with some literature that concludes that aid does not have disincentive effects by examining households in Ethiopia (Abdulai et. al, 2005).

2.4 Water in Kenya

Kenya is considered a water scarce country, since there is less than 1000m^3/year of renewable water available per person (USAID). Even though the country lies on the equator, with the coast on the one side and Mount Kenya on the other it has a variety of different climates, which can cause both floods and droughts. The majority of the water used in Kenya is derived from precipitation (UNWWAP 2006).

2.4.1 Water Availability

2.4.1.1 Precipitation

Average precipitation in the country is 630 mm/yr, while it varies between 200mm/yr and 1,800 mm/yr [AQUASTAT]. A precipitation map of Kenya is shown in the figure below.

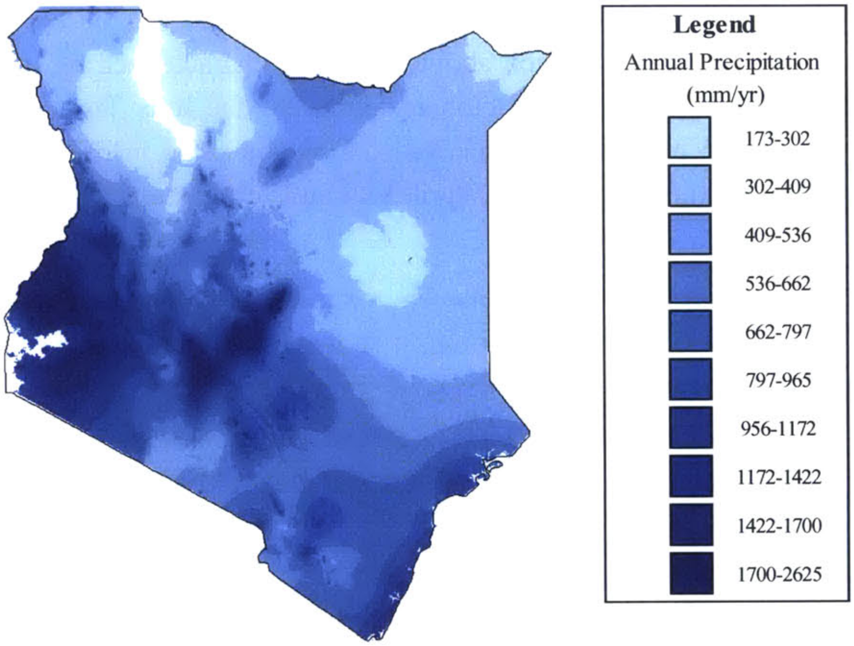


Figure 2.11: Precipitation (Annual) Map for Kenya
Source: Hijmans et al. 2005

The northern and eastern parts of Kenya receive very low amounts of precipitation (<700 mm/yr), and thus are considered deserts. The area of Kenya by the coast (on the South-East), receives higher amounts of precipitation, ranging between 600mm/yr and 1200mm/yr. The western part of the country also receives high amounts of rain (>1000mm/yr), primarily due to its proximity to Lake Victoria. Lastly, the central part of the country, around Mount Kenya, receives high rain (>1000mm/yr), due to the altitude.

Water also varies on a monthly basis. The graph below shows monthly precipitation.

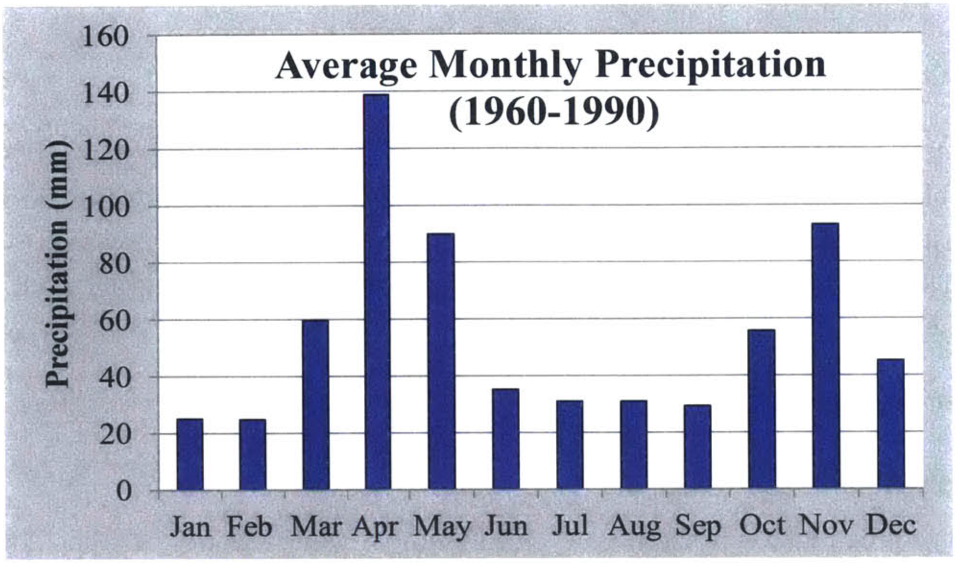


Figure 2.12: Average Monthly Precipitation
Source: (World Bank 2015b)

As we can see from the graph above, Kenya is characterized by two monsoon seasons: one in March and one that starts in October, defined by the Inter Tropical Convergence Zone. The minimum average precipitation observed during the years in this study was 25.1 mm in January, while the maximum occurs in April with an average precipitation of 138.8 mm across the whole country.

Lastly, precipitation varies between years. The graph below shows the average precipitation across the country. In addition, it shows the maximum and minimum precipitation in the country for that year.

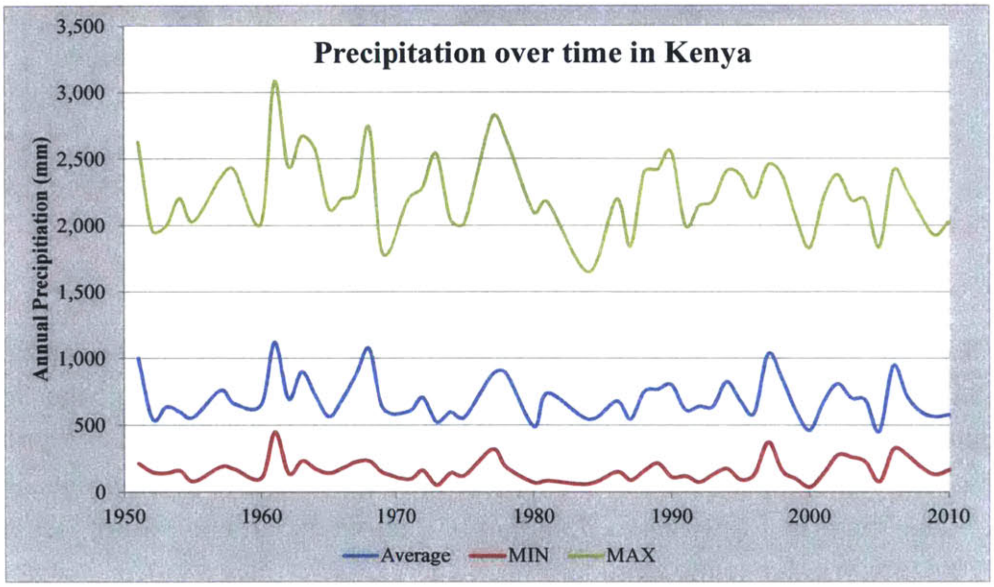


Figure 2.13: Annual Precipitation 1950-2010 in Kenya
Source: Willmott and Matsuura 2001

This graph indicates that inter-annual variability of rain is a common phenomenon. The case of 2000 is extraordinary, when average precipitation in the country went from 1039 mm/yr in 1997 to 465 mm/yr in 2000. It is also interesting to note that the year on year percentage change is more pronounced in the minimum series than the maximum series.

2.4.1.2 Surface Water

Surface water in Kenya comes from streams, rivers and lakes and provides an important source of water for the people (World Resources Institute 2007). A map of the main lakes and streams in Kenya is shown below.

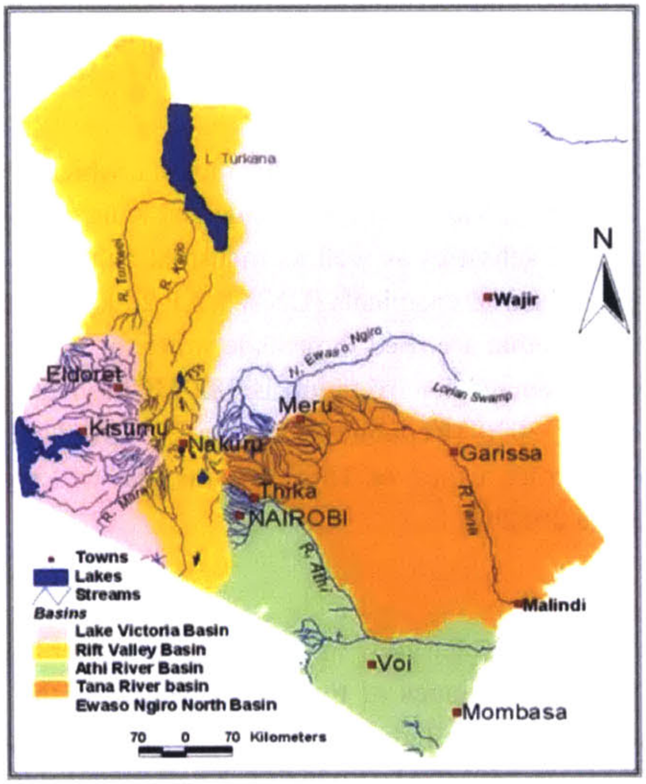


Figure 2.14: Map of Surface Water in Kenya [UNWWP,2006]

Kenya consists of five major drainage areas: Ewaso Ng'iro, covering 36.3% of the country, Tana River (21.7%), Rift Valley and inland lakes (22.5%), Althi River and Coast (11.5%), Lake Victoria (8%) (AQUASTAT 2005). Even though Lake Victoria is the smallest drainage area, it has the most renewable surface water, amounting to 46% of the total renewable surface water available (Republic of Kenya, 2012b). The Tana River basin is the second largest contributor to renewable surface water (28%). The table below shows the area of each basin as well as its renewable surface water.

Catchment	Catchment Area	Renewable Surface Water (2010)
	km2	MCM/yr
Lake Victoria	50,108	9,399
Rift Valley	130,452	2,457
Athi	58,639	1,198
Tana	126,026	5,858
Ewaso Ng'iro	210,226	1,725

Table 2.3: Surface Water Availability [Republic of Kenya, 2012]

As expected, the surface water availability is highly correlated with rainfall; however, it is discussed separately in an attempt to understand potential surface water sources of irrigation.

Lake Victoria Basin

As the name suggests, this basin includes Lake Victoria, which is a fresh water lake. The main rivers in this basin are Nzoia, Yala, Nyando, Sondu and Kuja (UNWWAP 2006). This area is characterized by agricultural activities as well as industrial activities; as a result the water is polluted by agricultural and industrial chemicals (UNWWAP 2006). In this basin there are a total of 848 small dams / water pans that are used to provide water for irrigation (Republic of Kenya 2012b). Currently, the water demand for irrigation is 182 MCM/yr but is projected to grow to 2,238 MCM/year by the year 2030 (Republic of Kenya 2012b). The Ministry of Water and Irrigation is planning to construct a total of 16 new dams that will provide 492 MCM/yr for irrigation (Republic of Kenya 2012b).

Tana River Basin

The Tana river is the main water body in this basin. The river has an average flow of 42 m^3/sec and flows from the eastern slopes of the Aberdares range, the southern slopes of Mt. Kenya and the Nyambene hills, into the Indian Ocean (UNWWAP 2006). Currently, irrigation in the basin demand 563 MCM/year, 59MCM of which is being provided by 640 small dams/water pans (Republic of Kenya 2012b). By 2030, the irrigation demand is projected to grow to 3,987 MCM/year by the addition of 440,000 ha of irrigation (Republic of Kenya 2012b). To meet this demand, there is a plan to construct dams of total 35 MCM (Republic of Kenya 2012b). This suggest that the remaining demand will be met by taking advantage of the other dams that are currently only being used for hydropower, small ponds, and partially by groundwater.

Rift Valley Basin

The Rift Valley Basin is home to most of Kenya's lakes: Lake Naivasha (fresh), Lake Turkana and Lake Baringo (both brakish), and Lake Magadi (saline) (UNWWAP 2006). Lake Naivasha, is heavily used to support the horticulture industry, and as a result its water quality is deteriorating (UNWWAP 2006). Currently, the water demand for irrigation in the area is 119

MCM, and is projected to grow to 459 MCM by 2030, by the addition of 41,600 ha of irrigation projects [Republic of Kenya, 2012]. Even though there is a plan to build 202 MCM of storage, there is excess supply right now, since Turkwell Dam has a capacity of 1,650 MCM [Republic of Kenya, 2006].

Ewaso Ng'iro Basin

The Ewaso Ng'iro basin is the largest one in Kenya, but the least populated one. The main river in the basin is the Ewaso Ng'iro North River, which flows from Mount Kenya to the Lorian Swamp (UNWWAP 2006). As this is a very arid region, agriculture is limited: 9,000 ha project to grow by 4,000 ha by 2030 [Republic of Kenya, 2012]. Currently, the main sources of irrigation for the basin are small dams and water pans; however, there is a plan to construct Kihoto Dam, which will have a capacity of 204 MCM (Republic of Kenya 2012b).

Athi Basin

The Athi Basin has the lowest renewable surface water in the country. The Athi river flows from the slopes of the Abardare Ranges into the Indian Ocean with an average depth 0.29m and an average flow of 6.76 m^3/sec (UNWWAP 2006). This basin contains the country's two biggest cities: Nairobi and Mombasa, whose population is increasing rapidly. As a result, it is projected to have the highest domestic and industrial demand in 2030 (899MCM and 179 MCM respectively) (Republic of Kenya 2012b).. Currently most of the irrigation water comes from small dams and water pans, but there is a plan to construct multiple dams, which will add 443MCM of water storage capacity for irrigation (Republic of Kenya 2012b).

2.4.1.3 Groundwater

Groundwater provides 5% of Kenya's renewable water resources, and about 43% of rural and 23% of urban people rely on it (Mumma et. al, 2012). Agriculture is the highest consumer of groundwater, using 11.75% of the groundwater abstracted (UNWWAP 2006). The groundwater safe yield (as 10% of the aquifer recharge for each basin is shown below). The table below also shows groundwater use in agriculture, and groundwater quality.

Basin	Safe Yield [1]		Agricultural Use [1]	Groundwater Quality [2]
	MCM/year			
	2010	2030	2030	
Lake Victoria	1,582	1,577	347	Good water Quality
Tana River	879	873	238	Generally fresh some have high fluoride levels
Athi	333	330	43	>50% have hard, saline water some have high fluoride levels
Ewaso Ng'iro	1,401	1,391	7	Often hard and saline Nitrate pollution due to livestock
Rift Valley	1,402	1,392	56	Mostly fresh 50% have high levels of fluoride

Table 2.4: Groundwater in Kenya; 1: [Republic of Kenya, 2012], 2: [UNWWAP, 2006]

In addition to the groundwater resources described above, in 2013 a large aquifer was discover in the region of Turkana, the north part of the Athi Basin [Kullish, 2013]. Five aquifers have been identified, two of which have been proven by UNESCO, the Lotipiki Basin Aquifer and the Lodwar Basin Aquifer (UNWWAP 2006). The total estimated capacity of the newly discovered deep aquifers is estimated to be 250 BCM, while their recharge is estimated at 1.35 BCM per year [Radar Technologies International, 2013]. The specific recharge rates of the two discovered aquifers, which are deep aquifers, are yet to be determined. Even though the groundwater quality still needs to be determined, this discovery has the potential to provide access to water for the people of Turkana, who currently have limited access to water (UNWWAP 2006).

2.4.3 Water Policy

As mentioned above, in 2007 the government of Kenya devised a plan to improve the water and sanitation sector in Kenya. With regards to better water resource management, the following measures are proposed (Republic of Kenya and Office of the Prime Minister, n.d.):

1. Enforcing regulations by the Water Resources Management Authority
2. Encouraging formation of water resources users' association by communities
3. Promoting fair allocation of water among users for sustainability
4. Rehabilitate and develop more hydrometric stations
5. Enabling Environment for Public-Private Partnerships
6. Use Sector-Wide Approach to planning as a tool

With regards to irrigation the following was proposed (Republic of Kenya and Office of the Prime Minister, n.d.):

1. Increase area under irrigation
2. Improve irrigation efficiency

3. Finalize policy, legal and institutional framework for irrigation
4. Develop a national irrigation master plan
5. Empowering communities to manage their schemes
6. Invest in human resource capacity development

2.4.4 Water Economics

Kenyan farmers incur two main costs: water related costs and equipment related costs. Since the Kenyan government owns all the water, it issues permits for its use at a cost. The applicant does not need to pay an application fee, but he does need to pay a licensing fee when the permit is granted [Republic of Kenya, 2015]:

- Category B (Surface Water): Ksh 7,500 (US $78)
- Category C (Storage): Ksh 25,000 (US $260)
- Category D (Groundwater):-Ksh 50,000 (US $518)

In addition, the users may be required to pay a volumetric charge for the water, but this is determined on a case by case basis.

After the water has been acquired, the farmers need to develop an irrigation system. Small scale farmers will have to pay between US $500 to US $1,500/ha for gravity-fed surface irrigation and between US $1,500 to US $4,000/ha for piped/sprinkler systems (AQUASTAT 2005). In the case of groundwater, the farmers also need to purchase pumps; these can be hand pumps, wind pumps, diesel pumps or solar-powered pumps. Some farmers pay up to US $60 per day on fuel to operate a diesel pump, so some of them have been switching to solar powered pumps.

National irrigation schemes are owned by the government, and usually operated by a private company. In this case, the farmers are employed by the company and are paid a working wage. National irrigation schemes also allocate land to small-farmers; even though these farmers do not have to directly pay for water, they have to pay an operation and maintenance fee for the irrigation, at about US $21 per acre per season (NIB 2014).

In addition, farmers also incur the cost of fertilizer, and the cost to take the goods to market. Sometimes, poor and inadequate rural infrastructure increase transaction costs for farmers (Alila and Atiento 2006). The lack of infrastructure not only limits the ability of farmers to take their products to farmers, but also affects their ability to acquire fertilizer. Overall, fertilizer application in Africa is much lower than in other parts of the world [Harsch, 2004]. Another constraint to using fertilizer is the lack of knowledge farmers have and the fact that information is not passed on from farmer to farmer [J-Pal]. Lastly, farmers also suffer from post-harvest losses related to pests and diseases (UNWWAP 2006).

Low-cost drip irrigation systems are currently being tested in the country by the Kenya Agricultural Research Institute (KARI). Using these technologies yield was increased by 3.3 times when compared to rain-fed, and 2.5 times, when compared to hand watering (Joint FAO/IAEA Programme 2013). These technologies are currently being transferred to the farmers in Kenya by KARI (Joint FAO/IAEA Programme 2013).

Chapter 3 – Methodology

The purpose of this thesis is to determine the optimal spatial and temporal allocation of land and water resources to maximize cereal production in Kenya in terms of calories. For this analysis three crops were used: maize, wheat and rice. These three crops are the main staple foods in the Kenyan diet, and together they account for 48% of the calories and 99% of the cereals consumed. Given the importance that cereals, and specifically maize, wheat and rice, occupy in the Kenyan diet, this analysis is a good first approximation to Kenya's ability to increase its food production. In addition, all three crops are currently being produced in Kenya to a varying extent.

3.1 Brief Overview of Methodology

For the purposes of this analysis two optimizations were used. The first one was a least squares estimation used to calibrate the model. The second one was a linear program used to produce an optimal allocation of resources (water and land) to maximize calories produced in Kenya for wheat, maize and rice. For both optimizations Kenya was divided into 759 0.25 by 0.25 degree pixels [see Appendix A.1 for grid of Kenya]. This methodology has been used in the past (McLaughlin and Hoisungwan) to estimate water and land allocations for China's growing population.

The first optimization was used to reproduce current conditions (for the year 2000). More specifically, average monthly values for precipitation and actual evapotranspiration for the years 1950-1999 for each pixel were used as inputs to the model. In addition, the fraction of each pixel currently grown by maize, wheat and rice was considered. The remaining fraction of the pixel was considered to be occupied by other crops and local vegetation. A mass balance constraint on water was imposed. Water sources in each pixel were precipitation, runoff from upstream or water from storage (groundwater). Water was consumed by crops and local vegetation (evapotranspiration), used to replenish storage, or exited as runoff. Using the mass balance, the model estimated precipitation and total evapotranspiration. These estimates were used in the least squares objective and compared to the observed values. The outputs from this model that were used in the second optimization were estimated precipitation and estimated non-crop evapotranspiration. This optimization is described in more detail in Section 3.4.

The second optimization was used to determine the optimal allocation of water and land that maximizes the calories produced in the country from growing maize, wheat and rice. As with the previous model, a mass balance constraint on water was imposed. In addition, a land balance constraint was used. The amount of land available in each pixel to grow each crop was limited by the soil characteristics. Here, we considered five soil grades with varying yields. In addition, the total land used for crops and non-crops could not exceed the total area available. The results gave the fraction of each pixel allocated to each crop.

3.2 Water Allocation Modeling

As briefly described above, a mass balance model was used to determine when and where water is available. This section explains the details of the source of the data (Section 3.2.1) and then elaborates on the water balance model used (Section 3.2.2).

3.2.1 Data Collection

3.2.1.1 Precipitation

Precipitation data was collected from Willmott and Matsuura (Wilmott and Matsuura 2001). This was a global dataset with monthly precipitation data available from 1900 to 2010 on a 0.5 by 0.5 degree grid. This data was in turn collected from multiple different sources including, but not limited to, the Global Historical Climatology Network (NOAA 2011), and the Global Surface Summary of Day (NCDC 2015). The data from this source is collected primarily from rainfall gauges across the globe, controlled for quality, and then is interpolated to the chosen grid. In addition, station-by-station cross validation was used (Wilmott and Matsuura 1995).

The retrieved data was then averaged for each pixel for the years in question (1950-1999). In addition, since the result was an average of 50 years worth of data, the standard deviation was also calculated. The precipitation values were then spatially interpolated to fit the 0.25 by 0.25 degree grid that was created for Kenya. This was done in GIS using the resampling tool. The resulting map – on the finer grid – had 3 missing data points, due to the coarser resolution of the inputted data. This was resolved by spatially interpolating the values these 3 pixels using the values of the neighboring pixels. It worth noting that the dataset used only included values over land masses, and since the pixels with the missing data were at the border of the country with the ocean only 3-4 surrounding pixels were used for the spatial interpolation rather than 8.

The map below is a rendering of the average annual precipitation (for years 1950-1999) across the country. In addition, a graph showing the average monthly precipitation across the country is also shown. This graph also shows the maximum and minimum precipitation in the country on a monthly basis. In addition, Appendix A.2 shows monthly precipitation maps for Kenya created from the dataset described above. Furthermore, Appendix A.3 shows a map of the average annual standard deviation of precipitation as a percentage of the average value. It also shows the monthly distribution for the standard deviations.

When the annual precipitation created from this dataset is compared to the one in Section 2.4.1.1 from Hijmans et. al 2005, which spams the same time period, we notice that the one in the previous section has much higher maximum precipitation values. Still, the overall precipitation pattern is the same. In addition, the Hijmans et. al dataset is for a much finer resolution (30 arc seconds ~ 0.01 deg). This would explain why the data set catches the finer details of the grid. However, the upscale of the Willmott and Matsuura is that the annual data is provided, and thus it can be used to conduct sensitivity analyses. Lastly, when the Hijmans et. al dataset is extracted to a coarser grid the extreme values are lost due to the interpolation and the maximum value becomes 1,949 mm/yr.

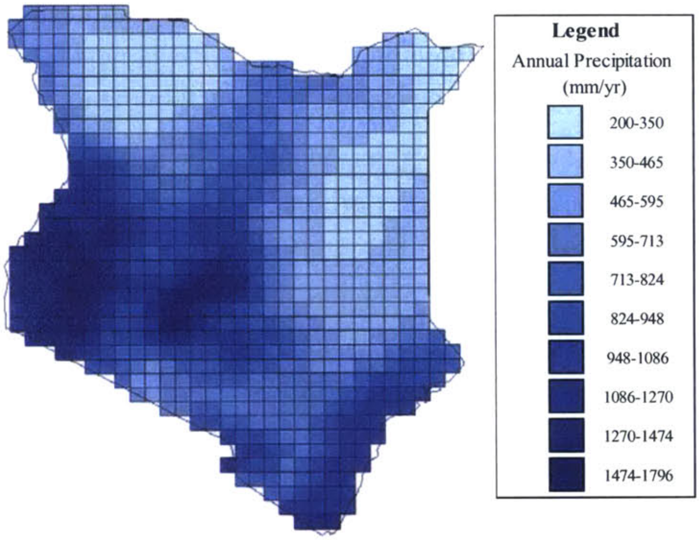


Figure 3.1: Average annual precipitation [Measured] Map of Kenya

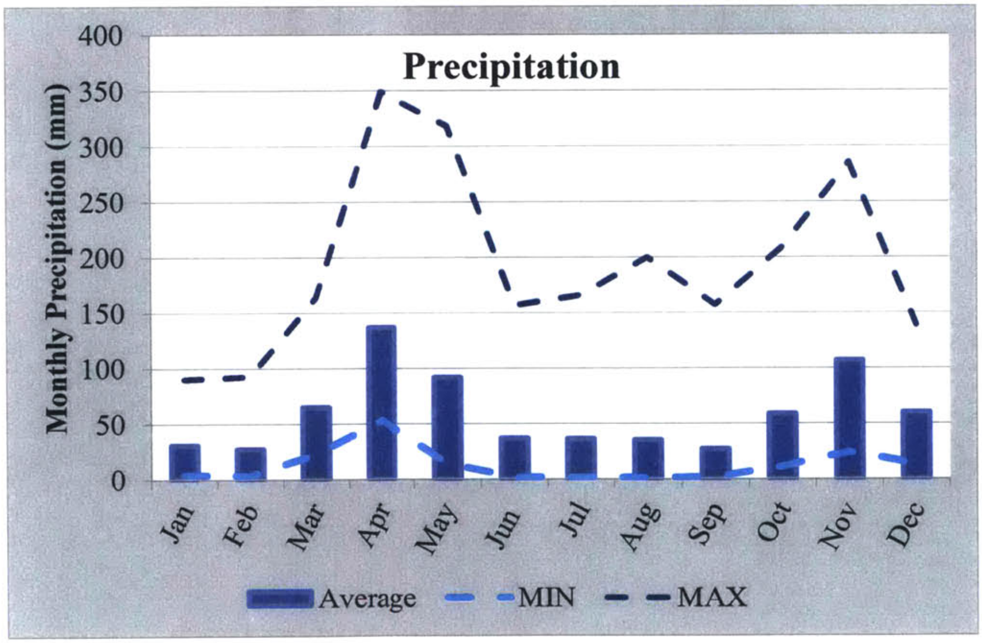


Figure 3.2: Monthly precipitation [Measured] of Kenya

3.2.1.2 Evapotranspiration

Actual Evapotranspiration

Similarly to precipitation, actual evapotranspiration was also retrieved from Willmott and Matsuura. More specifically, the data comes from "Terestrial Water Budget Data Archive." Actual evapotranspiration (AET) is equal to adjusted potential evapotranspiration (APE) if the difference between precipitation and APE is positive. Adjusted potential evapotranspiration is potential evaporation (PE), which is a function of temperature and heat, adjusted for month and day length. If the difference between precipitation and APE is negative, then AET is equal to precipitation plus the absolute value for the change in storage in the previous time period.

As with precipitation, an average monthly value for actual evapotranspiration between years 1950 and 1999 was calculated from the original dataset and then spatially interpolated for the 0.25 by 0.25 grid created for Kenya. The graph below shows the actual evaporation on a monthly basis for the country. Also, following the graph is a map of actual annual evaporation for Kenya. The maps for the actual monthly evaporation for Kenya are shown in Appendix A.3.

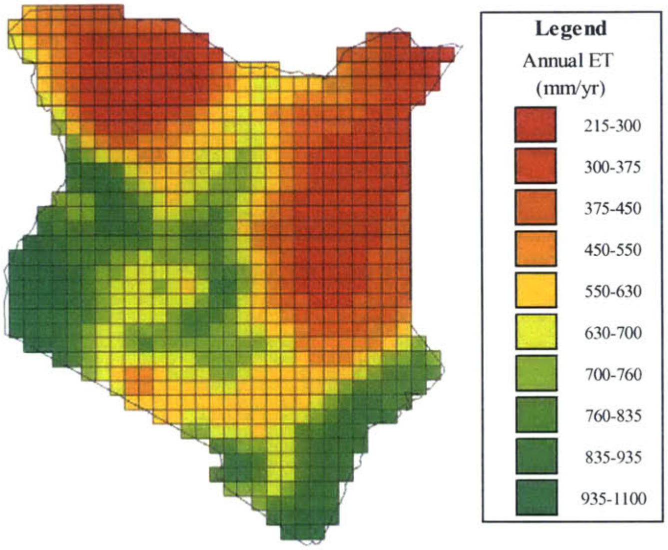


Figure 3.3: Average annual actual evapotranspiration [Measured] Map of Kenya

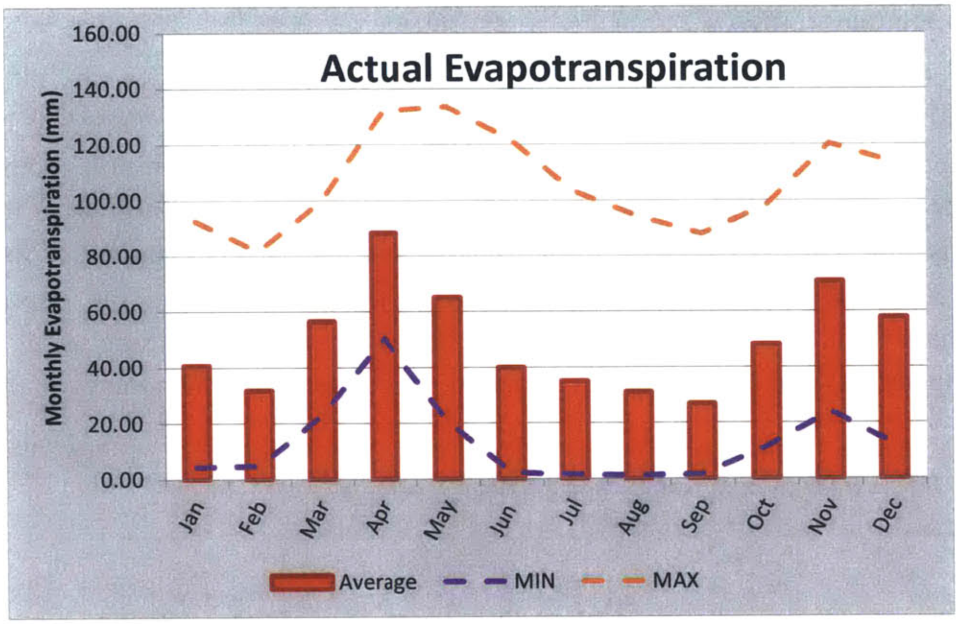


Figure 3.4: Monthly actual evapotranspiration [Measured] of Kenya

As with precipitation, actual evapotranspiration has two peaks during the year, one in April and one in November. However, it is clear that actual evapotranspiration greatly throughout the country. The desert areas identified above, also have low actual evapotranspiration values, as expected. Furthermore, the wettest parts of the country (by the coast and by lake Victoria) have the highest evaporation rates.

Crop Evapotranspiration

Crop Evapotranspiration is the amount of water that a crop evaporates while it grows. This section reviews the method used to estimate this for our model. Please note that this section is a summary of work conducted by Wenjia Wang; for the full details please see Wang 2015.

For this analysis we decided to examine three crops: maize, wheat and rice. For each of them we had to collect data in order to be able to estimate their evapotranspiration. The water requirement for each crop is a function of two parameters: the crop coefficient and a reference evapotranspiration (Natural Resources Management and Environment Department). The equation below shows this:

$$ET_{crop} = K_{crop} \times ET_0 \qquad \textbf{Eq. 1}$$

Reference Evapotranspiration

The reference evapotranspiration is the ET for a reference crop (usually either grass or alfa-alfa), with an assumed height 0.12m. Furthermore, the albedo is assumed to be 0.23, the surface resistance is fixed to 70s/m, and the plant is not short of water. Multiple methods exist to calculate reference evapotranspiration, but here we decided to use the Hargreaves method. The Hargreaves method was used because it does not require a significant amount of data, yet it is relatively accurate as mean difference between the predicted ET and the observed ET is relatively small. This method calculates the reference evapotranspiration as a function of observed temperatures and extraterrestrial radiation. More specifically (Zomer et al. 2006):

$$ET_0 = 0.0023 \times R_a \times (T_a + 17.8) \times (T_{max} - T_{min})^{0.5} \quad \text{Eq. 2}$$

where,

R_a = **Extraterrestrial Radiation [mm/month]**

T_a = **Mean Daily Temperature [°C]**

T_{min} = **Minimum Daily Temperature [°C]**

T_{max} = **Maximum Daily Temperature [°C]**

This was calculated using temperature data collected from WorldClim, and radiation data retrieved from CGIAR-CSI, created by Zomer et. al (2007, 2008). The results for the annual crop evapotranspiration our shown in the map below. In addition, the graph that follows shows the variation of the reference ET over the year.

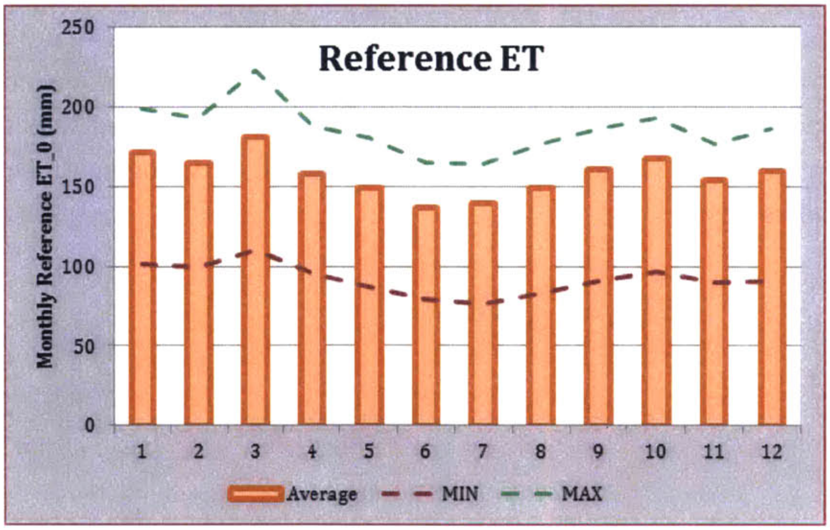


Figure 3.5: Monthly calculated reference evapotranspiration of Kenya

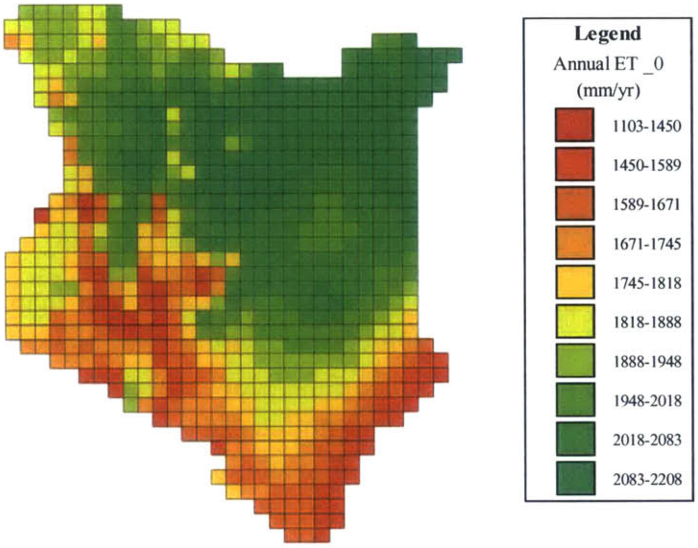


Figure 3.6 Calculated annual reference evapotranspiration Map of Kenya

Crop Coefficient

The second component of crop evapotranspiration is the crop coefficient. This coefficient relates the reference ET with the crop ET, and accounts for the variation in the water demand for each crop throughout its growing period. At the initial and final stages of growth the crop needs less water than during the middle period, which is the main growth period. Furthermore, each crop has a different growing period, not only terms of length but also in terms of months. The crop coefficient for each crop, for each month is shown in the table below (Natural Resources Management and Environment Department):

	Crop Coefficient per month											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Maize	0	0	0	0.3	1.2	1.2	1.2	1.2	0.48	0	0	0
Wheat	0	0	0	0	0	0	0.3	1.15	1.15	1.15	0.33	0
Rice	0	0	0	0	1.05	1.2	1.2	1.2	1.2	0.75	0	0

Table 3.1: Crop Coefficient for each crop per month

3.2.1.3 Flow Direction

Another component of the model used in this analysis was flow direction. More specifically, we wanted to know in what direction the water flowed out of each pixel. Multiple avenues were considered here: flow direction created from elevation maps, Total Runoff Integrated Pathways (TRIP), and Dominant River Tracing (DRT). All three are described here, and the reasons why DRT was finally selected are explained.

Flow Direction from Elevation Maps

In an attempt to have primary source data, a flow direction map was created from an elevation map. A digital elevation model (DEM) map with a resolution of 250m for Kenya was used. The flow direction map was created using the Flow Direction tool in GIS. The resulting map is shown in Appendix A4. This method was not considered to be the most accurate, because the original Flow Direction was in a 250 by 250m resolution. This means that the final map (0.25 by 0.25 deg) was an aggregate of the smaller map, and thus does not necessarily represent the macro scale.

Total Runoff Integrated Pathways - TRIP

Another potential source of flow direction data was the Total Runoff Integrated Pathways network, developed by Oki and Sud (1998). This is a global dataset at a 0.5 by 0.5 degree resolution (this was the finest resolution available). This network was created by a similar methodology than the above (from digital elevation model (DEM) files) and by considering rivers as vectors. The resulting map is shown in Appendix A4.

Dominant River Tracing – DRT

The Dominant River Tracing (DRT) algorithm was created by the Numerical Terradynamic Simulation Group at the University of Montan (Wu and Kimball). "This algorithm utilizes information on global and local drainage patterns from baseline fine scale hydrography to determine upscaled flow directions" (Wu and Kimball). By maintaining the original hierarchical structure of the basin, and prioritizing higher order basins, this algorithm preserves the rivers. The main advantage of this dataset is that it comes in a variety of different scales ranging from 1/16th of a degree to 2 degrees. The 0.25 degree resolution was chosen because it was considered fine enough to show details for a country of the size of Kenya, but coarse enough that computational problems could be avoided. Actually the location of the grid used in the DRT was the basis for the Kenya grid used in the analysis, to preserve flow direction. A map of the DRT flow direction is shown in Appendix A4.

Given Kenya's geography (elevation, and location of rivers), the DRT algorithm yielded results that were most appropriate. This was deemed as such because this model preserved the rivers to a great extent, and therefore could reveal where water is available for irrigation from a river source. However, there were 4 pixels that had no exit and were thus considered sinks in the DRT model. This created problems in our optimization model, so it was adjusted. The adjustment was that the flow for all 4 cells was directed to the ocean. This was deemed appropriate for multiple reasons: (1) given Kenya's geography it is reasonable that the flow in those locations would be directed to the ocean; and (2) the manual flow accumulation suggested that this would be the correct flow direction. The final flow direction map is shown below. In addition, the map next to it shows the main rivers in Kenya as produced from the flow accumulation constructed using the elevation data. This map does match the most of the main rivers as observed in Kenya (see Appendix A4). The main important difference is that the model suggests that the Ewaso Ng'iro river appears to go all the way to the boarder, however, this is not true as it stops at a swamp.

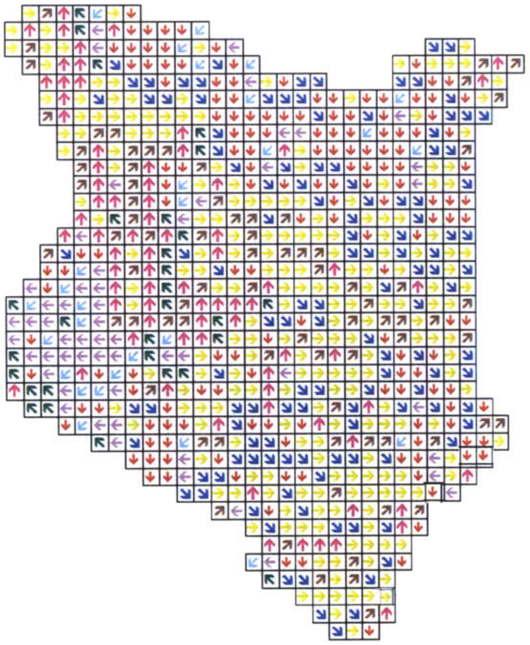


Figure 3.7: Flow direction map for Kenya

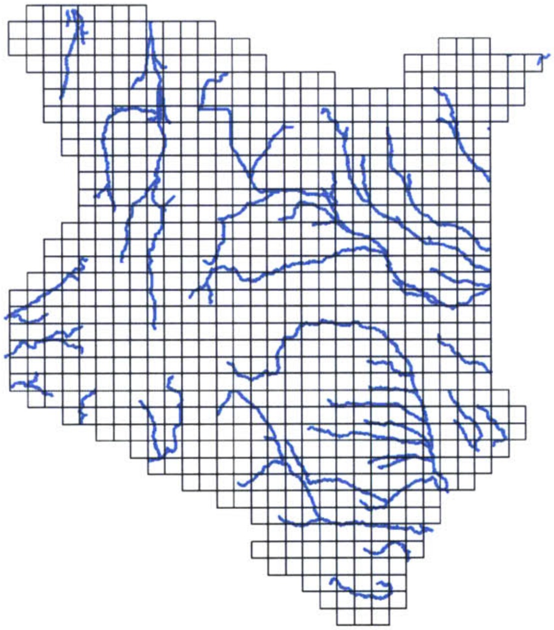


Figure 3. 8: Map of Main rivers in Kenya

That said, the flow direction map does match – overall – the rivers observed in Kenya. The flow direction is also consistent with the river network.

3.2.1.4 Change in Storage

The change in storage for each month was considered as the interaction between the surface and the groundwater table. Therefore, when there is excess water some of it stored into the groundwater, through replenishment. On the other hand, when there is a shortage of water, water can be pumped out of storage, and thus the change in storage is negative.

The magnitude of the change in storage was limited by the annual precipitation. More specifically, change in storage was bounded by 15% of annual precipitation. This was done in an attempt to model physical changes simply. The idea was that recharge and pumping could not happen at an indefinite amount, since this would allow for extremes in our model.

In addition, change in storage was considered to be cyclical on an annual basis. This means that the storage at the beginning of the year needs to equal the storage at the end of the year. This is an appropriate method in the name of sustainability; that is, storage is not depleted over time as only renewable sources of groundwater are used.

3.2.2 Water Balance Model

In order to determine when and where water is available for crop production a water mass balance model was used. The unit considered for the mass balance model was a pixel, a rendering of which is shown below.

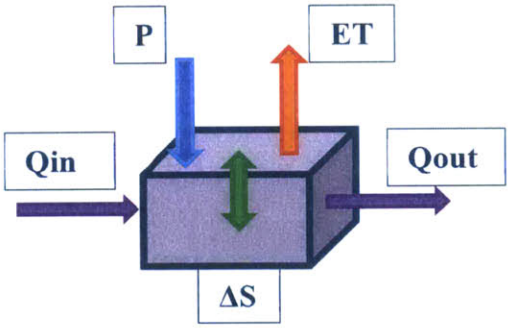


Figure 3.9: Representation of Water Mass Balance for a single pixel

For each pixel the inputs were Precipitation (P) and runoff from upstream (Qin). The outflows for each pixel were evapotranspiration (ET), which consists of crop and non-crop ET, and runoff to downstream (Qout). The change in storage (ΔS) could be either negative or positive depending on the time period.

This mass balance was conducted for every month on every pixel. The flow direction mentioned above was used to determine where the inflow (Qin) was coming from and where the outflow (Qout) is going. This was done by creating a flow direction matrix. An example is shown below to explain this principle.

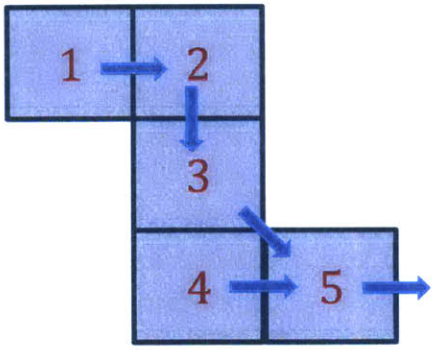


Figure 3.10: Flow direction example visualization

Consider the pixel formation above, with the flow directions as depicted by the arrows. Here we are considering only 5 pixels. Each pixel has an outflow; however, not every pixel needs to have an inflow (for example pixel 4). That said, a pixel can have multiple inflows (like pixel 5). The flow direction matrix is a 5 by 5 matrix, shown below.

	1	**2**	**3**	**4**	**5**
1	-1	0	0	0	0
2	1	-1	0	0	0
3	0	1	-1	0	0
4	0	0	0	-1	0
5	0	0	1	1	-1

Table 3.2: Flow direction matrix example

In this matrix, each element can take three values {-1,0,1}. A negative 1 (-1) is used to represent an outflow from the pixel. Since every pixel has an outflow the diagonal is populated by -1. A positive 1 (1) represents an inflow from the pixel of the column to the pixel of the row. So, for example, since the water from pixel 1 flows into pixel 2, then the element in row 2, column 1 is a one. And so on until the full matrix is created.

For the case of Kenya, 759 pixels were considered, therefore the flow direction matrix has dimensions 759 by 759. This matrix was created using MATLAB, and the code is shown in Appendix A.6.

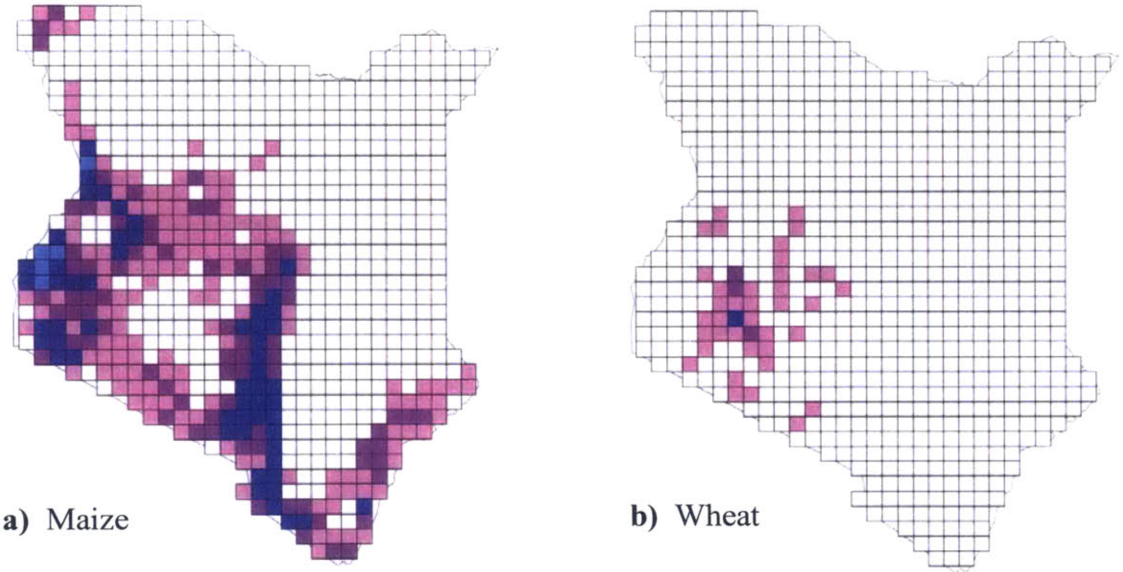
3.3 Land Allocation Modeling – A Summary

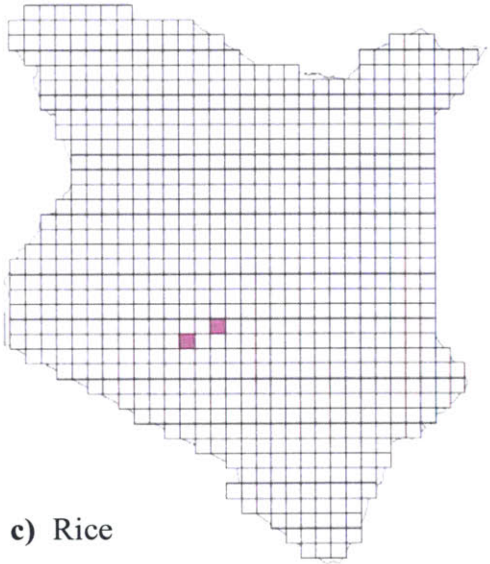
This section describes the criteria used to determine where land is suitable for cultivation for each crop. Please note that this section (3.3) is a summary of work conducted by Wenjia Wang; for the full details please see Wang 2015.

3.3.1 Current Land Occupied by crops

The first step in this process was to identify which land is currently occupied by the crop in question, namely: maize, wheat and rice. The data was collected from the Global Agro-ecological zones database issued by the FAO (FAO 2015). This dataset contained total harvested area per crop – both irrigated and rain-fed together. This data was converted to the fraction occupied by each pixel, given the know area of each pixel as calculated by GIS. The next page shows three maps – the fraction of each pixel occupied per crop. In addition, the page that follows also shows the total area occupied by each crop broken down by soil grade. The notion of soil grade is discussed in the section that follows.

The maps show that currently, the most cultivated crop of the three is maize, followed by wheat and then rice. Overall, this is consistent with what was reviewed in the context section.





Soil grade	Maize	Wheat	Rice
	Area planted (km^2)		
1	-	-	-
2	153	11	-
3	4,310	644	29
4	9,929	425	34
5	988	218	82
Total	15,380	1,297	145

Table 3.3: Area planted by each crop for each soil grade; Current Conditions

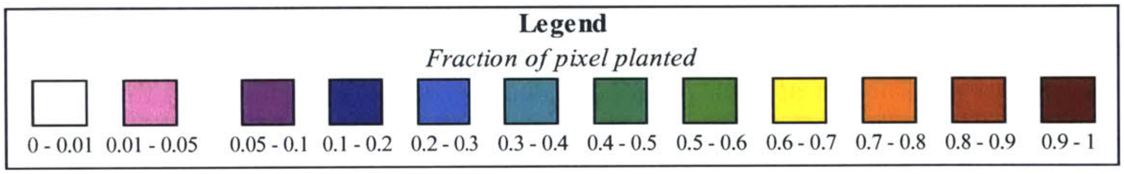


Figure 3.11: Fraction of pixel planted by each crop; Current Conditions

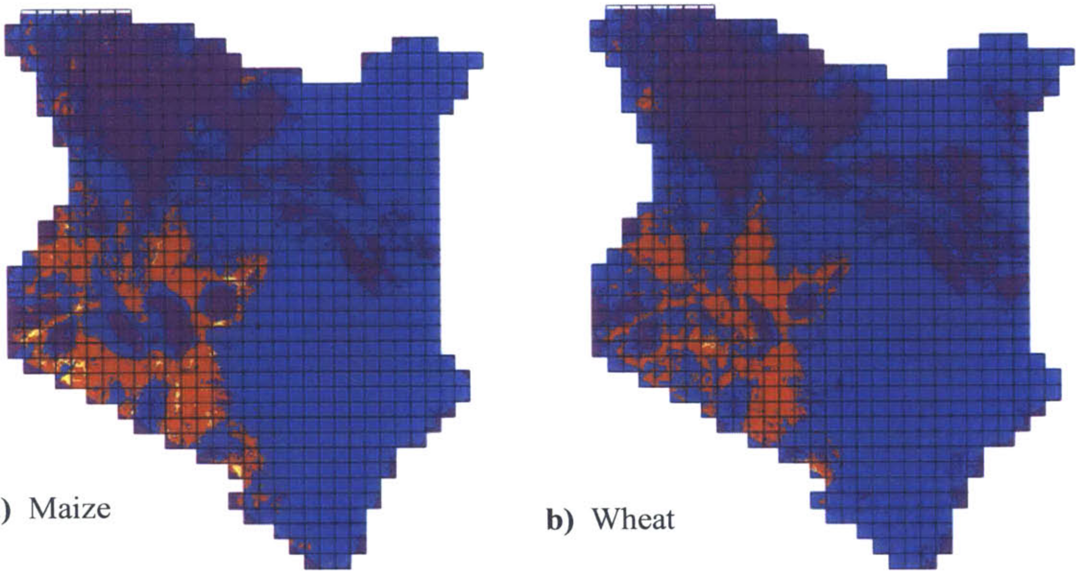
3.3.2 Land characterization by soil grade

Soil suitability was determined by considering three factors, using the method presented in Sys et. al (1993):

- Temperature: Temperature is important because it affects growth and development rate of crops. In addition, each crop has its own optimal temperature range under which it can perform photosynthesis most efficiently
- Land Slope: Land slope also needs to be considered because it affects the crop's ability to capture water. When the slope is too high rainfall does not get captured and it is less likely for irrigation to be efficient.
- Soil characteristics:
    - Physical characteristics: these include texture, calcium carbonate and gypsum contents, and "could affect the availability of the moisture, the oxygen and the foothold for rood development of the soil" (Wang 2015)
    - Fertility characteristics: these include apparent cations exchange capacity (CEC), soil acidity and organic carbon could determine the available nutrients necessary for the crop growths
    - Salinity and Alkalinity: these are important constraints to agricultural development.

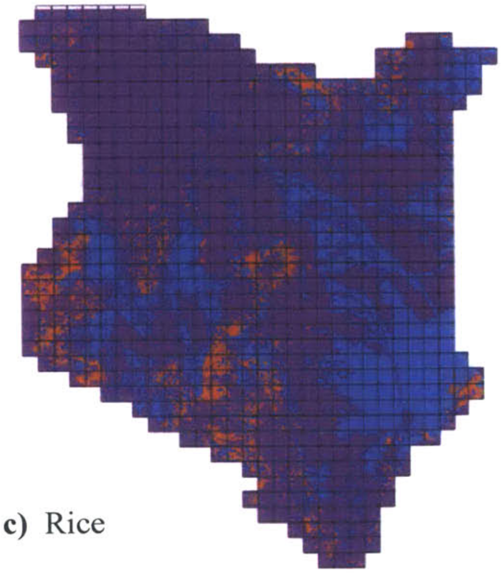
Each crop has different requirements for each of these factors. In addition, each crop has potentially 5 different grades. Grade 1 is the most suitable for planting, while grade 5 is the least suitable soil type the crops. A summary of the requirements for each crop for each grade is shown in Appendix A7.

These characteristics were used to determine the soil grade for each crop in Kenya. For a soil to suit a grade it need to at least meet every requirement in every category; this means that if a soil had one very good characteristic (in grade 1) but all the remaining of its characteristics were in the range of grade 3 soil, then it would be classified as a grade 3 soil. This analysis was conducted in a finer scale than above. The results are shown in the maps below. This information was converted to the fraction of each pixel occupied by each soil grade for all three crops, and was used in the second optimization.



a) Maize

b) Wheat



c) Rice

Soil grade	**Maize**	**Wheat**	**Rice**
	Area available (km^2)		
1	-	-	-
2	3,480	314	-
3	71,817	65,336	37,748
4	357,869	362,919	145,388
5	-	-	-
Total	433,165	428,569	183,136

Table 3.4: Area available for each crop by soil grade

Legend

Soil grade

🟩	🟨	🟥	🟦	🟪
1	2	3	4	5

Figure 3.12: Type of soil grade for each crop

This soil characterization is important because it affects the yield of the crops; more specifically, the better the land the higher the yield. The relationship between soil grade and yield is shown in the table below (Sys et. al 1993).

	Grade 1	Grade 2	Grade 3	Grade 4	Grade 5
Percent of Attainable Yield	95%	85%	60%	40%	0%

Table 3.5: Percent of attainable yield achieved by each soil grade

The effect of the soil grade on the yield is related the attainable yield of each crop. The attainable yield for each crop is shown in the table below (Mueller et. al 2012). Please note that his yield was determined specifically for Kenya, by taking into account land suitability and climatic conditions.

	Attainable Yield *ton/ha*
Maize	4.2
Wheat	4.46
Rice	6.52

Table 3.6: Attainable Yield per crop in Kenya

3.3.3 Excluded Areas

Even though soil grade characteristics determine which land is suitable for production, they do not fully describe the situation. Some lands are not available for production. For example, protected areas are, as the name suggests, protected and thus cannot be used for cultivation. In Kenya, these take the form of national parks and reserves used to protect the local vegetation and wildlife (data from GAEZ).

In addition, land currently being used to grow other crops was considered as inaccessible. Here we considered the areas currently occupied by tea, vegetables and sugarcane to be excluded from our optimization (data from GAEZ). This is a reasonable assumption since these crops are grown to be sold, either domestically or globally. These are high value crops which would not be easily replaced by staple foods by farmers.

	Area (km^2)	P(%) of total area
Tea	2,903	0.50%
Vegatables	1,371	0.23%
Sugarcane	478	0.08%
Protected Areas	40,339	6.90%
Total	45,091	7.72%

Table 3.7: Areas excluded from the optimization (other crops and protected areas)

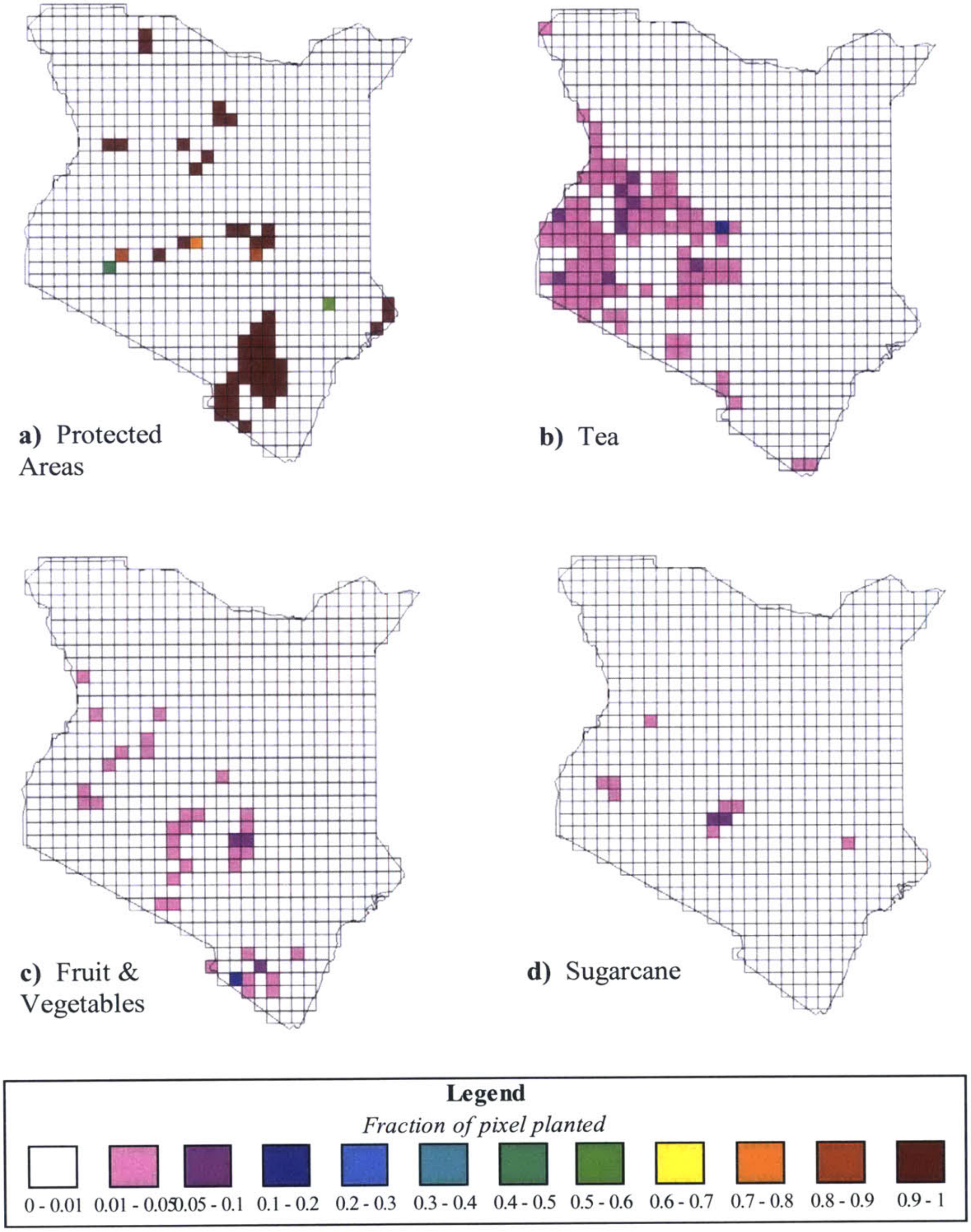


Figure 3.13: Fraction of excluded area by pixel for each category

3.4 Optimization 1 – Minimizing Least Squares

As briefly mentioned at the beginning of the chapter, the purpose of this optimization is to reproduce current conditions and in essence calibrate the model. This section explains in detail the optimization; a concise version of the equations can be found in Appendix A8, while the GAMS code used to run this optimization is in Appendix A9.

3.4.1 Decision Variables

The main decision variables of interest in this optimization were estimated precipitation (P_{est}) and non-crop evapotranspiration (ET_N). They are the main variables of interest because they are used as inputs for the second optimization. Another important decision variable is the estimated evapotranspiration (ET_{est}). The other two decision variables used in the optimization were change in storage (ΔS) and flow (Q). All variables related to water in this model are measured in volumetric terms [km^3 per month].

This optimization was run on a monthly basis (t) for every pixel (p). The three crops (c) considered were maize, wheat and rice.

3.4.2 Objective: Minimize Least Squares

The objective function for this optimization was a least squares minimization. The estimated precipitation and the estimated evapotranspiration should vary the least amount possible given the constraints imposed. Here least squares (LS) were minimized used a quadratic program – linear constraints, quadratic objective function. This is expressed mathematically in the equation below:

$$LS = \sum_t \sum_p \left(\frac{(P_{meas}(p,t) - P_{est}(p,t))^2}{(P_{meas}(p,t))^2} \right) + \sum_t \sum_p \left(\frac{(ET_{meas}(p,t) - ET_{est}(p,t))^2}{(ET_{meas}(p,t))^2} \right) \qquad \textbf{Eq. 3}$$

Note that here the terms are normalized by the measurement to ensure that every error contributes equally to the objective function. Furthermore, the resulting objective is a sum over all pixels and all months. Lastly, it should be noted that the measured data was recorded in millimeters, and was converted to a volume by multiplying it by the area of the pixel – this was calculated in GIS – and by applying the right unit conversions.

3.4.3 Water Balance Constraint

As explained in the water balance section, a mass balance constraint is used in this analysis: the amount of water in each pixel needs to balance every month. Here, the change in storage (ΔS) needs to be equal to the amount of precipitation coming in – note this is the estimated precipitation – minus the evapotranspiration from the pixel – note that this is the estimated evapotranspiration – plus the net flow to the pixel. The net flow is a product of the flow direction matrix (A) and the flow vector (Q); this way flow coming in to the pixel is added while the outflow is subtracted. This is shown in the following equation:

$$\Delta S(p,t) = P_{est}(p,t) - ET_{est}(p,t) + \mathbf{A}Q(p,t) \qquad \textbf{Eq. 4}$$

3.4.4 Crop and Non-crop ET Sum

This constraint says that the estimated evapotranspiration is the sum of the non-crop evapotranspiration and the crop evapotranspiration. Here, the crop evapotranspiration is the sum of the evapotranspiration for the three crops we are considering (which is further explained below). The non-crop evapotranspiration is a decision variable which takes up the slack between the known ET for the crops and the estimated ET. It is named non-crop because it mainly represents the evapotranspiration from the natural vegetation. However, in essence this variable also accounts for the other crops that are planted in the pixel.

$$ET_{est}(p,t) = ET_N(p,t) + \sum_c ET_{crop}(p,t,c) \qquad \textbf{Eq. 5}$$

3.4.5 Crop ET

Crop evapotranspiration, as explained in section 3.2.1.2 is a factor of the reference evapotranspiration (ET_0) and the crop factor (K). Therefore, in order to determine evapotranspiration for each crop in each pixel we need to multiply the reference ET with the crop coefficient, which varies depending on the development period of the crop. This gives us a nominal ET value for the specific crop in that month. Then we need to multiply by the area occupied by that crop in that pixel. We know the area of each pixel and the fraction currently cultivated by it. Thus to calculate the evapotranspiration by each crop in each pixel for every month we use the following equation:

$$ET(c,p,t) = K(c,t) \times ET\_0(p,t) \times \frac{Area(p)}{1000 \times 1000} \times \sum_{s} f(p,s,c,t) \qquad \text{Eq. 6}$$

3.4.6 Limit for Non-crop ET

Non-crop evapotranspiration has an upper bound set by the estimated precipitation. We impose this constraint in order to set a moisture limitation to the non-crop evapotranspiration (McLaughlin and Hoisungwan 2015).

$$ET_N(p,t) \leq P_{est}(p,t)$$

3.4.7 Change in Storage Limit

The change is storage is limited by the amount of annual precipitation. Specifically, the lower bound is set at -15% of the actual precipitation, while the upper bound is set at 15% of annual precipitation. This is the case in order to simulate a real aquifer that cannot be recharged or pumped at very fast rates.

$$-0.15 \sum_{t} P_{meas}(p,t) \leq \Delta S \leq 0.15 \sum_{t} P_{meas}(p,t) \qquad \text{Eq. 7}$$

3.4.8 Cyclical Storage

The cyclical storage constraint is used in order to simulate sustainable groundwater extraction. If the change in storage over a year is zero, then the aquifer is not depleted and thus this amount of use could continue into the future, without harming groundwater resources.

$$\sum_{t} \Delta S(p,t) = 0 \qquad \text{Eq. 8}$$

3.5 Optimization 2 – Maximizing Calories Produced

The second optimization was used to determine the optimal land and water allocation in order to maximize the calories produced from maize, wheat and rice in Kenya. This section explains in detail the optimization; the concise version of the equations can be found in Appendix A9, while the GAMS code used to run this optimization is found in Appendix A10.

3.5.1 Decision Variables

As with optimization 1, this optimization was conducted on a monthly time step (t) for each pixel (p) for all three crops considered (c). The added set that was considered in this optimization was the soil grade (s) in each pixel for every crop. In our optimization only soil grades 1, 2 and 3 were considered. Soil grade 5 was not considered because its yield is zero. Even though soil grade 4 has a positive yield it was not used in the optimization because it has a below average year. Allowing cultivation in grade 4 soil is considered as a sensitivity analysis (Scenario 1).

The main decision variable of interest for this optimization is the fraction of each pixel planted by each crop for each soil grade (f(p,s,c,t)). Similarly to optimization 1, change in storage (ΔS) and flow (Q) are decision variables. The last decision variable used is the non-crop fraction in each pixel (f_N) which is used to take up the slack for the area not planted. As with the first case, all water values are measured in terms of volume [km3 per month], while Area is in km2.

3.5.2 Objective: Maximize Calories Produced

The objective function for this optimization is shown in the equation below. The total calories are the calories produced from all three crops (T_Cal). Each crop has a caloric value (Crop_cal [kcal/ton]). Furthermore, each crop has an attainable yield appropriate for Kenya's climate (Y_max in [ton/km^2]). In addition, each soil grade can achieve a different percentage of the attainable yield (Y_per). Lastly, the total area planted by each crop is considered as the product between the fraction planted by each crop and the area of the pixel. Note that the fraction used to determine calories is the fraction for the month of July. July was used as the token month because all three crops are in their growing season in July (this was done for simplicity of equations).

$$T\_Cal = \sum_p \sum_s \sum_c Crop\_cal(c) \times Y\_\max(c) \times Y\_per(s,c) \times f(p,s,c,'7') \times Area(p) \qquad \text{Eq. 9}$$

3.5.3 Water Balance Constraint

The water balance constraint used here is similar to the one used in optimization 1. The main difference is that instead of using the estimated evapotranspiration, crop and non-crop evapotranspiration appear in the equation. How these were calculated is explained in the sections that follow.

$$\Delta S(p,t) = P_{est}(p,t) + \mathbf{A}Q(p,t) - \sum_{c} ET(c,p,t) - ET_N(p,t) \qquad \textbf{Eq. 10}$$

3.5.3.1 Crop Evapotranspiration

This is the crop evapotranspiration to be used in the water balance constraint is. This is explained in optimization 1.

$$\boldsymbol{ET(c,p,t) = K(c,t) \times ET\_0(p,t) \times \frac{Area(p)}{1000 \times 1000} \times \sum_{s} f(p,s,c,t)} \qquad \textbf{Eq. 4}$$

3.5.3.2 Non-crop Evapotranspiration

This equation defines the value for ET_N. Optimization 1 provides the input for this equation: ET_N(opt1) is the value of non-crop evapotranspiration estimated from the model. This is then used to calculate a reference non-crop evapotranspiration for each pixel (e_non). ET_N from optimization 1 is divided by the non-crop area of optimization 1 to yield a length of observed non-crop ET (e_non in [mm per month]).

$$e\_non(p,t) = \frac{ET_N^{Optimization1}(p,t)}{Area(p) \times f\_N^{Optimization1}(p)} \qquad \textbf{Eq. 11}$$

This value is then multiplied by the non-crop area in optimization 2 to get the volume of water evaporated from local vegetation and other crops.

$$ET_N(p,t) = e\_non(p,t) \times \frac{Area(p)}{1000 \times 1000} \times f\_N(p,t) \qquad \textbf{Eq. 12}$$

3.5.4 Change in Storage Limit

This change in storage limit is the same with the optimization 1.

3.5.5 Cyclical Storage

Again, similarly to optimization 1, we use a cyclical storage constraint to impose groundwater sustainability.

3.5.6 Optimal Land Constraint for each soil grade

This constraint sets the upper bound for the fraction of each pixel that can be planted by each crop for all soil grades (f_max). As explained in section 3.3 each crop has different criteria for soil grade. This constraint ensures that crops are only planted in locations where there is area suitable for the specific crop. The resulting fraction is then related to the appropriate yield for every soil grade.

$$f(p,s,c,t) \leq f\_\max(p,s,c) \qquad \textbf{Eq. 13}$$

3.5.7 Land Balance Constraint

This constraint is used to ensure that for every month every pixel is fully occupied by either crop or non-crop area. This is particularly important in order to ensure that when not in season, the crop area acts as a non-crop area. Even though this is not completely correct – fallow land has a different evapotranspiration from native vegetation – it is an approximation, as crop ET is much higher than non-crop ET.

$$f\_N(p,t) + \sum_{c}\sum_{s}(p,s,c,t) = 1 \qquad \textbf{Eq. 14}$$

3.5.8 Non-crop Land Constraint

The non-crop land constraint gives a minimum value (f_N_min) for the non-crop fraction. This was done to account for the areas excluded from the optimization as described in section 3.3.3, and the equation is shown below:

$$f\_N(p,t) \geq f\_N\_\min(p) \qquad \textbf{Eq. 15}$$

The minimum value for the minimum non-crop fraction was calculated by adding all the excluded fractions per pixel (tea, sugarcane, vegetables and protected areas). There are two things to note here about this approach: firstly, this value was corrected for inconsistencies. In some cases, the sum of the excluded area fractions and the currently planted fractions (maize, wheat and rice) exceeded one. In this case, the excluded area fraction was reduced by the appropriate amount so that the sum equaled one. Here, priority was given to the cultivated areas rather than the excluded areas, even though in reality that may not be the case. The second thing to note is that the excluded areas are not classified by soil grade. Therefore, even though this constraint sets a lower limit on the non-crop fraction, and implicitly an upper limit for the crop area available, it does not do so in a way that assures that the crops planted in that area are not planted in the areas that have been excluded according to the soil classification. Yet, this is a good approximation, that at the least ensures that no planting is planned for areas that are protected and thus completely out of bounds.

3.5.8 Land Constraints to avoid overlap

In some cases the suitable soil for two crops overlapped. These constraints were introduced in order to limit the overlap in planting between two or three crops for every pixel. To do this, the fraction of overlap fraction for every possible combination (all 4) of the three crops in question was calculated (f_overlap_crop1&crop2). These constraints essential says that the total amount of land planted in each pixel by two crops is less than or equal to the sum of the total land allowed for the two crops minus their overlap. Even though this does not cover the details of soil grade overlap, it does ensure that in total, in each pixel there is no land that is being planted by two crops when not suitable.

a. Maize & Rice

$$\sum_{s} f(p,s,'Maize',t) + \sum_{s} f(p,s,'Rice',t) \leq$$

$$\sum_{s} f\_\max(p,s,'Maize') + \sum_{s} f\_\max(p,s,'Rice') - f\_overlap\_MR$$

b. Maize & Wheat

$$\sum_{s} f(p,s,'Maize',t) + \sum_{s} f(p,s,'Wheat',t) \leq$$

$$\sum_{s} f\_\max(p,s,'Maize') + \sum_{s} f\_\max(p,s,'Wheat') - f\_overlap\_MW$$

c. Wheat & Rice

$$\sum_{s} f(p,s,'Wheat',t) + \sum_{s} f(p,s,'Rice',t) \leq$$

$$\sum_{s} f\_\max(p,s,'Wheat') + \sum_{s} f\_\max(p,s,'Rice') - f\_overlap\_WR$$

d. Maize, Wheat & Rice

$$\sum_{s} f(p,s,'Maize',t) + \sum_{s} f(p,s,'Wheat',t) + \sum_{s} f(p,s,'Rice',t) \leq$$

$$\sum_{s} f\_\max(p,s,'Maize') + \sum_{s} f\_\max(p,s,'Wheat') + \sum_{s} f\_\max(p,s,'Rice')$$

$$- f\_overlap\_MWR$$

3.5.11 Change in planted land fraction over the year

Each crop is planted for a specific period of time during the year. Therefore, if a fraction of land is planted by a crop it does not mean that it is planted for the whole year, rather it is just for the growing season. This implies that during the remainder of the year that land will have to be fallow. This was taken into account in order to make sure that outside the growing season, the fallow land has the evaporation of the non-crop land, rather than the evaporation of the crop. Even though this is not absolutely correct – fallow land does not have the same ET as natural vegetation – it does account for the fact that the ET for this land is lower than that of the crop. The equations below are used for that purpose for all three crops (note that the equations are different for every crop because each crop has a different growing period).

a. Maize

i. Fallow in January, February, March, October, November, December

$$f(p,s,'Maize','1') = 0 \qquad f(p,s,'Maize','2') = 0$$

$$f(p,s,'Maize','3') = 0 \qquad f(p,s,'Maize','10') = 0$$

$$f(p,s,'Maize','11') = 0 \qquad f(p,s,'Maize','10') = 0$$

ii. Planted in April through (including) September.

$$f(p,s,'Maize','4') = f(p,s,'Maize','5')$$

$$f(p,s,'Maize','5') = f(p,s,'Maize','6')$$

$$f(p,s,'Maize','6') = f(p,s,'Maize','7')$$

$$f(p,s,'Maize','7') = f(p,s,'Maize','8')$$

$$f(p,s,'Maize','8') = f(p,s,'Maize','9')$$

b. Wheat

i. Fallow in January through (including) June, and December

$$f(p,s,'\mathit{Wheat}','1')=0 \qquad f(p,s,'\mathit{Wheat}','2')=0$$
$$f(p,s,'\mathit{Wheat}','3')=0 \qquad f(p,s,'\mathit{Wheat}','4')=0$$
$$f(p,s,'\mathit{Wheat}','5')=0 \qquad f(p,s,'\mathit{Wheat}','6')=0$$
$$f(p,s,'\mathit{Wheat}','12')=0$$

ii. Planted in July through (including) November.

$$f(p,s,'\mathit{Wheat}','7')=f(p,s,'\mathit{Wheat}','8')$$
$$f(p,s,'\mathit{Wheat}','8')=f(p,s,'\mathit{Wheat}','9')$$
$$f(p,s,'\mathit{Wheat}','9')=f(p,s,'\mathit{Wheat}','10')$$
$$f(p,s,'\mathit{Wheat}','10')=f(p,s,'\mathit{Wheat}','11')$$

c. Rice

i. Fallow in January through (including) April, November and December

$$f(p,s,'\mathit{Rice}','1')=0 \qquad f(p,s,'\mathit{Rice}','2')=0$$
$$f(p,s,'\mathit{Rice}','3')=0 \qquad f(p,s,'\mathit{Rice}','4')=0$$
$$f(p,s,'\mathit{Rice}','3')=0 \qquad f(p,s,'\mathit{Rice}','12')=0$$

ii. Planted in May through (including) October.

$$f(p,s,'\mathit{Rice}','5')=f(p,s,'\mathit{Rice}','6')$$
$$f(p,s,'\mathit{Rice}','6')=f(p,s,'\mathit{Rice}','7')$$
$$f(p,s,'\mathit{Rice}','7')=f(p,s,'\mathit{Rice}','8')$$
$$f(p,s,'\mathit{Rice}','8')=f(p,s,'\mathit{Rice}','9')$$
$$f(p,s,'\mathit{Rice}','9')=f(p,s,'\mathit{Rice}','10')$$

3.6 Scenarios considered

For this analysis four different scenarios were considered. The first scenario was the base case. The other three scenarios were variations of the base case. For each of these three scenarios one parameter of the parameters of the base case scenario was changed; the remaining remained the same. This was done by either changing the inputs or changing/adding a constraint.

3.6.1 Base Case Scenario

The base case scenario is the nominal case considered. Here the average measured precipitation and actual evapotranspiration were used as inputs to the first optimization. The results of this optimization were then used in the second optimization. In the second optimization, planting was only allowed to happen in soil grades 1 through 3. The river flow was not constrained.

3.6.2 Scenario 1: Soil Grades 1-4

For this scenario the first optimization remains the same. Therefore, the inputs for the second optimization are the same as the in the base case. In the second optimization, planting was allowed to happen in soil grades 1 through 4. Therefore, we have added more land available for production. The purpose of this scenario is to explore, firstly, the distribution of land as more area is allowed to be planted, and secondly, the effects this has on the water balance. The river flow was not constrained.

3.6.3 Scenario 2: Low Precipitation

For this scenario a low precipitation was used. The standard deviation for each location was calculated on a monthly basis. An average annual standard deviation (as a percentage of the average value) map is shown in Appendix A.3. This map shows that the relative standard deviation varies with location: it is higher in areas with higher precipitation. This suggests that a uniform decrease in precipitation would not accurately represent the situation.

The first iteration for low precipitation that was attempted was to subtract one standard deviation from the low precipitation. This resulted in more than 10% negative precipitation values, and thus was not appropriate. The low precipitation that was used was the following: the original precipitation minus 20% of the standard deviation. This resulted in only 4% of values (note that these were marginally lower than zero). The negative values were then replaced by 0. A new precipitation map was generated and is shown in the figure that follows.

The resulting precipitation is on average 16% lower than the base case scenario. In addition, it is clear that the dry areas have been expanded. As a result, the high precipitation areas have become smaller. That said, the highest precipitation in the country is maintained, primarily on Mount Kenya and by Lake Victoria.

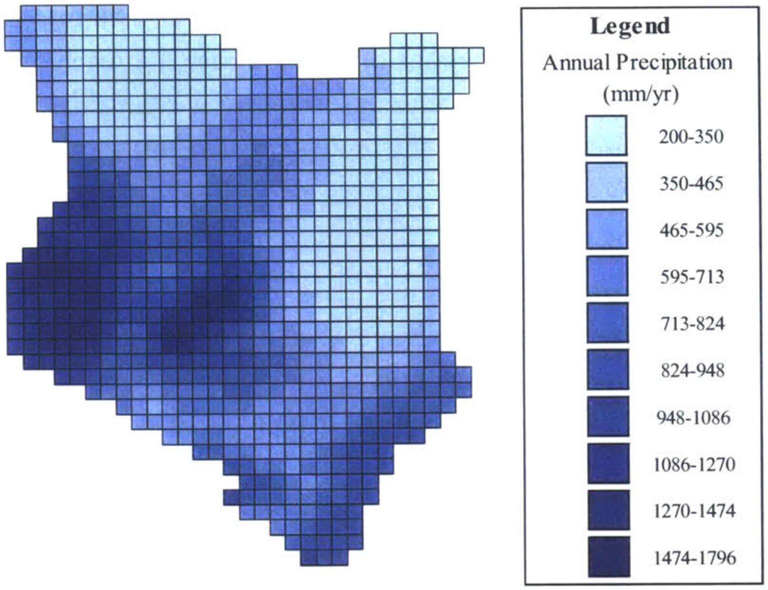


Figure 3.14: Annual precipitation map for Scenario 2 (Low precipitation)

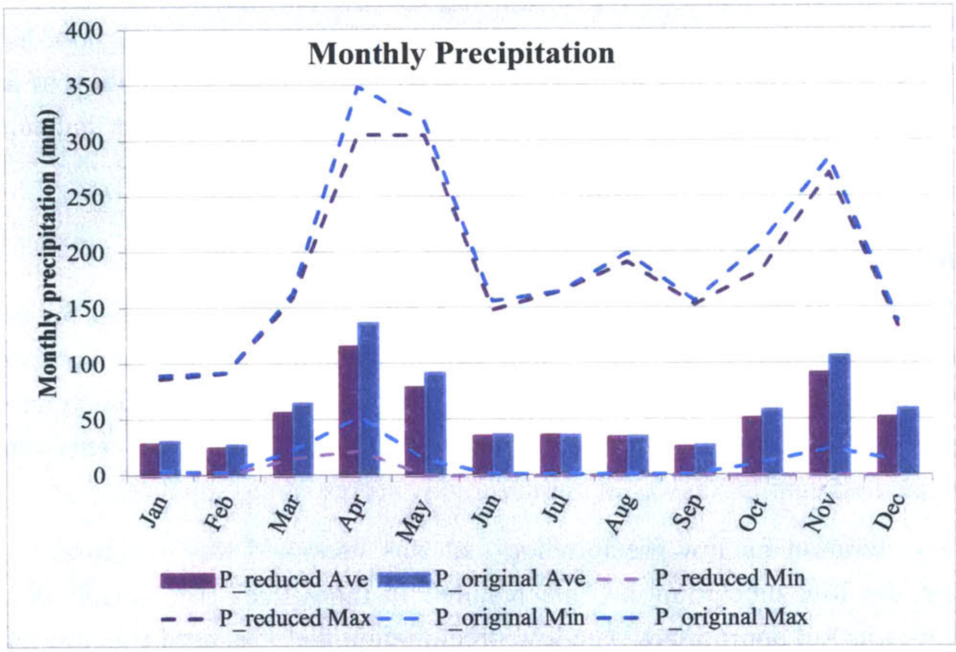


Figure 3.15: Monthly precipitation for Scenario 2

For this scenario, the first optimization was run with the new precipitation values. The new estimated precipitation and non-crop evapotranspiration were then used in the second optimization. The soil grades assumed to be available for cultivation in this scenario were 1 through 3. River flow was not constrained.

3.6.4 Scenario 3: Maintaining River Flows

Unfortunately, river flow data is not publicly available for the whole country. Therefore, we could not run an optimization where the observed river flow is maintained. Even though some data was available for river flow data it was not from a primary source and was only for selected rivers. This means that these values could not be accurately used in our least squares objective function as they might skew the estimated values for other parameters. Thus, the first optimization remains the same as the base case. That said, the data that was found for selected rivers is shown below (Appendix A5 shows the sources of the data, and the processing that used to retrieve this information). This is done so that at least a comparison can be made with some data.

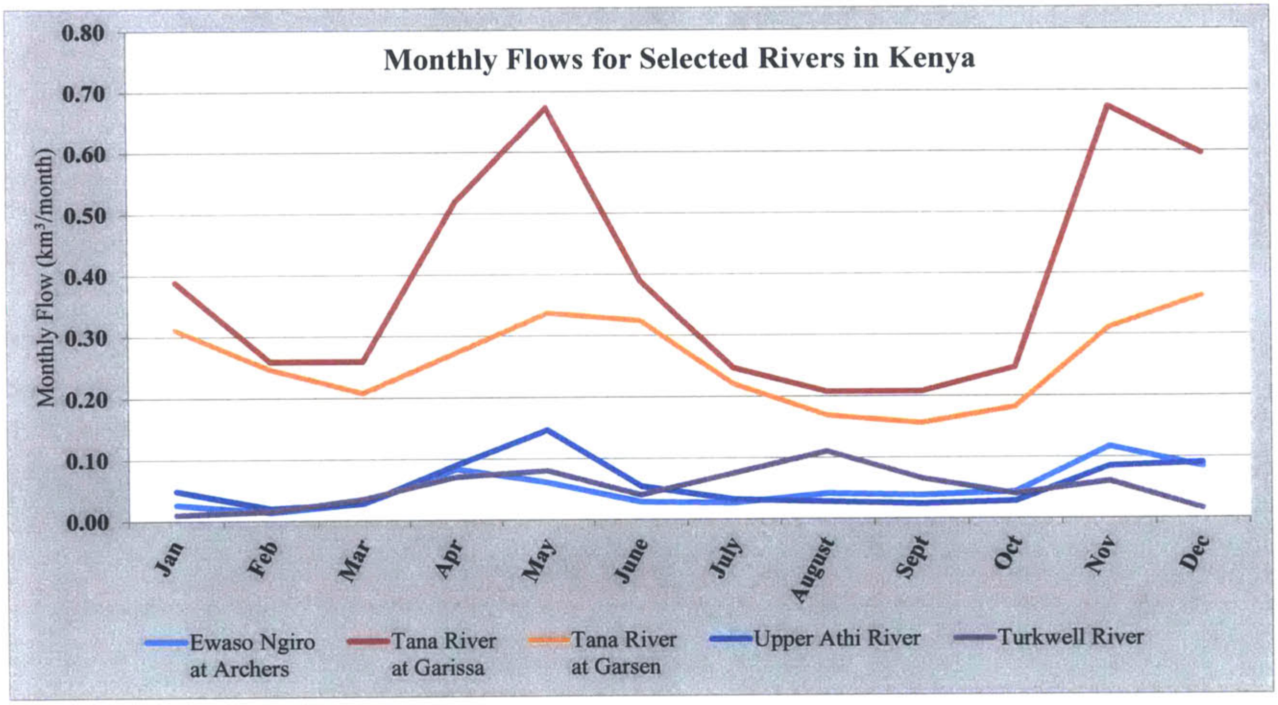


Figure 3.16: Monthly Flows for Selected Rivers in Kenya

The second optimization was then modified to restrict river flow. Specifically, the flow as estimated in the first optimization was considered to be the nominal flow. Then, the flow out (Q) of each pixel was restricted by a lower bound set at 75% of the nominal flow (Q_nom). Thus, the following constraint was added to the optimization:

$$Q(p,t) > 0.75 \times Q\_nom(p,t) \qquad \textbf{Eq. 16}$$

The remaining features of the second optimization remain the same: the land available for cultivation is of grade 1 through 3.

Chapter 4 – Results

4.1 Results: Base Case

4.1.1 Results for Base Case: Optimization 1

The objective function for the first optimization was meant to minimize the sum of the squared differences between measured and estimated values for precipitation and actual evapotranspiration. The sum of least squares for this optimization is shown below:

Sum of Least Squares	365

4.1.1.1 Precipitation and Actual Evapotranspiration

In order to evaluate the results from this optimization a percent change was calculated:

$$Percent\ Change = \frac{Estimated - Measured}{Measured}$$

The result were visualized in a histogram shown below. The total number of values for each variable was 9108 (759 cells, 12 months).

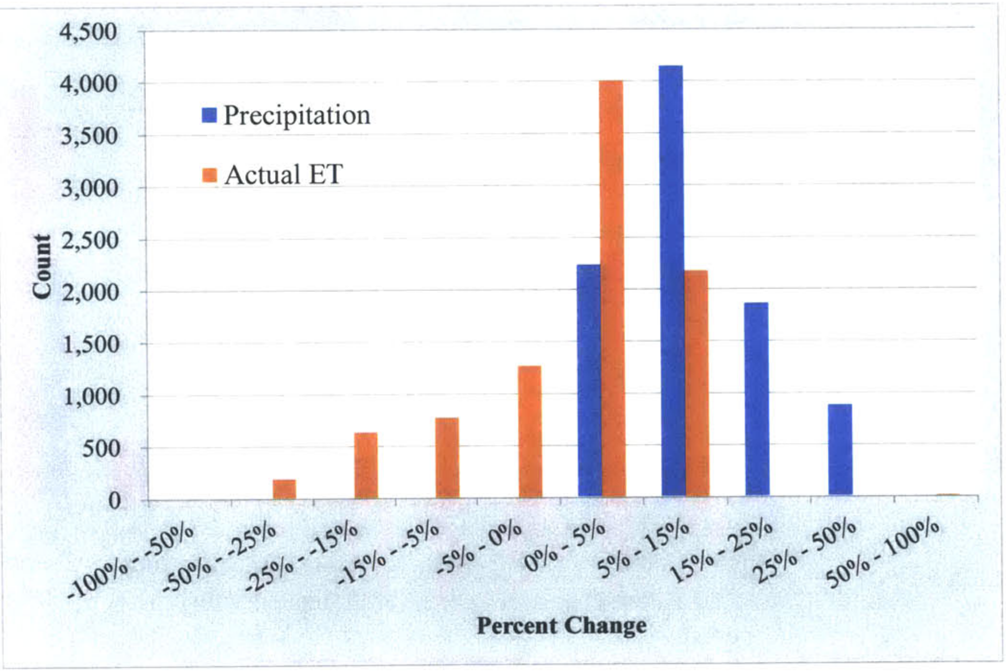


Figure 4.1: Percent Change for Precipitation and Evapotranspiration; Base Case

4.1.1.2 Crop Evapotranspiration

The crop is considered known for this optimization. The total fraction per pixel occupied by maize, wheat and rice are known and can be used to calculate the total area per crop. The crop requirement is calculated using Equation 1. The crop ET per pixel is the total ET in each pixel for each crop in mm/year. The total crop ET is the total volume of water consumed by each crop across the country. The results are summarized in the table below.

	Area	**Crop requirement**	**Crop ET per pixel**			**Total Crop ET**
			Average	*Min*	*Max*	
	km^2	*mm/year*	*mm/yr*			*km^3*
Maize	15,380	815.12	19.85	0	234.57	11.58
Wheat	1,297	643.22	1.16	0	62.24	0.68
Rice	145	987.25	0.24	0	22.46	0.14

Table 4.1: Crop Evaporation Summary; Base Case – Optimization 1

4.1.1.3 Other water fluxes

Non-crop evapotranspiration was used to take up the slack between the estimated evapotranspiration and the total crop evaporation. This was bounded by precipitation. The graph below shows what percentage of the estimated value for precipitation and actual evapotranspiration the non-crop evapotranspiration was, as estimated by the first optimization.

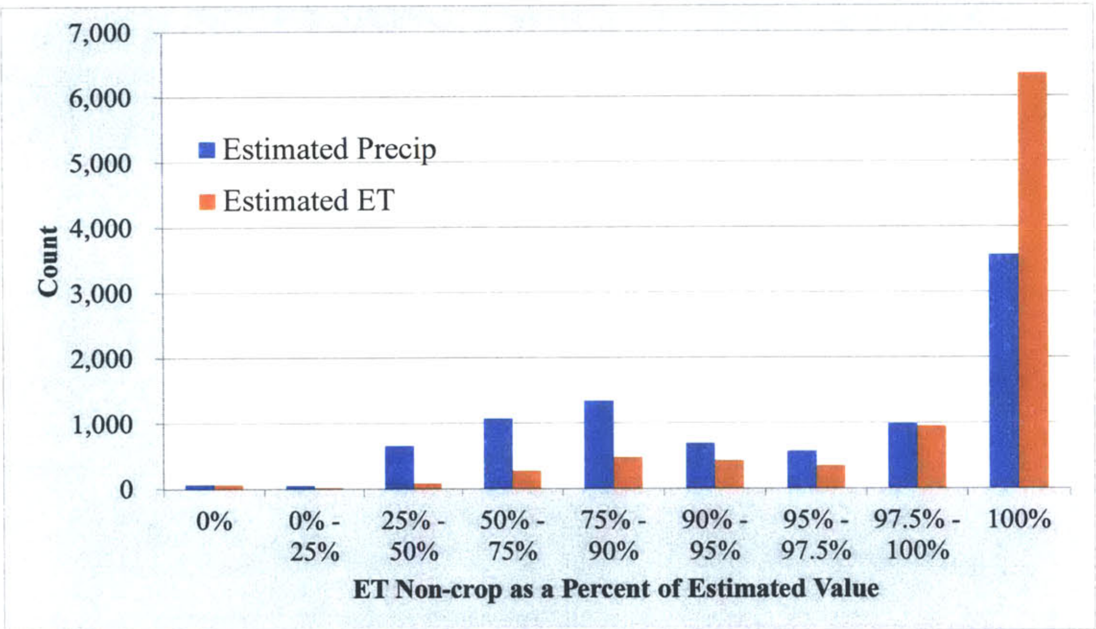


Figure 4.2: Non-ET as a percentage of estimated precipitation and ET; Base Case – Optimization 1

Non-crop evapotranspiration varies on a monthly basis. The minimum, maximum and average values of non-crop ET are shown in the table below. The same is done for the pixel outflow and change in storage

	Non-crop Evapotranspiration											
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
	mm/month											
Min	4.06	3.80	22.68	50.29	16.04	0.00	0.00	0.00	0.00	11.08	23.98	12.18
Max	83.27	80.67	128.85	131.99	133.14	121.62	96.96	82.95	88.31	97.84	120.17	113.52
Average	33.28	27.94	58.31	89.40	60.02	30.48	28.86	24.92	23.79	47.53	70.76	55.35

Table 4.2: Monthly non-crop evapotranspiration; Base Case – Optimization 1

	Pixel Outflow											
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
	km^3/month											
Min	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Max	16.97	5.62	0.72	0.98	1.35	1.62	0.47	2.36	1.33	4.44	3.75	5.55
Average	0.75	0.13	0.03	0.04	0.04	0.04	0.02	0.03	0.03	0.08	0.10	0.29

Table 4.3: Monthly pixel outflow; Base Case – Optimization 1

	Change in Storage											
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
	km^3/month											
Min	-0.21	-0.21	-0.18	-0.15	-0.17	-0.19	-0.13	-0.20	-0.20	-0.18	-0.20	-0.19
Max	0.17	0.17	0.17	0.21	0.20	0.16	0.18	0.16	0.18	0.13	0.18	0.14
Average	-0.04	-0.01	0.00	0.03	0.02	0.00	0.00	0.00	0.00	0.00	0.01	-0.01

Table 4.4: Monthly change in storage; Base Case – Optimization 1

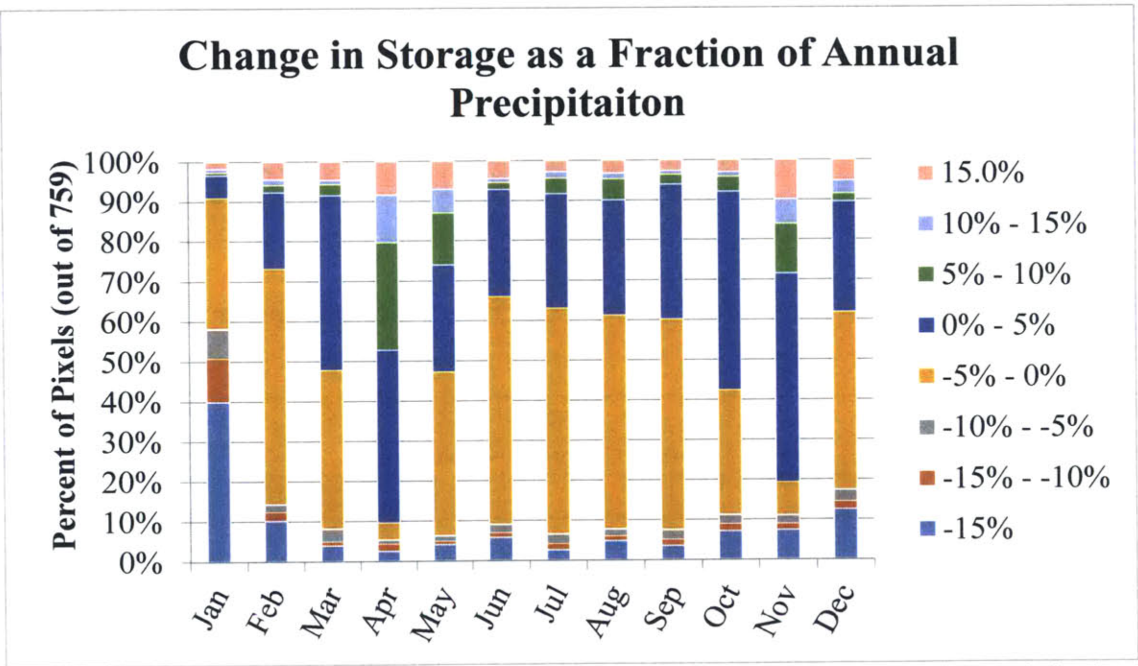
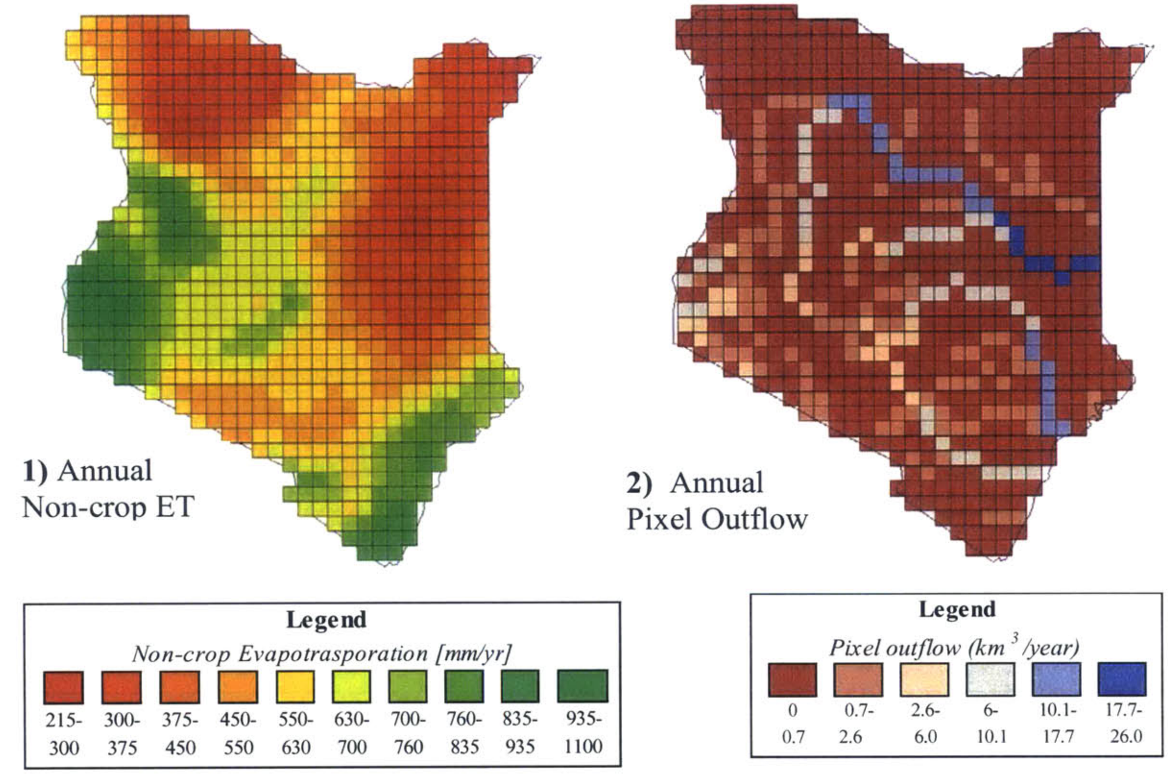


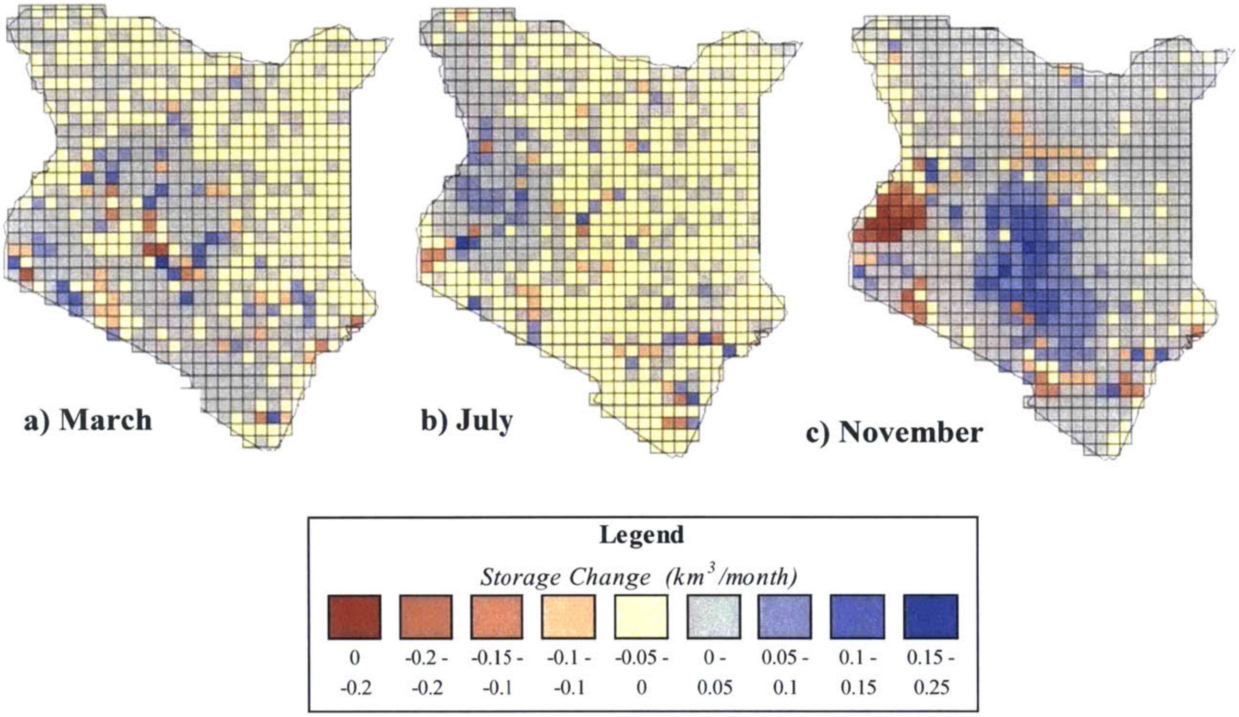
Figure 4.3: Monthly change in Storage as a Fraction of Annual Precipitation; Base Case – Optimization 1



1) Annual Non-crop ET

2) Annual Pixel Outflow

3) Monthly Change in Storage (Selected Months)



a) March

b) July

c) November

Figure 4.4: Maps for other water fluxes; Base Case – Optimization 1

4.1.1.4 Summary of the Results from Optimization 1

All the fluxes included in optimization 1 are summarized in the graph below for each month. The values displayed are the averages over the whole country. Note that here, net flow is shown rather than pixel outflow. Net flow is defined as the sum of the water inflows less the water outflows (the Q's associated with runoff). When then net flow is positive, the pixel has an outflow greater than the total inflows.

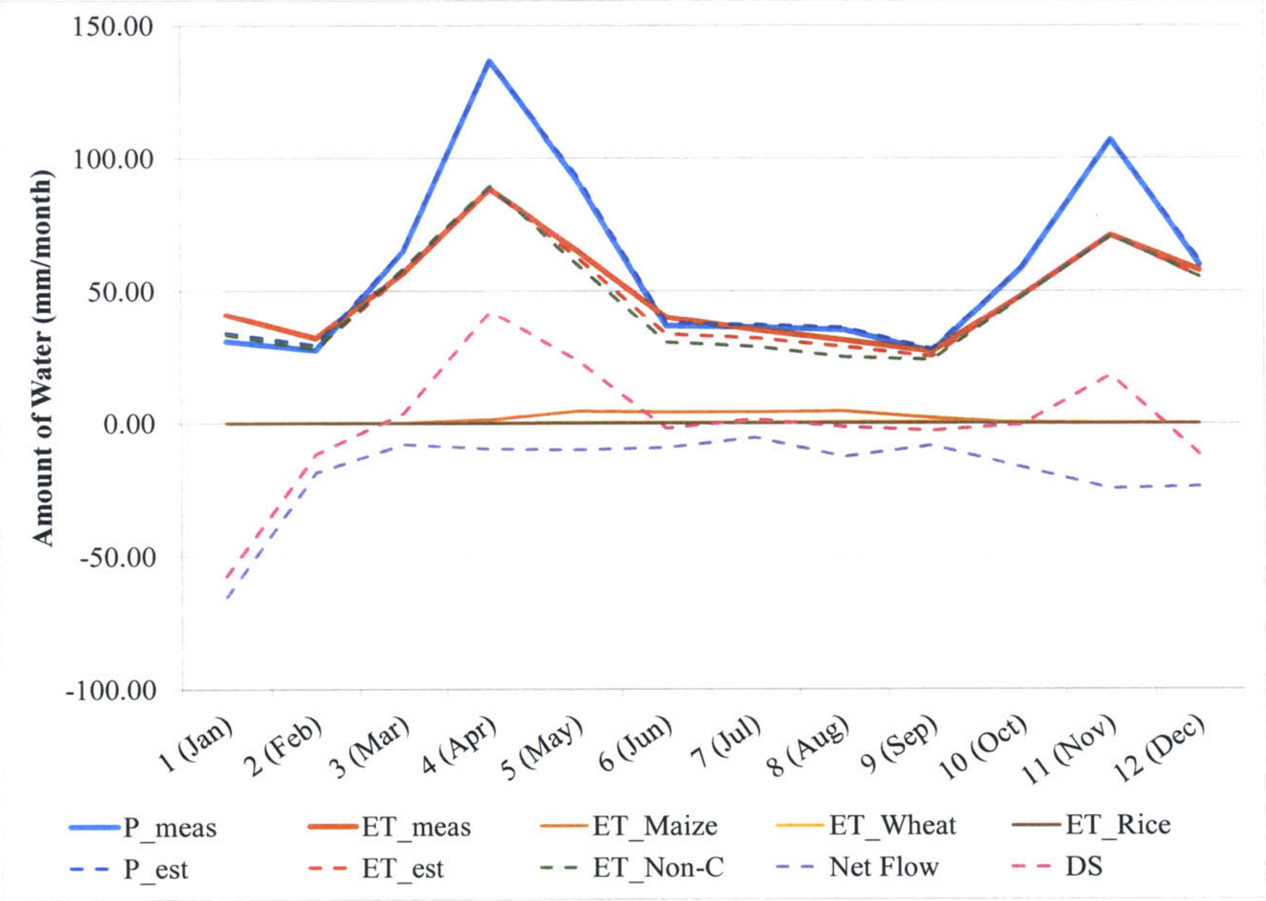


Figure 4.5: Summary of Results; Base Case – Optimization 1

4.1.2 Results for Base Case: Optimization 2

The results from optimization 1 were used as inputs to optimization 2 to determine what the optimal allocation of land and water is in order to maximize the calories produced from maize wheat and rice. The results are summarized in this section.

4.1.2.1 Calories Produced

The purpose of this optimization was to determine the increase in calories from optimizing the allocation of water and land. The optimized calories, as well as the calories produced are shown here. The change (Optimized/Now) is also shown.

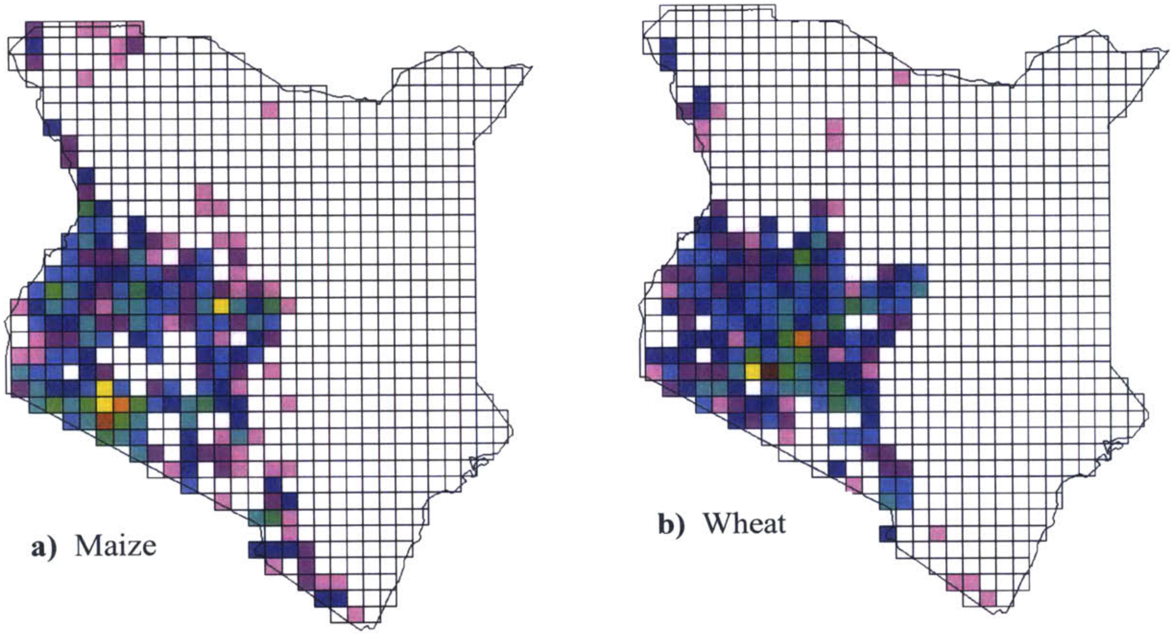
	Now *kcal/yr*	Optimized *10^9 kcal/yr*	Change *factor*
Maize	10,253	27,691	2.70
Wheat	830	22,705	27.36
Rice	74	38,156	518.19
TOTAL	**11,156**	**88,552**	**7.94**

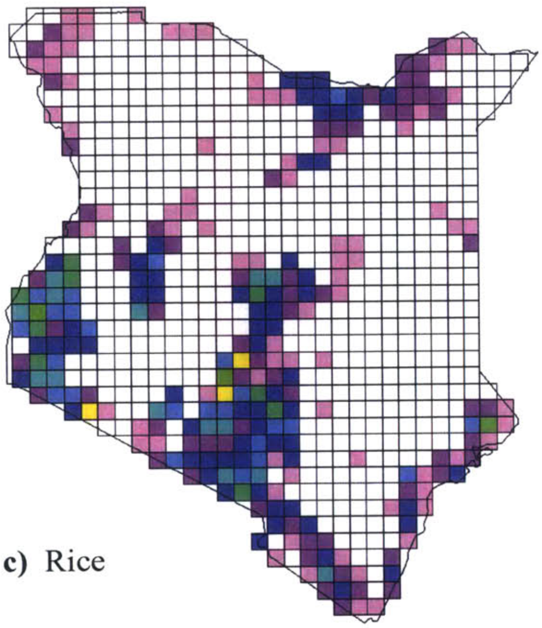
	Grade 1	Grade 2	Grade 3	Grade 4	Grade 5	Total
			10^9 kcal			
Maize	-	4,423.4	23,267.1	-	-	27,690.5
Wheat	-	392.1	22,313.0	-	-	22,705.1
Rice	-	-	38,156.2	-	-	38,156.2

Table 4.5: Calories produced: Now and Optimized Conditions per soil grade; Base Case

4.1.2.2 Area per Crop

The variable of most interest in this optimization was the fraction of area cultivated by each crop. Here, the results from each crop are presented separately. For each crop the current area (2000) cultivated is shown. In addition, the optimized area – the results from the optimization – is shown. Lastly, the maximum allowed area is shown; this is the area as determined by the viability of the soil. For each crop the results are broken down by soil grade. There are 5 soil grades. For the current conditions, all 5 grades are available. For the optimization, crops were only allowed to be planted in grades 1 through 3. For the maximum allowed, only grades 1 through 4 are shown; grade 5 has a zero yield. The area allocated to grade 5 is Kenya's total area (584,376.92 km^2) minus the total maximum area shown in the tables.





Soil grade	**Maize**	**Wheat**	**Rice**
	Area planted (km^2)		
1	-	-	-
2	3,449	314	-
3	26,192	26,133	28,089
4	-	-	-
5	-	-	-
Total	29,640	26,447	28,089

Table 4.6: Area planted by each crop for each soil grade; Base Case

Legend

Fraction of pixel planted

⬜	🟪	🟪	🟦	🟦	🟦	🟩	🟩	🟨	🟧	🟫	🟫
0 - 0.01	0.01 - 0.05	0.05 - 0.1	0.1 - 0.2	0.2 - 0.3	0.3 - 0.4	0.4 - 0.5	0.5 - 0.6	0.6 - 0.7	0.7 - 0.8	0.8 - 0.9	0.9 - 1

Figure 4.6 Fraction of pixel planted by each crop; Base Case

4.1.2.3 Crop Evapotranpiration

	Area	**Crop requirement**	**Crop ET per pixel**			**Total Crop ET**
			Average	***Min***	***Max***	
	km^2	*mm/year*	*mm/yr*			*km^3*
Maize	29,640	815.12	38.13	-	622.63	22.27
Wheat	26,447	643.22	26.69	-	498.60	15.59
Rice	28,089	987.25	45.27	-	647.40	26.45

Table 4.7: Crop Evapotranspiration summary; Base Case – Optimization 2

4.1.2.4 Other Fluxes

The non-crop evapotranspiration in this optimization was determined by using the non-crop ET estimated from the first optimization. Here, the non-crop ET did not have an upper bound.

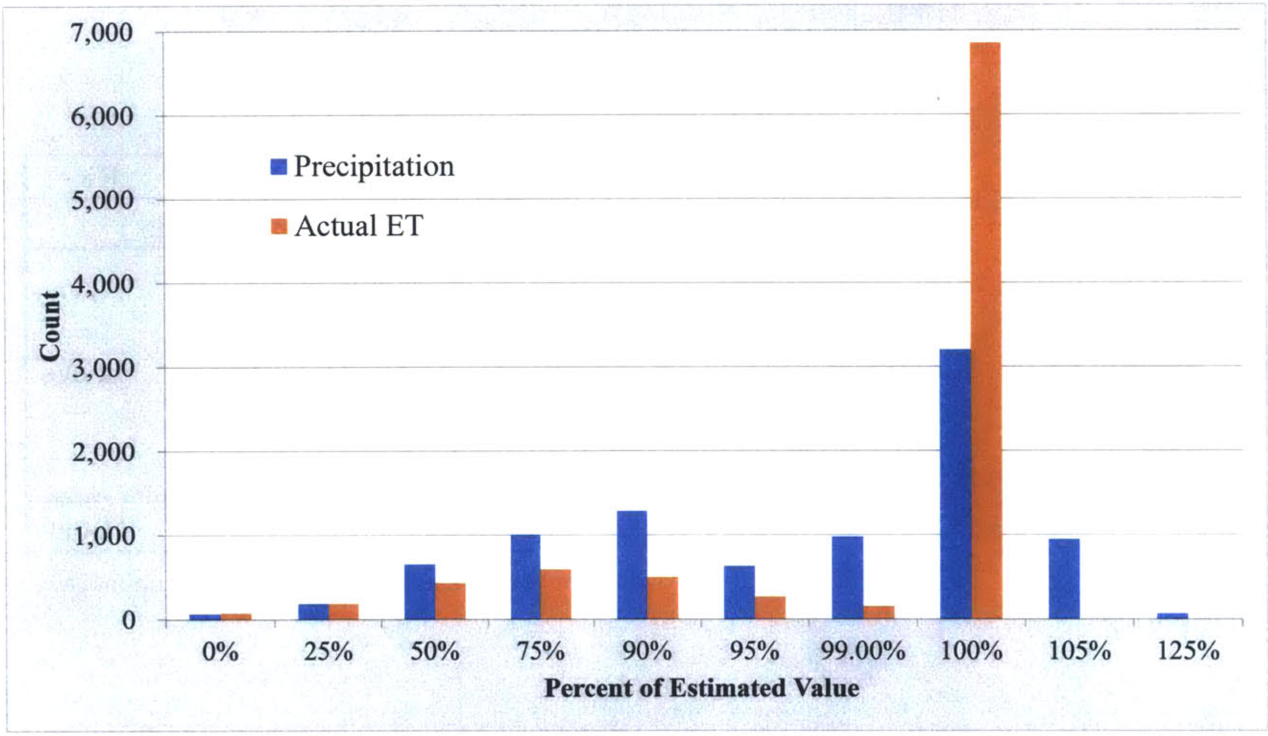


Figure 4.7: Non-crop ET as a percentage of estimated precipitation and ET; Base Case – Optimization 2

Since non-crop ET varies on a monthly time step, the minimum, maximum and average values per pixel across the country are shown in the table below.

	Non-crop Evapotranspiration											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
	mm/month											
Min	4.06	3.80	22.68	10.15	1.27	0.00	0.00	0.00	0.00	2.51	2.88	12.18
Max	83.27	80.67	128.85	131.99	128.72	115.94	91.93	78.28	75.77	88.73	120.17	113.52
Average	33.28	27.94	58.31	85.49	53.55	26.23	23.10	19.34	17.77	42.16	67.82	55.35

Table 4.8: Monthly estimated non-crop evapotranspiration; Base Case – Optimization 2

	Pixel Outflow											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
	km^3/month											
Min	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Max	2.04	2.99	1.55	4.42	5.01	3.10	0.35	0.26	0.30	0.52	8.46	0.66
Average	0.08	0.09	0.07	0.23	0.12	0.12	0.02	0.01	0.01	0.01	0.26	0.02

Table 4.9: Monthly pixel outflow estimated; Base Case – Optimization 2

	Storage Change											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
	km^3/month											
Min	-0.20	-0.20	-0.20	-0.21	-0.20	-0.18	-0.18	-0.19	-0.17	-0.18	-0.17	-0.13
Max	0.18	0.19	0.20	0.18	0.20	0.18	0.20	0.20	0.16	0.15	0.18	0.18
Average	-0.01	-0.01	0.00	0.01	0.01	-0.01	0.00	0.00	-0.01	0.00	0.01	0.00

Table 4.10: Monthly change in storage as estimated; Base Case – Optimization 2

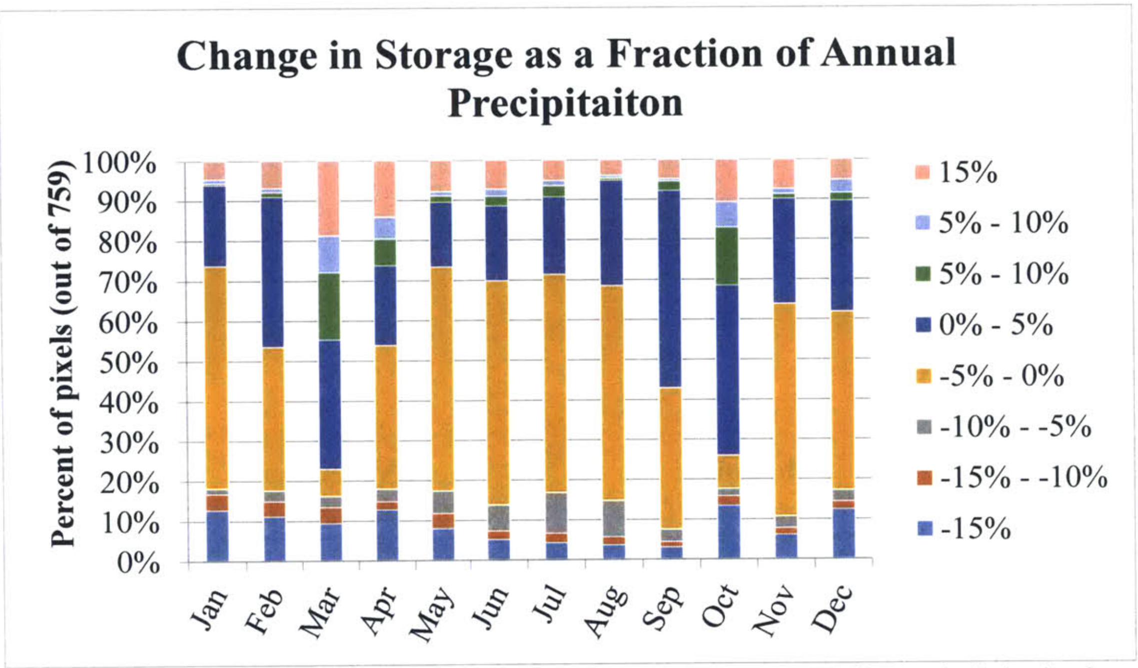
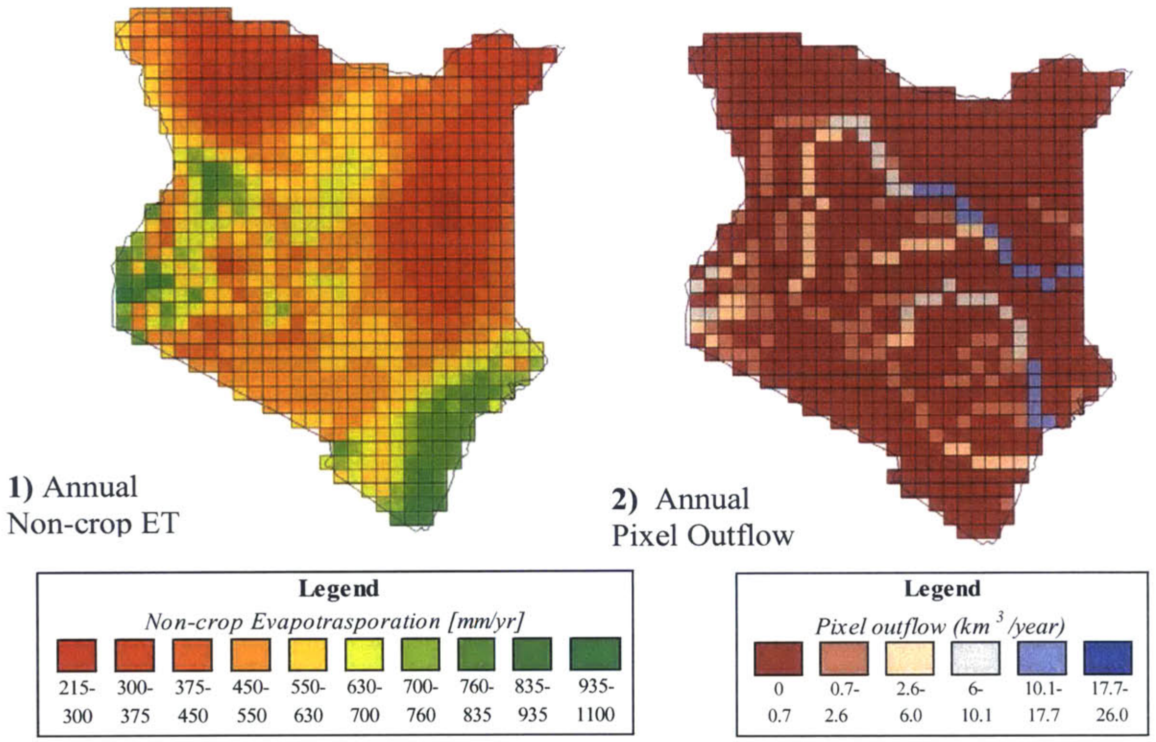


Figure 4.8: Change in Storage as a Fraction of Annual Precipitation; Base Case – Optimization 2



3) Monthly Change in Storage (Selected Months)

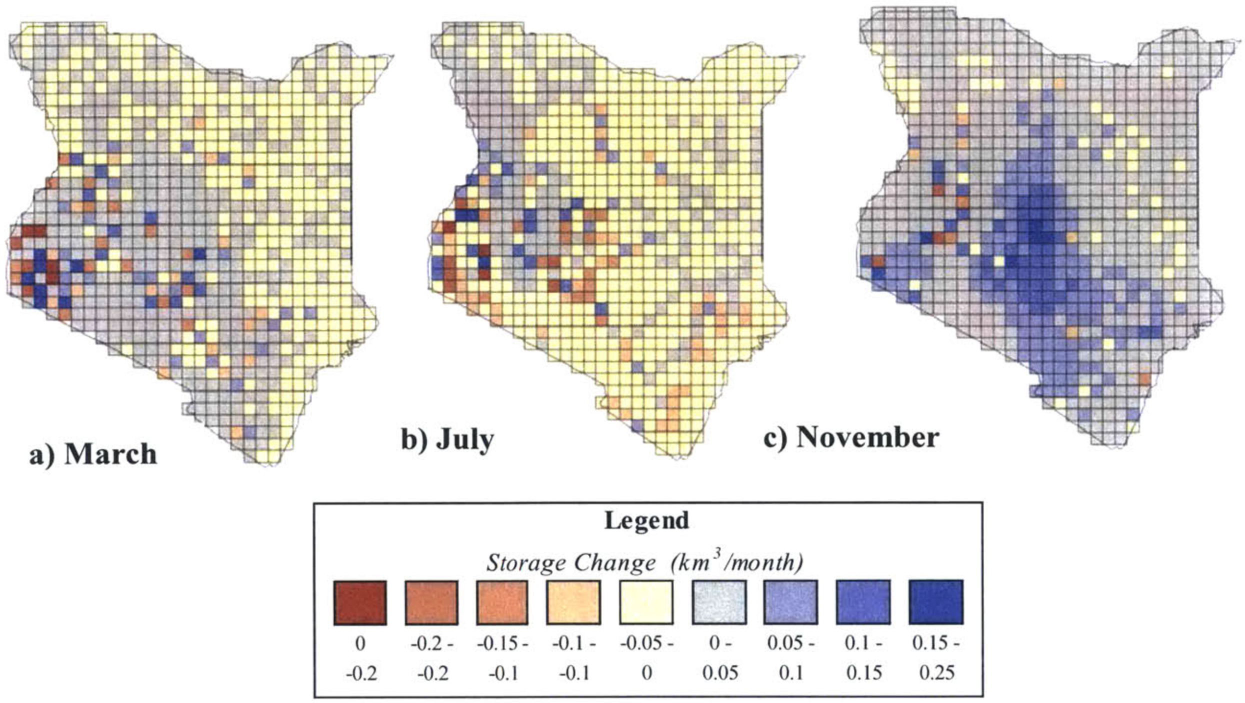


Figure 4.9: Maps for other water fluxes – Base Case; Optimization 2

4.1.2.7 Summary of Results for Optimization 2

The graph below shows the water related fluxes for this optimization.

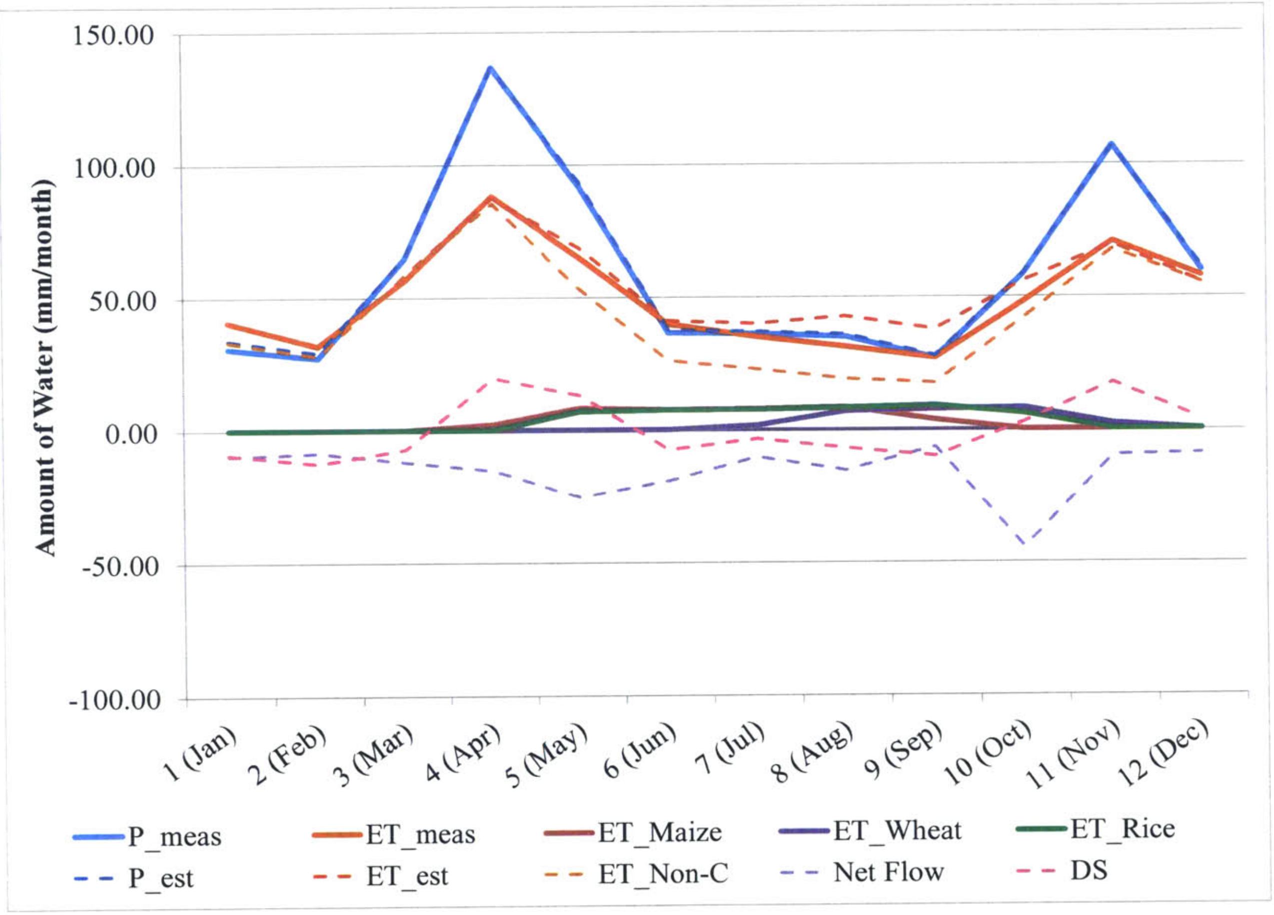


Figure 4. 10: Summary of Results; Base Case – Optimization 2

4.2 Results: Scenario 1 (Soil Grades 1-4)

4.2.1 Results for Scenario 1: Optimization 1

In this scenario the soil grades available for cultivation are grades 1-4. Since nothing changes in terms of the inputs of the first optimization, the results of the first optimization remain the same. Thus, the results for optimization 1 from the base case are used as inputs for the second optimization in this scenario.

4.2.2 Results for Scenario 1: Optimization 2

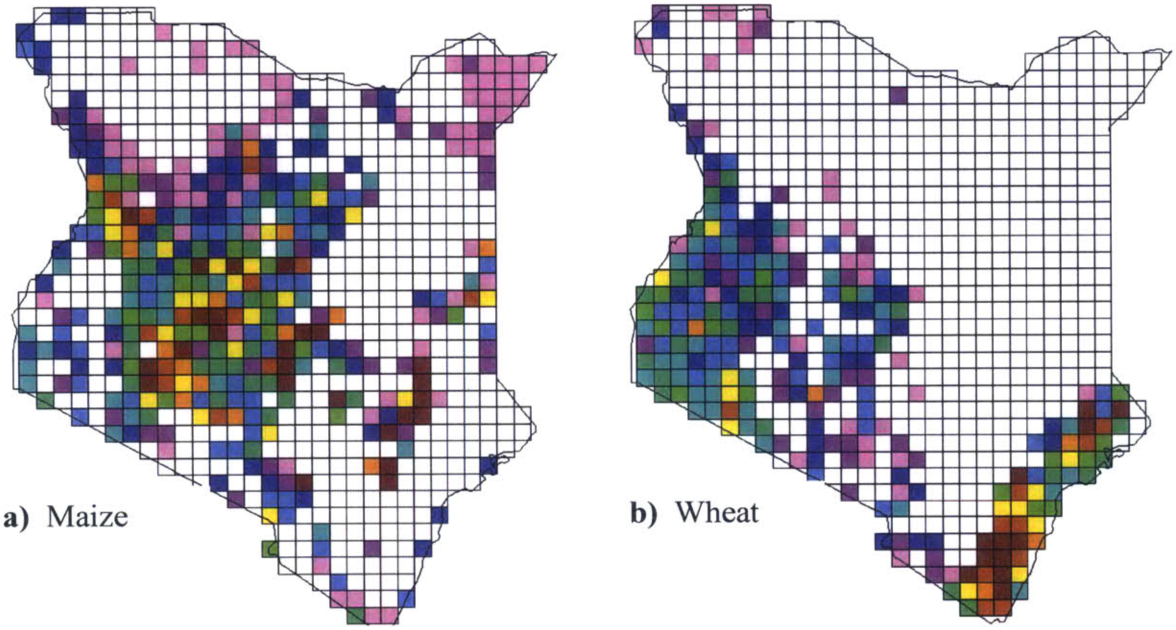
4.2.2.1 Calories Produced

	Now	**Optimized**	**Change**
	kcal/yr	*10^9 kcal/yr*	*factor*
Maize	10,253	48,215	4.70
Wheat	830	65,900	79.42
Rice	74	67,087	911.09
TOTAL	**11,156**	**181,203**	**16.24**

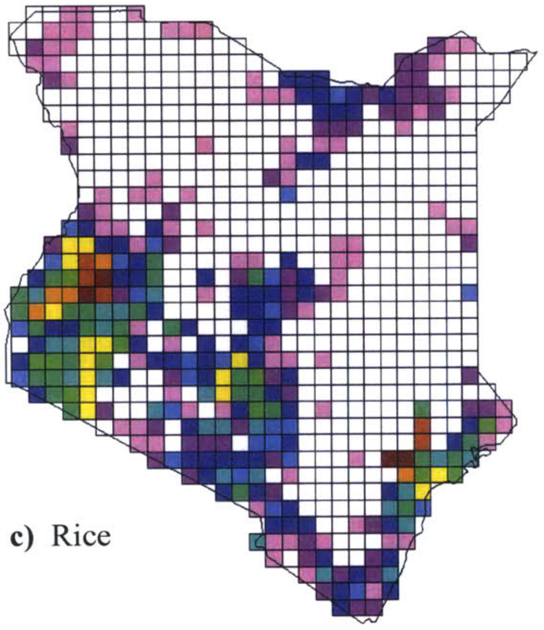
	Grade 1	**Grade 2**	**Grade 3**	**Grade 4**	**Grade 5**	**Total**
			10^9 kcal			
Maize	-	4,534.2	23,932.6	19,748.6	-	48,215.3
Wheat	-	392.1	32,901.7	32,606.4	-	65,900.2
Rice	-	-	40,635.6	26,451.7	-	67,087.2

Table 4.11: Calories produced: Now and Optimized Conditions per soil grade; Scenario 1

4.2.2.2 Area per Crop



a) Maize **b)** Wheat



c) Rice

Soil grade	Maize	Wheat	Rice
	Area planted (km²)		
1	-	-	-
2	3,480	314	-
3	26,019	37,371	28,440
4	32,206	55,530	27,788
5	-	-	-
TOTAL	**61,705**	**93,216**	**56,228**

Table 4.12: Area planted by each crop for each soil grade; Scenario 1

Legend

Fraction of pixel planted

☐	🟪	🟪	🟦	🟦	🟦	🟩	🟩	🟨	🟧	🟫	🟫
0 - 0.01	0.01 - 0.05	0.05 - 0.1	0.1 - 0.2	0.2 - 0.3	0.3 - 0.4	0.4 - 0.5	0.5 - 0.6	0.6 - 0.7	0.7 - 0.8	0.8 - 0.9	0.9 - 1

Figure 4.11: Fraction of pixel planted by each crop; Scenario 1

4.2.2.3 Crop Evapotranspiration

	Area	Crop requirement	Crop ET per pixel			Total Crop ET
			Average	*Min*	*Max*	
	km ^{2}	*mm/year*	*mm/yr*			*km* ^{3}
Maize	61,705	815.12	46.97	0	636.18	44.27
Wheat	93,216	643.22	84.96	0	714.45	49.92
Rice	56,228	987.25	70.38	0	875.96	41.10

Figure 4.12: Crop Evapotranspiration summary; Scenario 1 – Optimization 2

4.2.2.4 Other Fluxes

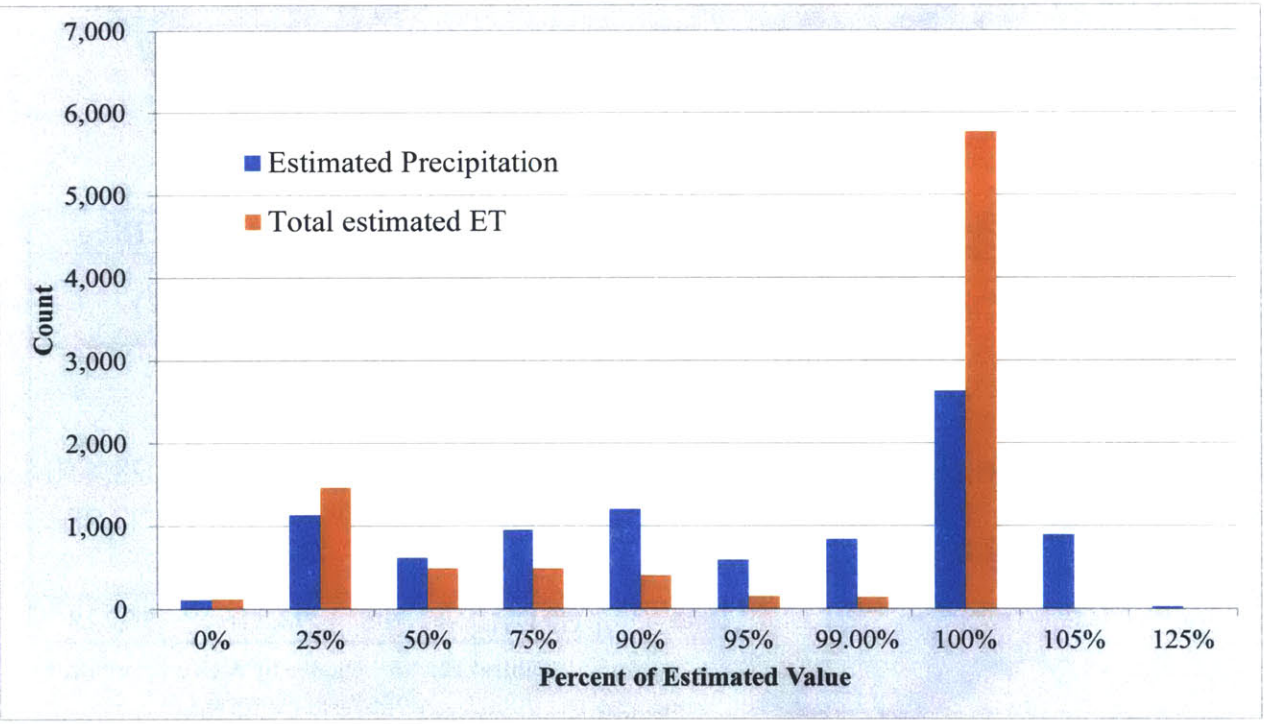


Figure 4.13: Non-crop ET as a percentage of estimated precipitation and ET; Scenario 1 – Optimization 2

	Non-crop Evapotranspiration											
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
	mm/month											
Min	4.06	3.80	22.68	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	12.18
Max	83.27	80.67	128.85	131.99	128.16	115.42	91.92	78.28	65.97	81.60	117.19	113.52
Average	33.28	27.94	58.31	79.39	43.50	17.76	12.03	10.18	8.47	32.64	58.66	55.35

Table 4. 13: Monthly estimated non-crop evapotranspiration; Scenario 1 – Optimization 2

	Pixel Outflow											
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
	km^3/month											
Min	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Max	0.38	0.43	0.91	2.24	0.43	0.35	0.36	0.35	0.36	0.47	0.42	0.28
Average	0.02	0.02	0.02	0.04	0.01	0.01	0.01	0.02	0.02	0.01	0.02	0.01

Table 4.14: Monthly estimated Pixel outflow; Scenario 1 – Optimization 2

	Storage Change											
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
	km^3/month											
Min	-0.21	-0.20	-0.20	-0.20	-0.18	-0.19	-0.20	-0.20	-0.21	-0.17	-0.15	-0.17
Max	0.18	0.20	0.19	0.20	0.20	0.20	0.17	0.20	0.17	0.18	0.20	0.18
Average	0.00	0.00	0.00	0.03	0.01	-0.01	-0.01	-0.03	-0.03	-0.01	0.03	0.00

Table 4.15: Monthly estimated change in storage; Scenario 1 – Optimization 2

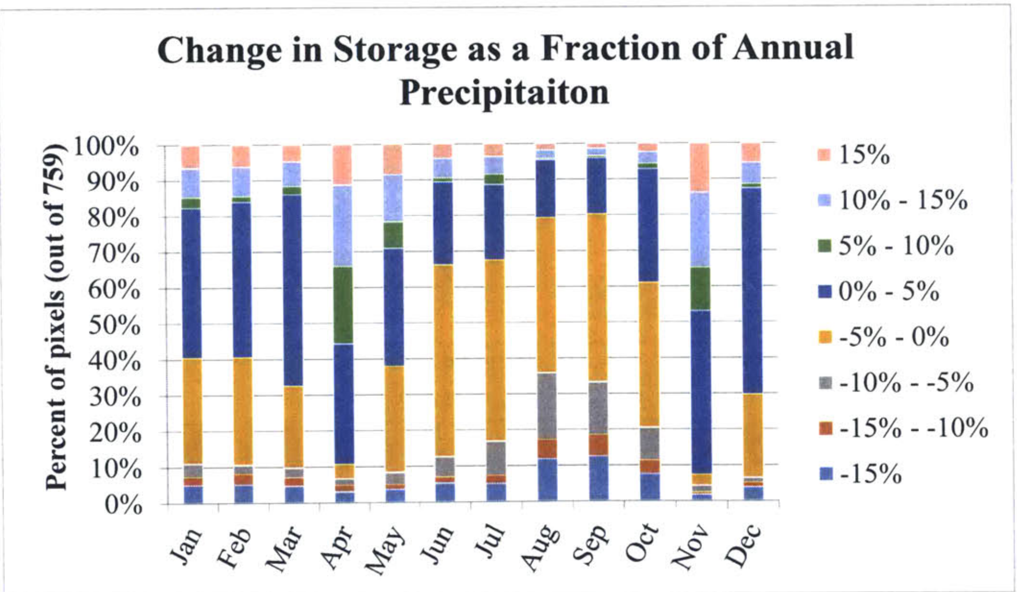
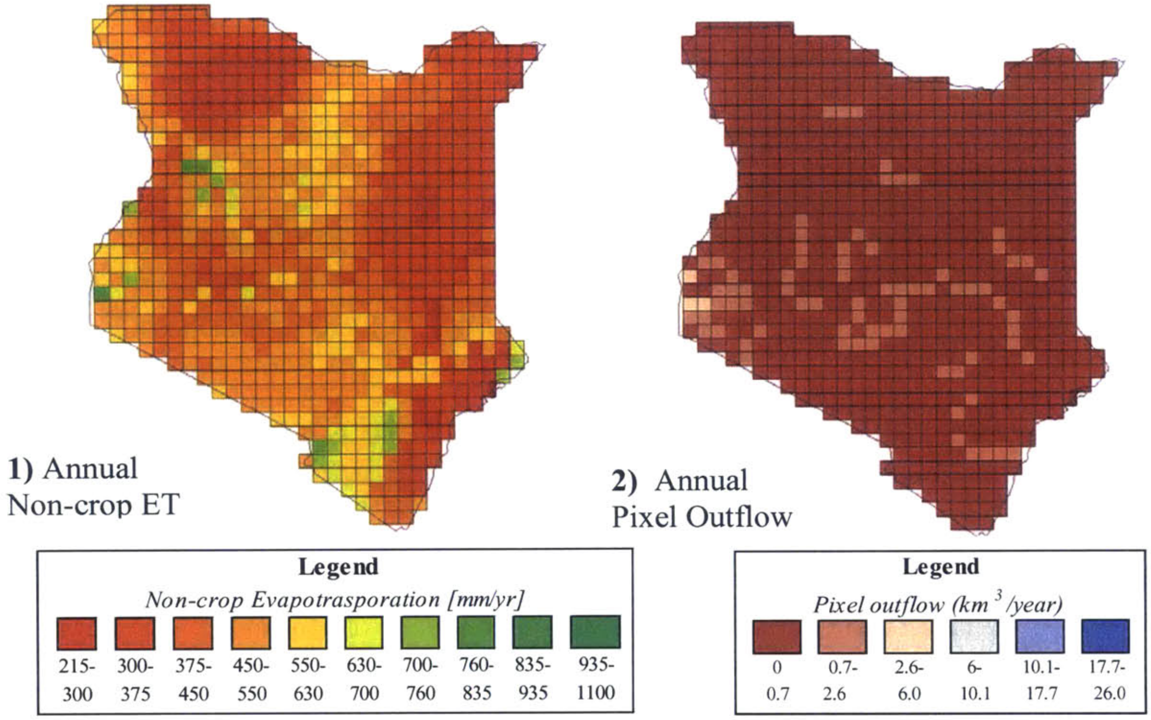


Figure 4.14: Change in Storage as a Fraction of Annual Precipitation; Scenario 1 – Optimization 2



3) Monthly Change in Storage (Selected Months)

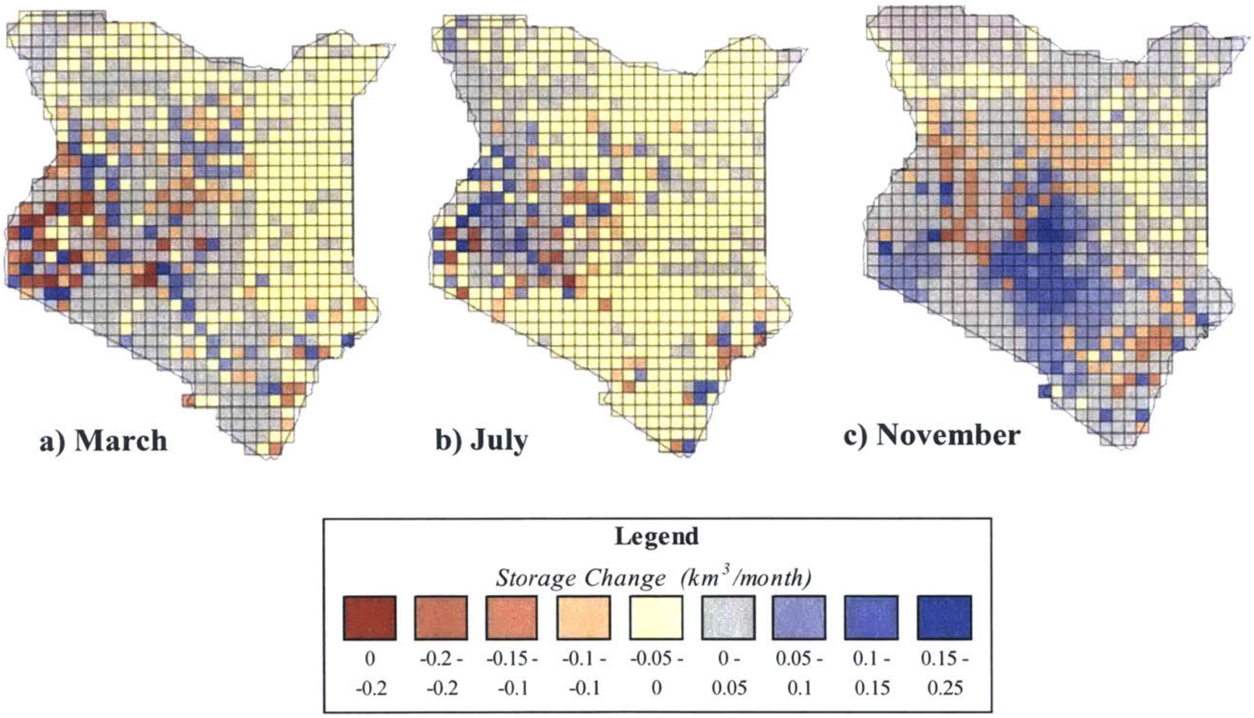


Figure 4.15: Maps for other water fluxes; Scenario 1 – Optimization 2

4.2.2.7 Summary of Results for Optimization 2

The graph below shows the water related fluxes for this optimization.

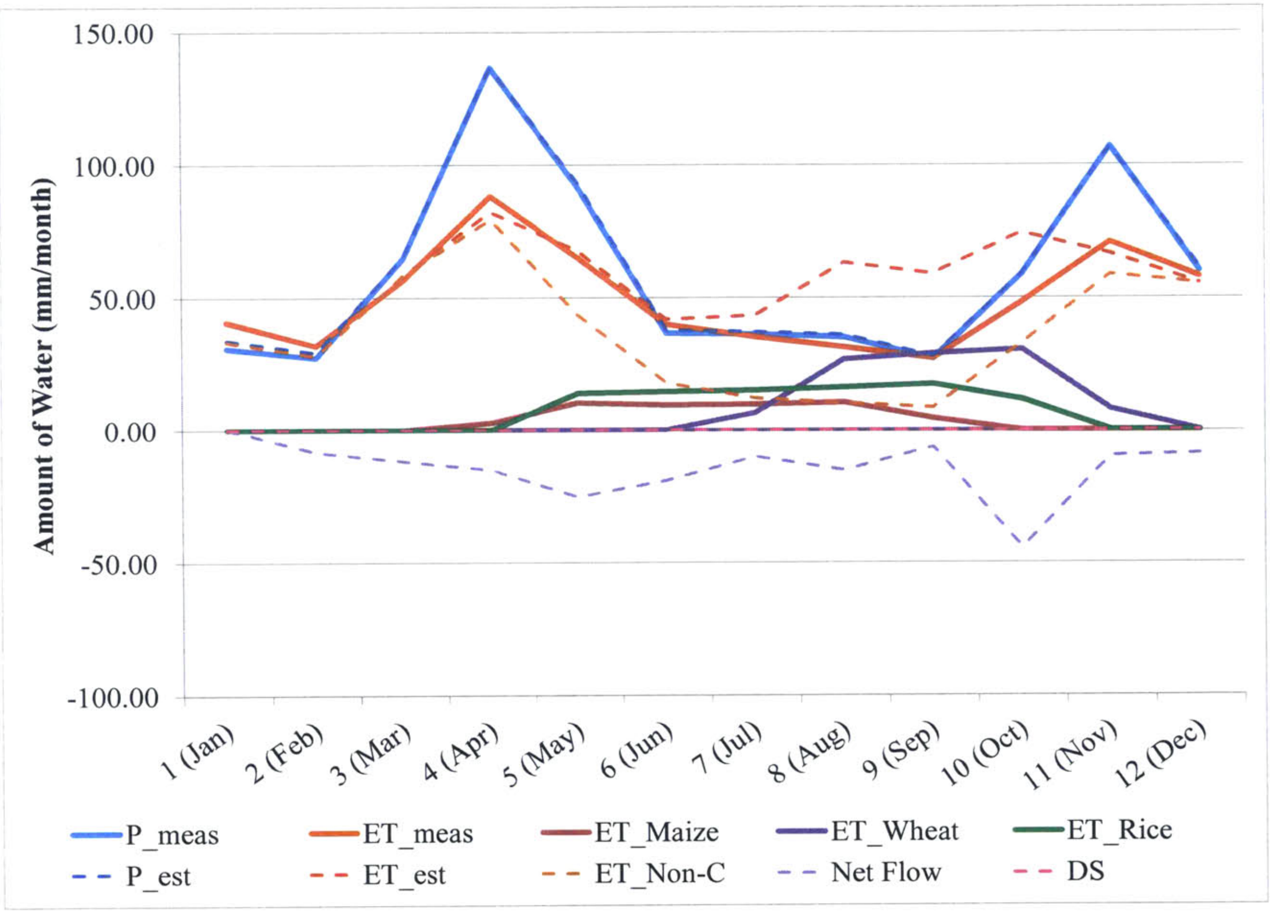


Figure 4.16: Summary of Results; Scenario 1 – Optimization 2

4.3 Results: Scenario 2 (Low Precipitation) .

4.3.1 Results for Scenario 2: Optimization 1

The resulting sum of least squares for this optimization is shown below:

Sum of Least Squares	1.00E-04

4.3.1.1 Precipitation and Actual Evapotranspiration

The result were visualized in a histogram shown below. The total number of values for each variable was 9108 (759 cells, 12 months).

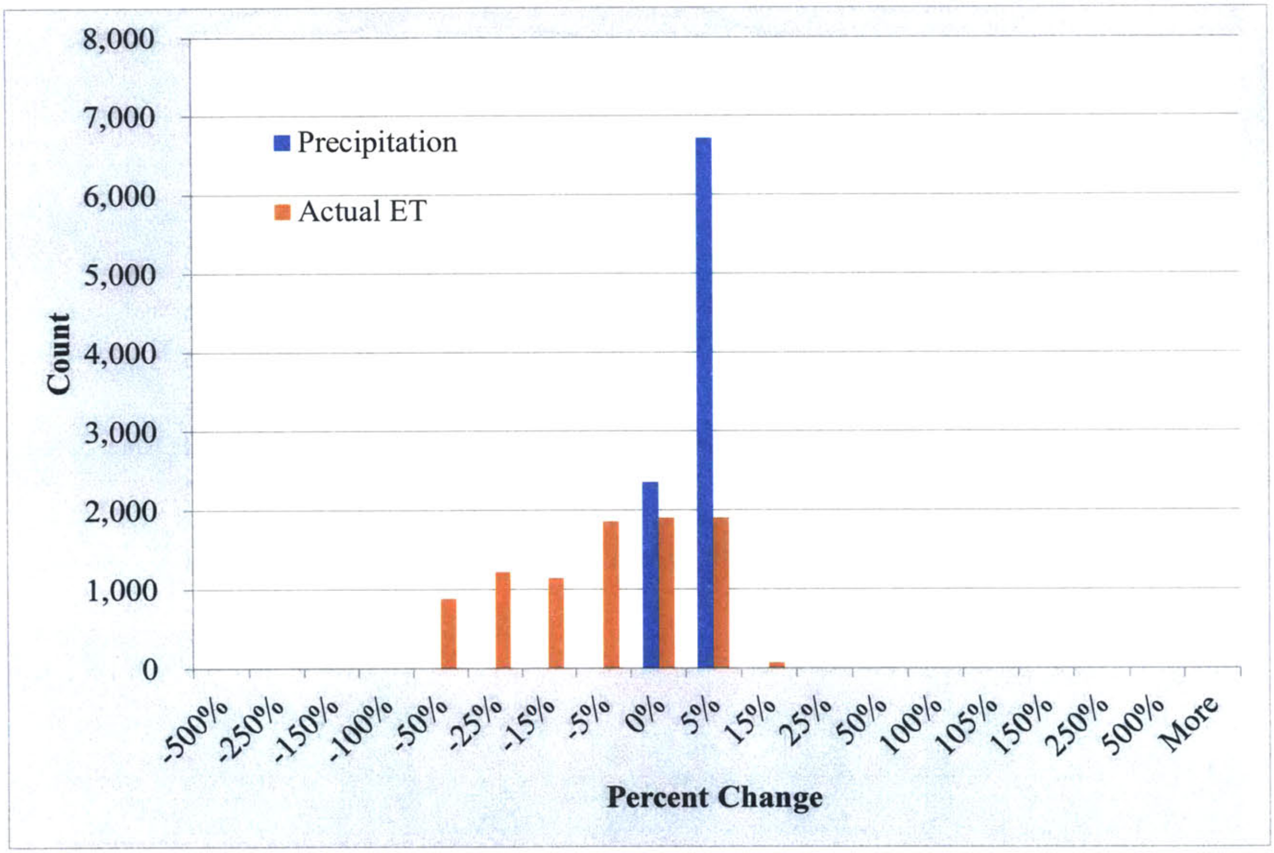


Figure 4.17: Percent Change for Precipitation and Evapotranspiration; Scenario 2 – Optimization 1

4.2.1.2 Crop Evapotranspiration

Since the distribution of crops has not changed this is the same.

4.2.1.3 Other Water Fluxes

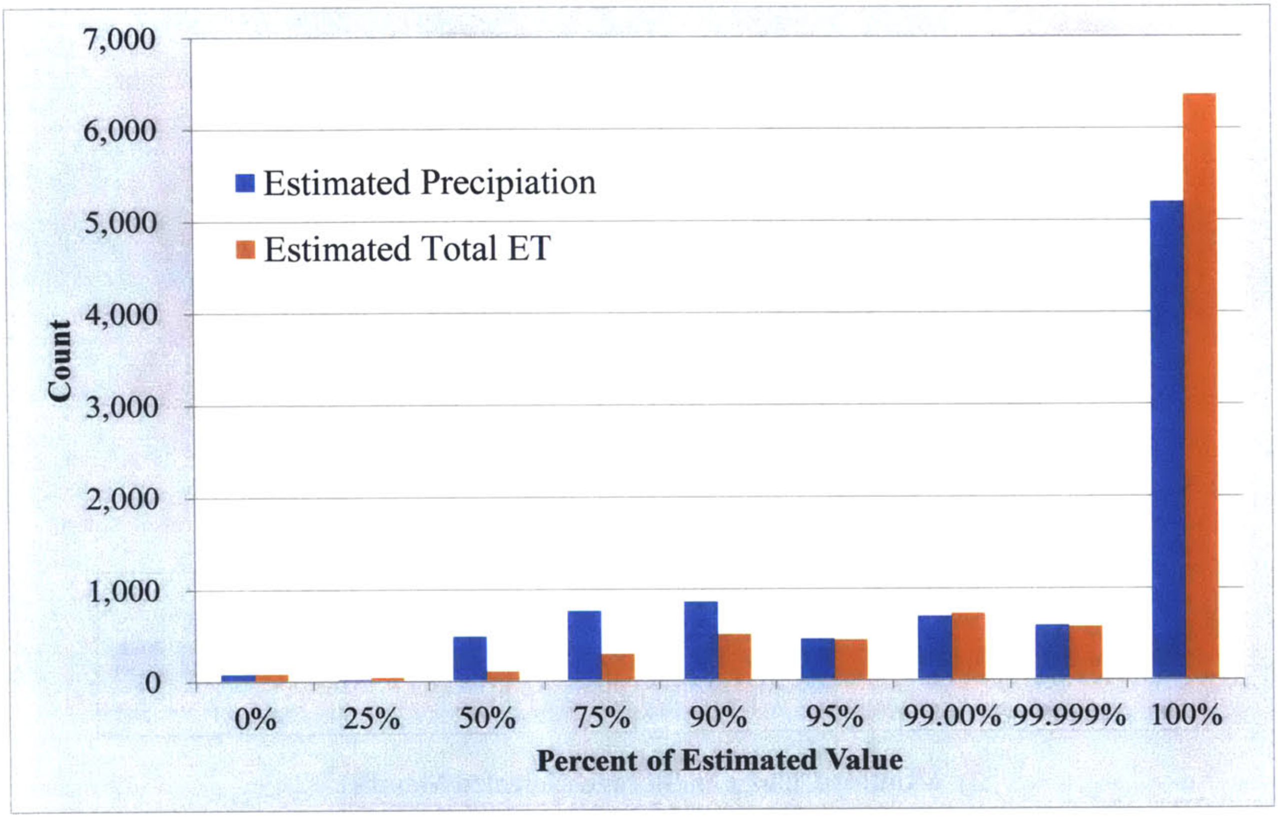


Figure 4.18: Non-crop ET as a percentage of estimated precipitation and ET; Scenario 2 – Optimization 1

	Non-crop Evapotranspiration											
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
	mm/month											
Min	2.63	0.73	17.80	26.76	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Max	82.43	80.20	128.85	134.39	133.14	123.29	96.77	84.37	91.33	102.49	125.26	115.66
Average	31.40	25.98	55.60	87.35	55.67	27.77	27.39	23.93	22.27	45.54	67.66	51.04

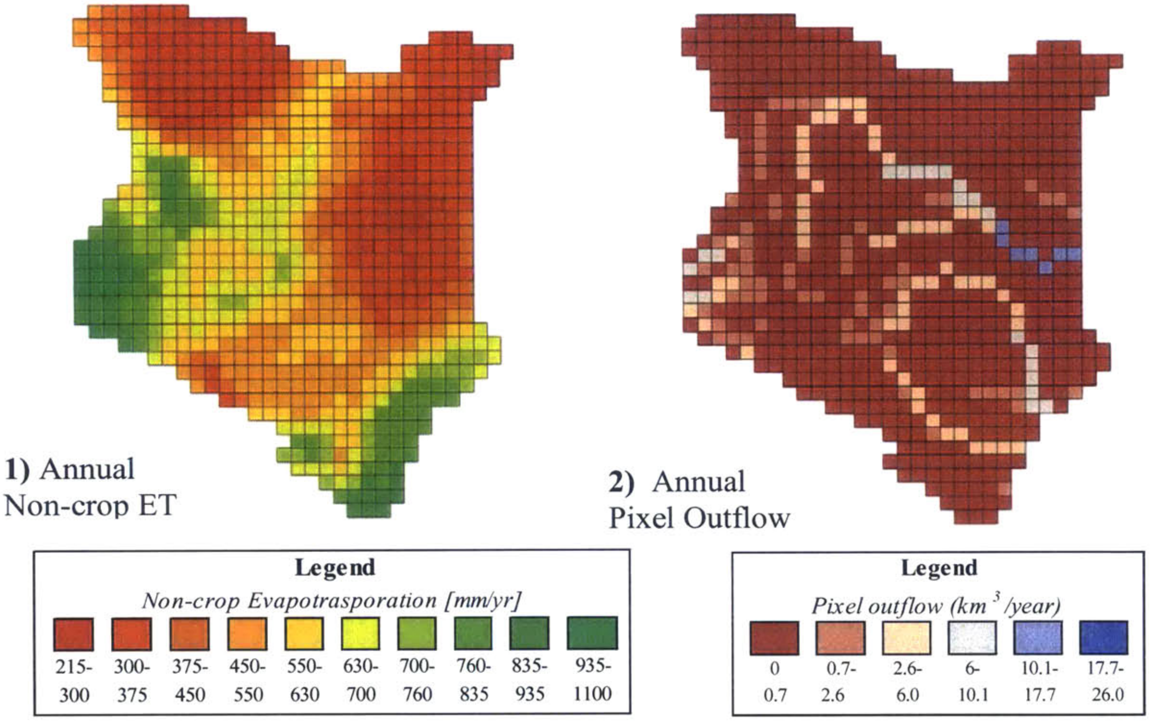
Table 4.16: Monthly estimated non-crop evapotranspiration; Scenario 2 – Optimization 1

	Pixel Outflow											
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
	km^3/*month*											
Min	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Max	11.36	2.47	0.41	0.62	3.28	2.25	0.87	0.77	0.41	0.41	2.34	0.41
Average	0.51	0.05	0.01	0.02	0.03	0.08	0.02	0.02	0.01	0.01	0.08	0.01

Table 4.17: Monthly estimated pixel outflow; Scenario 2 – Optimization 1

	Change in Storage											
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
	km^3/*month*											
Min	-0.17	-0.19	-0.13	-0.12	-0.19	-0.19	-0.17	-0.17	-0.14	-0.18	-0.19	-0.12
Max	0.13	0.12	0.12	0.16	0.16	0.16	0.14	0.19	0.19	0.17	0.16	0.12
Average	-0.03	-0.01	0.00	0.02	0.01	-0.01	0.00	0.00	0.00	0.00	0.01	0.00

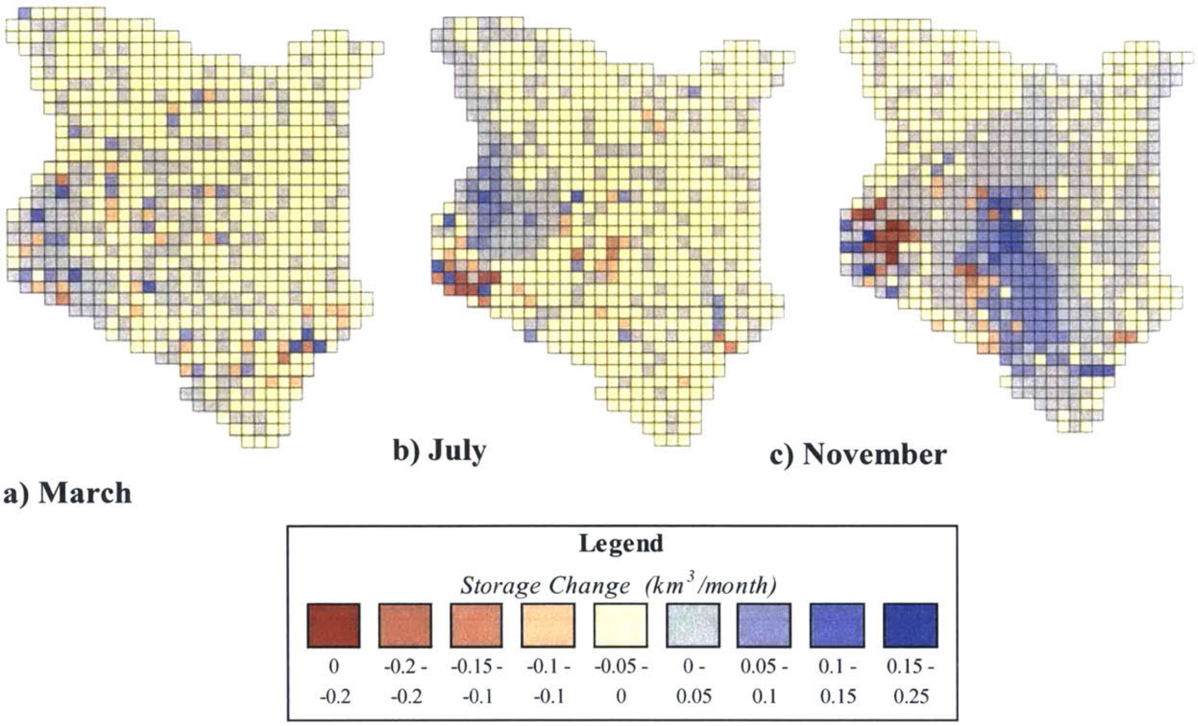
Table 4.18: Monthly estimated change in storage; Scenario 2 – Optimization 1



1) Annual Non-crop ET

2) Annual Pixel Outflow

3) Monthly Change in Storage (Selected Months)



a) March

b) July

c) November

Figure 4.19: Maps for other water fluxes; Scenario 2 – Optimization 1

4.3.1.4 Summary of the Results from Optimization 1

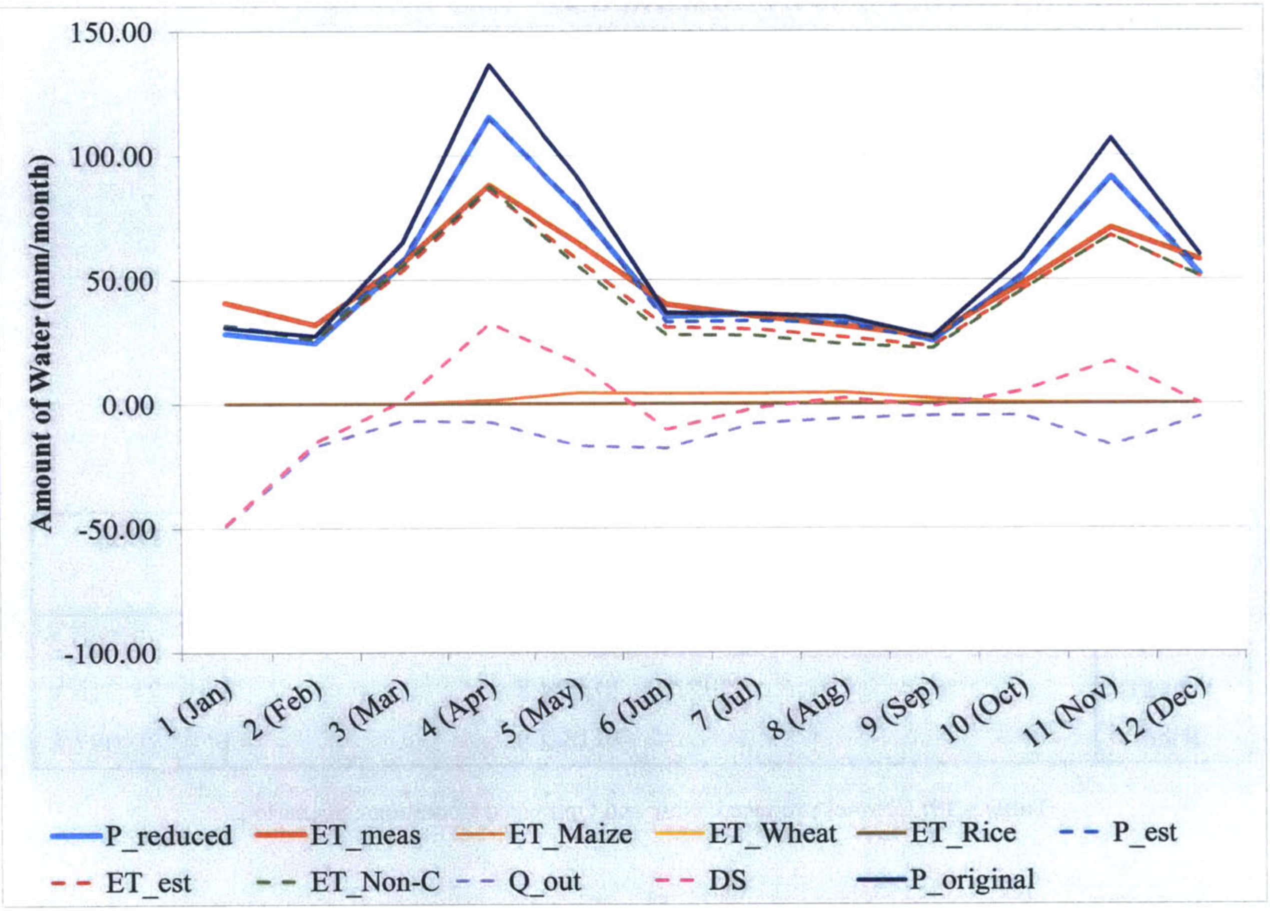


Figure 4.20: Summary of Results; Scenario 2 – Optimization 1

4.3.2 Results for Scenario 2: Optimization 2

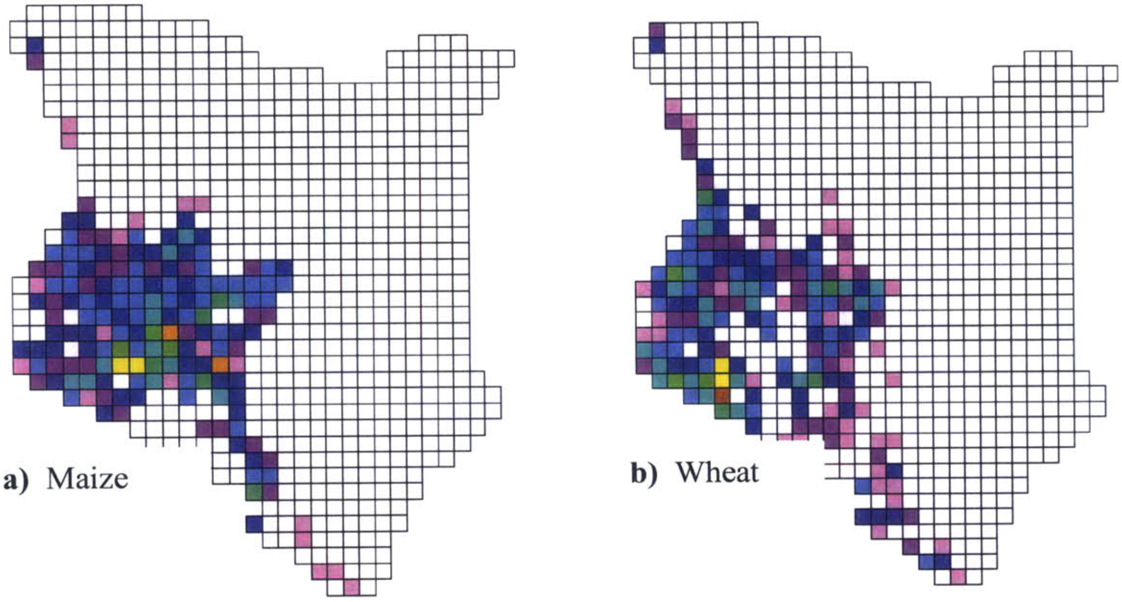
4.3.2.1 Calories Produced

	Now *10^9 kcal/yr*	**Optimized** *10^9 kcal/yr*	**Change** *factor*
Maize	10,253	22,760	2.22
Wheat	830	21,217	25.57
Rice	74	29,093	395.10
TOTAL	**11,156**	**73,070**	**6.55**

	Grade 1	**Grade 2**	**Grade 3**	**Grade 4**	**Grade 5**	**Total**
		10^9 kcal				
Maize	-	4,325.0	18,435.3	-	-	22,760.3
Wheat	-	392.1	20,824.8	-	-	21,216.9
Rice	-	-	29,092.8	-	-	29,092.8

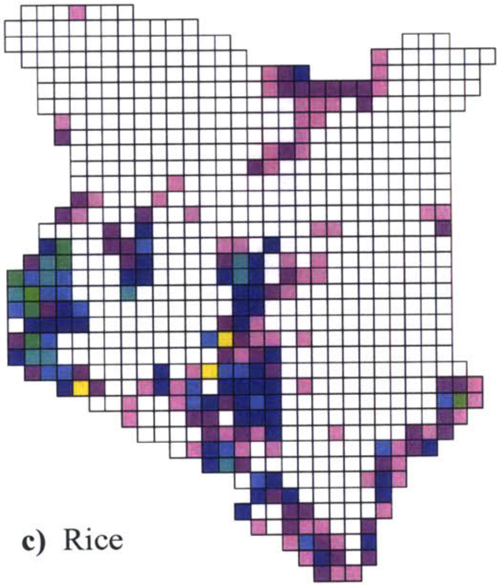
Table 4.19: Calories produced: Now and Optimized Conditions; Scenario 2

4.3.2.2 Area per Crop



a) Maize

b) Wheat



c) Rice

Soil grade	Maize	Wheat	Rice
	Area planted (km^2)		
1	-	-	-
2	3,319	314	-
3	20,043	23,654	20,356
4	-	-	-
5	-	-	-
TOTAL	**23,362**	**23,968**	**20,356**

Figure 4.21: Area planted by each crop for each soil grade; Scenario 2

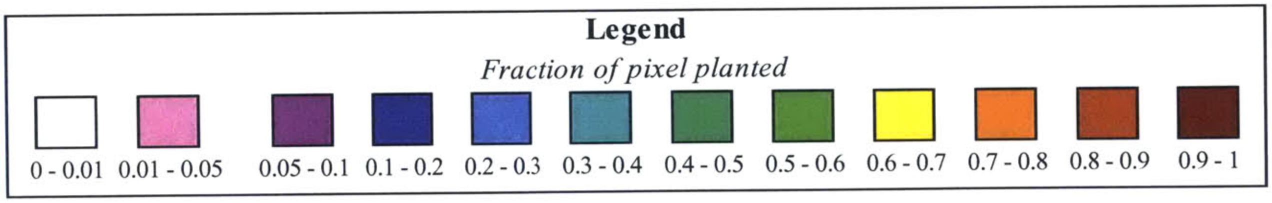


Figure 4.22: Fraction of pixel planted by each crop; Scenario 2

4.3.2.3 Crop Evapotranspiration

	Area	**Crop requirement**	**Crop ET per pixel**			**Total Crop ET**
			Average	***Min***	***Max***	
	km ^{2}	*mm/year*		*mm/yr*		*km ^{3}*
Maize	23,362	815.12	30.28	0	586.85	17.69
Wheat	23,968	643.22	23.93	0	446.46	13.98
Rice	20,356	987.25	32.88	0	647.40	19.21

Table 3.8: Crop Evapotranspiration; Scenario 2 – Optimization 2

4.3.2.3 Other Water Fluxes

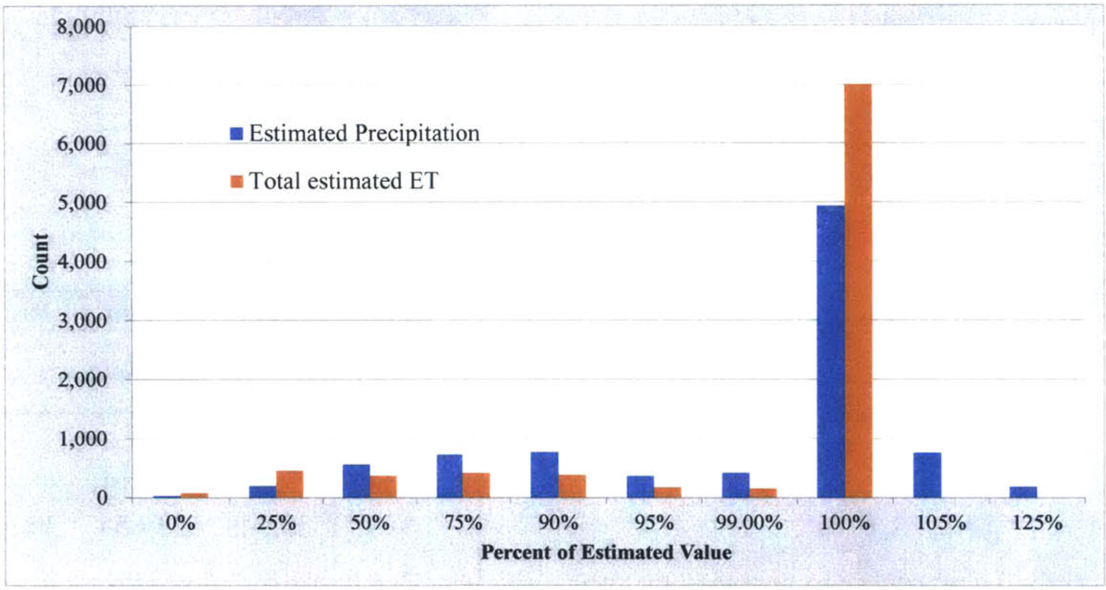


Figure 4.23: Non-crop ET as a percentage of precipitation and ET; Scenario 2 – Optimization 2

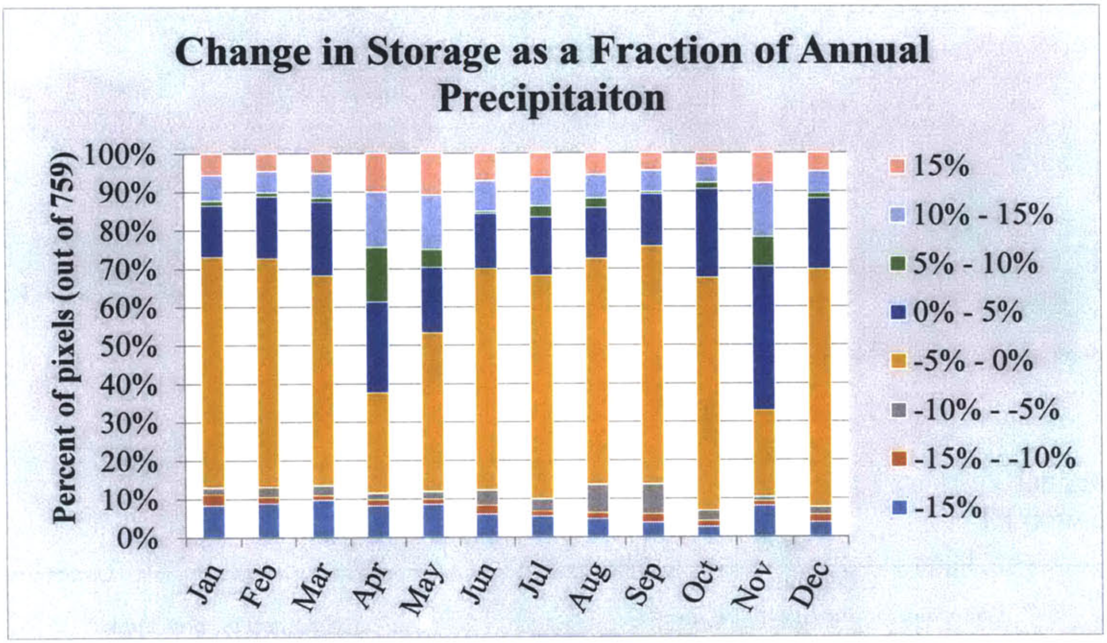


Figure 4.24: Monthly change in Storage as a Fraction of Annual Precipitation; Scenario 2 – Optimization 2

	Non-crop Evapotranspiration											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
	mm/month											
Min	2.63	0.73	17.80	12.68	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Max	82.43	80.20	128.85	134.39	128.72	115.94	91.37	80.68	74.78	89.56	125.26	115.66
Average	31.40	25.98	55.60	84.12	50.49	24.26	21.89	18.25	16.72	40.86	64.86	51.04

Table 4.20 Monthly estimated non-crop evapotranspiration; Scenario 2 – Optimization 2

	Pixel Outflow											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
	km^3/month											
Min	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Max	1.18	1.54	1.55	2.91	3.95	0.82	0.23	0.32	0.24	0.23	2.39	0.95
Average	0.04	0.04	0.04	0.06	0.10	0.03	0.01	0.01	0.01	0.01	0.07	0.01

Table 4.21: Monthly estimated pixel outflow; Scenario 2 – Optimization 2

	Storage Change											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
	km^3/month											
Min	-0.19	-0.19	-0.19	-0.19	-0.19	-0.19	-0.19	-0.17	-0.19	-0.16	-0.14	-0.12
Max	0.19	0.19	0.18	0.18	0.19	0.19	0.18	0.19	0.18	0.17	0.17	0.13
Average	0.00	-0.01	-0.01	0.01	0.01	0.00	0.00	0.00	-0.01	0.00	0.01	0.00

Table 4.22: Monthly estimated change in storage; Scenario 2 – Optimization 2

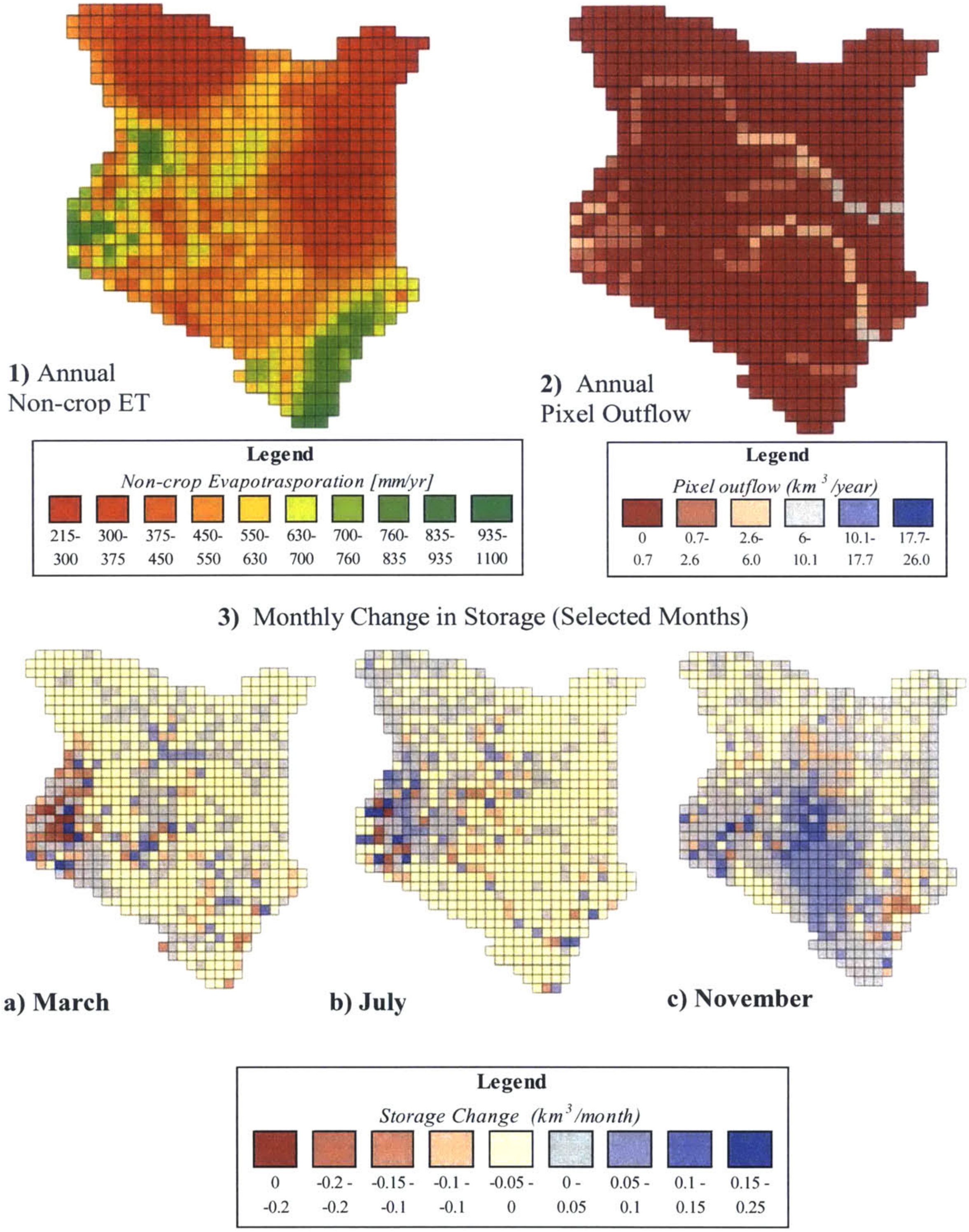


Figure 4. 25: Maps for other water fluxes; Scenario 2 – Optimization 2

4.3.2.4 Summary of Results for Optimization 2

The graph below shows the water related fluxes for this optimization.

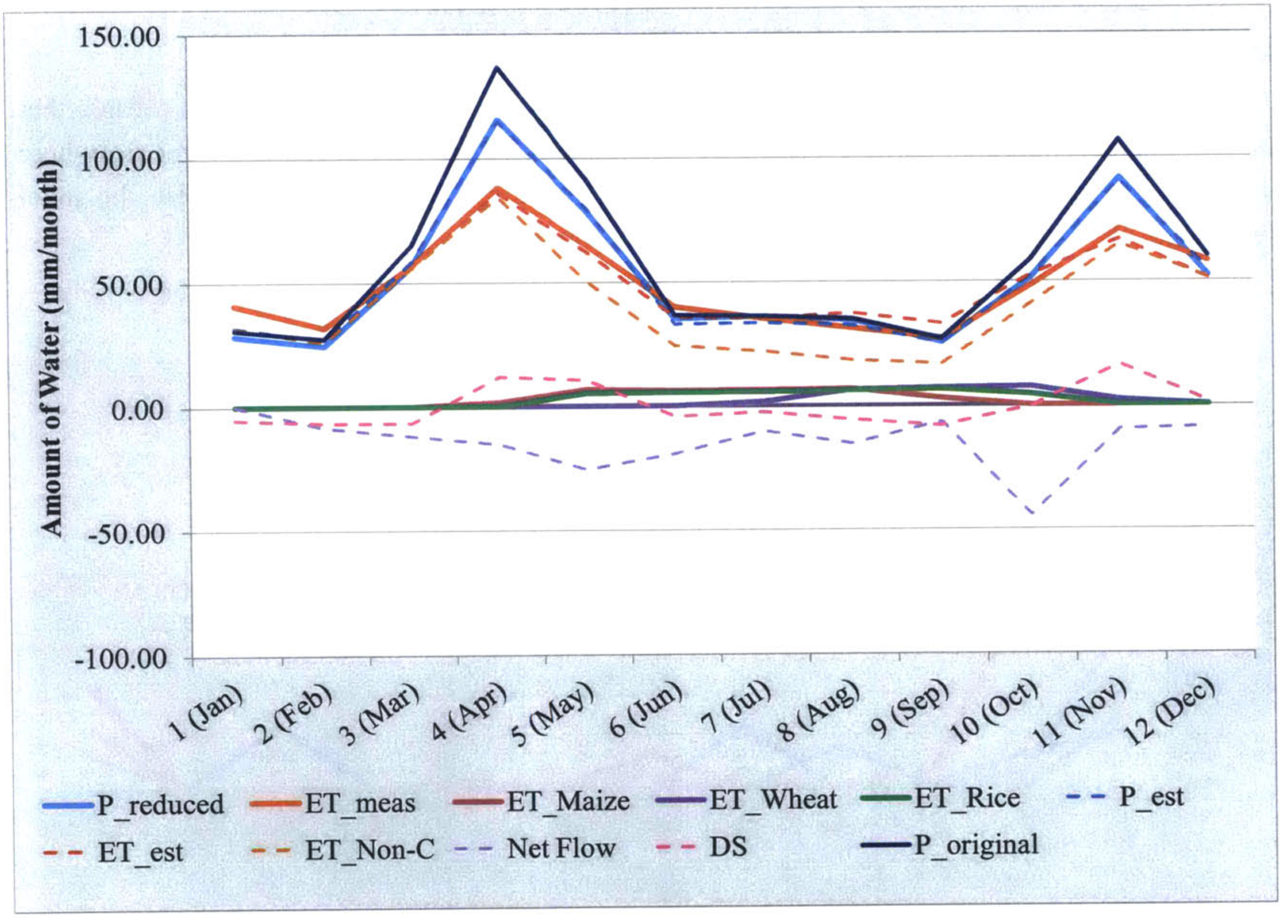


Figure 4.26: Summary of Results; Scenario 2 – Optimization 2

4.4 Results: Scenario 3 (Maintaining River Flow)

4.4.1.Results for Scenario 3: Optimization 1

For this scenario the same inputs as the base case scenario were used. This means, that the nominal precipitation, and the measured actual precipitation were used. The river flow here was not constrained. Rather it is used as an input in the second optimization. Here the pixel outflow for the rivers for which data is available is shown.

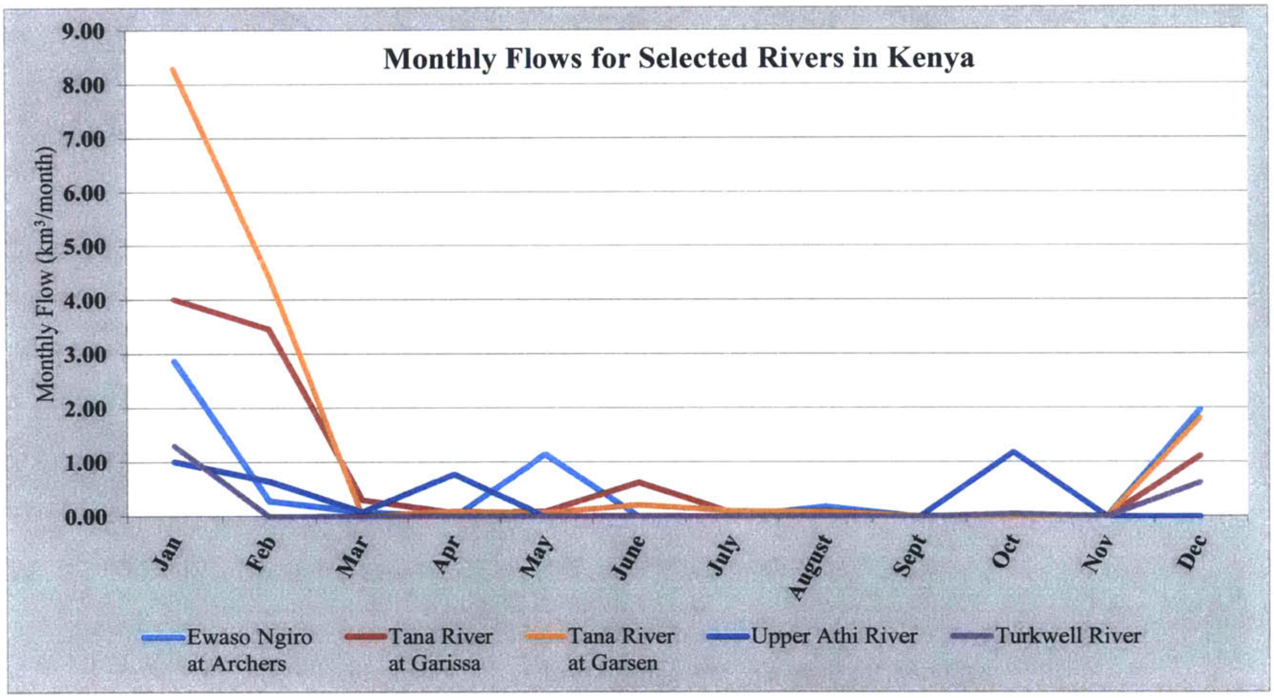


Figure 4.27: Monthly flow for selected rivers in Kenya; Scenario 3 – Optimization 1

4.4.2 Results for Scenario 3: Optimization 2

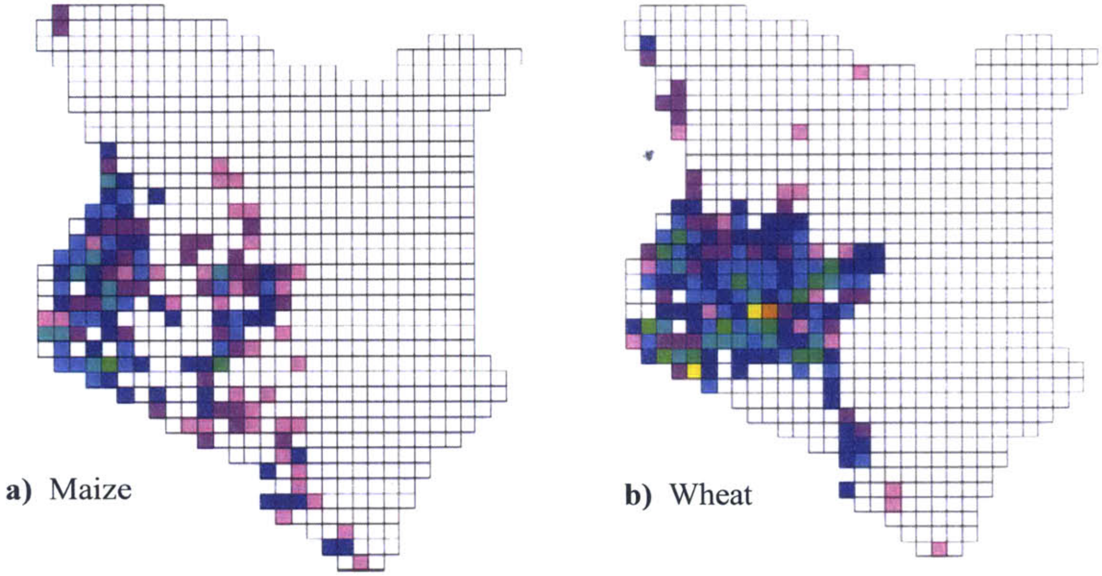
4.4.2.1 Calories Produced

	Now	**Optimized**	**Change**
	kcal/yr	*10^9 kcal/yr*	*factor*
Maize	10,253	14,828	1.45
Wheat	830	21,457	25.86
Rice	74	19,471	264.44
TOTAL	**11,156**	**55,757**	**5.00**

	Grade 1	**Grade 2**	**Grade 3**	**Grade 4**	**Grade 5**	**Total**
	10^9 kcal					
Maize	-	4,405.0	10,423.4	-	-	14,828.4
Wheat	-	392.1	21,065.2	-	-	21,457.3
Rice	-	-	19,471.5	-	-	19,471.5

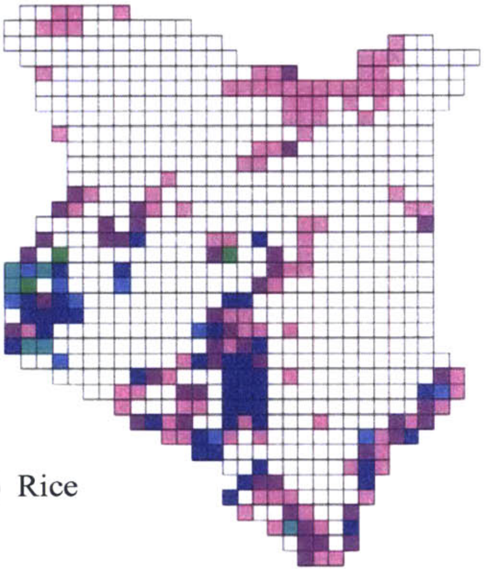
Table 4.23: Calories produced: Now and Optimized Conditions; Scenario 3

4.2.2.2 Area per Crop



a) Maize

b) Wheat



c) Rice

Soil grade	Maize	Wheat	Rice
	Area planted (km^2)		
1	-	-	-
2	3,381	314	-
3	11,332	23,927	13,618
4	-	-	-
5	-	-	-
Total	14,713	24,241	13,618

Table 4.24: Area planted by each crop for each soil grade; Scenario 3

Legend

Fraction of pixel planted

⬜	🟪	🟪	🟦	🟦	🟦	🟩	🟩	🟨	🟧	🟫	🟥
0 - 0.01	0.01 - 0.05	0.05 - 0.1	0.1 - 0.2	0.2 - 0.3	0.3 - 0.4	0.4 - 0.5	0.5 - 0.6	0.6 - 0.7	0.7 - 0.8	0.8 - 0.9	0.9 - 1

Figure 4.28: Fraction of pixel planted by each crop; Scenario 3

4.2.2.3 Crop Evapotranspiration

	Area	Crop requirement	Crop ET per pixel			Total Crop ET
			Average	*Min*	*Max*	
	km²	*mm/year*	*mm/yr*			*km³*
Maize	14,713	815.12	18.97	0	392.77	11.08
Wheat	24,241	643.22	24.47	0	384.99	14.56
Rice	13,618	987.25	21.99	0	468.18	12.85

Table 4.25: Crop Evapotranspiration; Scenario 3

4.4.2.4 Other Water Fluxes

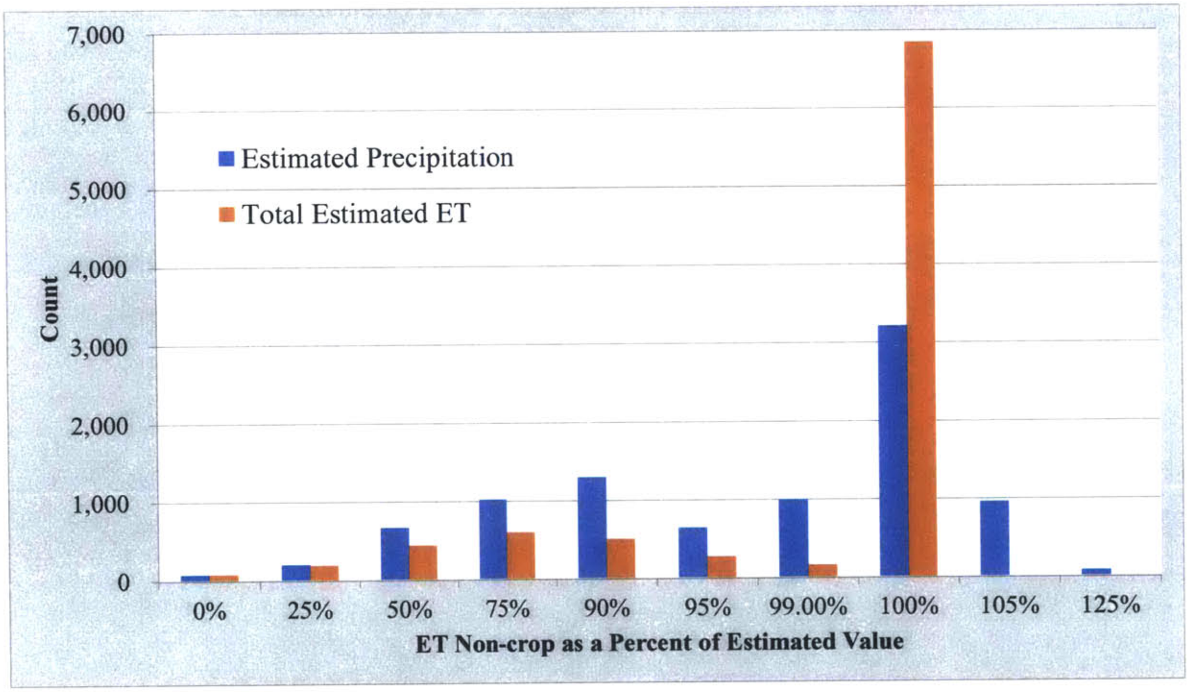


Figure 4.29: Non-crop ET as a percentage of precipitation and ET; Scenario 3 – Optimization 2

	Non-crop Evapotranspiration											
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
	mm/month											
Min	4.06	3.80	22.68	33.96	16.04	0.00	0.00	0.00	0.00	11.08	15.09	12.18
Max	83.27	80.67	128.85	131.99	128.72	115.94	91.93	78.28	75.77	88.73	120.17	113.52
Average	33.28	27.94	58.31	87.35	56.67	28.11	24.75	20.94	19.39	43.45	67.93	55.35

Table 4.26: Monthly estimated non-crop evapotranspiration; Scenario 3 – Optimization 2

	Pixel Outflow											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
	$km^3/month$											
Min	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Max	14.20	5.57	0.54	0.73	1.01	1.22	0.36	1.77	1.00	3.79	2.96	4.42
Average	0.62	0.13	0.03	0.03	0.04	0.03	0.01	0.03	0.02	0.07	0.08	0.23

Table 4.27: Monthly estimated pixel outflow; Scenario 3 – Optimization 2

	Storage Change											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
	$km^3/month$											
Min	-0.19	-0.21	-0.15	-0.10	-0.13	-0.17	-0.15	-0.20	-0.16	-0.14	-0.20	-0.14
Max	0.17	0.15	0.14	0.21	0.19	0.12	0.17	0.11	0.11	0.11	0.17	0.13
Average	-0.04	-0.01	0.00	0.03	0.02	0.00	0.00	0.00	-0.01	0.00	0.02	-0.01

Table 4.28: Monthly change in storage; Scenario 3 – Optimization 2

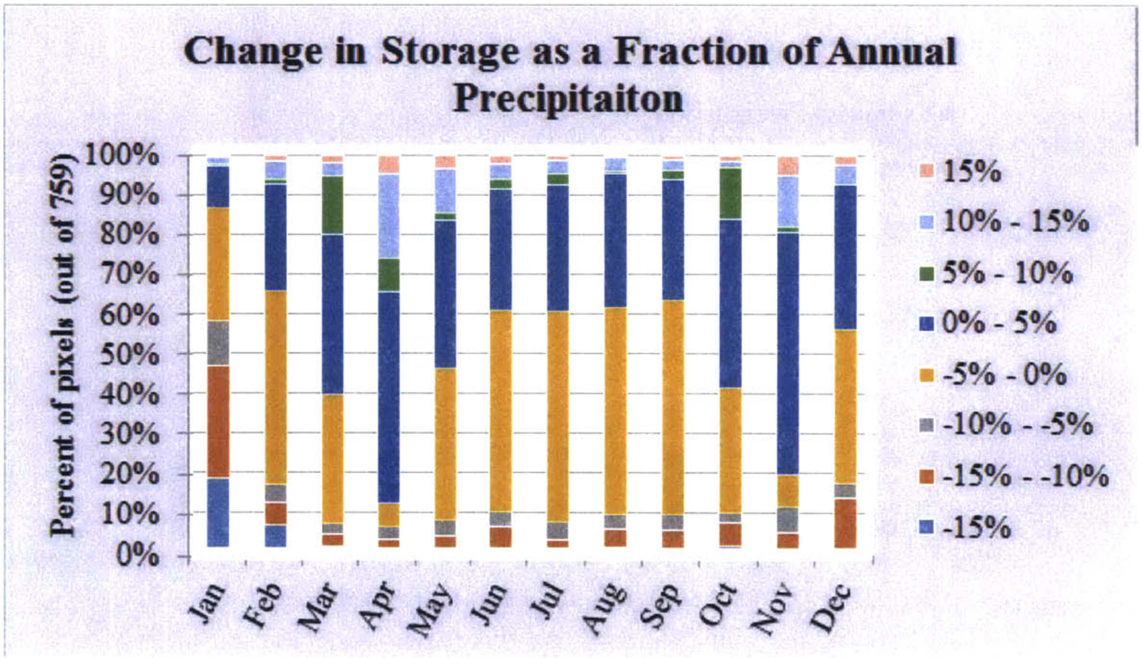


Figure 4.30: Summary of Results; Scenario 3 – Optimization 2

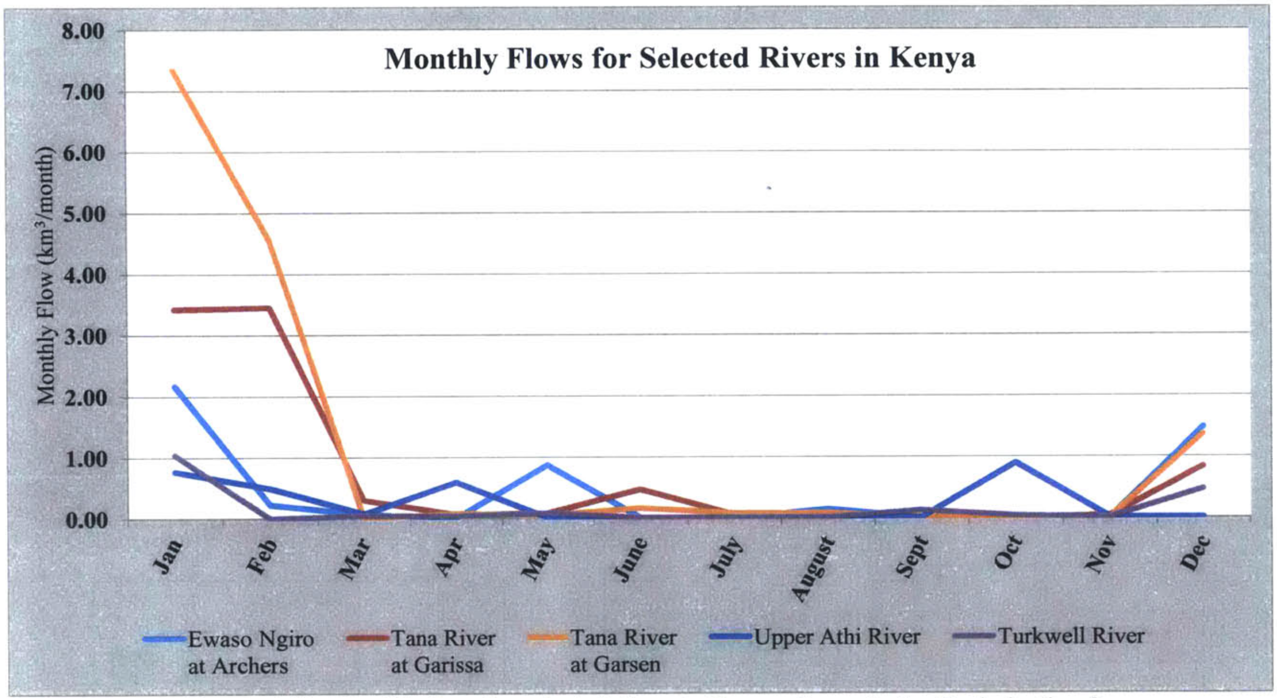
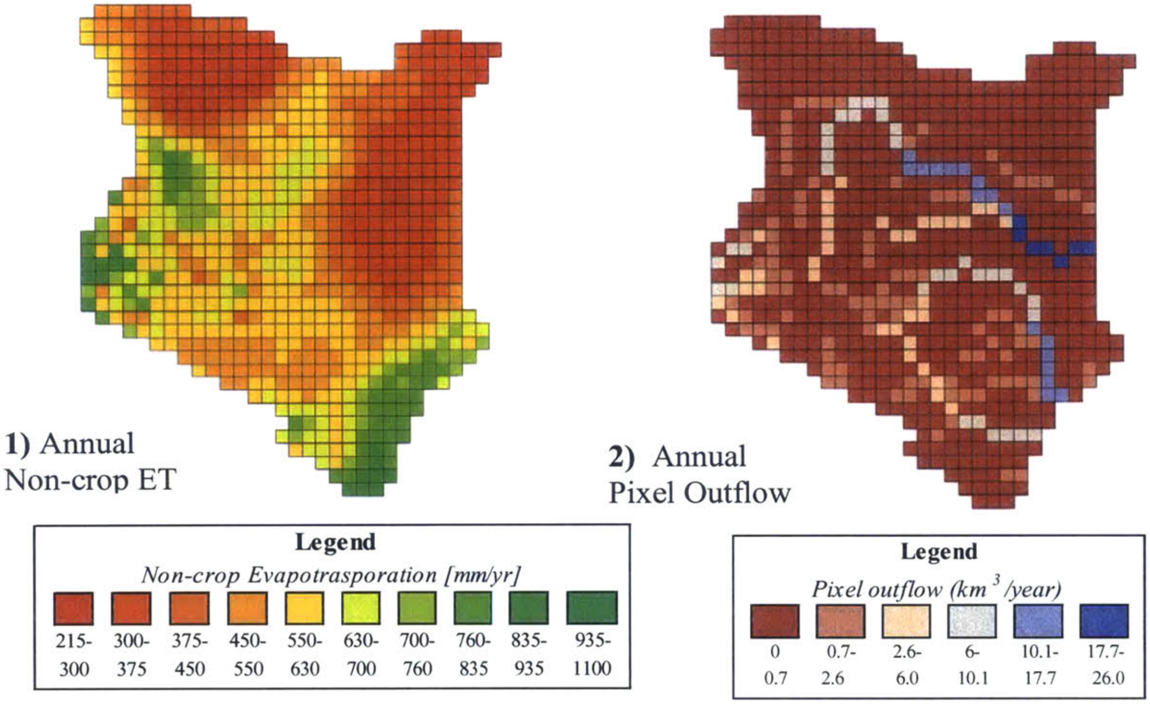


Figure 4.31: Monthly flow for selected rivers in Kenya; Scenario 3 – Optimization 2



3) Monthly Change in Storage (Selected Months)

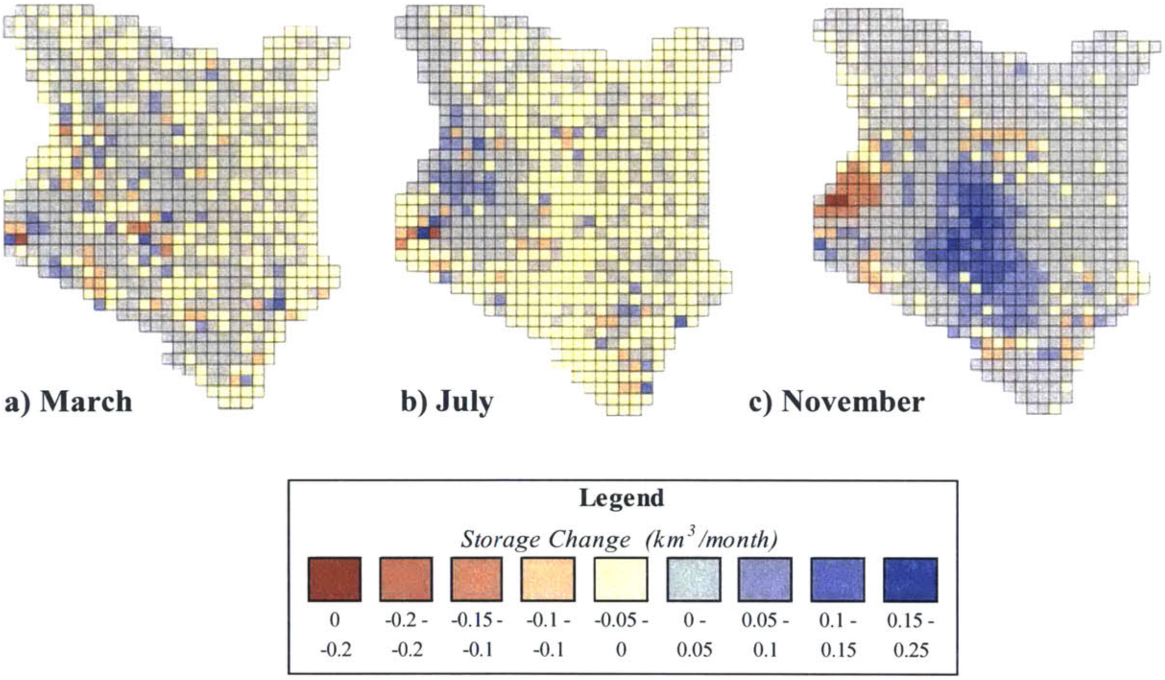


Figure 4.32: Maps for other water fluxes – Scenario 3; Optimization 2

4.4.2.5 Summary of Results for Optimization 2

The graph below shows the water related fluxes for this optimization.

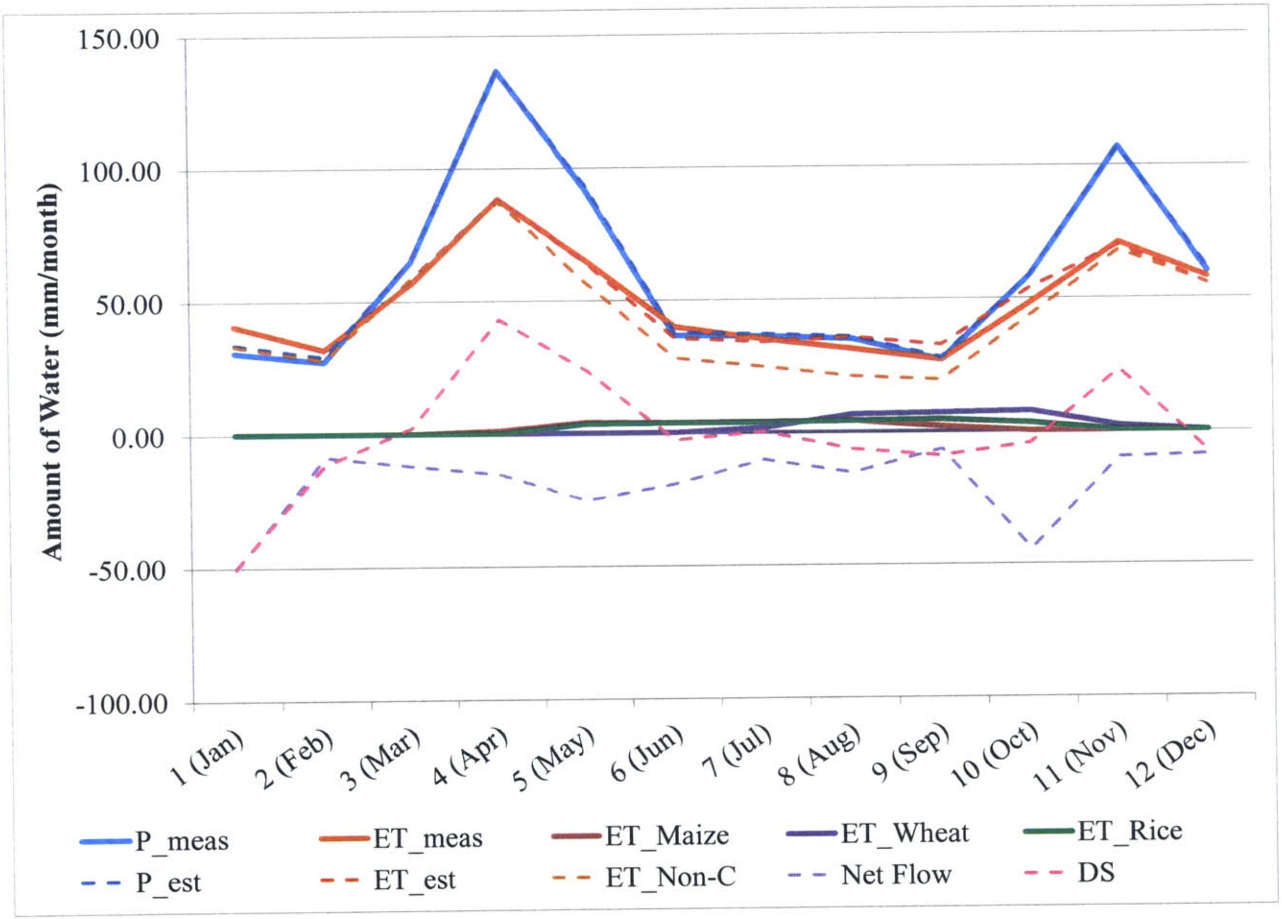


Figure 4. 33: Summary of Results; Scenario 3 – Optimization 2

4.5 Summary of Results

The table that follows summarizes the results of this analysis for all four scenario considered, plus the current conditions as reproduced by the first optimization in the base case. This table shows the calories produced, the area occupied and evapotranspiration for each crop, for each scenario. It also shows the annual non-crop evapotranspiration and the annual pixel outflow for the whole country. Lastly, it shows the total withdrawals from storage over a year.

		Current Conditions	**Base Case**	**Scenario 1** Grades 1-4	**Scenario 2** Low Precip	**Scenario 3** Maintaining River Flows
Calories (*10^9 kcal/year*)	Maize	10,200	27,700	48,200	22,800	14,800
	Wheat	830	22,700	65,900	21,200	21,500
	Rice	70	38,200	67,100	29,100	19,500
	Total	**11,100**	**88,600**	**181,200**	**73,100**	**55,800**
Area (*km^2*)	Maize	15,400	29,600	61,700	23,400	14,700
	Wheat	12,300	26,500	93,200	24,000	24,200
	Rice	14	28,100	56,200	20,300	13,600
	Total	**27,714**	**84,200**	**211,100**	**67,700**	**52,500**
Crop ET (*km^3/year*)	Maize	11.58	22.27	44.27	17.69	11.08
	Wheat	0.68	15.90	49.92	13.98	14.56
	Rice	0.14	26.24	41.10	19.21	12.85
	Total	**12.40**	**64.41**	**135.29**	**50.88**	**38.49**
Total Non-crop ET (*km^3/year*)		303	252	256	284	306
Total Pixel Outflow (*km^3/year*)		1,200	772	161	653	997
Storage Change Total Withdrawals (*km^3/year*)		115	118	122	95	108

Table 4. 29: Summary of Results

Chapter 5 – Discussion

Given the data used and the assumptions made in this analysis, the predicted production for the year 2000 is as follows. In addition, the actual production in 1000 metric tons for the same year is shown (FAOSTAT 2015B).

Staple Food Production		
	Predicted	Actual
	1000 metric tons	
Maize	2,809	2,160
Wheat	252	204
Rice	20	35

Table 5.1: Predicted and Actual production of staple foods.

The first thing to note is that our results are within the same order of magnitude of the actual production as estimated by FAOSTAT. However, there is between a 20% and 42% difference of our predicted production and the actual production. More specifically, the maize and wheat production our overestimated by our model. This might be the case for several reasons. Firstly, the area currently planted comes from a global dataset (GAEZ), which might not fully represent reality, and thus production in our model may be either overestimated or underestimated. The same applies for the soil characterization data: the data used to determine soil grades comes from a global dataset, and thus soil classification may be inaccurate at times. Furthermore, the scale of production is not taken into account. For example, maize is primarily produced by small-holder farmers who face problems with pests and can often not afford to purchase pesticides; this could – at least to some extent – explain why actual production is low than predicted. On the other hand, rice production is primarily done in a large scale by the National Irrigation Board; thus, even if the soil grade is not of high grade, efficient irrigation, improved management techniques, and application of fertilizer, may lead to higher than predicted production.

Even though there are a lot of limitations with our approach and it does not fully represent reality, it is a good approximation that can be used to identify potential for increasing production in areas of Kenya.

5.1 Discussion of Results for Base Case Scenario

5.1.1 Discusion of Results for Base Case Scenario: Optimization 1

5.1.1.1 Precipitation and Actual Evapotranspiration

The results of this optimization reveal that precipitation is, in general, slightly increased. Overall, precipitation changes do appear to have a small spatial correlation: precipitation changes are smaller in the wetter areas. This correlation is more pronounced temporally: precipitation changes are minimal in the wetter months – especially March and November. However, some values of precipitation show a decrease between 0 and 5%. Most of these increases are less than 0.1%, and thus are minimal

Contrary to precipitation, actual evapotranspiration is decreased in general. However, similarly to precipitation, these changes appear smaller in the months of high evapotranspiration, namely March and November. There are some cases though, in which the value of evapotranspiration was increased by more than 100% - these are not shown in the graph as there is a really small number of them, and thus they are not visible. These increases occur in the areas where maize is grown to a great extent.

These changes suggest that the data used in this analysis could plausibly represent the current situation observed in Kenya.

5.1.1.2 Crop Evapotranspiration

Crop evapotranspiration is calculated here in order to establish a baseline to which other scenarios can be compared. As expected, most of the water comes from maize, since it is the most planted staple food.

5.1.1.3 Other Water Fluxes

The main purpose of this optimization was to determine the nominal non-crop evapotranspiration that accounts for the local vegetation and other crops. As we can see in figure 4.2 the non-crop evapotranspiration, more often than not accounts for the total actual evapotranspiration. This happens primarily because the majority of the country in not currently planted by the crops in question and thus the evapotranspiration is accounted for by local vegetation and other crops. In some cases however, non-crop evapotranspiration accounts for a small percentage (or 0%) of the total evapotranspiration; this is the case in areas in which primarily maize is planted. In some cases, the non-crop ET even drops to zero in an attempt to allocate all the water to the crop.

In this optimization, ET non-crop was bounded by estimated precipitation. As a result, non-crop ET is often equal to all of the precipitation; this is primarily the case during the dry months. In addition, there are cases when non-crop ET is a small percentage of precipitation, or even 0%; as before, this happens in locations where crops are currently planted.

The pixel outflow was also estimated by this precipitation. As can be seen in figure 4.4.2 annual pixel outflows essentially delineate the main rivers in the country. This is a good sign that our optimization accurately directs flow within the country to the main rivers. There is one flaw in this delineation: the Ewaso Ng'iro River (see figure 2.14) does not flow into Somalia – the East; rather it stops at a swamp. This is not accounted for in the model. Pixel outflow however, does not seem to be correlated with precipitation. Rather it acts to balance water in each pixel together with change in storage. The case January is worth noting: the highest flows are observed during that period. This happens because water is withdrawn from storage and redirected into pixel outflow. This is possible in the model because there is no continuity implied in either pixel flow or storage, by which I mean that the pixel outflow, or the storage change between months are not related. As such, both these variables take up the slack from other variables in order to yield a mass balance. However, since they are independent, occurrences like the one in January are expected.

Contrary to pixel outflow, storage change is correlated with precipitation – with the exception of January. As expected, the increase in storage is higher in the wet months – April and November and almost zero, on average during the dry months when most of the precipitation is allocated to evapotranspiration. The spatial distribution of the change in storage is shown in figures 4.4.3. In March, a month with average precipitation outside the growing season, overall, storage is slightly replenished in the wet parts of the country, and slightly depleted in the drier parts of the country. In July, a month with low precipitation, in the middle of the growing season, storage is mostly depleted throughout the country. The main exception is a section of the country in the west where storage is increased. This happens primarily because this is an area with high rainfall and relatively small planted area. In addition, there is no need to redirect the flow downstream since the rivers flow to the south west, where there is plentiful precipitation. Lastly, the change in storage in November is shown, a month with high precipitation at the end of the growing season. As expected, recharge is high throughout the country, primarily in the wet areas.

5.1.1.3 Summary of Resuls from Optimization 1

The results from optimization 1 are summarized in figure 4.5. This graph shows that the estimated and measured precipitation match relatively well. The crop evapotranspiration from wheat and rice are minimal in the current situation, while the evapotranspiration from maize is significant enough that it makes non-crop ET slightly less than total estimated ET.

5.1.2 Discusion of Results for Base Case Scenario: Optimization 2

5.1.2.1 Calories Produced

The total calories produced in the base case were 88,592 billion kcal per year, resulting in a total increase of calories by a factor of approximately 8. Rice produces the most calories (38,156 B kcal/yr), followed by maize (27,691 B kcal/yr) and then wheat (38,156 B kcal/yr). Most of the calories produced come from grade 3 land, as more grade 3 land is available and allocated to the crops.

5.1.2.2 Area per Crop

The distribution of the area planted by each crop is shown in figure 4.6, while the area planted by soil grade is shown in table 4.6. For wheat all of the grade 2 land is used, while for maize 99% of the grade 2 land is used. For maize and wheat, approximately 26,000 km^2 of grade 3 land are planted, while for rice the grade 3 land is greater (28,000 km^2). This happens because rice has the highest attainable yield, and the highest calories along with maize.

It appears that for grade 2 land the main restriction is the area available as almost all of it is chosen for planting. For grade 3 land this is the case too, even though it is not as obvious. This is the case because there is a lot of overlap between the grade 3 available land, as can be seen in figure 3.12. Another thing to note about the resulting area of this optimization is that a big strip of land, currently occupied by maize ranging from the middle of the country to the south, is no longer being used. This happens because the area is characterized primarily as grade 4 land, which is not considered in this scenario.

5.1.2.3 Crop Evapotranspiration

Crop evapotranspiration has changed from the base case as expected, since the area planted has increased. As expected, rice ET has increased the most, followed by wheat ET.

5.1.2.4 Other Fluxes

Outside the planting season, non-crop evapotranspiration has not changed, as it should. However, overall non-crop ET has decreased during the cropping season. This results in a decrease in annual ET in the areas used for crops as seen in figure 4.7. However, in some cases the non-crop evapotranspiration becomes greater than precipitation, since it was not bounded by it. This happens in the places that were planted in optimization 1, but are no longer used in optimization 2, and thus the non-crop evapotranspiration in the original optimization was underestimated with regards to the second optimization.

When crop production is increased the total pixel outflow is decreased. Overall, total annual outflow decreases, as shown in figure 4.9.2 since the main rivers become depleted. One big change in the pixel outflow is that it becomes correlated with precipitation.

The change in storage retains the patterns we saw in the first optimization, with the exception of the outlier January. Overall, the average change in storage decreases during the planting season – suggesting that groundwater is used to water the crops. This evidence is supported by the fact that the maximum drawdown during the planting season is also higher than in the base case.

5.1.2.5 Summary of Results for Optimization 2

The summary for optimization 2 of the base case scenario can be found in figure 4.11. This graph shows that the crop evapotranspiration increases for all three crops. Even though non-crop evapotranspiration decreases to account for the land that is no longer available for this evapotranspiration, total evapotranspiration increases. As a result, total estimated ET becomes larger than what was measured. Even though, this ET may be possible given water availability, it may not be possible if a thermodynamic limit is applied. This graph also shows that the change in storage and net flow follow the observed precipitation pattern.

5.1.3 Implications of results of base case scenario

As is clear from the results presented in this section, the total area cultivated by all three crops can be increased by a significant amount. In addition, the total calories produced can also be increased. The table below shows the breakdown of people that can be fed by the increased production, given the current consumption of these three staple foods.

People Fed			
	Now *10^6 ppl*	**Optimized** *10^6 ppl*	**Change**
Maize	41.9	113.1	1.70
Wheat	8.9	243.9	26.36
Rice	2.1	1,066.7	517.19

Table 5.2: People fed under current conditions and base case scenario

The results suggest that if Kenya were to use the areas produced by this analysis, it could more than sufficiently feed its population in 2050. In 2050, it could even be an exporter of maize as it aims to be. That said, past that year it may not be able to produce enough maize if the diet composition remains the same given the assumptions of this scenario.

Under this scenario, more than half the country is allocated to production of these three staple. This is not only infeasible in terms of implementation, but also in terms of trade-offs.

Even though these three crops are the most important in the Kenyan diet, and as such the government supports efforts to increase production, they are also low value crops. If a farmer had to choose between growing these crops or some other high value crop, such as tea or fruits and vegetables, he would most likely choose the latter in an attempt to earn a higher income.

In addition, this model assumes that irrigation is used, by either using runoff accumulated in river or streams. Specifically, out of the 419 pixels selected for cultivation, only 220 have enough water for rain-fed production, which is currently the norm in Kenya. Even though it suggests that there is still a very high potential if irrigation is not considered, it does show that if Kenya wants to reach its goal of self-sufficiency it does need to invest in irrigation. The table below summarizes irrigation requirements for this scenario:

Irrigation				
	Area		Water Requirement	
	km^2	*% of total*	*km^3*	*% of total*
Maize	12,210	41.2%	8.68	39.0%
Wheat	12,561	47.5%	7.17	46.6%
Rice	16,299	58.0%	15.43	58.3%

Table 5.3: Irrigation Requirements; Base Case Scenario

This is especially true for rice: more than 40% of the pixels selected for planting do not have enough rainfall – on a monthly basis – to grow rice. Actually the model has determined that there are 1.6 million hectares available for rice cultivation under irrigated conditions, while there are 1.2 million hectares available for rice under rain-fed conditions. This is within the realm of what the Ministry of Agriculture has estimated (1 M ha and 0.5 M ha respectively). However, the question of spatial distribution arises: we predict much higher development in the Ewaso Ng'iro (North-East) and Rift Valley (North-West) basins, than the government of Kenya has estimated have potential for irrigation. That said, the former basin has very high availability of groundwater, and the latter one has had an aquifer recently discovered.

Overall, the results of this scenario are very positive, and show that there is high potential for increasing staple food production in Kenya. That said, the results need to be interpreted cautiously for two reasons:

(1) This is a macro scale analysis with limitations (discussed in section 6.2)

(2) The results presented set an upper bound to potential production. The extent to which this upper bound is reached also depends on current conditions in the land as well as implementation methods used.

5.2 Discussion of Results for Scenario 1

This scenario considers soil grades 1 through 4 to be available for cultivation. The results are discussed here.

5.2.1 Discusion of Results for Scenario 1 : Optimization 1

The results for this scenario are the same as the results for the base case scenario as the inputs to this optimization have not changed. Please refer to section 5.1.1.

5.2.2 Discusion of Results for Scenario 1 : Optimization 2

5.2.2.1 Calories Produced

The first thing to note about the results of this optimization is that the calories produced almost double, by allowing cultivation in grade 4. This shows that by having grade 4 in production, creates a much greater potential for agriculture. The most interesting thing to note here is that even though maize and rice appear to almost double in calories produced, wheat more than doubles.

5.2.2.2 Area per Crop

Overall, each crop is allocated approximately 50,000 km^2. More specifically, for both maize and wheat all the available area for grade 2 soil is being used, similarly to before (maize area is increased by 1%). For soil grade 3 the most land is occupied by wheat, followed by rice and the wheat, with approximately 38,000 km^2, 28,000 km^2 and 26,000 km^2 respectively. Lastly, for soil grade 4, wheat occupies the most area, followed by maize and then rice.

The spatial distribution of the crops reveals that new areas are opened up for cultivation. Specifically, maize is further expanded to the north, wheat is expanded towards the coast, and rice is expanded to the highlands. It should be noted that here there are several instances where the whole pixel (average size 770 km^2) is allocated to production. This would either entail large-scale production, or small-holder farms distributed with some loss to the total area.

Again, the interesting thing to note here is the prevalence of wheat. One possible explanation for this is that if there is an overlap between grade 4 maize and grade 3 wheat, then preference is given to grade 3 wheat due to the higher caloric content produced per unit area.

5.2.2.3 Crop Evapotranspiration

However, the most likely explanation as to why wheat is expanded by so much is given by crop evapotranspiration. The water requirement for wheat is much lower than that for maize or rice. As a result, if there is potential for production, and some water left to balance, then preference will be given to wheat if water is scarce in that pixel. As a result, wheat is primarily co-located with the other crops in its production. Here, please note that the maximum wheat consumption is greater than the crop requirement. This is the case because reference evapotranspiration varies across the country, and an average value was used to calculate the crop requirement.

5.2.2.4 Other Fluxes

It is clear from the evapotranspiration map that overall, non-crop evapotranspiration decreases substantially across the country. This is due to the fact that during the growing season non-crop evapotranspiration is significantly reduced since area is taken up by the crops.

Furthermore, pixel outflow decreases significantly; by at least an order of magnitude at the areas of interest, which are the main rivers in the country. As the figure shows, after the increase in agricultural area, the rivers are barely visible.

Lastly, the change in storage decreases overall. More specifically, the maximum drawdown goes down as does the average. Furthermore, the groundwater seems to reach its lower bound in multiple case in August and October. This is the case because these months have low precipitation and the river flow is most likely not enough to provide enough water.

5.2.2.5 Summary of Results for Optimization 2

The summary of the results are shown in figure 4.16. The most interesting thing to note here is that the estimated evapotranspiration (total crop and non-crop ET) has increased significantly during the growing season. Again, since a thermodynamic limit is not applied, we cannot be certain that there is enough energy to do so; however, it is very likely given the climate in Kenya. Another interesting thing to note is that the net flow remains approximately the same.

5.2.3 Implications of results of Scenario 1

As with the base case scenario the number of people that can be fed is shown below:

People Fed			
	Now 10^6 ppl	Optimized ppl	Change
Maize	41.86	196.87	3.70
Wheat	8.92	708.03	78.42
Rice	2.06	1,875.52	910.09

The case for irrigation is even greater here. Out of the 557 pixels selected for cultivation, 195 need to be irrigated throughout the season, while 432 will require irrigation at least at some point during the season. Even though rice is the crop with the highest water requirement, wheat is the one that requires irrigation in the most locations. However, rice requires more irrigation volume in total. This is the case because more wheat is planted opportunistically rather than strategically.

This analysis suggests, that if worse than average land is used for cultivation, then Kenya has a massive opportunity to increase production. As with the base case scenario, the results here are merely representing an upper bound given the assumptions made. There is value to this scenario with respect to two main points:

(1) There are other areas within the country that could be viable for production that were not shown in the base case scenario. Even though this soil is below average, there is sufficient water in the dry (but not driest) regions of the country. This means, that people who are living in those areas, can still find a way to be employed in agriculture (assuming either enough water is available through precipitation or they have access to irrigation.

(2) Without regulation and with increased agriculture, the rivers are at high risk. As is clear there is a very high potential that rivers will get depleted if extraction from them is not monitored and production is left to grow uncontrollably. Even though in this scenario groundwater depletion is bounded relative to precipitation, it is clear that the drawdown is at the limit during the dry months of the growing season. This suggests that as with the rivers, similarly with groundwater, if left uncontrolled it may be threatened.

	Irrigation			
	Area		**Water Requirement**	
	km ^{2}	*% of total*	*km* ^{3}	*% of total*
Maize	40,609	65.8%	28.26	63.8%
Wheat	10,374	43.3%	5.95	42.6%
Rice	82,394	88.4%	52.03	89.2%

Table 5.4: Irrigation requirements; Scenario 1

One last thing to note about this scenario is that it has very high requirements for irrigation. Particularly, rice will require almost all of its water to come from irrigation as is currently done in Kenya. This is why the depletion of the rivers is so high.

5.3 Discussion of Results for Scenario 2

5.3.1 Discusion of Results for Scenario 2 : Optimization 1

In this scenario the first optimization was run with different inputs: precipitation that was lower by 20% of the standard deviation. The first thing to note here is that the least squares error is extremely small and several orders of magnitude lower than that of the base case scenario.

5.1.1.1 Precipitation and Actual Evapotranspiration

The first thing to note here is that the patterns of the percentage change in the estimated values is different – it no longer looks like a normal distribution. As before, in general, the precipitation increases, while the evapotranspiration decreases. However, the distribution of the percent change is very different. The number of percent changes slightly over zero have almost doubled here. This happens because the lower precipitation cannot account for all the observed evapotranspiration. Therefore, the model selects to slightly increase precipitation and decreases evapotranspiration proportionately more in order to yield the appropriate mass balance.

These changes lead to an extremely small least squares error. This suggests that the estimated values from this model are a better fit the measured values, than in the case of the base case scenario.

5.1.1.2 Other Water Fluxes

As the precipitation in this scenario is lower, the non-crop evapotranspiration is on average a greater percentage of the non-crop evapotranspiration. Overall, the average minimum and maximum non-crop evapotranspiration have decreased. This is expected since the non-crop evapotranspiration is bounded by precipitation. An interesting thing to note here is that the minimum value of evapotranspiration is zero for more months. This happens because the new low precipitation has a significant number of instances where precipitation is zero for a month. Even though this is extreme, it is an approximation of a potential low precipitation pattern. The spatial distribution of evapotranspiration has also slightly changed: the dry areas have been expanded.

With less water available, the pixel outflow has also decreased on most counts with the exception of May, June and July. This happens because the estimated evapotranspiration is lower than the estimated evapotranspiration in those months (this is visible in the summary of the results). This is the case because these months are in the growing season and thus more water is most likely required than is available. Figure 4.19.2 shows that the river flow has also fallen due to the lower precipitation.

For the storage change we observed that on average it is more negative, meaning that more groundwater is being used. In addition, the maximum storage change values are also lower, meaning that the recharge is not that high. Exceptions to this are August and September, mostly likely because of the increase ET due to planting.

5.1.1.3 Summary of Resuls from Optimization 1

The summary of the results show that the measured precipitation for this scenario is in general much lower than the base case measured precipitation primarily in the wet months. In addition, we see that the estimated precipitation is a very good match to the measured precipitation. The estimated evapotranspiration does not match the measurements as well in this scenario – it is mostly lower in the cropping season. The change in storage does vary with precipitation as does the net flow.

5.3.2 Discusion of Results for Scenario 2: Optimization 2

5.3.2.1 Calories Produced

The calories produced in this scenario are increased by a factor of 6.55. Even though this is still very high, it is lower than the change observed in the base case scenario. Specifically, calories produced by maize almost double, while calories produced from rice increase by a factor of almost 400; both these changes are lower than in the base case scenario. However, wheat calories remain approximately at the same level as they were for the base case scenario.

5.3.2.2 Area per Crop

The pattern observed in the calories is also observed for the calories produced. The areas planted by maize and rice decrease proportionally more than wheat does relative to the base case scenario. Spatial patterns have in general stayed the same as with the base case, with the exception of planting of maize and rice in the north. This is most likely the case because under the new precipitation, these areas receive less precipitation and do not have access to major rivers.

5.3.2.3 Crop Evapotranspiration

The changes observed in the crop evapotranspiration follow patterns similar to those observed in area and calories. An interesting thing to note here is that the maximum evaporation for rice is the same in the two scenarios. This means that even though less rice is planted in total, same areas maintain their high rice potential under the low precipitation conditions.

5.3.2.4 Other Fluxes

As with the previous scenarios, non-crop evapotranspiration decreases during the growing season. The overall pattern of non-crop evapotranspiration remains similar to that of the base case scenario, however, the values are much lower due to the lower precipitation.

Overall, the pixel outflow decreases as can be seen by the map. This results in significantly lower annual flow in the main rivers. On a monthly basis, the average pixel outflow is lower, due to the lower precipitation. However, it is interesting to note that in April and November, the high precipitation maps, the pixel outflow increases. This happens so that water can be carried downstream for irrigation.

In general, for the storage change we observe that the minimum drawdown is lower, suggest that more groundwater is withdrawn. This is also evident in figure 4.24, where in approximately 10% of instances, every month, water is withdrawn from the ground.

5.3.3 Implications of results of Scenario 2

In this scenario we explored what happens when precipitation is lower than in the base case. As expected, the amount produced is lower since there is less water available. Overall, the calories produced are 17% lower than in the base case, while the reduced precipitation was 16% lower than in the base case. Thus, there is a very distinct correlation between precipitation and production. The following table shows the number of people that can be fed in this scenario given the current consumption of these three staple foods:

	People Fed		
	Now 10^6 ppl	**Optimized** ppl	**Change**
Maize	41.86	92.93	1.22
Wheat	8.92	227.95	24.57
Rice	2.06	813.33	394.10

Table 5.5: People fed under current conditions and scenario 3

This suggests, that if Kenya were to experience lower than average precipitation for a prolonged period of time, its ability to feed its people with regards to maize will deteriorate. The population of Kenya is expected to approach 100 million by the year 2050. The results here suggest that production of maize under these condition may not suffice for feeding the increased population. This of course assumes that the tradeoff between maize wheat and rice is being taken into consideration. Having a high yield, and the same calories as maize, rice produces more calories even with less area. This therefore presents a dilemma: if precipitation is expected to be low in the future should an investment be placed in rice, which is more water intensive, but has a higher yield, or maize which requires less water, but at a lower yield? Given that rice has a higher production per unit of water used, the investment should be made in rice, at least in theory. In practice, maize is the main staple food of the Kenyan diet and is somewhat of an issue of national pride. On the other hand, rice is the staple food with the lowest contribution to the diet, and is mostly consumed in the cities.

However, this decision also depends on water availability. The table below summarizes the irrigation potential as identified in this optimization.

	Irrigation			
	Area		Water Requirement	
	km^2	*% of total*	*km^3*	*% of total*
Maize	7,764	33.2%	5.61	31.7%
Wheat	10,374	43.3%	5.95	42.6%
Rice	9,169	45.0%	8.68	45.2%

Table 5.6: Irrigation requirements; Scenario 2

The table above suggests that approximately half of the area identified for rice will need to be irrigated. Therefore, the choice between rice and maize is also complicated by water availability. This is especially an issue for small-holder farmers who do not have easy access to irrigation. In addition, there is another dimension that has not been considered: high value crops. Here, we are trading off crops with regards to their caloric value and not monetary value. However, when water is scarce, the farmer needs to make a decision between growing cereals (whose values are vulnerable to precipitation) or fruits, vegetables, tea, and so on, whose values are more staple and higher are they are sold abroad.

5.4 Discussion of Results for Scenario 3

5.4.1 Discusion of Results for Scenario 3 : Optimization 1

The results shown for this optimization are the pixel outflows at selected locations: these locations represent four of the main rivers in Kenya. From the results we can see that the flow in at least one month for each location is zero. This does not represent what the data suggest: that most of the rivers are permanent. This happens because the flow is not constrained in this optimization, other than by the fact that it has to be positive.

The data retrieved suggests that the Tana and Upper Athi River have flows that are correlated with precipitation. However, this is not the case in the results of this optimization. The flows predicted by the model seem to be uncorrelated with precipitation, with the exception of River Athi, which does peak in April and October in the results, but in May and November in the data.

5.4.2 Discussion of Results for Scenario 3: Optimization 2

5.4.2.1 Calories Produced

As we can see from table 4.23 this scenario produces an allocation of land and water such that calorie production can be increased by a factor of 5. Specifically, maize production can be more than doubled, while wheat and rice production are increased by a factor of 27 and 265 respectively.

It should be noted that the resulting calorie production is lower than what the base case scenario produces. This is because in this case, almost half the amount of rice and maize are produced. However, wheat production is only slightly reduced from the base case. The distribution of calories per soil grade also reveals that approximately a third of the calories produced from maize come from grade 2.

5.4.2.2 Area per Crop

Overall, the pattern of cultivation remains the same as with the base case scenario, with some minor exceptions. Particularly, maize is no longer grown at the northern part of country – in the Turkana region, or in some parts of the Lake Victoria basin. The same applies for rice as well. In addition, the fraction planted in each pixel is smaller than it was in the nominal case, resulting in less area cultivated in total.

5.4.2.3 Crop Evapotranspiration

The ranking of crop evapotranspiration has changed as well: wheat evaporates the most water, followed by rice and then maize. This happens because wheat has the lowest crop requirement, and therefore, when the amount of water available in each pixel is constrained, it is preferred even though it has less calories.

5.4.2.4 Other Fluxes

With regards to non-crop evapotranspiration we see that it increases overall, and accounts for a larger part of total ET and precipitation. This is the case because the total crop evapotranspiration is lower than it was in the base case scenario and as a result, the ET non-crop increases. It is interesting to note that the non-crop ET in November in scenario 3 is almost equal to the non-crop ET of scenario of the base case in the same month. In November, the only crop planted is wheat, and thus this once more reveals the extent to which wheat is planted in this scenario.

In this scenario the pixel outflow was bounded by 75% of the nominal value. This constraint has achieved its goal: the flow of the rivers is almost perfectly preserved. When compared to the nominal flow we see that overall, both the average and the maximum are slightly lower. The results are more interesting when compared to the pixel outflow from the base case optimization 2. Firstly, the pixel outflow in the areas of interest – the rivers – is on average higher in the second optimization as can be seen from the maps. However, the interesting thing to note is that in April, May, Jun July and November, the average flow in the base case scenario is higher. This is most likely the case because water is accumulated in the rivers to be carried downstream and later withdrawn for agriculture.

Regarding the storage change we see that it overall maintains the same pattern as before. In addition, we see that on average, this scenario has lower storage change values. This suggests that since the pixel outflow needs to be maintained, then water is withdrawn from storage, either to replenish the rivers or, most likely, water the crops. Furthermore, it is interesting to note that the drawdown reaches its lower limit 3 times more often in the base case scenario. This can also be seen by the fact that the minimum values for storage change are lower in the base case scenario. This means that even though the rivers need to be maintained, having less cultivated area, really affects the amount of water withdrawn from storage.

5.4.2.5 Summary of Results for Optimization 2

The summary of the results for this optimization reveals that most of the patterns are very similar to those in the base case. The main difference is that the crop evapotranspiration is not as high, and as a result the non-crop evapotranspiration is not as low. The other difference is that the Change in storage and net flow are extremely low in January. This is because the flow was constrained to the values of the nominal flow and as a result the inconsistency in January remains.

5.4.3 Implications of results of Scenario 3

This scenario has shown that being sustainable comes at a small cost. Specifically, a great increase in production can still be achieved. However, this increase is not equally distributed among the crops. The table below shows the number of people that can be fed with the production from this optimization:

People Fed			
	Now *10^6 ppl*	**Optimized** *ppl*	**Change**
Maize	41.9	60.5	0.45
Wheat	8.9	230.5	24.86
Rice	2.1	544.4	263.44

Table 5.7: People fed under current conditions and Scenario 3

The table above shows that the expected population of 100 million people may not have enough maize to be self-sufficient under this scenario. However, they will have more than enough wheat and rice. These results suggest that maybe being self-sufficient in maize should not have so much emphasis placed on it. Even though wheat has less calories, it has a much lower water requirement. In addition, its suitable land area is approximately distributed in the same way as that for maize is. This is particularly important given the context for wheat: currently it is primarily produced by large scale farmers. However, it seems like wheat would be suitable for production by small-holder farmers given that it does not require much water. That said, the main limitation at the moment is lack of management and good seeds. Therefore, there is a great opportunity here: increasing wheat through small-holder production.

The question of water sources thus arises. The irrigation requirements per crop are summarized in the table below:

Irrigation				
	Area		**Water Requirement**	
	km^2	*% of total*	*km^3*	*% of total*
Maize	1,762	12.0%	1.24	11.2%
Wheat	9,717	40.1%	5.74	40.1%
Rice	4,226	31.0%	4.02	31.3%

Table 5.8: Irrigation Requirements; Scenario 3

As we can see from the table above, wheat has the highest water only in absolute value, but also relative to the total water requirement for the crop. This means, that even though wheat has the lowest water crop requirement, it needs to be irrigated in the scenario. At the same time, rice, which has the highest water crop requirement, needs less water in this scenario. This happens because of what was described above: wheat is selected to essentially fill in the gaps.

This means though that it will be relatively harder to purse what was recommended above: expand wheat by engaging small-holder farmers. This is the case for two reasons: firstly, because pumping groundwater is expensive – and as we can see in figure 4.26 it is being used in November in areas planted by wheat. The second reason developing an irrigation system needs to be done by the government.

That said, the case for maize is very positive in this scenario. Even though it is not cultivated to the extent it was in the base case scenario, here it is done so in a way that requires minimal irrigation. This means that small-holder farmers could opt to grow maize. This is always a safe choice for farmers since the way to the market for maize is well developed and prices are sometimes controlled by the government to protect the farmers.

The implications of this scenario are that Kenya can still have a large potential to increase its cereal production, even if some environmental constraints (such as maintaining river flows, and sustainable groundwater extraction) are impose. This scenario needs to be further explored, maybe even as a base, but the results are promising.

Chapter 6 – Conclusion

6.1 Can Kenya increase its production of cereals?

The analysis conducted here suggests that Kenya can increase its production of cereals (maize, wheat and rice). The different scenarios explored in this thesis show that are different combinations of producing these three crops that yield very different results. The increase in total calories varies between a factor of 5 and a factor of 16 when compared to current production. In addition, each scenario has different implications. The main conclusions that can be drawn are summarized here:

(1) **Kenya does have the potential to increase its production of cereals**. The degree to which they achieve this depends on what parameters are being considered. Nonetheless, neither land nor water limit the country's ability to produce to an extent that causes worry.

(2) **Irrigation will be essential in increasing the production of cereals**. In most scenarios, at least 30% of the total allocated land to production needs to be irrigated either using groundwater or surface water. Investment will be required to develop these schemes. This can either come from the government or from the small-holder farmer directly.

(3) **The effects on river flow and groundwater need to be considered.** Overall, all cases reveal that increasing production will lead to a decrease of the river flow and an in half the cases an increased withdrawal of groundwater. This means, that with the expansion of agriculture, the country's water resources need to be protected.

Even though Kenya is currently facing a food security problem, at least to some extent, this thesis has shown that it is an optimistic case: water and land resources are available. The government of Kenya has identified the large potential that the country has in terms of agriculture and is taking steps to take full advantage of it.

6.2 Limitations

The analysis conducted here is not without limitations. The main limitations are discussed here.

Maintaining River Flow

The main limitation to this analysis is that maintaining river flow is not considered in a way that fully represents current conditions. As a result, as crop production increases the main rivers in Kenya become depleted to extreme low levels. Currently, monthly data for river flows is not publicly available from a reliable source, and as such it has not been considered in this analysis. In addition, the environmental/water reports that have been issued by the Kenyan government have not quantified the "safe" flow for the rivers as to guide abstractions. That said, maintaining the flow of the main rivers in Kenya is important in sustainably increasing food production for the country. This has been shown in this analysis (Scenario 3), but a more thorough analysis would better portray the tradeoffs.

Groundwater

Contrary to river flow, groundwater was assumed to be used sustainably in this analysis. However, the amount of groundwater available has not been quantified regionally in an absolute manner, rather it quantified relative to precipitation. Even though currently groundwater is not used to a great extent in Kenya, or agriculture in Kenya, the analysis has shown that it hold an important role in reaching the potential production suggested by this report.

Soil classification

The data suggests that currently Kenyans are growing maize, wheat and rice on soil that has been classified as grade 5; we would thus expect that this soil would yield no output. However, given that this soil is being used it most likely is fertile, at least to some extent. This suggests that there might be some missing information in the analysis conducted. Vast amounts of the country are classified as low-yield or infertile land. Even though, the potential to increase production is still very high, should the classifications for soil grades 4 and 5 be different, it would open up opportunities for production in other parts of the country – mainly the North and North-East.

6.3 Recommended Further Research

6.3.1 Addressing the limitations

As mentioned in the previous section, there are some limitations to this approach. Addressing these limitations is the first recommendation for further research on this topic. Specifically, constraining the flow of the main rivers in Kenya to a minimum acceptable level for each month will enhance the validity of the model and will, to some extent, ensure sustainable food production increases.

In addition, groundwater availability can be more considered in more detail. Examining the water table in the different regions of Kenya will allow for a more accurate prediction of the potential to expand agriculture in Kenya. The aquifer discovered in the Turkana region, may play an important role in increasing food production in the region and should thus also be considered.

Lastly, even though the soil qualification was done on a fine scale and in a detailed manner, the information came from a global dataset, and thus it is possible that some of the soil has not been classified correctly. Addressing this issue, might yield minimal changes in the results but may also reveal that there is potential in other parts of the country as well

6.3.2 Conducting a multi-dimensional analysis

This thesis was primarily focused on the technical aspects of food production: water and land availability on a spatial and temporal scale. The financial aspect of agriculture has not been quantified. Including the financial determinants that farmers use when making decisions about harvesting will yield another dimension to this analysis. This will be particularly interesting if other crops are taken into consideration, especially the major cash crops in Kenya – tea, coffee, sugarcane – and fruits and vegetables. Currently, a large share of small-holder farmers grow tea, fruits and vegetables for exports as they are high value crops. In addition, flowers hold an important role in the Kenya agricultural economy and should be taken into account when allocating land for other production.

In addition, agricultural practices in the region could be considered in this research, and would add another dimension. Irrigation techniques vary in the country depending on the access to technology. These technologies affect the efficiency of irrigation and thus have an impact on the water balance. Furthermore, currently, fertilizer and pesticide use are low; considering them may reveal that due to lack of access to these resources some regions may not be able to reach their true potential, while other regions may become viable.

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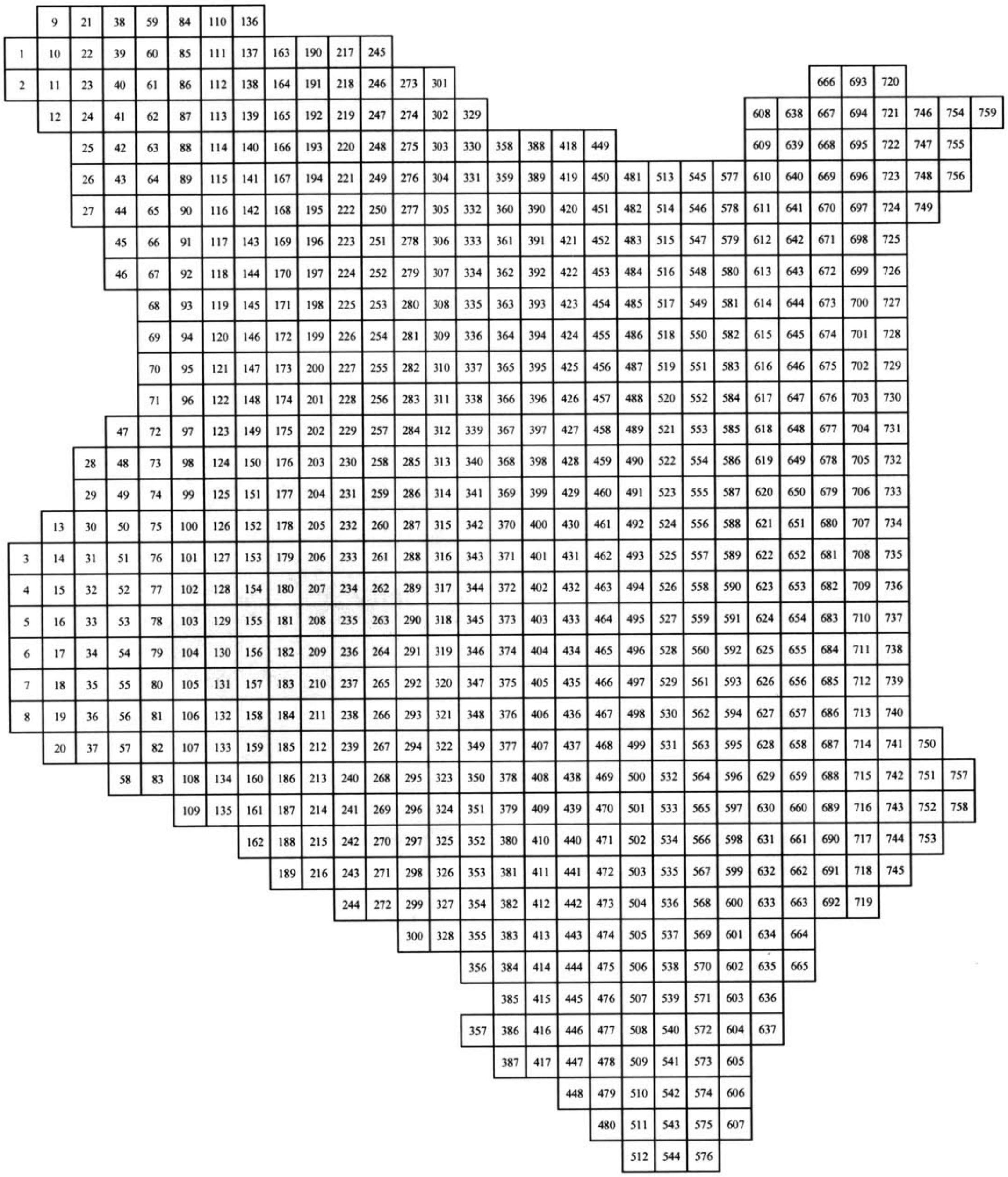
Appendix

Supplementary Material for Methodology Chapter

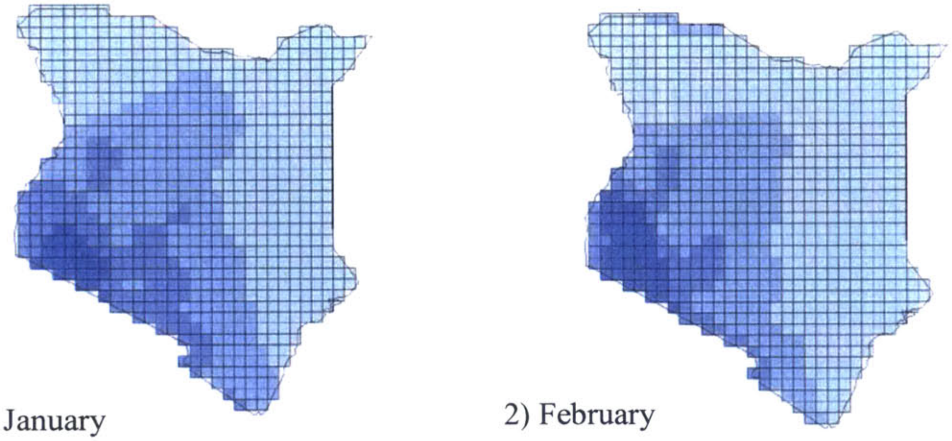
A1. Grid of Map of Kenya



	9	21	38	59	84	110	136																							
1	10	22	39	60	85	111	137	163	190	217	245																			
2	11	23	40	61	86	112	138	164	191	218	246	273	301												666	693	720			
	12	24	41	62	87	113	139	165	192	219	247	274	302	329									608	638	667	694	721	746	754	759
		25	42	63	88	114	140	166	193	220	248	275	303	330	358	388	418	449					609	639	668	695	722	747	755	
		26	43	64	89	115	141	167	194	221	249	276	304	331	359	389	419	450	481	513	545	577	610	640	669	696	723	748	756	
		27	44	65	90	116	142	168	195	222	250	277	305	332	360	390	420	451	482	514	546	578	611	641	670	697	724	749		
			45	66	91	117	143	169	196	223	251	278	306	333	361	391	421	452	483	515	547	579	612	642	671	698	725			
			46	67	92	118	144	170	197	224	252	279	307	334	362	392	422	453	484	516	548	580	613	643	672	699	726			
				68	93	119	145	171	198	225	253	280	308	335	363	393	423	454	485	517	549	581	614	644	673	700	727			
				69	94	120	146	172	199	226	254	281	309	336	364	394	424	455	486	518	550	582	615	645	674	701	728			
				70	95	121	147	173	200	227	255	282	310	337	365	395	425	456	487	519	551	583	616	646	675	702	729			
				71	96	122	148	174	201	228	256	283	311	338	366	396	426	457	488	520	552	584	617	647	676	703	730			
			47	72	97	123	149	175	202	229	257	284	312	339	367	397	427	458	489	521	553	585	618	648	677	704	731			
		28	48	73	98	124	150	176	203	230	258	285	313	340	368	398	428	459	490	522	554	586	619	649	678	705	732			
		29	49	74	99	125	151	177	204	231	259	286	314	341	369	399	429	460	491	523	555	587	620	650	679	706	733			
	13	30	50	75	100	126	152	178	205	232	260	287	315	342	370	400	430	461	492	524	556	588	621	651	680	707	734			
3	14	31	51	76	101	127	153	179	206	233	261	288	316	343	371	401	431	462	493	525	557	589	622	652	681	708	735			
4	15	32	52	77	102	128	154	180	207	234	262	289	317	344	372	402	432	463	494	526	558	590	623	653	682	709	736			
5	16	33	53	78	103	129	155	181	208	235	263	290	318	345	373	403	433	464	495	527	559	591	624	654	683	710	737			
6	17	34	54	79	104	130	156	182	209	236	264	291	319	346	374	404	434	465	496	528	560	592	625	655	684	711	738			
7	18	35	55	80	105	131	157	183	210	237	265	292	320	347	375	405	435	466	497	529	561	593	626	656	685	712	739			
8	19	36	56	81	106	132	158	184	211	238	266	293	321	348	376	406	436	467	498	530	562	594	627	657	686	713	740			
	20	37	57	82	107	133	159	185	212	239	267	294	322	349	377	407	437	468	499	531	563	595	628	658	687	714	741	750		
			58	83	108	134	160	186	213	240	268	295	323	350	378	408	438	469	500	532	564	596	629	659	688	715	742	751	757	
					109	135	161	187	214	241	269	296	324	351	379	409	439	470	501	533	565	597	630	660	689	716	743	752	758	
							162	188	215	242	270	297	325	352	380	410	440	471	502	534	566	598	631	661	690	717	744	753		
								189	216	243	271	298	326	353	381	411	441	472	503	535	567	599	632	662	691	718	745			
										244	272	299	327	354	382	412	442	473	504	536	568	600	633	663	692	719				
												300	328	355	383	413	443	474	505	537	569	601	634	664						
														356	384	414	444	475	506	538	570	602	635	665						
															385	415	445	476	507	539	571	603	636							
														357	386	416	446	477	508	540	572	604	637							
															387	417	447	478	509	541	573	605								
																	448	479	510	542	574	606								
																		480	511	543	575	607								
																			512	544	576									

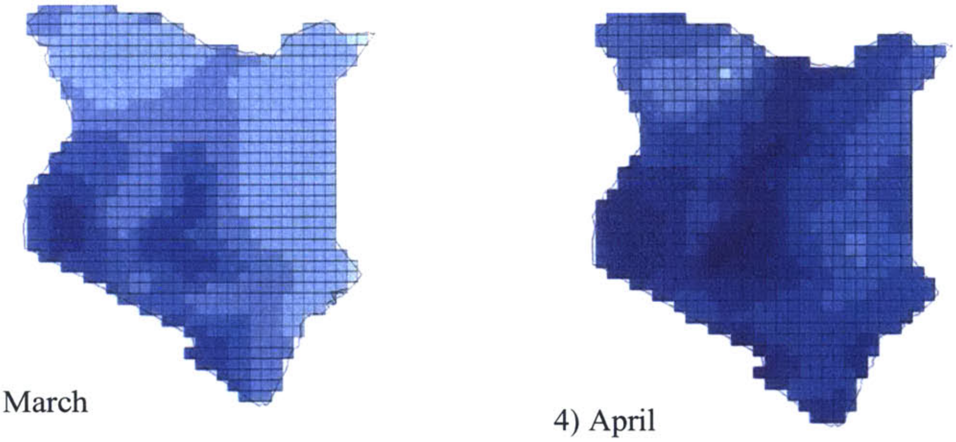
Figure A.1: Map of grid for Kenya

A2. Monthly Precipitation Maps for Kenya [Measured]



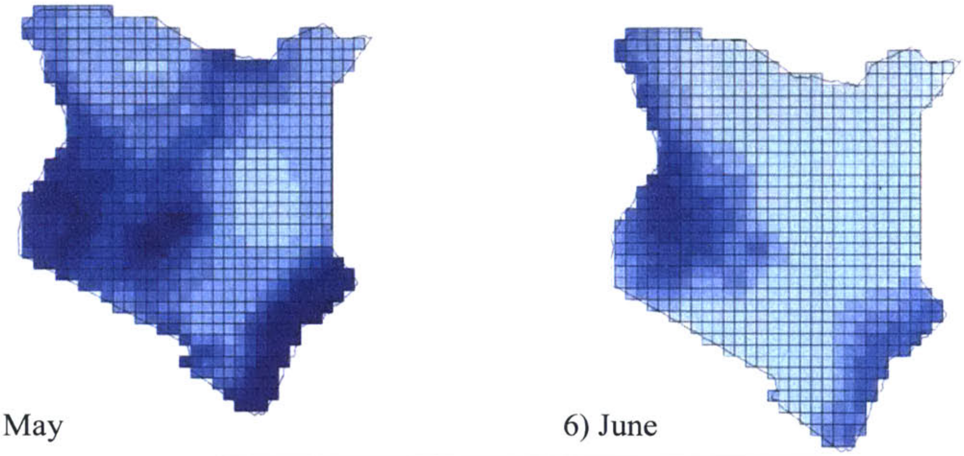
1) January

2) February



3) March

4) April



5) May

6) June

Legend

Monthly Precipitation [mm/month]

■	■	■	■	■	■	■	■
0-25	25-50	50-75	75-100	100-150	150-200	200-300	300-400

Figure A.2: Monthly precipitation Maps for Kenya (January – June)

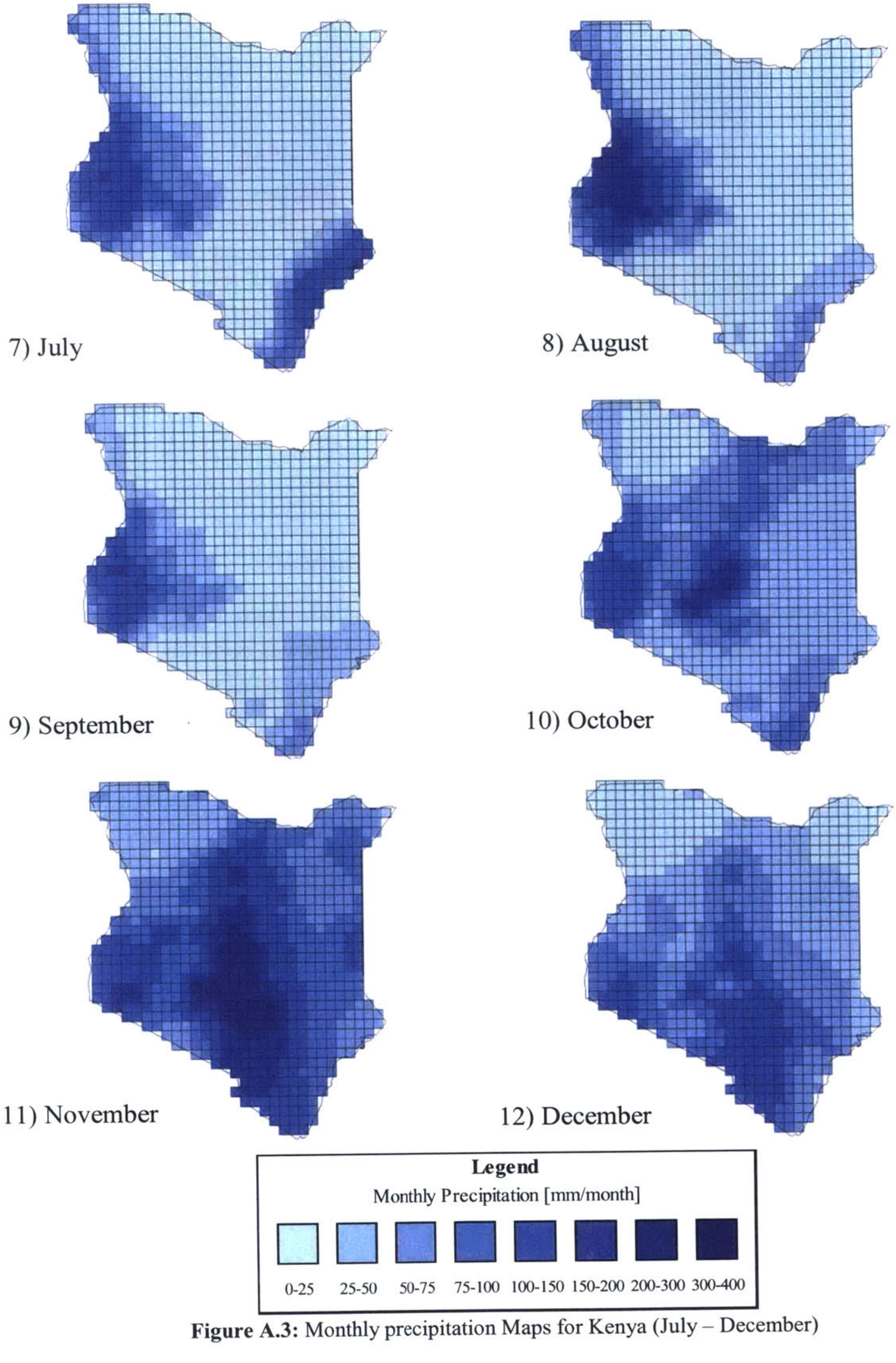


Figure A.3: Monthly precipitation Maps for Kenya (July – December)

A3. Precipitation Standard Deviation

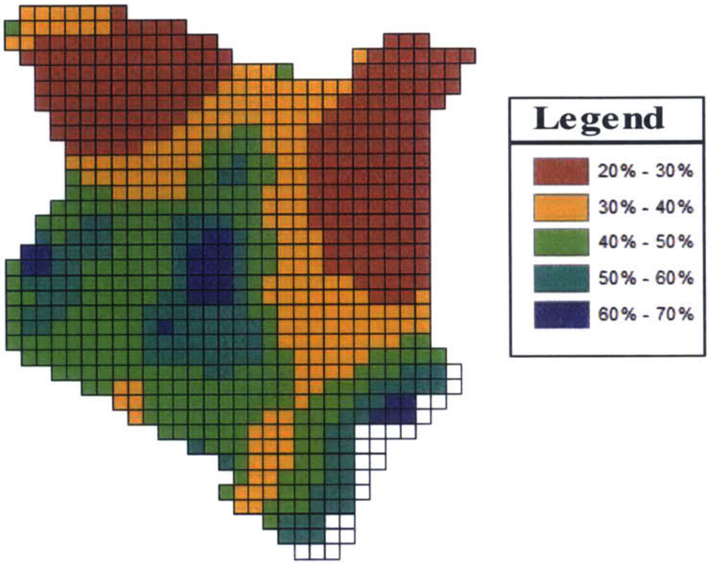


Figure A.4: Standard Deviation for precipitation

The standard deviation for precipitation was calculated. Then it was divided by the average to determine what percentage of precipitation it was. This was done for every month and every pixel. The values for every month were averaged to get an average yearly value for the relative standard deviation for every pixel.

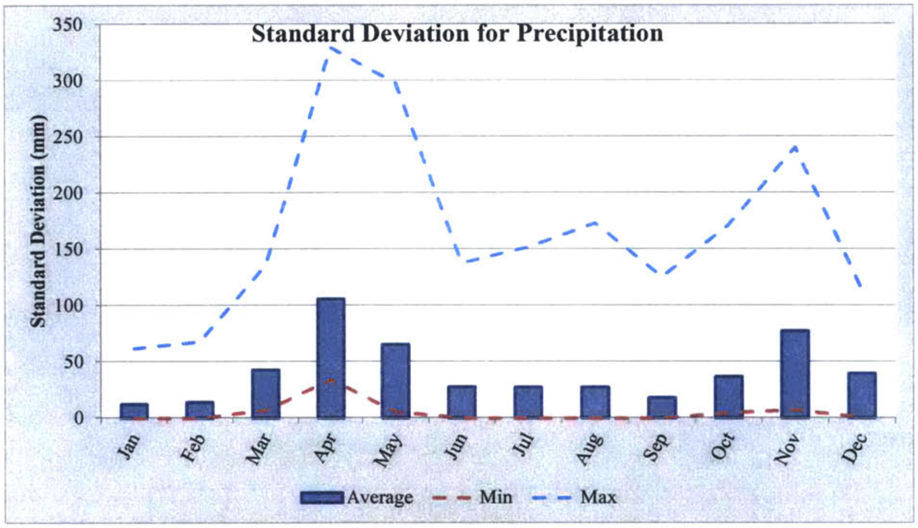


Figure A.5: Average Monthly Standard Deviation

A4. Monthly Actual Evapotranspiration Maps for Kenya [Measured]

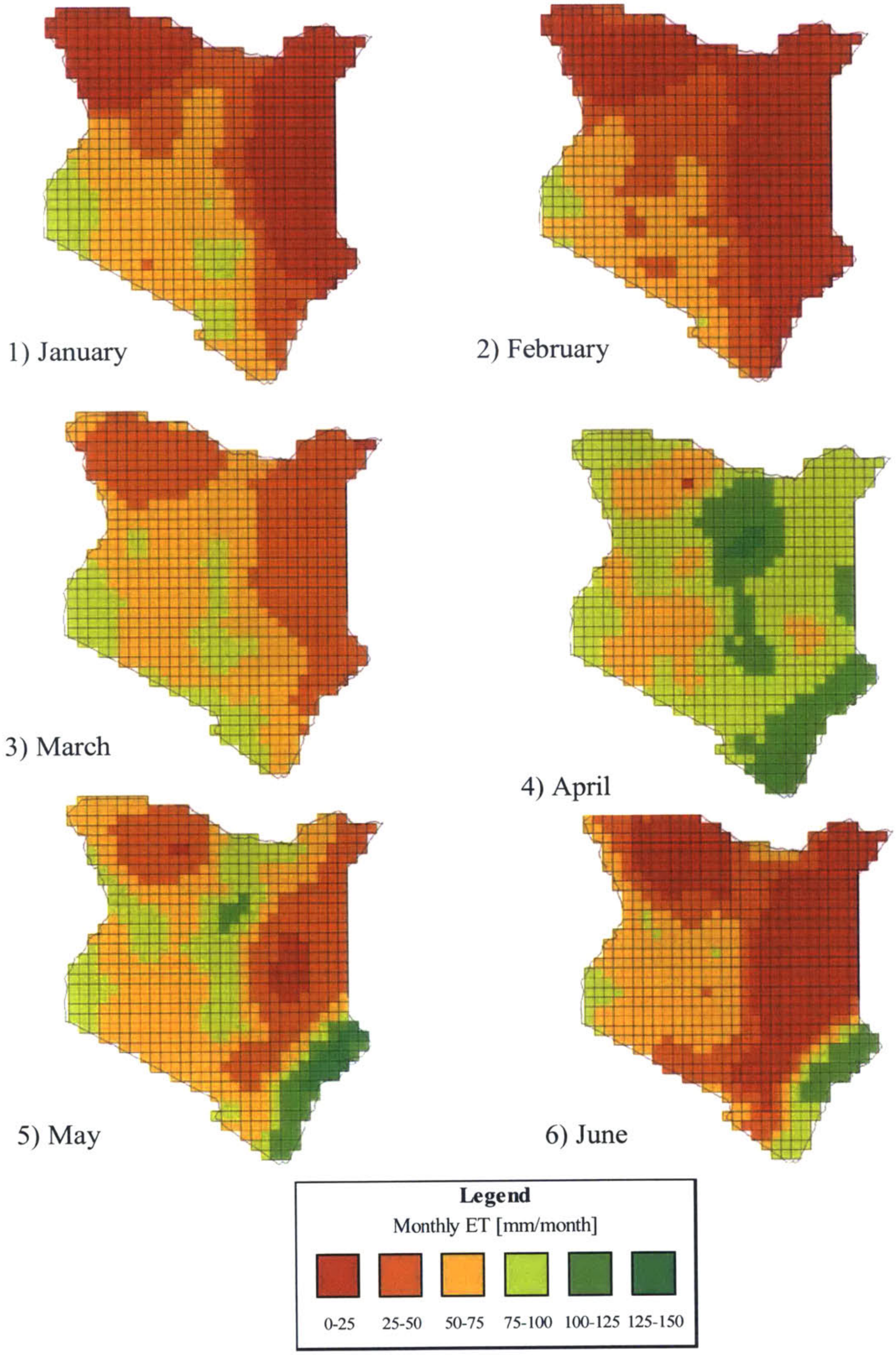
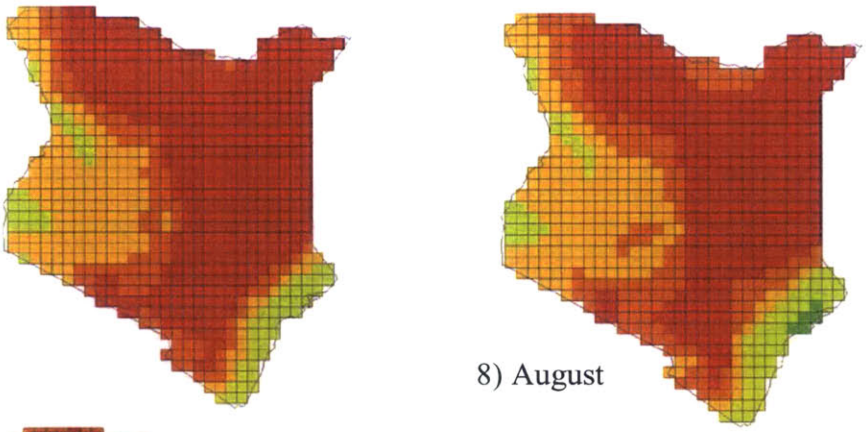
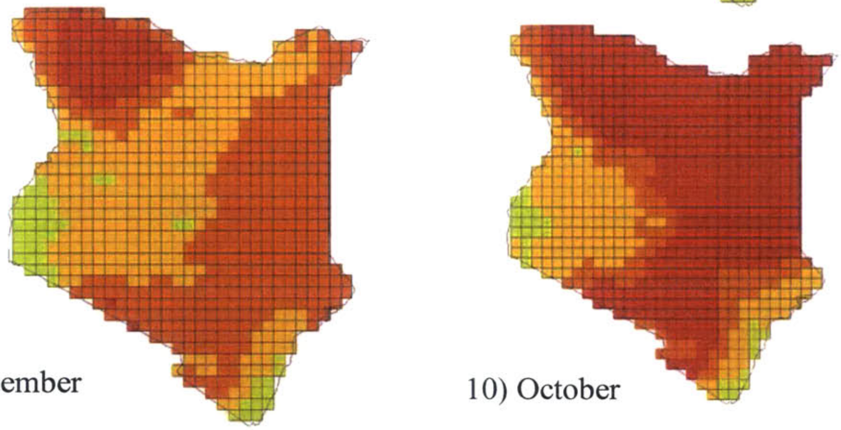


Figure A.6: Monthly actual evapotranspiration Maps for Kenya (January – June)



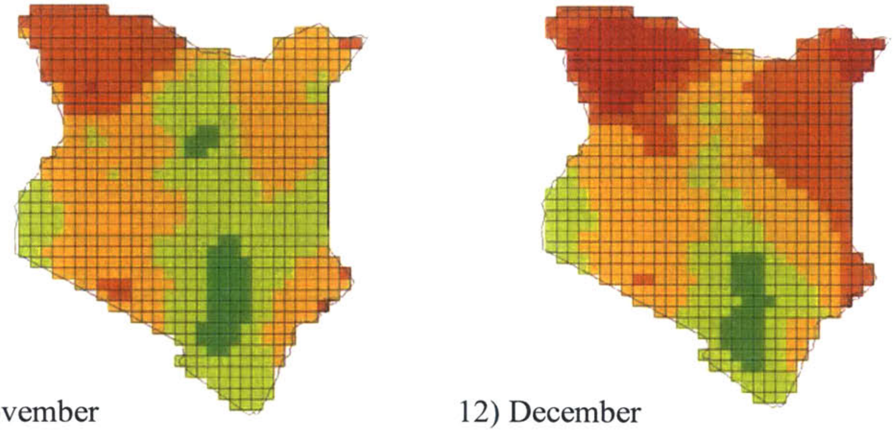
7) July

8) August



9) September

10) October



11) November

12) December

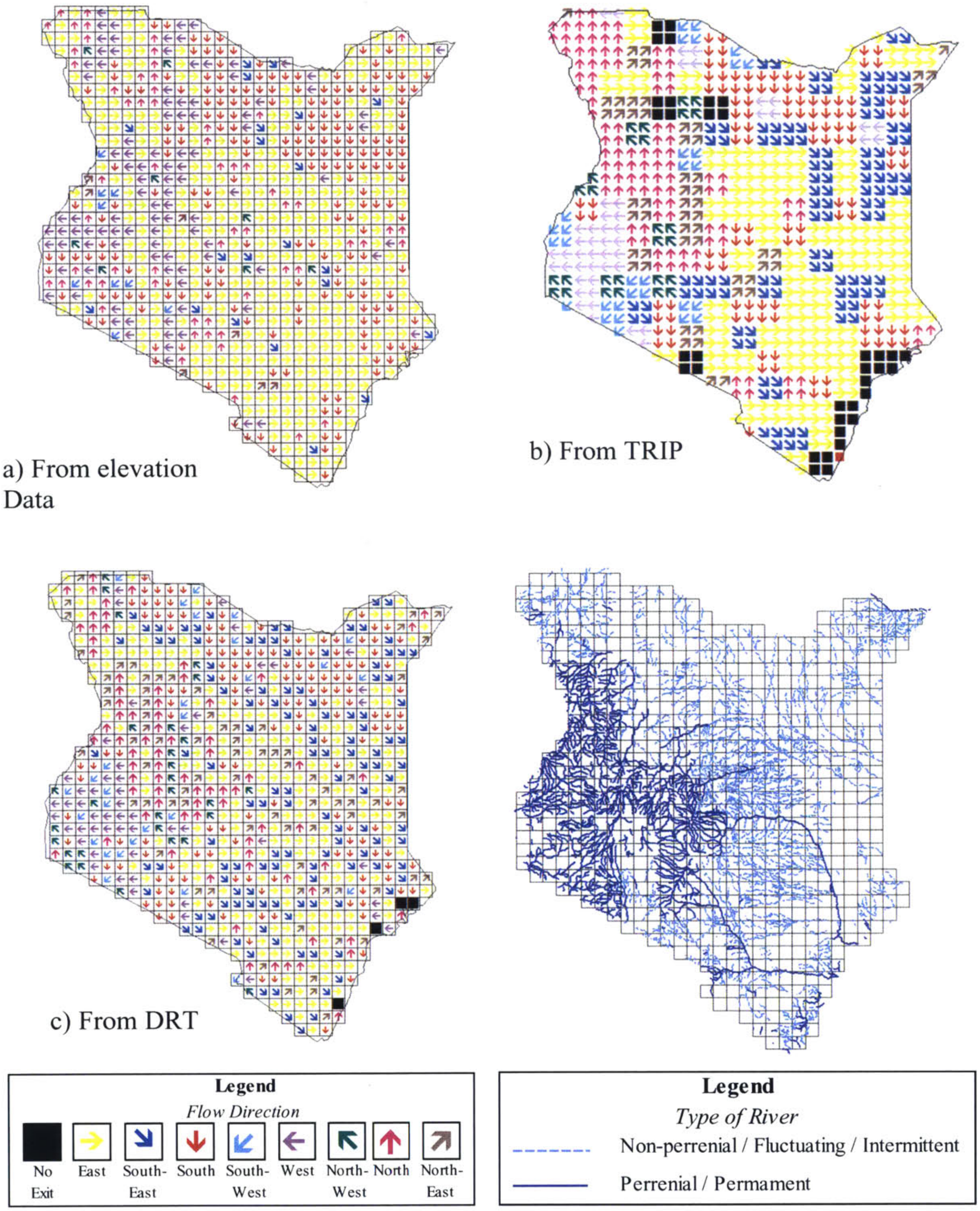
Legend

Monthly ET [mm/month]

🟥	🟥	🟧	🟩	🟩	🟩
0-25	25-50	50-75	75-100	100-125	125-150

Figure A.7: Monthly actual evapotranspiration Maps for Kenya (July – December)

A5. Flow Direction Maps and Representation of Main Rivers



a) From elevation Data

b) From TRIP

c) From DRT

A6. MATLAB Code to Create Flow Direction Matrix from DRT Data

```
% Creating the Flow Direction Matrix from the DRT Data

%% Clean Slate

clear all
close all
clc

%% Import Data -- at 0.25 x 0.25 Grid

Flow_Dir = xlsread('All_Data.xls','AC2:AC760'); % Flow Direction (DRT)

%% Tracker/
% A tracker was used for convenience
% The tracker file is a 31 x 37 matrix of Kenya with the numbers of the
% cells

Grid = importdata('track_M.txt',' '); % Will serve as tracker; -9999 = No Cell there
Grid(:,32)=-9999; Grid(:,33)=-9999;Grid(:,34)=-9999;
Grid(:,35)=-9999; Grid(:,36)=-9999; Grid(:,37)=-9999;

% Number of Pixels
j=37; % Biggest dimension in grid
N = j^2;
num = 759; % number of entries

Grid_vec = reshape(Grid,N,1);
Index=My_ID;
Tracker=zeros(N,1); Tracker=Tracker-9999;

Index_Grid=vec2mat(Tracker,j);
Index_Grid=Index_Grid';

% Renumbering the tracker for convenience, given the way that matlab
% re-shapes vectors and matrices
z=1;
i=1;
```

```
k=1;
while z<j^2;
   if Grid_vec(i)<0;
      i=i+1;
      z=z+1;
      continue;
   else;
      Tracker(i)=Index(k);
      i=i+1;
      k=k+1;
      z=z+1;
      continue;
   end;
end;

%% Creating A

F=zeros(N,1); F=F-9999;
A = zeros(N,N);
z=1;
i=1;
k=1;
while z<j^2;
   if Grid_vec(i)<0;
      i=i+1;
      z=z+1;
      continue;
   else;
      F(i)=Flow_Dir(k);
      i=i+1;
      k=k+1;
      z=z+1;
      continue;
   end;
end;

% Define A -- inflows and outflows in each cell (0,1,-1)
% 1. Flow Direction: DRT
   % 1=E; 2=SE; 4=S; 8=SW; 16=W; 32=NW; 64=N; 128=NE;
   % -9999 = No Cell there/No Data.

   for i=1:N;

```

```
        % Outflow from each pixel
        if F(i)>0;
            A(i,i)=-1;
        end;

         %Inflow to each pixel
        if F(i)==4;
            if i+1>0;
                A(i+1,i)=1;
            end;
        elseif F(i)==2;
            if i+1+j>0;
                A(i+1+j,i)=1;
            end;
        elseif F(i)==1;
            if i+j>0;
                A(i+j,i)=1;
            end;
        elseif F(i)==128;
            if i+j-1>0;
                A(i+j-1,i)=1;
            end;
        elseif F(i)==64;
            if i-1>0;
                A(i-1,i)=1;
            end;
        elseif F(i)==32;
            if i-j-1>0;
                A(i-j-1,i)=1;
            end;
        elseif F(i)==16;
            if i-j>0;
                A(i-j,i)=1;
            end;
        elseif F(i)==8;
            if i-j+1>0;
                A(i-j+1,i)=1;
            end;
        end;
    end;

% remove extra rows/columns
A(Tracker==-9999,:)=[];
```

```
A(:,Tracker==-9999)=[];
% Export
A=[Index,A];
xlswrite('A_Mat.xlsx',A);
dlmwrite('My_Tracker.txt',Index_grid,'delimiter',' ');
```

A7. Summary of Crop Requirements for each crop

Note to reader: This appendix (A.6) is a summary of work conducted by Wenjia Wang; for the full details please see Wang 2015.

		Grade 1	Grade 2	Grade 3	Grade 4	Grade 5
Temp	**Mean Temperature (°C)**	22 – 26	18 – 22; 26 – 32	16 – 18; 32 - 35	14 – 16; 35 – 40	< 14; > 40
Topology	**Slope (%)**	0 – 4	4 – 8	8 – 16	16 – 30	> 30
Soil Properties	**Texture**	SiC, SiCL, Si, SiL, CL	C<60v, SC, C>60s, L, SCL	C>60v, SL, LfS, LS	fS, L, LcS	Cm, SiCm, cS
	CaCO3 (%)	0 – 6	6 – 15	15 – 25	25 – 35	> 35
	Gypsum (%)	0 – 2	2 – 4	4 – 10	10 – 20	> 20
	Apparent CEC (cmol (+)/kg clay)	>24	24 – 16	< 16 (-)	< 16 (+)	-
	Base Saturation (%)	>80	80 – 50	50 – 35	35 – 20	< 20
	pH H_2O	6.2 – 7.0	6.2 – 5.8; 7.0 – 7.8	5.5 – 5.8; 7.8 – 8.2	5.2 – 5.5; 8.2 – 8.5	< 5.2; > 8,5
	Organic Carbon (%)	>4.0	2.4 – 4.0	1.3 – 2.4	<1.3	-
	ECe (dS/m)	0 – 2	2 – 4	4 – 6	6 – 8	> 8
	ESP (%)	0 – 8	8 – 15	15 – 20	20 – 25	> 25

Table A.1: Crop requirements for Maize

		Grade 1	Grade 2	Grade 3	Grade 4	Grade 5
Temp	**Mean Temperature (°C)**	15 – 20	12 – 15; 20 – 23	10 – 12; 23 – 25	8 – 10; 25 – 30	< 8; > 30
Topology	**Slope (%)**	0 – 4	4 – 8	8 – 16	16 – 30	> 30
Soil Propertics	**Texture**	C<60s, SiC,	C<60v, SC, C>60s, L	C>60v, SCL	SL, LfS	Cm, SiCm,
	CaCO3 (%)	3 – 20	0 – 3;	30 – 40	40 – 60	>60
	Gypsum (%)		20 – 30			
	Apparent CEC (cmol (+)/kg clay)	0 – 3 >24	3 – 5 24 – 16	5 – 10 < 16 (-)	10 – 20 < 16 (+)	>20 -
	Base Saturation (%)	>80	80 – 50	50 – 35	< 35	-
	pH H_2O	6.5 – 7.5	6.0 – 6.5; 7.5 – 8.2	5.6 – 6.0; 8.2 – 8.3	5.2 – 5.6; 8.3 – 8.5	< 5.2; > 8.5
	Organic Carbon (%)	> 6.1	3.7 – 6.1	1.5 – 3.7	< 1.5	-
	ECe (dS/m)	0 -1	1 – 3	3 – 5	5 – 6	>6
	ESP (%)	0 – 15	15 – 20	20 – 35	35 – 45	>45

Table A.2: Crop requirements for Wheat

		Grade 1	Grade 2	Grade 3	Grade 4	Grade 5
Temp	**Mean Temperature (°C)**	15 – 20	12 – 15; 20 – 23	10 – 12; 23 – 25	8 – 10; 25 – 30	< 8; > 30
Topology	**Slope (%)**	0 – 4	4 – 8	8 – 16	16 – 30	> 30
Soil Properties	**Texture**	C<60s, SiC,	C<60v, SC, C>60s, L	C>60v, SCL	SL, LfS	Cm, SiCm,
	CaCO3 (%)	3 – 20	0 – 3;	30 – 40	40 – 60	>60
	Gypsum (%)		20 – 30			
	Apparent CEC	0 – 3	3 – 5	5 – 10	10 – 20	>20
	(cmol (+)/kg clay)	>24	24 – 16	< 16 (-)	< 16 (+)	-
	Base Saturation (%)	>80	80 – 50	50 – 35	< 35	-
	pH H_2O	6.5 – 7.5	6.0 – 6.5; 7.5 – 8.2	5.6 – 6.0; 8.2 – 8.3	5.2 – 5.6; 8.3 – 8.5	< 5.2; > 8.5
	Organic Carbon (%)	> 6.1	3.7 – 6.1	1.5 – 3.7	< 1.5	-
	ECe (dS/m)	0 - 1	1 – 3	3 – 5	5 – 6	>6
	ESP (%)	0 – 10	10 – 20	20 – 30	30 – 40	> 40

Table A.3: Crop requirements for Rice

Data Sources for Land Characterization	
Data	**Source**
Characterization of Soils (requirements for each crop)	Sys et. al 1993
Temperature	WorldClim
Slope	Calculated from elevation data (SoK et. al 1996)
pH-H_20 Organic Carbon	ISRIC 2013
All Other Soil Properties	FAO et. al 2012

Table A.4: Sources for Data for Land Characterization

A8. Equations for Optimization 1 (Minimizing Least Squares)

Objective: Minimize Least Squares

$$LS=\sum_{t}\sum_{p}\left(\frac{(P_{meas}(p,t)-P_{est}(p,t))^{2}}{(P_{meas}(p,t))^{2}}\right)+\sum_{t}\sum_{p}\left(\frac{(ET_{meas}(p,t)-ET_{est}(p,t))^{2}}{(ET_{meas}(p,t))^{2}}\right)$$

Subject to:

1. Water Balance Constraint

$$\Delta S(p,t)=P_{est}(p,t)-ET_{est}(p,t)+\mathbf{A}Q(p,t)$$

2. Crop and Non-crop ET Sum

$$ET_{est}(p,t)=ET_{N}(p,t)+\sum_{c}ET_{crop}(p,t,c)$$

3. Limit for Non-crop ET

$$ET_{N}(p,t)\leq P_{est}(p,t)$$

4. Change in Storage Limit

$$-0.15\sum_{t}P_{meas}(p,t)\leq\Delta S\leq0.15\sum_{t}P_{meas}(p,t)$$

5. Cyclical Storage

$$\sum_{t}\Delta S(p,t)=0$$

A9. GAMS Code for Optimization 1 (Least Squares)

```
*** Optimization 1 - Modeling the Current Situation: Least Squares Estimation ***
* Maize, Rice, Wheat *

** Define Sets **

Sets
      p          Pixel                    [-]
                 /    1*759   /
      q          Pixel                    [-]
                 /    1*759   /
      t          Month                     [-]
                 /    1*12   /
      c          Crop                     [-]
                 /Maize, Rice, Wheat/
;

** Import all Data **
*Import everything in MM and then convert

Parameter K(t,c)       Crop Factor                  [-];
$call    GDXXRW.EXE  K_factor.xlsx trace=3 par=K rng=Sheet1!a1 rdim=1 cdim=1
$GDXIN   K_factor.gdx
$LOAD    K
$GDXIN

Parameter Precip(p,t)   Measured Precipitation              [MM per month];
$call    GDXXRW.EXE  Precip_Data.xlsx trace=3 par=Precip rng=Precip!a1
$GDXIN   Precip_Data.gdx
$LOAD    Precip
$GDXIN

Parameter AET(p,t)      Measured Actual Evapotranspiration    [MM per month];
$call    GDXXRW  ET_Data.xlsx trace=3 par=AET rng=ET!a1
$GDXIN   ET_Data.gdx
$LOAD    AET
$GDXIN

Parameter Flow_Dir(p,q)  Flow Direction Matrix             [-1 0 1];
$call    GDXXRW  Flow_Dir.xlsx trace=3 par=Flow_Dir rng=Sheet1!a1 rdim=1 cdim=1
$GDXIN   Flow_Dir.gdx
```

```
$LOAD   Flow_Dir
$GDXIN

Parameter Area(p)       Area per pixel                  [KM^2];
$call   GDXXRW  Area.xlsx par=Area rng=Sheet1!a1:a759  rdim=1 cdim=0
$GDXIN   Area.gdx
$LOAD   Area
$GDXIN

Parameter AR(q)        Area per pixel                   [KM^2];
* For "Accounting" Purposes Only
$call   GDXXRW  Area.xlsx par=AR rng=Sheet1!a1:a759  rdim=1 cdim=0
$GDXIN   Area.gdx
$LOAD   AR
$GDXIN

Parameter ET_0(p,t)    Reference ET per month             [MM per month];
$call   GDXXRW  ET_0.xlsx trace=3 par=ET_0 rng=Sheet1!a1 rdim=1 cdim=1
$GDXIN   ET_0.gdx
$LOAD   ET_0
$GDXIN

Parameter f(p,c)       Fraction of pixel area planted by crop c  [-];
$call   GDXXRW  Fraction.xlsx trace=3 par=f rng=Sheet1!a1 rdim=1 cdim=1
$GDXIN   Fraction.gdx
$LOAD   f
$GDXIN


Parameter f_t(p,c,t)          Fraction per month           [-];
*To account for fallow land *
*Maize
f_t(p,’Maize’,'1')=0;
f_t(p,’Maize’,'2')=0;
f_t(p,’Maize’,'3')=f(p,’Maize’);
f_t(p,’Maize’,'4')=f(p,’Maize’);
f_t(p,’Maize’,'5')=f(p,’Maize’);
f_t(p,’Maize’,'6')=f(p,’Maize’);
f_t(p,’Maize’,'7')=f(p,’Maize’);
f_t(p,’Maize’,'8')=f(p,’Maize’);
f_t(p,’Maize’,'9')=f(p,’Maize’);
f_t(p,’Maize’,'10')=0;
f_t(p,’Maize’,'11')=0;
```

```
f_t(p,’Maize’,'12')=0;

*Wheat
f_t(p,’Wheat’,'1')=0;
f_t(p,’Wheat’,'2')=0;
f_t(p,’Wheat’,'3')=0;
f_t(p,’Wheat’,'4')=0;
f_t(p,’Wheat’,'5')=0;
f_t(p,’Wheat’,'6')=0;
f_t(p,’Wheat’,'7')=f(p,’Wheat’);
f_t(p,’Wheat’,'8')=f(p,’Wheat’);
f_t(p,’Wheat’,'9')=f(p,’Wheat’);
f_t(p,’Wheat’,'10')=f(p,’Wheat’);
f_t(p,’Wheat’,'11')=f(p,’Wheat’);
f_t(p,’Wheat’,'12')=0;

*Rice
f_t(p,’Rice’,'1')=0;
f_t(p,’Rice’,'2')=0;
f_t(p,’Rice’,'3')=0 ;
f_t(p,’Rice’,'4')=0;
f_t(p,’Rice’,'5')=f(p,’Rice’);
f_t(p,’Rice’,'6')=f(p,’Rice’);
f_t(p,’Rice’,'7')=f(p,’Rice’);
f_t(p,’Rice’,'8')=f(p,’Rice’);
f_t(p,’Rice’,'9')=f(p,’Rice’);
f_t(p,’Rice’,'10')=f(p,’Rice’);
f_t(p,’Rice’,'11')=0;
f_t(p,’Rice’,'12')=0;

*Convert from MM to KM^3
Parameter P_meas(p,t)         Precip                  [KM^3 per mo];
      P_meas(p,t)=Precip(p,t)*Area(p)/(1000*1000)
;
Parameter AET_meas(p,t)       AET                     [KM^3 per mo];
      AET_meas(p,t)=AET(p,t)*Area(p)/(1000*1000)
;
Parameter ET_crop(p,t,c)      ET_Maize                [KM^3 per mo] ;
      ET_crop(p,t,c) = K(t,c)*ET_0(p,t)*f_t(p,c,t)*Area(p)/(1000*1000)
;

*Other Calc's - For "Accounting" Purposes
Parameter P_an(p)             Annual Precip           [KM^3 per year];
```

```
        P_an(p)=sum(t,P_meas(p,t))
;
Parameter ET_crop_MM(p,t,c)     ET_Crop                  [MM] ;
        ET_crop_MM(p,t,c) = K(t,c)*ET_0(p,t)*f_t(p,c,t)
;

*Display to check that all is good
Display P_meas;
Display AET_meas;
Display Flow_Dir;
Display Area;
Display ET_0;
Display f;
Display K;

** Define all Variables **

Positive Variables
        P_est(p,t)          Estimated Precip          [KM^3 per month]
        ET_est(p,t)         Estimated ET              [KM^3 per month]
        ET_N(p,t)           Non-crop ET               [KM^3 per month]
        Q_out(q,t)          Outflow from each pixel   [KM^3 per month] * NOTE: This is q,t and not p,t to facilitate calculations in GAMS (A*Q); p and q are the same: number of pixel
        f_N(p,t)            Fraction of non crop      [- each month]
;
Variable
        LS                  Least Squares Variable    [-]
        DS(p,t)             Storage                   [KM^3 per month]
;

** Define all Equations **

Equations
        Least_Squares_V
        Mass_Balance(p,t)
        ET_Eq(p,t)
        ET_N_Max(p,t)
        Storage_Min(p,t)
        Storage_Max(p,t)
        Storage_Change(p)
        Land_Balance(p,t)
;
        Least_Squares_V..     LS =e= sum((p,t),((P_est(p,t)-P_meas(p,t))*(P_est(p,t)-P_meas(p,t)))/((P_meas(p,t))*(P_meas(p,t)))+((ET_est(p,t)-AET_meas(p,t))*(ET_est(p,t)-
```

```
AET_meas(p,t)))/((AET_meas(p,t))*(AET_meas(p,t))));

     Mass_Balance(p,t)..   DS(p,t) =e= P_est(p,t)- ET_est(p,t)+ sum(q,Flow_Dir(p,q)*Q_out(q,t)) ;

     ET_Eq(p,t)..
     ET_N_Max(p,t)..       ET_N(p,t) =l= P_est(p,t);

     Storage_Max(p,t)..    DS(p,t) =l= 0.15*P_an(p);
     Storage_Min(p,t)..    DS(p,t) =g= -0.15*P_an(p);
     Storage_Change(p)..   sum(t,DS(p,t)) =e= 0;

     Land_Balance(p,t)..   f_N(p,t)+sum(c,f_t(p,c,t)) =e= 1;

option reslim = 100000;

** Solve **

Model LS_opt1_V20 /all/              ;
Solve LS_opt1_V20 using qcp minimizing LS;

****** DONE ********

** Process Results **

*Convert from KM^3 to MM
Parameter P_est_MM(p,t)        Precip              [MM per month];
     P_est_MM(p,t)=P_est.l(p,t)*(1000*1000)/Area(p)
;
Parameter ET_est_MM(p,t)       AET                 [MM per month];
      ET_est_MM(p,t)=ET_est.l(p,t)*(1000*1000)/Area(p)
;
Parameter ET_N_MM(p,t)         ET_N                [MM per month];
      ET_N_MM(p,t)=ET_N.l(p,t)*(1000*1000)/(Area(p)*f_N.l(p,t))
;
Parameter Q_out_MM(q,t)        Q_out               [MM per month] ;
     Q_out_MM(q,t)=Q_out.l(q,t)*(1000*1000)/AR(q)
;
Parameter DS_MM(p,t)           DS                  [MM per month] ;
     DS_MM(p,t)=DS.l(p,t)*(1000*1000)/Area(p)
;
*Calculate Changes (For "accounting" purposes only)
Parameter P_dif_abs(p,t)       Precip Difference Abs   [KM^3 per month];
     P_dif_abs(p,t)= P_est.l(p,t)-P_meas(p,t);
```

```

Parameter P_dif_rel(p,t)       Precip Difference Rel  [-];
        P_dif_rel(p,t)=P_dif_abs(p,t)/P_meas(p,t);

Parameter AET_dif_abs(p,t)      AET Difference Abs      [KM^3 per month];
        AET_dif_abs(p,t)= ET_est.l(p,t)-AET_meas(p,t);

Parameter AET_dif_rel(p,t)      AET Difference Rel      [-];
        AET_dif_rel(p,t)=AET_dif_abs(p,t)/AET_meas(p,t);

Parameter ET_N_rel_Meas(p,t)        ET_N as a % of AET_Meas  [-];
        ET_N_rel_Meas(p,t)=ET_N.l(p,t)/AET_meas(p,t);

Parameter ET_N_rel_Est(p,t)         ET_N as a % of AET_Meas  [-];
        ET_N_rel_Est(p,t)=ET_N.l(p,t)/ET_Est.l(p,t);

* Net Flow per Pixel
Parameter Net_Flow(p,t)         Qin-Qout                [KM^3 per month];
        Net_Flow(p,t)  = sum(q,Flow_Dir(p,q)*Q_out.l(q,t))     ;

Parameter Net_Flow_MM(p,t)      Qin-Qout                [MM per month];
        Net_Flow_MM(p,t)  = sum(q,Flow_Dir(p,q)*Q_out.l(q,t))*(1000*1000)/Area(p)     ;

** Export Results **

Execute_Unload  'Results_OPT1_V20.gdx' ;

*Original Data
Execute  'GDXXRW Results_OPT1_V20.gdx par=Precip rng=P_meas!a2:m761';
Execute  'GDXXRW Results_OPT1_V20.gdx par=AET rng=AET_meas!a2:m761';
Execute  'GDXXRW Results_OPT1_V20.gdx par=ET_crop_MM rng=ET_crop!a2';

*Precip and all ET data in MM
Execute  'GDXXRW Results_OPT1_V20.gdx par=P_est_MM rng=P_est!a2:m761';
Execute  'GDXXRW Results_OPT1_V20.gdx par=ET_est_MM rng=ET_est!a2:m761';
Execute  'GDXXRW Results_OPT1_V20.gdx par=ET_N_MM rng=ET_N!a2:m761';
Execute  'GDXXRW Results_OPT1_V20.gdx par=Q_out_MM rng=Q_out_MM!a2:m761';
Execute  'GDXXRW Results_OPT1_V20.gdx par=DS_MM rng=DStorage_MM!a2:m761';

Execute  'GDXXRW Results_OPT1_V20.gdx var=Q_out rng=Q_out!a2:m761';
Execute  'GDXXRW Results_OPT1_V20.gdx var=DS rng=DStorage!a2:m761';

Execute  'GDXXRW Results_OPT1_V20.gdx par=Net_Flow rng=Net_Flow!a2:m761';
```

```
Execute 'GDXXRW Results_OPT1_V20.gdx par=Net_Flow_MM rng=Net_Flow_MM!a2:m761';

*Stats - "Accounting"
Execute 'GDXXRW Results_OPT1_V20.gdx par=P_dif_abs rng=P_dif_abs!a2:m761';
Execute 'GDXXRW Results_OPT1_V20.gdx par=P_dif_rel rng=P_dif_rel!a2:m761';

Execute 'GDXXRW Results_OPT1_V20.gdx par=AET_dif_abs rng=AET_dif_abs!a2:m761';
Execute 'GDXXRW Results_OPT1_V20.gdx par=AET_dif_rel rng=AET_dif_rel!a2:m761';

Execute 'GDXXRW Results_OPT1_V20.gdx par=ET_N_rel_Meas rng=ET_N_rel_meas!a2:m761';
Execute 'GDXXRW Results_OPT1_V20.gdx par=ET_N_rel_est rng=ET_N_rel_est!a2:m761s';
```

A10. Equations for Optimization 2 (Maximizing Calories Produced)

Objective: Maximize Calories Produced

$$T\_Cal = \sum_p \sum_s \sum_c Crop\_cal(c) \times Y\_\max(c) \times Y\_per(s,c) \times f(p,s,c,'7') \times Area(p)$$

Subject to:

1. Water Balance Constraint

$$\Delta S(p,t) = P_{est}(p,t) + \mathrm{A}Q(p,t) - \sum_c ET(c,p,t) - ET_N(p,t)$$

1.1. ET crop

$$ET(c,p,t) = K(c,t) \times ET\_0(p,t) \times \frac{Area(p)}{1000 \times 1000} \times \sum_s f(p,s,c,t)$$

1.2. ET non-crop

$$ET_N(p,t) = e\_non(p,t) \times \frac{Area(p)}{1000 \times 1000} \times f\_N(p,t)$$

3. Change in Storage Limit

$$-0.15 \sum_t P_{meas}(p,t) \leq \Delta S \leq 0.15 \sum_t P_{meas}(p,t)$$

4. Cyclical Storage

$$\sum_t \Delta S(p,t) = 0$$

5. Optimal Land Constraint for each soil grade

$$f(p,s,c,t) \leq f\_\max(p,s,c)$$

6. Land Balance Constraint

$$f\_N(p,t) + \sum_c \sum_s (p,s,c,t) = 1$$

7. Non-crop Land Constraint

$$f\_N(p,t) \geq f\_N\_\min(p)$$

8. Land Constraints to avoid overlap

    a. Maize & Rice

$$
\begin{aligned}
&\sum_{s} f(p,s,\text{'}\mathit{Maize}\text{'},t)+\sum_{s} f(p,s,\text{'}\mathit{Rice}\text{'},t)\leq \\
&\sum_{s} f\_\max(p,s,\text{'}\mathit{Maize}\text{'})+\sum_{s} f\_\max(p,s,\text{'}\mathit{Rice}\text{'})-f\_overlap\_MR
\end{aligned}
$$

    b. Maize & Wheat

$$
\begin{aligned}
&\sum_{s} f(p,s,\text{'}\mathit{Maize}\text{'},t)+\sum_{s} f(p,s,\text{'}\mathit{Wheat}\text{'},t)\leq \\
&\sum_{s} f\_\max(p,s,\text{'}\mathit{Maize}\text{'})+\sum_{s} f\_\max(p,s,\text{'}\mathit{Wheat}\text{'})-f\_overlap\_MW
\end{aligned}
$$

    c. Wheat & Rice

$$
\begin{aligned}
&\sum_{s} f(p,s,\text{'}\mathit{Wheat}\text{'},t)+\sum_{s} f(p,s,\text{'}\mathit{Rice}\text{'},t)\leq \\
&\sum_{s} f\_\max(p,s,\text{'}\mathit{Wheat}\text{'})+\sum_{s} f\_\max(p,s,\text{'}\mathit{Rice}\text{'})-f\_overlap\_WR
\end{aligned}
$$

    d. Maize, Wheat & Rice

$$
\begin{aligned}
&\sum_{s} f(p,s,\text{'}\mathit{Maize}\text{'},t)+\sum_{s} f(p,s,\text{'}\mathit{Wheat}\text{'},t)+\sum_{s} f(p,s,\text{'}\mathit{Rice}\text{'},t)\leq \\
&\sum_{s} f\_\max(p,s,\text{'}\mathit{Maize}\text{'})+\sum_{s} f\_\max(p,s,\text{'}\mathit{Wheat}\text{'})+\sum_{s} f\_\max(p,s,\text{'}\mathit{Rice}\text{'}) \\
&-f\_overlap\_MWR
\end{aligned}
$$

9. Change in planted land fraction over the year

    a. Maize

        i. Fallow in January, February, March, October, November, December

$$
\begin{aligned}
&f(p,s,\text{'}\mathit{Maize}\text{'},\text{'1'})=0 \qquad && f(p,s,\text{'}\mathit{Maize}\text{'},\text{'2'})=0 \\
&f(p,s,\text{'}\mathit{Maize}\text{'},\text{'3'})=0 \qquad && f(p,s,\text{'}\mathit{Maize}\text{'},\text{'10'})=0 \\
&f(p,s,\text{'}\mathit{Maize}\text{'},\text{'11'})=0 \qquad && f(p,s,\text{'}\mathit{Maize}\text{'},\text{'10'})=0
\end{aligned}
$$

        ii. Planted in April through (including) September.

$$f(p,s,'Maize','4')=f(p,s,'Maize','5')$$
$$f(p,s,'Maize','5')=f(p,s,'Maize','6')$$
$$f(p,s,'Maize','6')=f(p,s,'Maize','7')$$
$$f(p,s,'Maize','7')=f(p,s,'Maize','8')$$
$$f(p,s,'Maize','8')=f(p,s,'Maize','9')$$

b. Wheat

i. Fallow in January through (including) June, and December

$$f(p,s,'Wheat','1')=0 \qquad f(p,s,'Wheat','2')=0$$
$$f(p,s,'Wheat','3')=0 \qquad f(p,s,'Wheat','4')=0$$
$$f(p,s,'Wheat','5')=0 \qquad f(p,s,'Wheat','6')=0$$
$$f(p,s,'Wheat','12')=0$$

ii. Planted in July through (including) November.

$$f(p,s,'Wheat','7')=f(p,s,'Wheat','8')$$
$$f(p,s,'Wheat','8')=f(p,s,'Wheat','9')$$
$$f(p,s,'Wheat','9')=f(p,s,'Wheat','10')$$
$$f(p,s,'Wheat','10')=f(p,s,'Wheat','11')$$

b. Rice

i. Fallow in January through (including) April, November and December

$$f(p,s,'Rice','1')=0 \qquad f(p,s,'Rice','2')=0$$
$$f(p,s,'Rice','3')=0 \qquad f(p,s,'Rice','4')=0$$
$$f(p,s,'Rice','3')=0 \qquad f(p,s,'Rice','12')=0$$

ii. Planted in May through (including) October.

$$f(p,s,'Rice','5')=f(p,s,'Rice','6')$$
$$f(p,s,'Rice','6')=f(p,s,'Rice','7')$$
$$f(p,s,'Rice','7')=f(p,s,'Rice','8')$$
$$f(p,s,'Rice','8')=f(p,s,'Rice','9')$$
$$f(p,s,'Rice','9')=f(p,s,'Rice','10')$$

(10. Minimum required flow; Scenario 3)

$$Q(p,t)\geq 0.75\times Q\_nom(p,t)$$

A11. GAMS Code for Optimization 2 (Maximize Calories Produced)

```
*** Optimization 2 - Maximizing Calories Produced: Optimizing for the Future ***
** Base Case Scenario **

* Maize, Rice, Wheat *

** Define Sets **

Sets
        p           Pixel
                    /    1*759   /
        q           Pixel
                    /    1*759   /
        t           Month
                    /    1*12   /
        s           Soil Grade
                    /    1*3    /
        c           Crop
                    /Maize, Rice, Wheat/
;

Parameter Y_max(c)
                    / Maize      .420
                      Rice      .652
                      Wheat      .446/
;

Parameter crop_cal(c)
                    / Maize       3650
                      Wheat       3290
                      Rice       3650/

;
Scalar MM_to_KM3 Conversion ;
      MM_to_KM3=1000*1000;

** Import all Data **
*Import everything in MM and then convert

Parameter K(t,c)

```

```
$call  GDXXRW.EXE  K_factor.xlsx trace=3 par=K rng=Sheet1!a1 rdim=1 cdim=1
$GDXIN  K_factor.gdx
$LOAD  K
$GDXIN

Parameter f_max(p,s,c)

$call  GDXXRW  Fraction_OPT_grades.xlsx trace=3 par=f_max rng=Sheet1!a1 rdim=1 cdim=2
$GDXIN  Fraction_OPT_grades.gdx
$LOAD  f_max
$GDXIN

Parameter f_now(p,s,c)   Current fraction of pixel area planted by crop c for soil grade s  [-];

$call  GDXXRW  Fraction_grades.xlsx trace=3 par=f_now rng=Sheet1!a1 rdim=1 cdim=2
$GDXIN  Fraction_grades.gdx
$LOAD  f_now
$GDXIN

Parameter f_N_min(p)     Minimum non-crop fraction - to account for cash crops;

$call  GDXXRW  Fraction_other_new.xlsx trace=3 par=f_N_min rng=Sheet1!a1 rdim=1 cdim=0
$GDXIN  Fraction_other_new.gdx
$LOAD  f_N_min
$GDXIN

Parameter f_overlap_MW(p)  Overlap Fraction of pixel area by Maize and Wheat  [-];

$call  GDXXRW  Fraction_overlap_MW.xlsx trace=3 par=f_overlap_MW rng=Sheet1!a1 rdim=1 cdim=0
$GDXIN  Fraction_overlap_MW.gdx
$LOAD  f_overlap_MW
$GDXIN

Parameter f_overlap_MR(p)  Overlap Fraction of pixel area by Maize and Rice  [-];

$call  GDXXRW  Fraction_overlap_MR.xlsx trace=3 par=f_overlap_MR rng=Sheet1!a1 rdim=1 cdim=0
$GDXIN  Fraction_overlap_MR.gdx
$LOAD  f_overlap_MR
$GDXIN

Parameter f_overlap_WR(p)  Overlap Fraction of pixel area by Wheat and Rice  [-];

```

```
$call   GDXXRW  Fraction_overlap_WR.xlsx trace=3 par=f_overlap_WR rng=Sheet1!a1 rdim=1 cdim=0
$GDXIN  Fraction_overlap_WR.gdx
$LOAD   f_overlap_WR
$GDXIN

Parameter f_overlap_MWR(p) Overlap Fraction of pixel area by Maize Wheat and Rice  [-];

$call   GDXXRW  Fraction_overlap_MWR.xlsx trace=3 par=f_overlap_MWR rng=Sheet1!a1 rdim=1 cdim=0
$GDXIN  Fraction_overlap_MWR.gdx
$LOAD   f_overlap_MWR
$GDXIN

Parameter y_p(s,c)

$call   GDXXRW  Yield_grades.xlsx trace=3 par=y_p rng=Sheet1!a1 rdim=1 cdim=1
$GDXIN  Yield_grades.gdx
$LOAD   y_p
$GDXIN

Parameter P_est(p,t)

$call   GDXXRW.EXE  P_est.xlsx trace=3 par=P_est rng=P_est!a1
$GDXIN  P_est.gdx
$LOAD   P_est
$GDXIN

Parameter e_non(p,t)    Estimated Non-Crop Evapotranspiration

$call   GDXXRW.EXE  ET_N_new.xlsx trace=3 par=e_non rng=ET_N!a1
$GDXIN  ET_N_new.gdx
$LOAD   e_non
$GDXIN

Parameter Flow_Dir(p,q)  Flow Direction Matrix

$call   GDXXRW  Flow_Dir.xlsx trace=3 par=Flow_Dir rng=Sheet1!a1 rdim=1 cdim=1
$GDXIN  Flow_Dir.gdx
$LOAD   Flow_Dir
$GDXIN

Parameter Area(p)  Area per pixel [KM^2]

```

```
$call   GDXXRW  Area.xlsx par=Area rng=Sheet1!a1:a759  rdim=1 cdim=0
$GDXIN   Area.gdx
$LOAD    Area
$GDXIN


Parameter AR(q)
* For "Accounting" Purposes Only
$call   GDXXRW  Area.xlsx par=AR rng=Sheet1!a1:a759  rdim=1 cdim=0
$GDXIN   Area.gdx
$LOAD    AR
$GDXIN


Parameter ET_0(p,t)  Reference ET [MM per month]

$call   GDXXRW  ET_0.xlsx trace=3 par=ET_0 rng=Sheet1!a1 rdim=1 cdim=1
$GDXIN   ET_0.gdx
$LOAD    ET_0
$GDXIN

Parameter Q_in(q,t)  Outflow - Initializing

$call   GDXXRW  Q_out.xlsx trace=3 par=Q_in rng=Q_out!a1 rdim=1 cdim=1
$GDXIN   Q_out.gdx
$LOAD    Q_in
$GDXIN

Parameter DS_in(p,t)    Change in storage - initializing

$call   GDXXRW  DS.xlsx trace=3 par=DS_in rng=DS!a1 rdim=1 cdim=1
$GDXIN   DS.gdx
$LOAD    DS_in
$GDXIN

Parameter Animals(p,t)     Animal water demand                 [KM per month per KM^2];

$call   GDXXRW  Animal_WD.xlsx trace=3 par=Animals rng=Sheet1!a1 rdim=1 cdim=1
$GDXIN   Animal_WD.gdx
$LOAD    Animals
$GDXIN

Parameter Y(s,c)
```

```
*Calculate yield for each soil grade for every crop
        Y(s,c) = Y_max(c)*y_p(s,c);

* Display
Display f_max;
Display f_now;
Display y_p;
Display Y;

Display P_est;
Display e_non;
Display Flow_Dir;
Display Area;
Display ET_0;

*Convert from MM to KM^3
Parameter Precip(p,t)
        Precip(p,t)=P_est(p,t)*Area(p)/MM_to_KM3
;
Parameter Q_0(q,t)
        Q_0(q,t)=Q_in(q,t)*AR(q)/MM_to_KM3
;
Parameter DS_0(p,t)
        DS_0(p,t)=DS_in(p,t)*Area(p)/MM_to_KM3
;
Parameter P_an(p)
        P_an(p)=sum(t,Precip(p,t))

** Define all Variables **

Positive Variables
        f(p,s,c,t)
        Q_out(q,t)
        f_N(p,t)
;
Variable
        Tot_Cal
        DS(p,t)
;

** INITIALIZE **
* Use results from optimization 1*
*f.l(p,s,c,t)=f_now(p,s,c);
```

```
Q_out.l(q,t)=Q_0(q,t);
DS.l(p,t)=DS_0(p,t);


** Define all Equations **

Equations
        Total_Calories
        Mass_Balance(p,t)
        Storage_Min(p,t)
        Storage_Max(p,t)
        Storage_Change(p)
        Land_Max(p,s,c,t)
        Land_Balance(p,t)
        Land_Overlap_MW(p,t)
        Land_Overlap_MR(p,t)
        Land_Overlap_WR(p,t)
        Land_Overlap_MWR(p,t)
        Land_Non-crop(p,t)

        Land_Maize_1(p,s)
        Land_Maize_2(p,s)
        Land_Maize_3(p,s)
        Land_Maize_4_5(p,s)
        Land_Maize_5_6(p,s)
        Land_Maize_6_7(p,s)
        Land_Maize_7_8(p,s)
        Land_Maize_8_9(p,s)
        Land_Maize_10(p,s)
        Land_Maize_11(p,s)
        Land_Maize_12(p,s)

        Land_Wheat_1(p,s)
        Land_Wheat_2(p,s)
        Land_Wheat_3(p,s)
        Land_Wheat_4(p,s)
        Land_Wheat_5(p,s)
        Land_Wheat_6(p,s)
        Land_Wheat_7_8(p,s)
        Land_Wheat_8_9(p,s)
        Land_Wheat_9_10(p,s)
        Land_Wheat_10_11(p,s)
        Land_Wheat_12(p,s)
```

```

        Land_Rice_1(p,s)
        Land_Rice_2(p,s)
        Land_Rice_3(p,s)
        Land_Rice_4(p,s)
        Land_Rice_5_6(p,s)
        Land_Rice_6_7(p,s)
        Land_Rice_7_8(p,s)
        Land_Rice_8_9(p,s)
        Land_Rice_9_10(p,s)
        Land_Rice_11(p,s)
        Land_Rice_12(p,s)

;
        Total_Calories..      Tot_Cal =e= sum((p,s,c),Y(s,c)*crop_cal(c)*f(p,s,c,'7')*Area(p));
*July was used because in July all crops are either planted or not

        Mass_Balance(p,t)..   DS(p,t) =e= Precip(p,t)+ sum(q,Flow_Dir(p,q)*Q_out(q,t))-ET_0(p,t)*sum((s,c),K(t,c)*f(p,s,c,t))*Area(p)/(MM_to_KM3)-e_non(p,t)*f_N(p,t)*Area(p)/(MM_to_KM3);

        Storage_Max(p,t)..    DS(p,t) =l= .15*P_an(p);
        Storage_Min(p,t)..    DS(p,t) =g= -.15*P_an(p);
        Storage_Change(p)..   sum(t,DS(p,t)) =e= 0;

        Land_Max(p,s,c,t)..   f(p,s,c,t) =l= f_max(p,s,c);
        Land_Balance(p,t)..   f_N(p,t) + sum((s,c),f(p,s,c,t)) =e= 1;
        Land_Non_Crop(p,t)..  f_N(p,t) =g= f_N_min(p);

        Land_Overlap_MW(p,t).. sum(s,f(p,s,’Maize’,t)+f(p,s,’Wheat’,t)) =l= sum(s,f_max(p,s,’Maize’)+f_max(p,s,’Wheat’))-f_overlap_MW(p);
        Land_Overlap_MR(p,t).. sum(s,f(p,s,’Maize’,t)+f(p,s,’Rice’,t)) =l= sum(s,f_max(p,s,’Maize’)+f_max(p,s,’Rice’))-f_overlap_MR(p)  ;
        Land_Overlap_WR(p,t).. sum(s,f(p,s,’Wheat’,t)+f(p,s,’Rice’,t)) =l= sum(s,f_max(p,s,’Wheat’)+f_max(p,s,’Rice’))-f_overlap_WR(p)  ;
        Land_Overlap_MWR(p,t).. sum(s,f(p,s,’Maize’,t)+f(p,s,’Wheat’,t)+f(p,s,’Rice’,t)) =l= sum(s,f_max(p,s,’Maize’)+f_max(p,s,’Wheat’)+f_max(p,s,’Rice’))-f_overlap_MWR(p)  ;

        Land_Maize_1(p,s)..   f(p,s,’Maize’,'1')=e= 0;
        Land_Maize_2(p,s)..   f(p,s,’Maize’,'2')=e= 0;
        Land_Maize_3(p,s)..   f(p,s,’Maize’,'3')=e= 0;
        Land_Maize_4_5(p,s).. f(p,s,’Maize’,'4')=e= f(p,s,’Maize’,'5');
        Land_Maize_5_6(p,s).. f(p,s,’Maize’,'5')=e= f(p,s,’Maize’,'6');
        Land_Maize_6_7(p,s).. f(p,s,’Maize’,'6')=e= f(p,s,’Maize’,'7');
        Land_Maize_7_8(p,s).. f(p,s,’Maize’,'7')=e= f(p,s,’Maize’,'8');
```

```
        Land_Maize_8_9(p,s)..   f(p,s,’Maize’,'8')=e= f(p,s,’Maize’,'9');
        Land_Maize_10(p,s)..    f(p,s,’Maize’,'10')=e= 0;
        Land_Maize_11(p,s)..    f(p,s,’Maize’,'11')=e= 0;
        Land_Maize_12(p,s)..    f(p,s,’Maize’,'12')=e= 0;

        Land_Wheat_1(p,s)..     f(p,s,’Wheat’,'1')=e= 0;
        Land_Wheat_2(p,s)..     f(p,s,’Wheat’,'2')=e= 0;
        Land_Wheat_3(p,s)..     f(p,s,’Wheat’,'3')=e= 0;
        Land_Wheat_4(p,s)..     f(p,s,’Wheat’,'4')=e= 0;
        Land_Wheat_5(p,s)..     f(p,s,’Wheat’,'5')=e= 0;
        Land_Wheat_6(p,s)..     f(p,s,’Wheat’,'6')=e= 0;
        Land_Wheat_7_8(p,s)..  f(p,s,’Wheat’,'7')=e= f(p,s,’Wheat’,'8');
        Land_Wheat_8_9(p,s)..  f(p,s,’Wheat’,'8')=e= f(p,s,’Wheat’,'9');
        Land_Wheat_9_10(p,s).. f(p,s,’Wheat’,'9')=e= f(p,s,’Wheat’,'10');
        Land_Wheat_10_11(p,s).. f(p,s,’Wheat’,'10')=e= f(p,s,’Wheat’,'11');
        Land_Wheat_12(p,s)..    f(p,s,’Wheat’,'12')=e= 0;

        Land_Rice_1(p,s)..      f(p,s,’Rice’,'1')=e= 0;
        Land_Rice_2(p,s)..      f(p,s,’Rice’,'2')=e= 0;
        Land_Rice_3(p,s)..      f(p,s,’Rice’,'3')=e= 0;
        Land_Rice_4(p,s)..      f(p,s,’Rice’,'4')=e= 0;
        Land_Rice_5_6(p,s)..    f(p,s,’Rice’,'5')=e= f(p,s,’Rice’,'6');
        Land_Rice_6_7(p,s)..    f(p,s,’Rice’,'6')=e= f(p,s,’Rice’,'7');
        Land_Rice_7_8(p,s)..    f(p,s,’Rice’,'7')=e= f(p,s,’Rice’,'8');
        Land_Rice_8_9(p,s)..    f(p,s,’Rice’,'8')=e= f(p,s,’Rice’,'9');
        Land_Rice_9_10(p,s)..   f(p,s,’Rice’,'9')=e= f(p,s,’Rice’,'10');
        Land_Rice_11(p,s)..     f(p,s,’Rice’,'11')=e= 0;
        Land_Rice_12(p,s)..     f(p,s,’Rice’,'12')=e= 0;

option iterlim = 999999;
option reslim = 10000;

** Solve **

Model LS_opt2_Maize /all/               ;
Solve LS_opt2_Maize using lp maximizing Tot_Cal;

****** DONE ********

** Process Results **

* Calculate Calories [kcal/yr produced]
Parameter Cal_Now_Maize;
```

```
Cal_Now_Maize = 1000000*(sum((p,s),Y(s,’Maize’)*crop_cal(‘Maize’)*f_now(p,s,’Maize’)*Area(p)))
;
Parameter Cal_Now_Wheat;
Cal_Now_Wheat = 1000000*(sum((p,s),Y(s,’Wheat’)*crop_cal(‘Wheat’)*f_now(p,s,’Wheat’)*Area(p)))
;
Parameter Cal_Now_Rice;
Cal_Now_Rice = 1000000*(sum((p,s),Y(s,’Rice’)*crop_cal(‘Rice’)*f_now(p,s,’Rice’)*Area(p)))
;
Parameter Tot_Cal_Now;
Tot_Cal_Now= (Cal_Now_Maize+Cal_Now_Wheat+Cal_Now_Rice)
;
Parameter Cal_Opt_Maize;
Cal_Opt_Maize = 1000000*(sum((p,s),Y(s,’Maize’)*crop_cal(‘Maize’)*f.l(p,s,’Maize’,'7')*Area(p)))
;
Parameter Cal_Opt_Wheat;
Cal_Opt_Wheat = 1000000*(sum((p,s),Y(s,’Wheat’)*crop_cal(‘Wheat’)*f.l(p,s,’Wheat’,'7')*Area(p)))
;
Parameter Cal_Opt_Rice;
Cal_Opt_Rice = 1000000*(sum((p,s),Y(s,’Rice’)*crop_cal(‘Rice’)*f.l(p,s,’Rice’,'7')*Area(p)))
;
Parameter Tot_Cal_Opt;
Tot_Cal_Opt = 1000000*Tot_Cal.l
;

*Selected fraction (results)
Parameter f_sol(p,s,c)  Solution for fraction            [-];
        f_sol(p,s,c)=f.l(p,s,c,'7')
;

*Calculate Areas
Parameter A(p,s,c)      Area planted optimal             [km^2];
        A(p,s,c)=f.l(p,s,c,'7')*Area(p)
;
Parameter A_opt(p,s,c)  Area planted limit               [km^2];
        A_opt(p,s,c)=f_max(p,s,c)*Area(p)
;
Parameter A_now(p,s,c)  Area planted now                 [km^2];
        A_now(p,s,c)=f_now(p,s,c)*Area(p)
;
Parameter A_N(p,t)      Area non-crop optimal            [km^2];
        A_N(p,t)=f_N.l(p,t)*Area(p)
;

```

```
** Parameters for mass balance check
* Volumetric

Parameter Net_Flow(p,t)        Qin-Qout                    [KM^3 per month];
        Net_Flow(p,t)  = sum(q,Flow_Dir(p,q)*Q_out.l(q,t))
;
Parameter ET_crop(p,t,c)       ET_Maize                    [KM^3 per mo];
        ET_crop(p,t,c) = K(t,c)*ET_0(p,t)*sum(s,f.l(p,s,c,t))*Area(p)/MM_to_KM3
;
Parameter ET_N(p,t)            ET_Maize                    [KM^3 per mo];
        ET_N(p,t)=e_non(p,t)*(1-sum((s,c),f.l(p,s,c,t)))*Area(p)/(MM_to_KM3)
;

*Convert to MM
Parameter ET_crop_MM(p,t,c)    Crop ET                     [MM per mo];
        ET_crop_MM(p,t,c) = K(t,c)*ET_0(p,t)*sum(s,f.l(p,s,c,t))
;
Parameter Q_out_MM(q,t)        Q_out                       [MM per month];
        Q_out_MM(q,t)=Q_out.l(q,t)*MM_to_KM3/AR(q)
;
Parameter DS_MM(p,t)           DS                          [MM per month];
        DS_MM(p,t)=DS.l(p,t)*MM_to_KM3/Area(p)
;
Parameter ET_N_MM(p,t)         ET_Maize                    [KM^3 per mo];
        ET_N_MM(p,t)=ET_N(p,t)*MM_to_KM3/A_N(p,t)
;

Execute_Unload  'Results_OPT2_V25.gdx' ;

*Fractions
Execute  'GDXXRW Results_OPT2_V25.gdx vpr=f_sol rng=f_optimized!a2';
Execute  'GDXXRW Results_OPT2_V25.gdx par=f_max rng=f_limit!a2';
Execute  'GDXXRW Results_OPT2_V25.gdx par=f_now rng=f_now!a2';
Execute  'GDXXRW Results_OPT2_V25.gdx var=f_N rng=f_N!a2';

*Areas
Execute  'GDXXRW Results_OPT2_V25.gdx par=A rng=A_optimized!a2';
Execute  'GDXXRW Results_OPT2_V25.gdx par=A_opt rng=A_limit!a2';
Execute  'GDXXRW Results_OPT2_V25.gdx par=A_now rng=A_now!a2';
Execute  'GDXXRW Results_OPT2_V25.gdx par=A_N rng=A_N!a2';
Execute  'GDXXRW Results_OPT2_V25.gdx par=Area rng=Area!a2';

*Water [MM]
```

```
Execute 'GDXXRW Results_OPT2_V25.gdx par=P_est rng=P_est!a2';
Execute 'GDXXRW Results_OPT2_V25.gdx par=ET_crop_MM rng=ET_crop_MM!a2';
Execute 'GDXXRW Results_OPT2_V25.gdx par=ET_N_MM rng=e_non!a2';
Execute 'GDXXRW Results_OPT2_V25.gdx par=Q_out_MM rng=Q_out_MM!a2';
Execute 'GDXXRW Results_OPT2_V25.gdx par=DS_MM rng=DStorage_MM!a2';

*Water [KM^3]
Execute 'GDXXRW Results_OPT2_V25.gdx par=Precip rng=Precip!a2';
Execute 'GDXXRW Results_OPT2_V25.gdx var=DS rng=DS!a2';
Execute 'GDXXRW Results_OPT2_V25.gdx par=Net_flow rng=Net_flow!a2';
Execute 'GDXXRW Results_OPT2_V25.gdx par=ET_crop rng=ET_crop!a2';
Execute 'GDXXRW Results_OPT2_V25.gdx par=ET_N rng=ET_N!a2';

*Calories
Execute 'GDXXRW Results_OPT2_V25.gdx par=Tot_Cal_Opt rng=Stats!G17';
Execute 'GDXXRW Results_OPT2_V25.gdx par=Tot_Cal_Now rng=Stats!F17';
Execute 'GDXXRW Results_OPT2_V25.gdx par=Cal_Now_Maize rng=Stats!f14';
Execute 'GDXXRW Results_OPT2_V25.gdx par=Cal_Now_Wheat rng=Stats!f15';
Execute 'GDXXRW Results_OPT2_V25.gdx par=Cal_Now_Rice rng=Stats!f16';
Execute 'GDXXRW Results_OPT2_V25.gdx par=Cal_Opt_Maize rng=Stats!g14';
Execute 'GDXXRW Results_OPT2_V25.gdx par=Cal_Opt_Wheat rng=Stats!g15';
Execute 'GDXXRW Results_OPT2_V25.gdx par=Cal_Opt_Rice rng=Stats!g16';
```

A12. Flow Information for Selected Rivers in Kenya

	River Flow											
	km^3/month											
River	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**June**	**July**	**August**	**Sept**	**Oct**	**Nov**	**Dec**
Ewaso Ngiro at Archers	0.026	0.013	0.028	0.083	0.060	0.028	0.026	0.040	0.037	0.043	0.116	0.083
Tana River at Garissa	0.389	0.259	0.259	0.518	0.674	0.389	0.246	0.207	0.207	0.246	0.674	0.596
Tana River at Garsen	0.311	0.246	0.207	0.272	0.337	0.324	0.220	0.168	0.156	0.181	0.311	0.363
Upper Athi River	0.048	0.020	0.028	0.089	0.146	0.054	0.031	0.027	0.023	0.028	0.084	0.089
Turkwell River	0.010	0.015	0.035	0.070	0.080	0.040	0.075	0.110	0.065	0.040	0.060	0.015

Table A.5: Monthly Flows for Selected Rivers in Kenya

River	Source	Processing
Ewaso Ngiro at Archers	Earth Water Ltd 2013	Monthly Values Available; Averages calculated Years: 1949-2011 Missing Data: 9%
Tana River at Garissa	Duvail et. al 2012	Monthly values approximated from graph Years: 1950 - 1998
Tana River at Garsen	Duvail et. al 2012	Monthly values approximated from graph Years: 1950 - 1998
Upper Athi River	Earth Water Ltd 2013	Monthly Values Available; Averages calculated Years: 1949-2011
Turkwell River	Kotut et. al 1999	Average Values as reported by author Years: 1957-1985

Table A.6: Sources for Monthly flows for Selected Rivers