Using a Water Balance Model to Analyze the Implications of Potential Irrigation Development in the Upper Blue Nile Basin

by

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B.S. Civil and Environmental Engineering,
University of Michigan, 2009

SUBMITTED TO THE ENGINEERING SYSTEMS DIVISION IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF SCIENCE IN TECHNOLOGY AND POLICY

AT THE

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

JUNE 2012

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Submitted to the Engineering Systems Division
on June 1, 2012 in partial fulfillment of the
requirements for the degree of
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Abstract

More than 200 rivers in the world cross at least one political border. Any development project including hydropower or irrigation that is implemented in a trans-boundary river is in essence a claim on the resource. Managing a trans-boundary resource will require coupling not only of the physical aspect, but also the economics and political state of the region. The goal in this thesis is to study one case of a trans-boundary river: the Nile. The Nile is shared by 10 countries, but the case study will focus on the three countries that constitute the Eastern Nile region: Egypt, Sudan, and Ethiopia. In particular, the paper focuses on Ethiopia's irrigation potential in the Upper Blue Nile basin (UBN) and seeks to understand the physical constraints, the maximum water use, and the downstream hydrological and political impacts of developing irrigation. The approach taken is to construct a physically based optimization model in the General Algebraic Modeling System (GAMS) to determine the upper bound of water withdrawal possible by Ethiopia, paying particular attention to seasonal variability.

The results show that both land and climate constraints impose significant limitations on agricultural production in the UBN. Only 25% of the land area is considered arable and suitable for irrigation due to the soil, slope and temperature conditions. When precipitation is also considered, on an annual average, only 11% of current land area could be used in a way that increases water consumption. The results suggest that Ethiopia could consume an additional 3.75 billion cubic meters (bcm) of water per year, through changes in land use and storage capacity, representing a 70 percent increase over existing water use. By exploiting this irrigation potential, Ethiopia could potentially decrease the annual flow downstream of the UBN by 8 percent.

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Acknowledgements

I would like to express my deepest appreciation to the following people who in one way or another have contributed to the success of this thesis:

First, thank you to my advisors, Professor McLaughlin and Professor Eltahir for their support, valuable comments and suggestions. Their wisdom and guidance was instrumental in the direction of this project and their advice was relevant and encouraging. They both share an absolute passion for what they teach; it is truly inspiring and has helped me enjoy the process. I appreciate their willingness to work on a tight schedule and help me graduate in a timely manner.

Over the years, I have been fortunate to enjoy the aid of fellowships, which have made my education possible. I would like to thank all the donors and the Office of Dean for Graduate Education for their support through a scholarship. Their investments in science education made this dream a reality for me. I hope others, like them, continue to stand with science.

I would like to show gratitude to Ms. Christine Sherrat and Ms. Anne Graham from MIT Libraries who did an outstanding job tracking down valuable sources. Thank you also to Mr. Daniel Sheehan from the GIS Lab, who helped me acquire the necessary GIS skills. Thank you to Ms. Piyatida Hoisungwan whose dissertation and early guidance helped form the groundwork for this thesis.

I give a sincere thank you to the TPP professors and administration, especially Krista Featherstone and Ed Ballo who are willing to extend themselves selflessly.

Thank you to my Parsons Lab-mates, the "oobergroup," and my lab group: Mohammed Siam, Noriko Endo, Mekki Seidahmed, Bec Giannoti, Marc Marcella, TeresaYamana and Mariam Allam, They aided with what may seem like small, but ultimately crucial pieces, like data sharing, computer and software management, problem discussions, late night conversations, and general camaraderie.

Thanks to my TPP classmates for making this journey through MIT incredibly fun. A hug and thanks to my friends, Genevieve Ho, Rudy Dieudonne, Shweta Mehta, Akshaya Verghese, Jonathan Lau, Yangue Zhang, Godine Chan, Luvena Ong, Greg Michel, and all others who have been there for me when the sun shines and the rain pours.

To Josh Cregger; to my sister, Indira Jain Figueroa; and to my parents, Rethelny and Adish: words cannot express my gratitude. Your love and friendship inculcated in me the values of sacrifice, kindness and hard work. Thank you for listening to all my worries and knowing what to do. Your willingness to roll up your sleeves and help me has enabled me to graduate and complete this thesis. This work is dedicated to my loving family. I owe all successes to them.

Rejoice with your family in the beautiful land of life! ~Albert Einstein

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Table of Acronyms

The following is a list of acronyms that appear in the thesis.

bcm	billion cubic meter, equivalent to 1km^3
CFA	Cooperative Framework Agreement
CRU	Climate Research Unit
DEM	Digital Elevation Map
DRT	Dominant River Tracing
ET	Evapotranspiration
FAO	Food and Agriculture Organization
GAMS	General Algebraic Modeling System
GDP	Gross Domestic Product
GW	Giga watt
HWSD	Harmonized World Soil Database
IFPRI	International Food Policy Research Institute
kc	Crop Coefficient
LGP	Length of Growing Period
MoWR	Ministry of Water Resources
NBI	Nile Basin Initiative
NTSG	Numerical Terradynamic Simulation Group
P	Precipitation
PET	Potential Evapotranspiration
SRTM	Shuttle Radar Topography Mission
TRMM	Tropical Rainfall Monitoring Mission
UBN	Upper Blue Nile
UN	United Nations
UNDP	United Nations Development Program
UNEP	United Nations Environment Program
USGS	United States Geological Survey
WM	Willmott and Matsuura
WSDP	Water Sector Development Plan

Chapter 1

Introduction

Water, a key natural resource, is essential for socio-economic development and environmental sustainability. Apart from the fact that it sustains life, it is also an important economic driver, important for irrigation, power generation (e.g. hydropower) and for many other industrial applications.

During the 21st century, attention has shifted to the question of how nations can address water scarcity. Water scarcity is defined as the point where aggregate demand for water cannot be satisfied by the available supply or quality (United Nations, 2006). Nations who have less than 1,000 cubic meters of clean water per person are classified as "water scarce." Water scarcity can be a natural and man-made. Those countries in arid or semi-arid regions which already experience water scarcity are particularly vulnerable (Figure 1); especially as their populations grow and their climates change (Arsano and Tamarat, 2005).

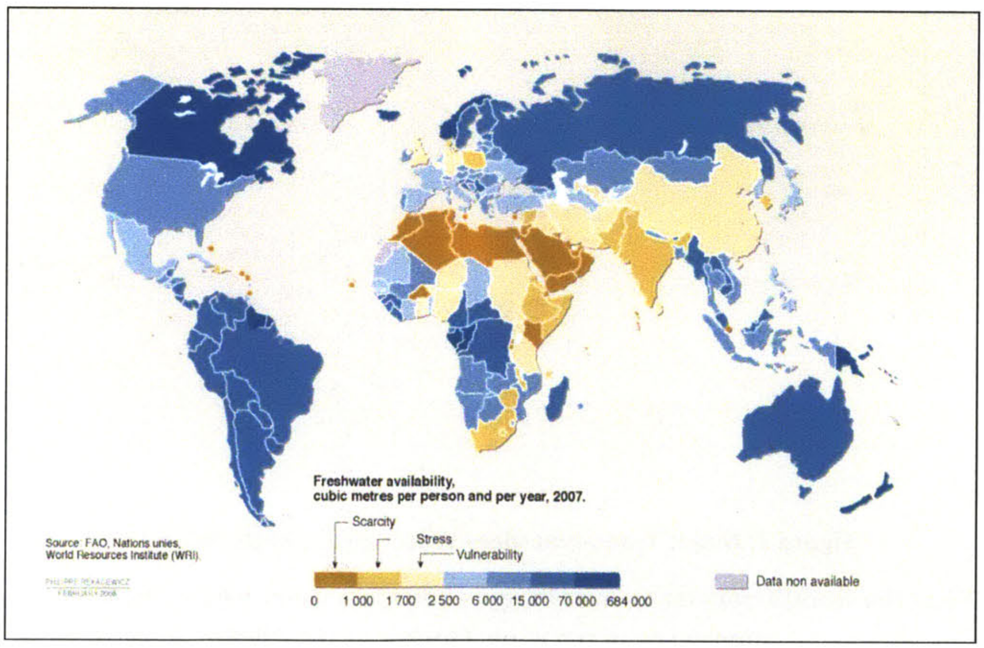

Figure 1: Global Freshwater Availability in 2007 (m3/person)

North East Africa is already experiencing an acute water shortage and scarcity. Climate change and growing populations can exacerbate this (Source: Vital Water Graphics. UNEP, 2008).

Worldwide, more than 200 rivers cut through national boundaries (Figure 2) and 40% of the world's populations live in these trans-boundary water basins (UNEP, 2011). These trans-boundary water resources, such as lakes, rivers or aquifers flow from one sovereign state to another. Consequently, there is a political dimension to water scarcity that makes the problem more complex. Such problems are best handled in an interdisciplinary realm combining both technology and policy. The sheer number of people affected, on a global scale, makes this a very important issue. The management of trans-boundary water resources can promote sustainable development and increase stability in a region but it will require collective action among riparian states in order to garner cooperation and overcome myopic self-interests.

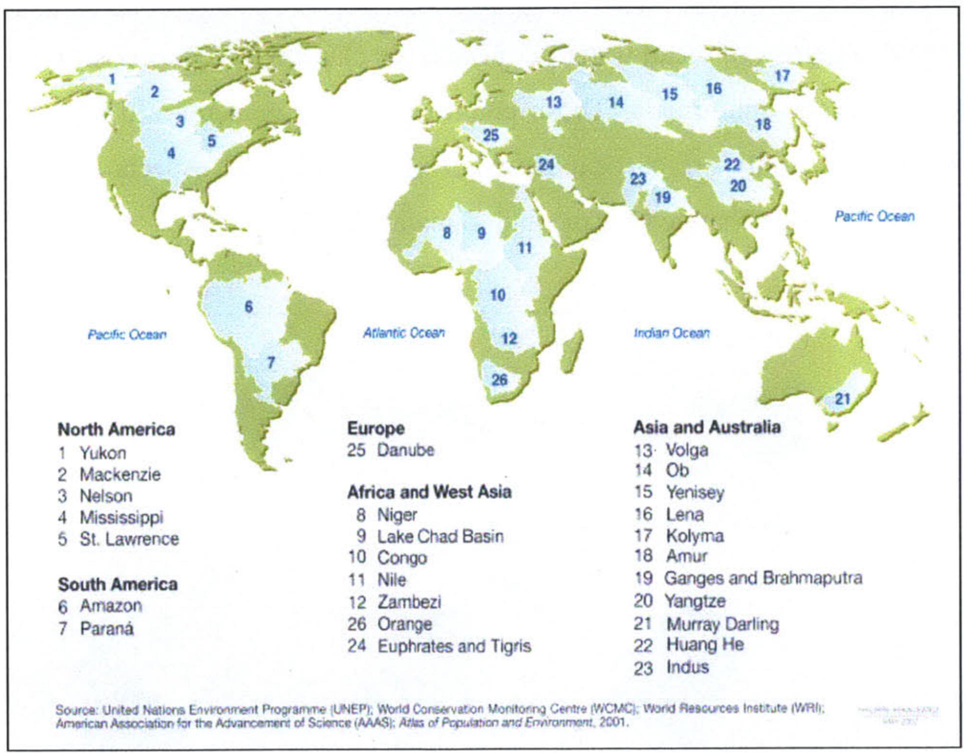

Figure 2: Major Trans-boundary Water Basins in the World

Over 40% of the world's population lives in trans-boundary water basins, demonstrating the importance of the issue. (Source: UNEP, 2008)

This case of the trans-boundary Nile basin in Africa will be the focus of this study. Of the eleven countries and 160 million people that share the Nile waters, the major conflict of interests in the Nile basin grip three nations: Egypt, Sudan, and Ethiopia (Waterbury, 2002). North East Africa already has an acute water shortage as shown in Figure 1. Egypt who receives little to no rainfall depends almost entirely on the Nile's waters. Nearly one hundred percent of Egypt's renewable water resources originate outside of its borders while 80 percent of Sudan's originate outside the country (Aquastat, 2012). Ethiopia, on the other hand, enjoys high rainfalls. In fact, Ethiopia's geographic location, rainfall, and higher elevation makes it the "water tower" of the region since many of the major rivers emanate from here (Arsano and Tamarat, 2005). Despite being drought-prone, Ethiopia, has, until now, used almost none of the Nile river waters. Recently, Ethiopia has set development priorities to ensure food security through expanded irrigation, increasing hydropower production, and providing water for industrial development (WSDP, 2000).

The Egyptians understand their dependence on the Nile. They are fearful that if Ethiopia develops the ability to regulate river flows, they will control the river and harm Egypt, and if Ethiopia develops irrigation and water storage, they will deduct from Egypt's share of Nile waters. To change an economy to adapt to less water is difficult, and as the strongest economic nation in the region, Egypt sees the problem as one of national security. The concern for water is so serious that responsibility for Nile basin issues is delegated not only to the water and foreign affairs ministries but also to Egypt's intelligence and security chief (Shenker, 2010).

Many scholars have forecast that such tensions over a scarce and irreplaceable resource like water could lead to water wars. In fact, Egypt's President Anwar Sadat said in 1979, "The only matter that could take Egypt to war again is water." Ten years later, former Egyptian president Hosni Mubarak threatened to send demolition squads to a dam project in Ethiopia. Although conflict over water are not unheard of, according to Fisher (2001) they stem from a narrow way of thinking of water: By approaching the issue as zero-sum game with no substitute where two parties claim the same water and the water that one party gets is not available for the other. Fisher suggests that there is another way to think about water problems that can lead to a policy of cooperation and optimal water management. Think about water from a perspective of its value such that it can be traded for other things. Water itself for nourishment is not a major source of water consumption. Water is a means towards economic growth whether it's through industry, hydropower generation or agriculture. To develop water use policies, it is essential to see water, not as an end in itself, but as a means towards a goal that can help open doors to trade; this is what Sadoff and Grey (2002) call "benefits beyond the river."

1.1 Motivation

In examining the dynamics that drive conflict and cooperation in river basins, Sadoff and Grey (2002) determine that perceptions of the relative costs and benefits drive the decision. In the Nile basin, there are several perceptions regarding water. Some are listed as follows:

1. Ethiopia needs to divert substantial quantities of water to obtain agricultural benefits.
2. Ethiopia needs large irrigation investments for food security.
3. Dams in the Blue Nile basin in Ethiopia could negatively impact downstream riparian users and threaten water supply reliability to Egypt.
4. The benefits of cooperation and the costs of non-cooperation are not great.
5. Allocation of the Nile waters is a zero sum game.
6. A full Aswan reservoir is the only way for Egypt to have water security.

The motivation for this thesis stemmed from the desire to address some of the perceptions of developing the Nile and attaining food and water security in the region, particularly the first two perceptions in the list above. The goal is to understand whether the mistrust between Egypt and Ethiopia is founded on reasonable grounds or not. It is possible that the historical mistrust between these nations stems in part from lack of knowledge of the potential impacts of development. By illuminating some of the impacts of development, there may be reasons or ways for cooperation. The Nile, as a trans-boundary watershed could serve as forum for cooperation and could enhance regional development and security. Each nation has unique interests in the Nile. Egypt must deal with water scarcity, Sudan often has seasonal flooding and Ethiopia has recurrent drought. Through cooperation, perhaps each nation could address its national interest and achieve better regional integration (Figure 3).

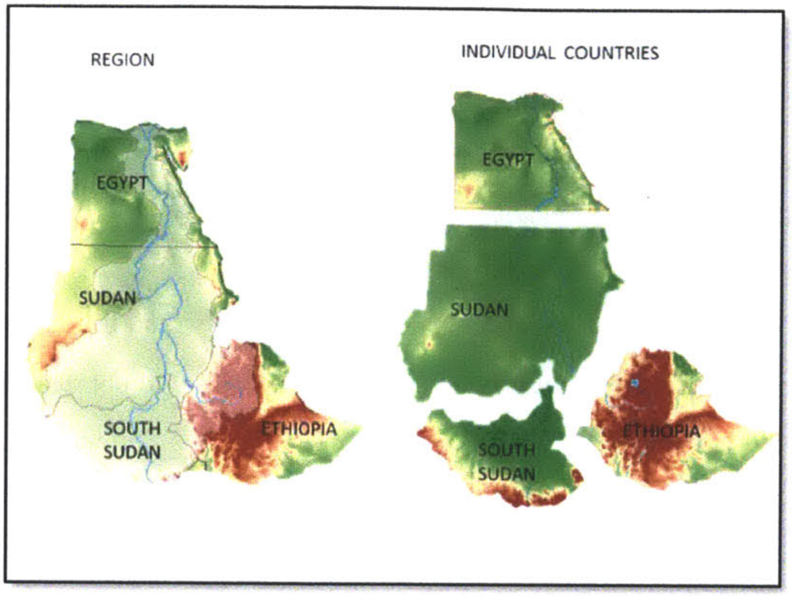

Figure 3: Major Countries for Regional Integration in the Nile Basin

Of the eleven countries that share the Nile, Egypt, Sudan, South Sudan, and Ethiopia have the biggest stake; cooperation among them to achieve regional integration may lead to better management of the Nile Basin

Egypt asserts that non-consumptive water uses such as hydropower and increased water-use efficiency are more acceptable development projects for Ethiopia. The impact of irrigation, however, continues to be a question. Currently there are agreements to establish irrigation pilot projects in order to test the impacts that irrigation development in Ethiopia could have on the water quality and quantity of downstream countries (Arsano and Tamarat, 2005). These pilot projects, however, have been stalled and have not moved beyond the agreement phase. The basis for the methods selected in the thesis is that some understanding of the downstream effects of irrigation can be gained through a modeling effort. As part of the thesis, we develop a mathematical model that is a simple representation of part of a real-world system. The advantage of numerical models over field experiments is that models can be less expensive, less time-consuming, can scale much more easily and offer generalized findings with the ability to conduct "what if" analysis.

1.2 Research Questions

One of the main objectives in this thesis is to study Ethiopia's irrigation potential in the Nile Basin and the impact of its development on the downstream hydrology, paying particular attention to seasonal variability and the constraints imposed by soil type, topography, water availability and climate. The questions explored are threefold:

- Is Ethiopia's ability to use irrigation water constrained by land limitations?
- What is the maximum irrigation potential measured as a volume of water per month that Ethiopia could consume?
- What are the downstream hydrologic and political impacts of using this irrigation potential?

This is a bounding exercise to understand the biggest effect that irrigation development in Ethiopia could have on downstream countries like Sudan and Egypt.

1.3 Objectives

To answer the research questions, we establish the following objectives:

- Identify the potential irrigable land in the Upper Blue Nile Basin in Ethiopia
- Develop a model to assess potential irrigation development and its implication for basin hydrology.
- Present the results in a way that can inform the decision-making process.

1.4 Literature Review

1.4.1 Water Scarcity

Vörösmarty et al. (2000) assessed the impact of climate change and population growth on global water availability using a general circulation models (GCM) and annual water demand figures. The results showed that in several regions the impact of population growth and economic development on water resources was greater than the estimated impact of climate change. Falkenmark (1997) investigated whether the water resources could meet the food needs of an expanding population in Africa and Asia and found that in a 30 year time frame, assuming a need of 900 m3 of water per person per year and a reasonable capacity to mobilize water, the water needed for agriculture to support local populations was not available. Vörösmarty et al.

(2005) claimed that in Africa, modest increases in water use could reduce constraints on economic development, pollution, and challenges to human health. Although useful, these studies at large national scales tend to mask variation in water security at local scales. A better picture of water security requires assessments at several scales including local and national for both human and ecosystem needs. Several of these studies have considered the question of water scarcity without considering the inter-year or intra-year variability.

1.4.2 Upper Blue Nile Basin

There have been several studies on the Nile, and the Upper Blue Nile since it provides the largest runoff contribution to the Nile. Conway studied the climate and hydrology of the Upper Blue Nile and created a water balance model (2000). He has looked at the climate variability and climate adaptation (1996, 2005) and fluctuations in precipitation and runoff (1993, 2005).Others who have studied the climate and hydrology of the Upper Nile Basin include Mishra and Hata (2006), Johnson and Curtis (1994), Hurst (1950), and Shahin (1985). Very few have published hydrological data from the Blue Nile and its tributaries. Hurst conducted a series of studies covering the entire Nile River basin. Then in 1958-1963, the U.S. Bureau of Reclamation conducted a land and water resource survey. This is the only study of its kind, and it provides data for one to four years for a number of watersheds within the Blue Nile Basin. The Ethiopian government has probably commissioned smaller scale studies but the data is not made available. Consequently, most of the recent literature on the Blue Nile has used the USBR study or Hurst data directly or indirectly (Guariso and Whittington, 1987; Waterbury, 1988; Collins, 1990; Johnson and Curtis, 1994).

Many studies have focused on the climate change impacts and the possibility for adaptation (Gleick, 1991; Conway and Hulme, 1993; Strzepek et al., 1995; Yates and Strzepek, 1998a; Kim, 2008), Most of the studies that focus on climate change are concerned with changes in the availability or supply of water.

Other studies have focused on the effects of development such as the most economic dam operations (Block, 2006) and the economic value of cooperation (Whittington et al., 2005). The Food Policy Research Institute (IFPRI) has conducted several studies in the Upper Blue Nile basin that focus on integrated management of development projects (Block et al., 2007), improving water and land management to improve food security (Awulachew, 2010). Our work extends on previous studies by focusing on changes in demand of water due to agricultural development.

1.4.3 Nile Basin Models

Given the limited data, many hydrologic models that simulate hydrologic response of the Blue Nile under extreme changes have been developed. Johnson and Curtis (1994) present a simple water balance based on Schaake and Chunzhen (1989). They used discharge data of less than 4 years to develop a monthly water balance and understand the rainfall-runoff relationship for forecasting. They aimed to develop a method for calibrating water balance coefficients for those small basins lacking any available data. Conway and Hulme (1996) created a distributed runoff model of the Blue Nile and of Lake Victoria sub-basin. Conway used a grid based water balance, which required limited data inputs, few parameters and monthly time step. But the main drawback was the spatially invariant treatment of soil characteristics and vegetation. His model served as a runoff simulator. Olivera et al. (2000) used the generalized version of the unit hydrograph model to route Nile flow. Diao et al. (2005, 2007) used an economic model of Ethiopia's eleven administrative regions to simulate the impact of economic growth under different investment scenarios, including expansion of irrigation and fertilizer use. The model includes only benefits, and focuses on the agriculture sector, with 34 agricultural commodities and two aggregate nonagricultural commodities.

NileSim created by the FAO, outputs volumes for lakes and swamps and models only the river network and storage sites. It is useful for policy makers to understand the effects of building storage. NileSim models the river and storage projects along it and can be used to modify storage plans and release plans. Agricultural projects are not treated explicitly but can be modeled as abstractions. Block (2006) developed "The Investment Model for Planning Ethiopian Nile Development" (IMPEND) which captures the transient stages of reservoir filling, the downstream effect and the economics to decide which dam projects are better. Most optimization models such as IMPEND and WAS (Fisher, 2005) have focused on the economic aspects and tradeoffs between irrigation and storage projects. Georgakakos and Yao (1997) developed the Nile Decisions Support Tool. This model has certain limitations since it has many parameters that are calibrated and hard wired, making changes quite difficult. There are other models in the literature including Guariso and Whittington, 1987; Levy and Baecher, 1999; Georgakakos, 2004; Whittington et al., 2005. Still, the size and complexity of the Blue Nile, coupled with the limited data are major problems with modeling this region and using sophisticated hydrological models.

Many of the models assume there is plentiful or adequate data for the major components: precipitation, potential evaporation, and stream flow. Often more data is necessary to account for varying soil type, land use, vegetation, even soil moisture. The Upper Blue Nile basin, however, has scant in-situ data. Very few stream gauges exist along the Blue Nile River within Ethiopia, and those that do tend to have spotty or limited records, and are often not publicly available. In the thesis, to overcome the limited data problem, we try to make use of the growing availability of satellite-based data. Although many of these data sets are still being tested against observations, they offer the promise of modeling the Blue Nile Basin hydrology using more complete time series estimates. Unlike some of the previous models, we explore a spatially varying soil and land use condition.

1.5 Thesis Organization

The thesis is organized as follows. In Chapter 1, the motivation, research question, objectives are addressed and relevant literature is reviewed. Chapter 2 provides background information covering a description of the Nile Basin, the hydro-politics in the region and socio-economic factors. Chapter 3 provides a detailed description of the study area including geography, topography, soil types and climate. Chapter 4 covers the 3-phase modeling framework and relevant data sets. Each phase is described in a separate chapter, encompassing Chapters 5, 6 and 7. Chapter 8 explains the results and political implications and proposes future research work and model improvements.

Chapter 2

Context

This section provides contextual information necessary to understand the research problem. It is necessary to characterize the location, delineate and provide a general description of the basin. The second part is a characterization of the socio-economic factors. A trans-boundary river by definition crosses a boundary; this boundary, however, is not natural but one created by people to demarcate culture, identity and property. In studying a trans-boundary resource, a thorough socio-economic analysis is essential to understand the use and access, the economic perspective and the legal dimension of water. This section provides an overview of the Nile basin, the geography, climate, history and socio-economic issues that have led to the present hydro-political issue.

2.1 Nile Description

The Nile River is one of the most famous rivers of the ancient world. The Nile River gets its name from the Greek word "Nelios", meaning River Valley (NBI, 2010). It is the dominant geographic feature of northeastern Africa and the longest river on Earth. The Nile basin covers a surface area of nearly 2.9 million square kilometers, representing over 10% of the African continent. Flowing south to north, the Nile traverses about 6,700 kilometers. Eleven nations share the waters of the Nile: Tanzania, Uganda, Rwanda, Burundi, Congo, Kenya, Ethiopia, Sudan, South Sudan, Eritrea and Egypt (Figure 4). More striking than the number of nations that share the basin, is the land surface and the population of each nation that falls within the basin. Each country contributes differently to the basin and has different needs for the water resources (Table 1). Combined, the countries that share the Nile have a population of 424 million people; of these, 232 million live in the Nile Basin (NBI, 2010).

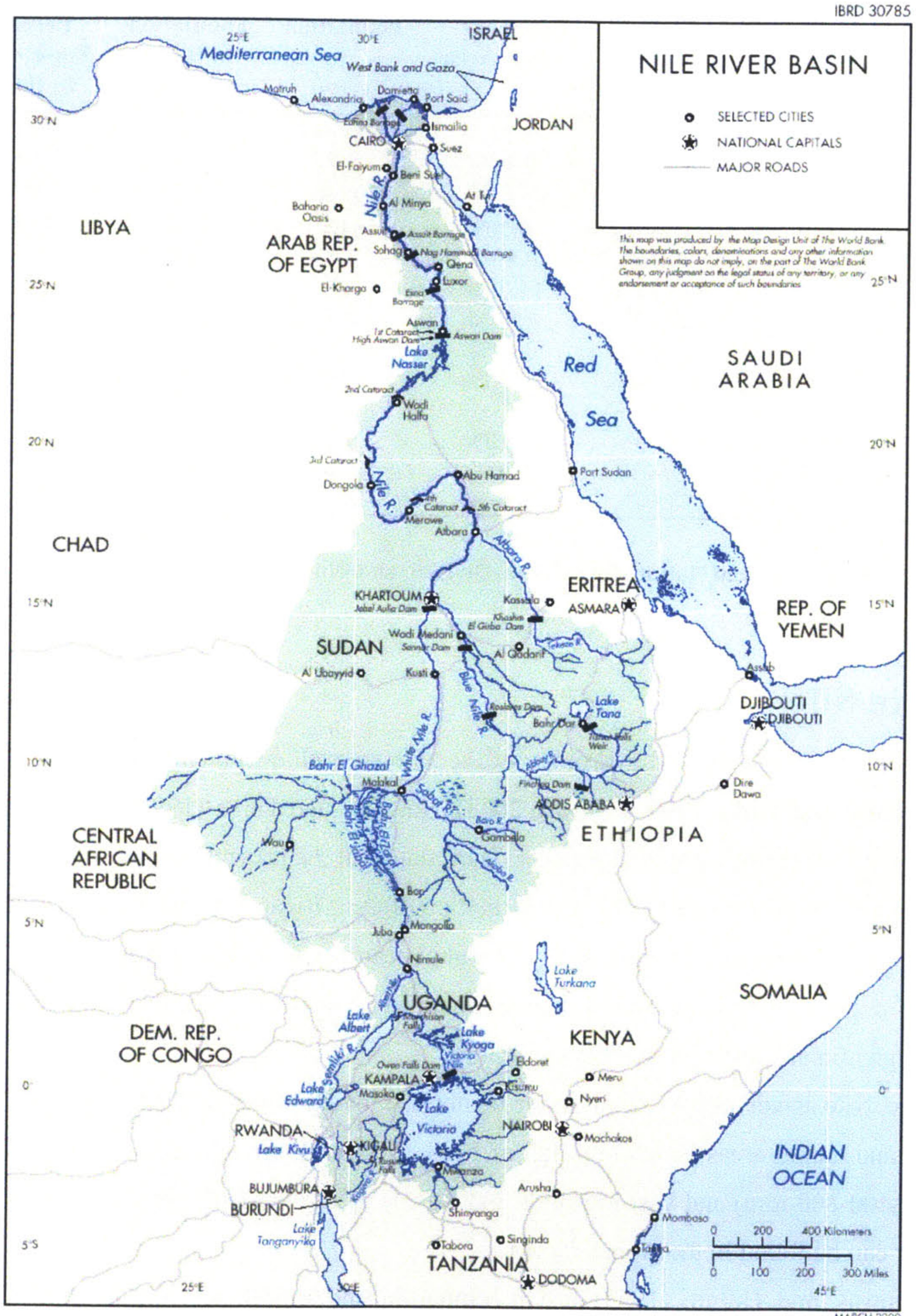

Figure 4: Nile Basin Map

The main tributaries to the Nile are the White Nile and the Blue Nile which join at Khartoum.

(Source: World Bank)

Table 1: Countries that Share the Nile: National Areas, Populations and Percentage in the Nile Basin

	National Area	Percent Area in Basin	Percent Basin Area	Population	Population In Basin	Percent Population In Basin
	(000 km2)	*%*	*%*	*millions*	*m*	*%*
Burundi	27.8	47.60%	0.40%	8.5	5.1	60%
Congo	2344.9	0.90%	0.70%	67.8	2.6	4%
Egypt	1001.5	32.60%	10.50%	84.5	82.9	98%
Eritrea	121.9	20.40%	0.80%	5.2	1.6	31%
Ethiopia	1100	33.20%	11.70%	85	34.1	40%
Kenya	580.4	8.00%	1.50%	40.9	16.3	40%
Rwanda	26.3	75.50%	0.60%	10.3	8.4	82%
South Sudan	615.9	100.00%	19.80%	43.2	38.7	90%
Sudan	1889.9	72.10%	43.80%			
Tanzania	945.1	8.90%	2.70%	45	9.3	21%
Uganda	235.9	98.10%	7.40%	33.8	33.6	99%

(Source: United Nations Population Division and World Bank Database, 2012)

2.2 Main Nile

The water resources and hydrology of the Nile are well documented (Hurst 1957, Shahin 1985, Sutcliffe and Parks 1999, Conway 2005). Sutcliffe and Parks (1999) provide a detailed outline of the Nile Basin's physical aspects. They state that the present shape of the Nile River is believed to be only 10,000 years old. The formation of the African Rift changed the hydrology so that rivers in the Ethiopian plateau and Equatorial plateau would drain towards the Nile. The Nile crosses 25 degrees of latitude from 4 degrees south to 32 degrees north. Consequently, the Nile exhibits high climatic and topographic variability.

The Nile River moves from south to north, moving water and silt from mountainous highlands and humid areas (annual rainfall of 1200-1500 mm) through semi-arid regions (annual rainfall of 400-800 mm) and vast lowlands and deserts up to the Mediterranean. A profile of the Nile River can be found in the Appendix A1.

Conway and Hulme (1993) use precipitation and runoff analysis to distinguish two homogenous zones of origin: The Ethiopian highlands and the Equatorial Lakes. These zones represent the two headwaters of the main tributaries to the Nile River: the Blue Nile and the

White Nile, respectively (Figure 4). From its major source, Lake Victoria, the White Nile flows north to Khartoum, Sudan, where it meets the principal tributary, the Blue Nile.

2.2.1 Nile Annual Flow

A striking feature of the Nile, given its great length, is the low annual stream flow. The long term average annual flow of the Nile is typically taken as 84 billion cubic meters (bcm) as measured at the Aswan High Dam in Egypt (Shahin, 1985). Compared to other major world rivers, the Nile has a very low flow with only 2% of the Amazon, 6% of the Congo, 12% of the Yangtze, 17% of the Niger and 26% of the Zambezi Rivers' annual flow (Grey, 2010). The low flow, however, does not detract from the importance of the Nile to riparian nations.

The Blue Nile rises in the Ethiopian highlands and contributes about 60% of the flow that reaches Aswan Dam in Egypt. The Blue Nile and the Atbara are both highly seasonal with the majority of their contribution from June to October (Figure 5). These waters are supplemented by the White Nile which supplies a steady flow rising in the Equatorial Lakes.

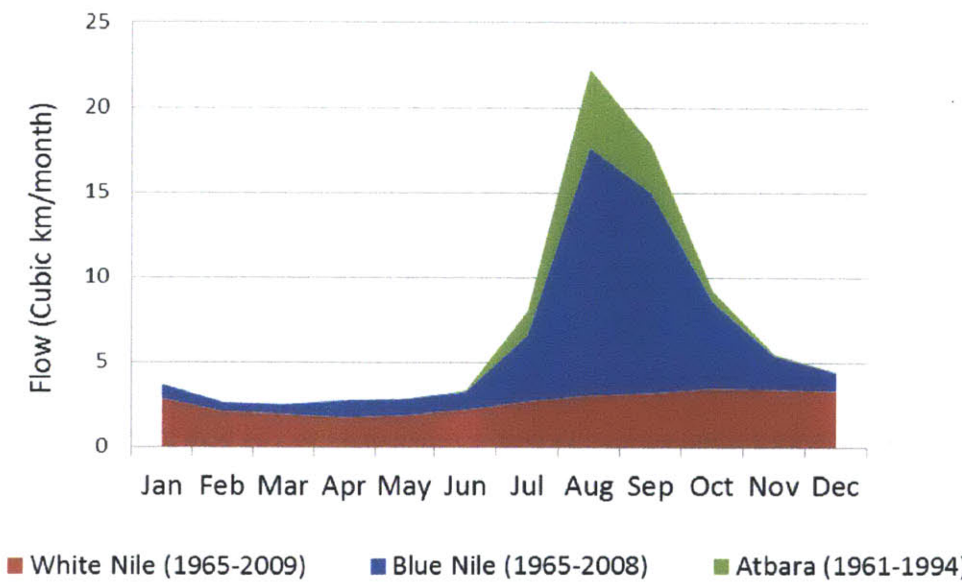

Figure 5: Mean Monthly Nile River Flow

The annual Nile Flow is taken as 84 bcm but this is not uniformly distributed. The major flow contribution is from the Blue Nile in the months from June to October.

2.2.2 Variability in Annual Flow

It is important to note that there has been considerable variability in the Nile's annual flow. Conway and Hulme (1993) provide a coherent record of flows at Dongola from 1890-1990 separated into two series 1890-1962 and 1963-1990. Over the complete 100 year period, the mean annual discharge is 89.9 bcm, but year to year there is great variability. Several studies including Conway's, point out certain events: 1) above average flows form 1890-1898, 2) large increase in storage volume of 151bcm in Lake Victoria and consequently higher outflows from 1961-1964 and 3) a long period of lower than average annual flow from 1965 on with only four years above average. In fact, our own unpublished data suggest that the lowest decade mean flow in the Nile occurred from 1978 -1987 and show that in the past 40 years, the annual flow has ranged from 42 to 104 bcm as shown in Figure 6.

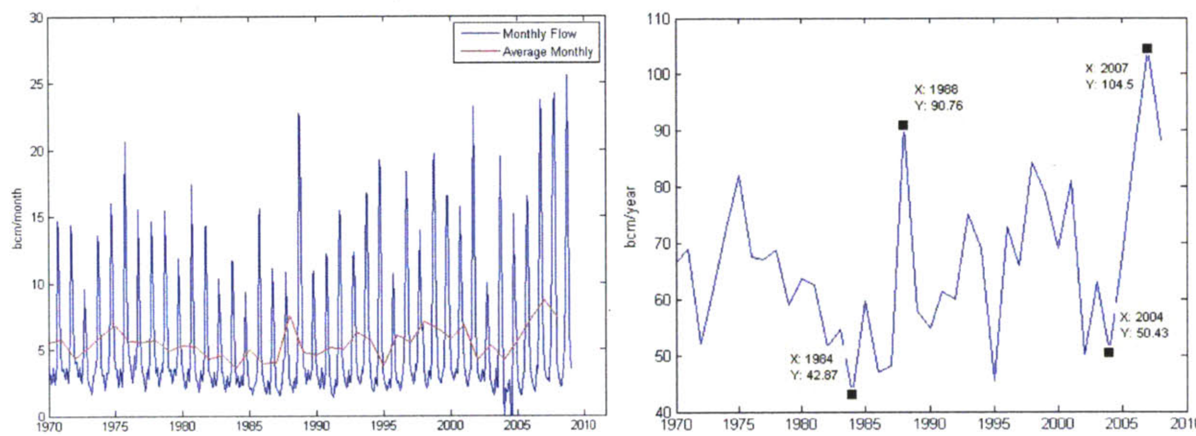

Figure 6: Monthly and Annual Nile Flow measured at Tamaniat from 1970-2008

The Nile has had large annual variability with a range of 42 to 104 bcm in the past 30 years.

This high variability highlights the importance of sound hydrology informing the process of writing agreements. The Nile Basin's 6000 years of ancient civilizations were attuned to the seasonal, yearly and even decadal variability of the Nile flows, citing seven years of prosperity followed by seven years of dearth in ancient civilization stories. In 1951, Hurst, through his work in the Nile also noted that low and high flow years tended to be grouped together. He found that the frequency distribution was normally distributed.

The completion of the High Aswan Dam in (HAD) in 1971 in Egypt made the Nile discharge to the delta, highly regulated. The regulating effect of HAD manifests itself in the hydrology in three ways: peak discharges have been decreased, minimum discharges have been increased, and the timing of the peak has been altered. Prior to the HAD, the peak mean monthly discharge occurred in September, and the minimum discharge in April. Now, due to the operation of the dam, the peak discharge occurs in July, and the minimum discharge occurs in January (Saad, 2002). Other development projects on the Nile such as irrigation or dams could also alter the downstream hydrology.

2.2.3 Climatology

The variability in the Nile discharge is due in a large part to the changes in precipitation primarily over the Ethiopian plateau and secondly over the upper White Nile region (Conway, 1993). The hydro-climatology of the Nile is temporally and spatially variable. Rainfall and vegetation cover ranges from equatorial forest in the south, to semi-arid and arid climates in the central and lower parts of the basin. Rainfall is bimodal in the Equatorial Lakes Region and uni-modal in the Ethiopian highlands, varying from over 2000 mm per year at the sources to nothing in the Sahara desert. The White Nile does not fluctuate as much because the number of swamps and wetlands has a smoothing effect. The four-month rainy season over the Blue Nile provides 80% of the Nile water (Awulachew, 2010).

2.2.4 Main Tributaries and Sub-basins

Conway and Hulme (1993) identify eight major sub-basins where rainfall contributes to the flow of the Nile (Figure 7): Atbara, Blue Nile, Sobat, Lake Victoria, Bahr el Ghazal, Central Sudan, Sudd, and Equatorial Lakes. This section describes the main features of each sub-basin and the flow of the Nile as shown in Figure 8.

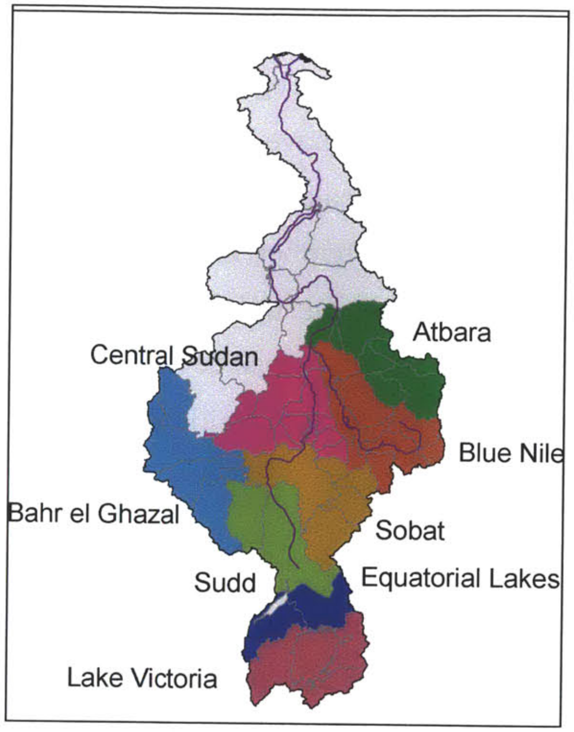

Figure 7: Major Nile Sub-basins

2.2.4.1 Lake Victoria Sub-basin

Lake Victoria has a surface area of about 67,000 km 2 and is located in Uganda, Kenya and Tanzania. Given the large storage, the lake helps moderate seasonal and short-term fluctuations in water supply and outflow to the Nile (Sutfcliff and Parks, 1999). The Kagera River is the main tributary to Lake Victoria but the biggest water contribution is direct rainfall. Lake Victoria basin has a bi-modal distribution of rainfall with peaks in March-May and then November-December and varies from 750mm in the east to 2,000mm in the north-west (Conway and Hulme, 1993). The annual mean precipitation, as a depth, is about 1,500 mm, or 100 bcm as a volume. Figure 8 shows that mean annual precipitation over the lake is quite high but the evaporation loss is also high. The Owen Falls dam and international operations agreements control the outflow of the Lake. The lake has an annual discharge of 23.5 bcm, which means it contributes about 28% of the annual flow of the main Nile.

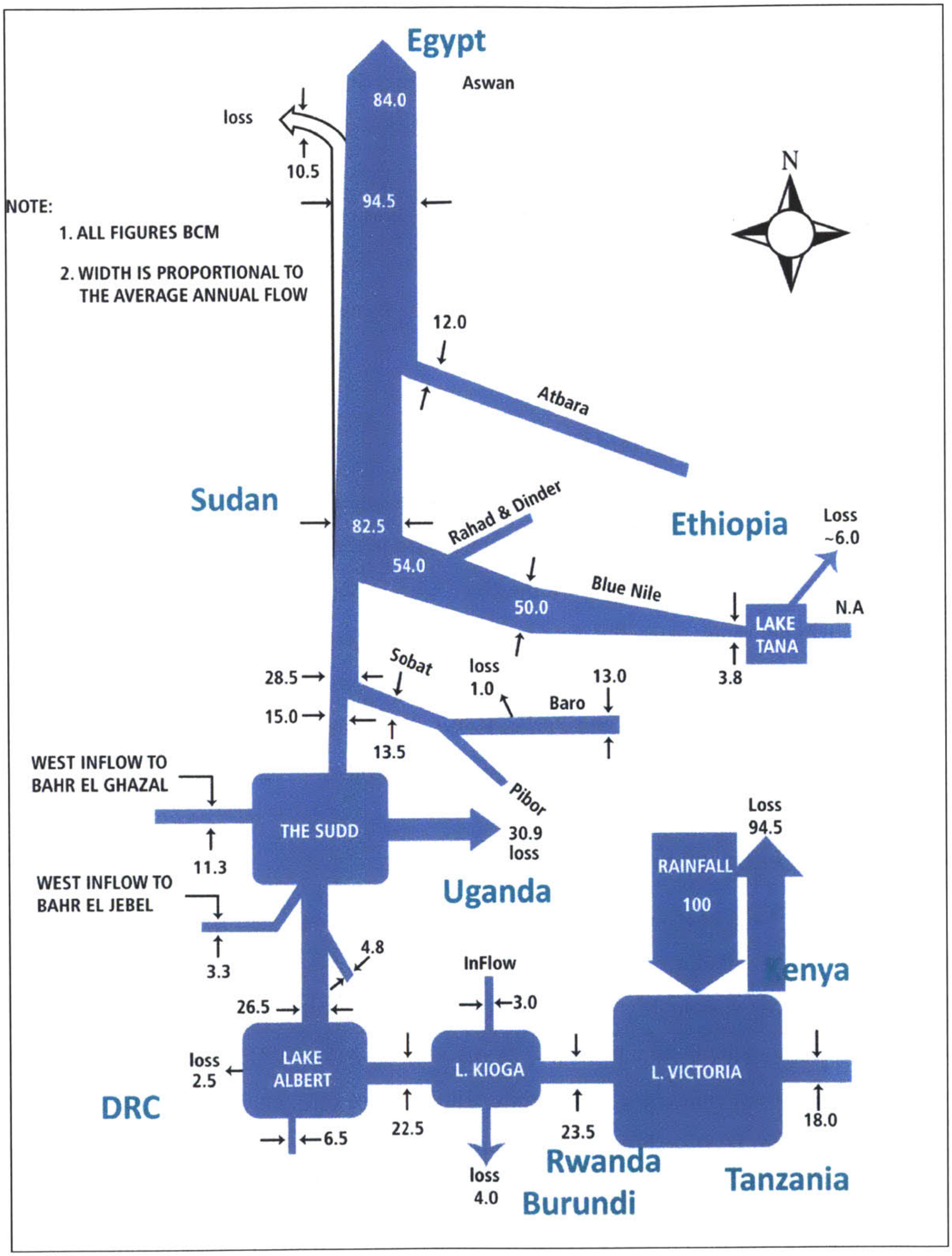

Figure 8: Schematic of the Nile River Flow Fluxes

(Source: Grey, 2010)

2.2.4.2 Equatorial Lakes Sub-basin

Following the schematic in Figure 8, the Victoria Nile flows 130 km to Lake Kyoga. This lake is a grass filled valley and in some periods produces a net water loss, and in others, a net water gain (Sutfcliffe and Parks, 1999). The river then flows west to reach Lake Albert. Along with Lake George and Lake Edward, Albert and Victoria, comprise the Great Lakes system (Kyoga is not considered a Great lake). Lake Albert presents high evaporative losses and ultimately, the region of the Equatorial Lakes adds only about 8 bcm annually to the main Nile, a 9% annual contribution.

2.2.4.3 Bahr el Ghazal and the Sudd Sub-basins

The Bahr el Ghazal and Sudd sub-basins present a net loss to the system. In both of these basins, high flows spill into swamps. Evaporation from the swamps greatly exceeds rainfall which only occurs in a few months before the river rises. About half of the White Nile river flow spills over and evaporates from the Sudd. To prevent these losses, water resource planners proposed a cut channel in 1904, the Jonglei Canal, which would bypass the swamps and divert the water for better uses (Sutfcliffe and Parks, 1999). The complexity of the canal and instability in the region has hindered progress on the Jonglei Canal project.

2.2.4.4 Sobat and Central Sudan Sub-basins

The White Nile is joined by the Sobat which drains the southwestern Ethiopian Highlands. The main tributaries to Sobat are the highly seasonal Baro, and the Pibor. They combine to dampen the seasonality. At the Ethiopian-Sudan border, the Baro River spills into the Machar marshes. The annual stream flow of Sobat is estimated at 13.5 bcm, which means about a 16% contribution to the main Nile. The White Nile's course through Central Sudan, from Sobat to the confluence with the Blue Nile at Khartoum is simple as there are no additional tributaries. The area becomes increasingly semi-arid. The construction of Jebel Aulia dam in 1937 above the Blue Nile confluence helps regulate flow downstream to Egypt during the low flow season. The dam has made irrigation easier given the raised level of the river upstream but has resulted in higher evaporation losses estimated at 2 bcm (Conway and Hulme, 1993).

2.2.4.5 Blue Nile Sub-basin

The major contribution to the main Nile at Khartoum is provided by the Blue Nile. The Blue Nile basin is shared by Sudan and Ethiopia but much of the water originates in Ethiopia. This water carries 90% of the Nile sediments. It has been depositing these sediments in the banks of Egypt making them rich and fertile for several centuries. Although the erosion of the Blue Nile has degraded the watershed and caused it to lose productivity, it still has potential for irrigation. A more detailed discussion of the Blue Nile basin is undertaken in Chapter 3.

2.2.4.6 Atbara

The Atbara, above its confluence with the Setit drains about 31,400 km2 of the mountains north of Lake Tana and the plains to the west. It has several intermittent streams ("khors") and an estimated annual rainfall of 950 mm with a rainfall season shorter than the Blue Nile Basin and concentrated in August and September (Hurst et al., 1959).

2.3 Socio-Economic Factors

The Nile Basin is a region of extremes and great diversity. Physically, as discussed in section 2.2, it has high climatic variability and drastic varieties of topographies. Socio-economically, it has five of the world's ten poorest nations (Sadoff and Grey, 2002). Several studies have investigated the relationship between geography and economic development. However, only a few have included an explicit treatment of water availability and water variability (Sachs 2001; Awulachew 2010; World Bank, 2006; Grey and Sadoff, 2006). Awulachew et al. (2010) mapped rural poverty in the basin (Figure 9) and show that income poverty at the sub national level range from 17% in Egypt to over 50% in five of the other ten nations.

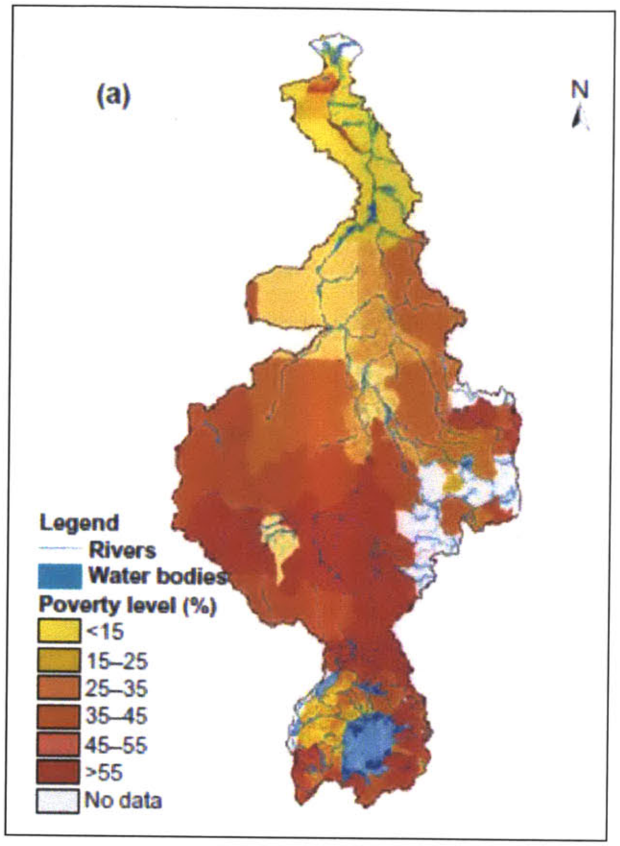

Figure 9: Poverty Level in the Nile Basin

(Source: Awulachew, 2010)

2.3.1 Historical Mistrust

The relations between the North African Nile Basin nations have historically been fraught with suspicion, especially between Egypt and Ethiopia. International cooperation between Ethiopia and Egypt was unthinkable before the end of the Cold War. In colonial times, the use and management of the Nile was dictated by Great Britain. Great Britain held a strong position and drafted agreements to protect its own interests: its cotton fields in Egypt and Sudan. In the 1920's, Britain published the Century Storage system, a comprehensive water development projects plan. All the projects were located outside of Egyptian territory and the Egyptians saw this as a way for Britain to control Egypt even though they had received conditional independence from Britain in 1922 (Waterbury, 2002). In 1952, one year before becoming a republic, Egypt proposed the Aswan Dam, a project within its own borders. After seven years of negotiation with Sudan, the 1959 Agreement for the Utilization of the Nile was drafted. It was primarily an agreement in order to obtain funding for the Aswan Dam, but it had the following provisions: the average annual flow of the Nile (84 bcm) was divided by providing Egypt with 66% (55.5 bcm), Sudan with 22% (18.5bcm) and allowing 12% (10 bcm) for losses. Any increase in average flow would be divided equally and a technical committee would discuss any decrease. Egypt and Sudan agreed that the combined needs of other riparian nations would not exceed 1-2 bcm per year and that any claims would be met with one unified Egyptian-Sudanese position. The allocations of the 1959 Treaty have been held to until the present and are representative of the "status quo." Not surprisingly, as beneficiaries of these agreements, Egypt and Sudan endorse it as reasonable and necessary to protect countries with little rainfall. Ethiopia, on the other hand, believes this "status quo" excludes several nations and as non-signatories to the agreement, the country does not feel bound to this allocation.

During the Cold War, cooperation was also difficult: the riparian nations were caught in the midst of the ideological war of the two superpowers, the United States and the USSR. Egypt and Ethiopia found themselves on opposing sides and often switching allegiances (Waterbury, 2002).The timeline in Figure 10 shows the times when the country was allied with the United States (light blue bars) and times when they were allied with the USSR (red bars). Their political philosophies have rarely overlapped.

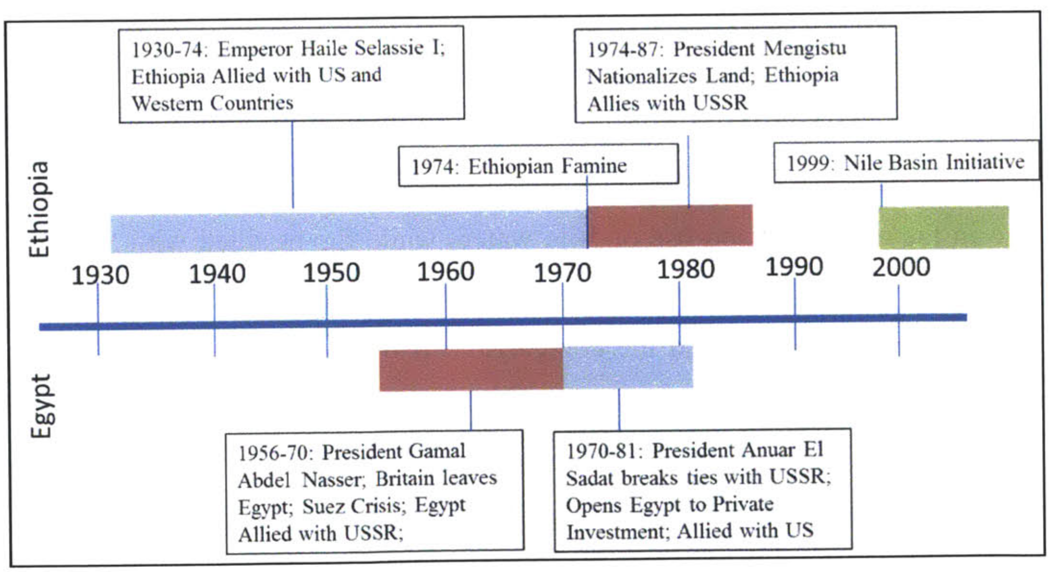

Figure 10: Geopolitical History in the Nile

Historically, Egypt and Ethiopia have had opposing ideological philosophies

There have been several initiatives for integration of the Nile region including Hydromet to collect and distribute hydrologic data; Undugu, to establish development projects and enhance trade; and TECCONILE (Technical Cooperation Committee for the Promotion of Development and Environmental Protection of the Nile Basin), to establish a Nile Basin Action Plan (the plan did not address water utilization). Ethiopia saw several of these initiatives as an Egyptian maneuver to preempt development in Ethiopia (Waterbury, 2002). Undugu, Swahili, for "Brotherhood," was aimed at Egypt aiding in the development of the hydropower of the Congo. Ethiopia saw this as a way to keep its own hydropower and irrigation capabilities inhibited. At the end of the Cold War, Egypt had started to look towards modernization and had become a respected player in the international arena. In the African region, TECCONILE was established. In order to attract investments from the World Bank and get back into the international arena, Ethiopia became an active participant but given, its suspicions, it did not become a full member. Ethiopia proposed a project that was to be financed by the World Bank. Although Egypt never vetoed the project, they successfully delayed the project by calling for more information to ensure that no appreciable harm would come to them. This confirmed to the Ethiopians the Egyptians intention to stunt their development. While Egypt's ability to project its strength may be waning, it still has a formidable veto power. Egypt has been successful in imposing the status quo for four decades, and it will surely shape any change in the status quo.

2.3.2 Comparing Egypt, Sudan and Ethiopia

Although the Nile Basin is shared by eleven nations, the nations in the Equatorial Lakes Region are not as active about seeking change to the status quo. It is Ethiopia that is pushing for a change in the allocation and use of Nile waters while Egypt allied with Sudan tries to block major changes. It is in essence a three-party collective action problem (Waterbury, 2002). As a result, this section will focus on the comparison of the socio-economic status of these three: Egypt, Sudan and Ethiopia.

Egypt and Ethiopia have comparable sizes of about 1 and 1.1 million square kilometers, respectively with nearly equal populations of around 85 million people. Sudan is somewhat larger with about 2.5 million square kilometers (of these, 616 thousand square km form the independent nation of South Sudan) and holds only about half the population as the other two nations. (World Bank, 2012) All three nations are experiencing high population growths. As the human populations increase in the Nile Basin, the pressure on resources increases and the margin for adaptability decreases (Table 2).

Each nation is endowed with different resources: Egypt has petroleum, natural gas and some rare earth metals; the nation has made huge investments in infrastructure and telecommunication. Sudan relies primarily on its petroleum resources. Although endowed with rich natural resources, Sudan remains comparatively underdeveloped with a GDP of $2,500 per person, primarily as a result of prolonged civil strife. Ethiopia has a few metals (platinum, copper, small reserves of gold), but its main resource endowment is its great hydropower potential. Ethiopia is the least developed of the three nations with a GDP of only $1,000 per person.

Table 2: Socio-economic Comparison of Egypt, Sudan and Ethiopia

	Egypt	Sudan*	Ethiopia
Area (km2)	**1.0 M**	**2.5 M**	**1.1 M**
GDP/capita (2010) (USD)	**$6,400**	**$2,500**	**$1,000**
Population (2010)	**84.5 M**	**43.2 M**	**85 M**
Population Doubling Time	**35 y**	**28 y**	**22 y**

*includes South Sudan

(Source: World Bank Database, 2012)

The three nations are also endowed with different climatological resources (Figure 11). Egypt has virtually no rainfall and depends entirely on the Nile Waters. Sudan has minimal rainfall and high temperatures. Ethiopia has a more humid climate with lower constant temperature throughout the year and high rainfall in the rainy season (July-September).

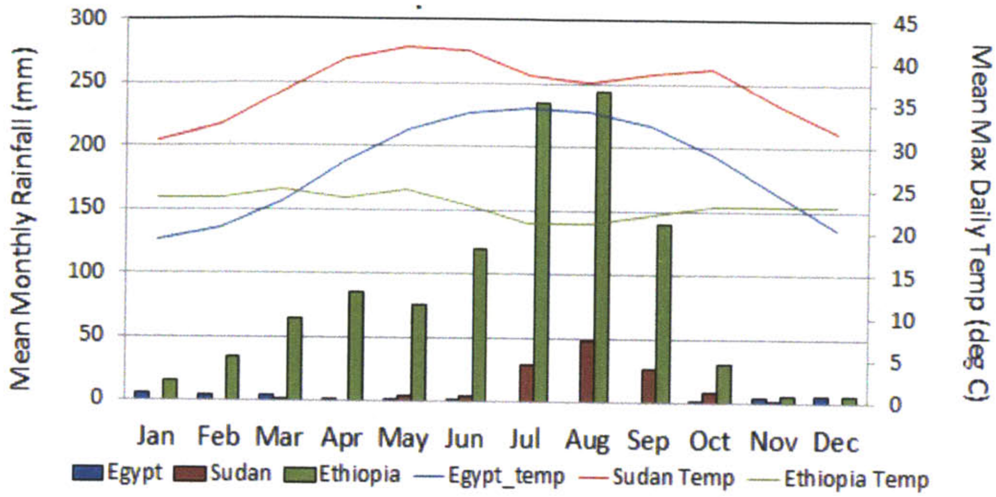

Figure 11: Average Ranfall and Temperature 1971-2000 in the Capitals of Egypt, Sudan and Ethiopia

(Source: Worldweather.org)

Egypt has consistently argued that other nations in the Nile have an alternative to the river because in comparison to Egypt they receive relatively high rainfall. The major problem with this argument, however, is that rainfall in the semi-arid tropics is highly variable both spatially and temporally and may fall in areas that are unsuitable for cultivation such as mountains or swamps. Having storage capacity for the water is essential to reduce this variability.

2.3.3 Economic Composition of GDP

Since the development of early Egyptian civilization, the Nile has had a unique religious, cultural, and economic importance. No river has had such a profound effect upon those who dwell along its banks. For thousands of years, the annual floods deposited sediments and made the banks of the Nile fertile fields for agriculture in the middle of a great desert. The flow of the Nile dictated the cycles of plenty and famine. Coupled with the Nile waters and the constant high temperatures, the fertile soils became the epitome of productive agricultural land. The ancient Egyptian civilization developed systems of basin irrigation and were able to build a wealthy empire on an economy based on agriculture. The economic activities were concentrated in the Nile Valley and in fact, even today, 99% of Egyptians continue to reside on 5.5 percent of the land around the Nile River (Awulachew, 2010)

Although the economic activities in Egypt continue to take place in the Nile Valley, agriculture no longer plays such a large role in the economic industries of Egypt. The perception that Egypt continues to be agriculturally based is not accurate. Figure 12 shows that Egypt's GDP relies primarily on services such as tourism which make up 45.8 percent of the GDP. Ethiopia and Sudan, on the other hand are primarily driven by agriculture and a large part of their labor force depends on agriculture for income. This is especially true for Ethiopia where 85 percent of the population works in agriculture.

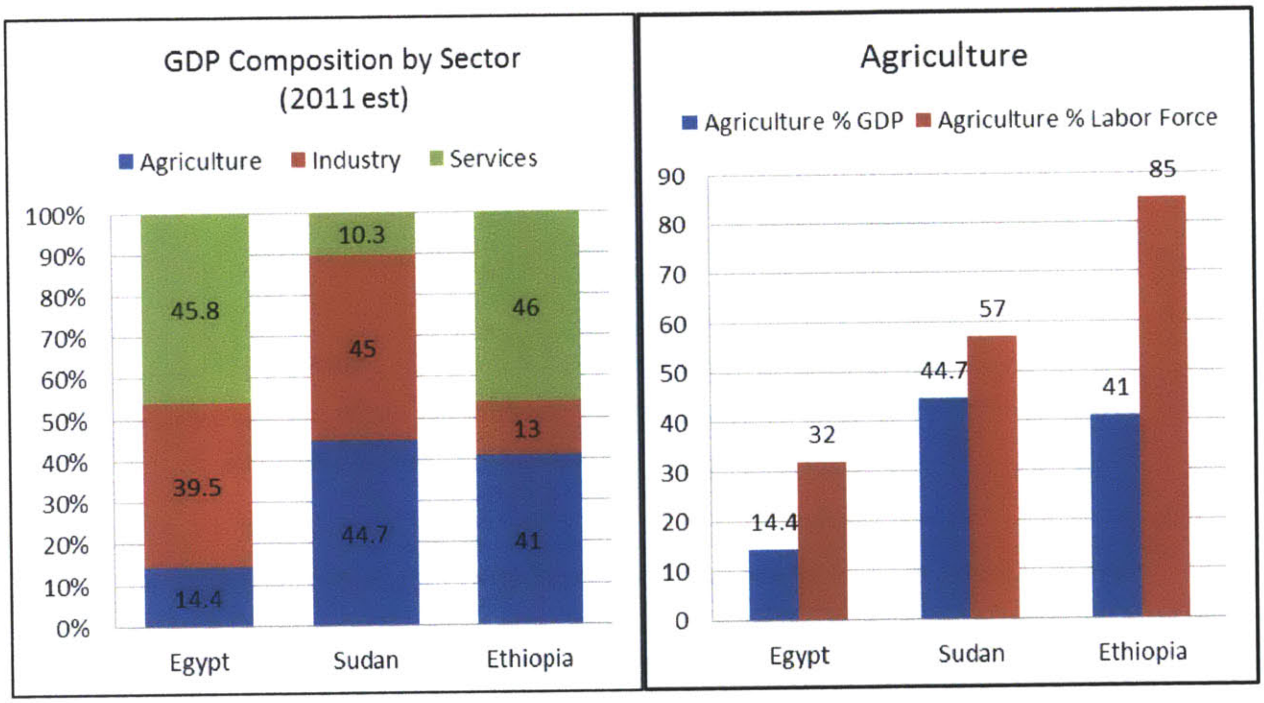

Figure 12: GDP Composition and Agricultural Labor Force in Egypt, Sudan and Ethiopia

(Source: CIA World Fact Book, 2011)

2.3.4 Agriculture: Linking Water and the Economy

The optimal allocation of the Nile's waters among different sectors requires a good understanding of each sector in the area. Agriculture is the biggest consumptive use of water worldwide. The agricultural sector, with substantial water use, is obviously linked to a range of social and environmental factors, such as food security, poverty alleviation, conservation of the natural environment and biodiversity. As shown in Figure 13, for Egypt, Sudan and Ethiopia, agricultural water demands represent 86%, 97% and 94% of their water withdrawals, respectively. The agricultural sector is by far the biggest water user. Egypt is withdrawing 119% of its internal renewable resources (excluding Nile water allocations), similarly Sudan is withdrawing 57.6% and Ethiopia is using only 4.6% of its internal renewable resources.

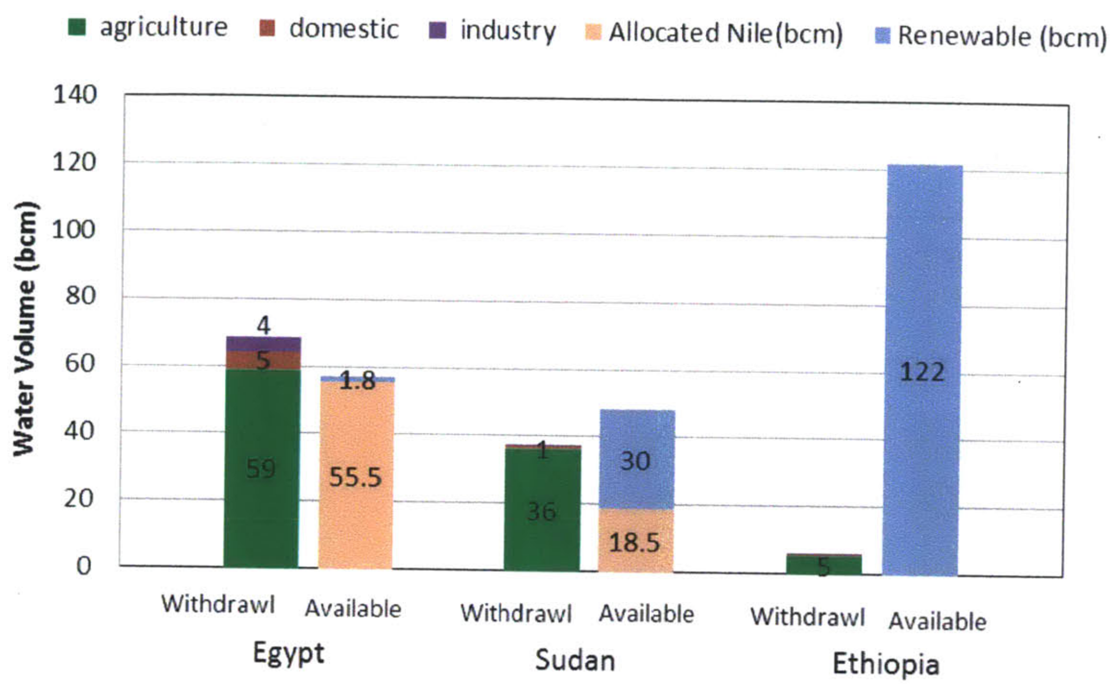

Figure 13: Water Availability and Withdrawals (bcm) in Egypt, Sudan and Ethiopia (Source: World Bank Database, 2012)

The variability in rainfall in the Nile basin is reflected in the agricultural systems in the basin. The upper parts of the basin which have abundant rain, such as Ethiopia, the Equatorial Lakes Region, and the middle and lower part of Sudan, have primarily rainfed systems. In contrast, irrigated agriculture dominates central Sudan and southern Egypt (Awulachew, 2010).

2.3.5 Egypt's Food Imports

One indicator of the level of water deficit in an economy is the amount of food imports. Zeitoun et al. (2009) looked at the virtual water traded among Nile basin countries. Egypt is a net importer of water as shown in Figure 14.

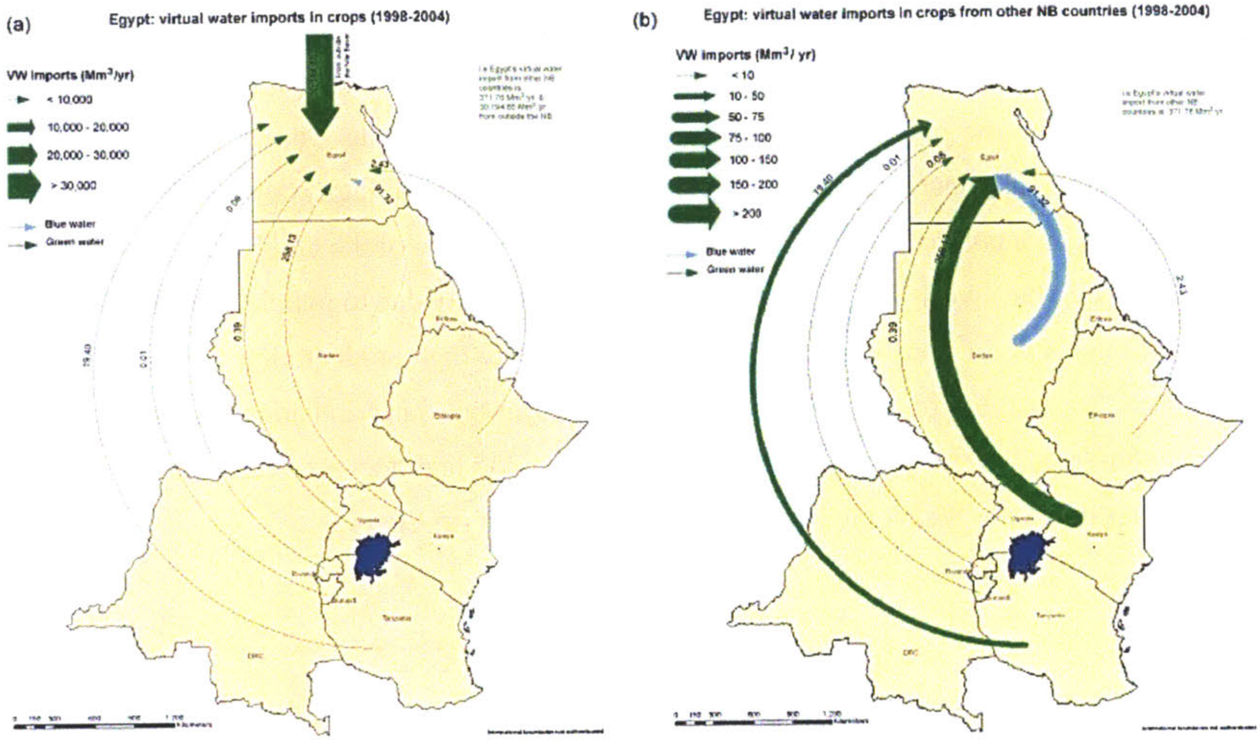

Figure 14: Virtual Water Flow in Nile Basin Countries

(Source: Zeitoun et al., 2010)

There is a need for irrigation in all the Nile countries, but the most dependent on irrigation is Egypt where it is seen as a matter of life importance. Egypt could grow virtually no food without water from the Nile or underground aquifers. Despite the irrigation and water withdrawals, Egypt is not achieving food security; currently Egypt is one of the largest importers of cereals. This begs the question, why spend so much of the precious water resources on the agricultural sector that represents only 14% of the economy (32% labor force) when it seems water has higher value added in the other sectors? In part, this might be due to the high productivity and efficiencies. Egypt has very high water efficiency and water use (Awulachew, 2010). The country aims at producing higher priced crops such as fruits for the European market and is trying to take advantage of the high land and water productivity. As shown in Figure 15 the productivity of a hectare of land in Egypt is ten times greater than that in Ethiopia. The water productivity is three times greater in Egypt, earning a high economic value near 0.17 cents/m3 and only 0.06 cents/m3 in Ethiopia. The high water productivity is an argument Egypt uses to contend that Egypt should maintain its current Nile water allocation as it represents the most efficient use for a unit of water. Other nations argue that Egypt is using more than its fair share. Egypt is developing irrigation schemes in Sinai and in the Southern Valley (New Valley Project) to reclaim desert land and relieve population in the Nile Valley and Delta. These planned irrigation projects will certainly increase Egypt's water demand and expected high water productivity may not be realized in a politically unstable climate. This was the case of the Gezira scheme in Sudan which proved to have very low water productivities, particularly due to policies, institutional and market problems in the conflict-ridden nation. In addition to high productivity, Egypt has a high water recycling rate. Egypt recycles 5 bcm per year of drainage water and aims to increase this to 7 bcm (Abu-Zeid, 1992). Egyptians argue that because of the high recycle and reuse rates, a unit of water in Ethiopia or Sudan might translate to multiple units in Egypt.

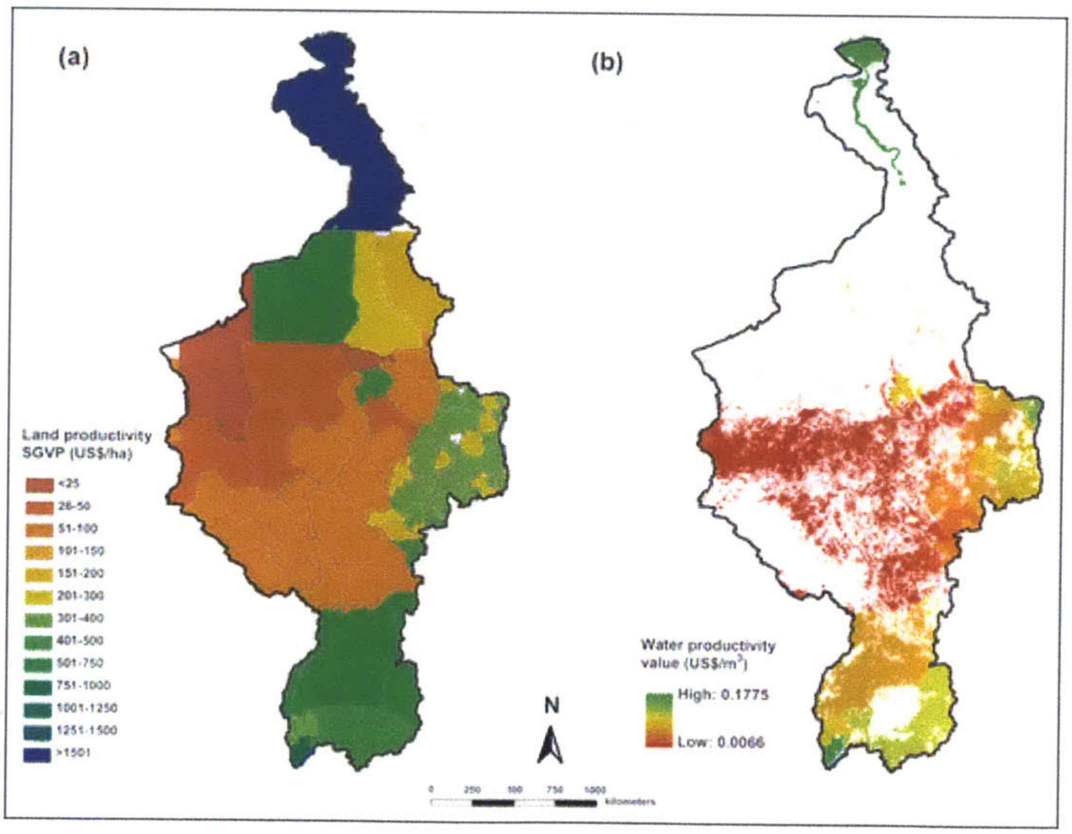

Figure 15: Land and Water Productivity in the Nile Basin

(Source: Awulachew, 2010)

2.3.6 Ethiopian Agriculture

In contrast to the irrigated agriculture of Egypt, the Ethiopian economy is dominated by subsistence rainfed agriculture. Only 63,170 ha (0.7 percent) of the total cultivated area of 8.92 million ha under smallholder agriculture was under traditional irrigation in 1998/99 (MoWR, 2002). This dependence on rainfall without the ability to store or transport water has restrained the Ethiopian economy which has suffered droughts and floods and is now a region chronically prone to famines. Grey and Sadoff, (2006) found that in Ethiopia the occurrence of droughts and floods reduced economic growth by more than one third. Figure 16 shows the relationship between rainfall variability and GDP change in Ethiopia. Notice how closely they follow each other. Most of the rainfall in the country occurs in a span of four months. Rainfed agriculture depends on the arrival of the rainy season and farmers have to decide when to plant: too early and the seeds will not germinate, too late and the wet season may end before the crop has matured. The most common response to decouple the food production from the variability of the rainfall is to construct water storage infrastructure which offers control over the water so that it can be stored for low flow times or moved to dry areas.

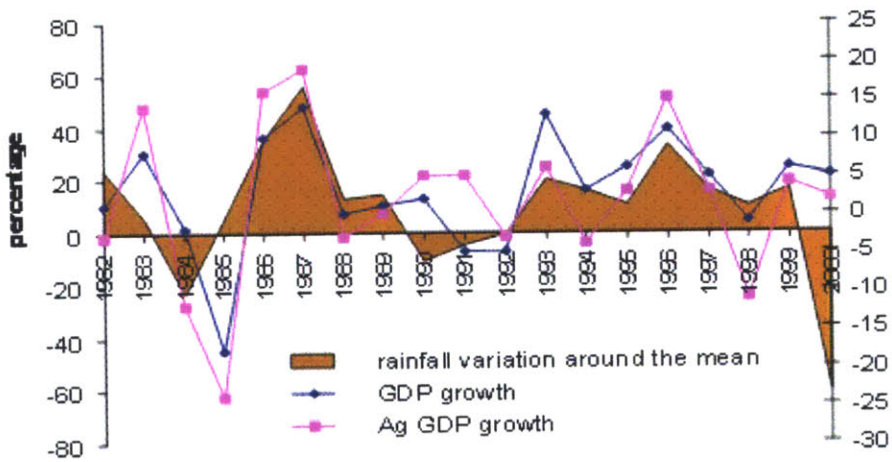

Figure 16: Link between Economic Growth and Rainfall Variability in Ethiopia

(Source: World Bank, 2006)

According to Fan et al. (2009) agricultural spending generally has the largest positive effects on growth and poverty reduction. Block (2006) showed that for Ethiopia an investment in irrigation development has a better cost benefit ratio than other investments such as roads. Block (2008) used a dynamic climate agro-economic model of Ethiopia to assess irrigation and road construction investment strategies in comparison to a baseline scenario over a 12-year time horizon. Although both investments create positive economic boosts, the irrigation investment outperforms the road investment, producing an average GDP growth rate of 0.95% versus 0.75% over the baseline scenario, along with lower associated poverty and malnutrition rates. The benefit-cost ratio for the project also favors the irrigation investment. Several authors have supported the idea that Ethiopia should invest in water control and irrigation. The development of irrigation is not only a good idea for Ethiopia, but also a likely possibility.

In Ethiopia, the single most important strategic interest is striving to attain food security. Ethiopia has used only a small portion of its total surface water, or 0.6% of the water resources of the Nile basin, thus if it can find a use, it has the possibility to expand (Arsano and Tamarat, 2005). In 1960, the US Bureau of Reclamation (USBR) attempted to quantify the irrigation potential in the Nile. Other scholars have used this information and estimated potential irrigation land and water. Figure 17 shows the estimates by Javonvic (1985) including some USBR estimated. This suggests a total water use of 22.5 bcm inside the Nile basin for 15,300 sq. km (6 bcm in the Blue Nile basin for 4,300 sq. km). The study did not make explicit which crops could be grown in what regions.

Quantity of water required for irrigation

Basin	Irrigable land in 1000 ha			Water for irrigation in 10^9 m^3		
	Inside Nile Basin	Outside Nile Basin	Total	Inside Nile Basin	Outside Nile Basin	Total
Main Nile	500	600	1100	7.5	9.0	16.5
Blue Nile	430*	500	930	6.0	7.5	13.5
White Nile	600	–	600	9.0	–	9.5
Total	1530	1100	2630	22.5	16.5	39.0

*Bureau of Reclamation figure. All other figures are estimates.

Figure 17: Existing Estimates for Irrigation Potential in the Nile Basin

(Source: Javonvic, 1985)

The Ethiopian Water Sector Development Project (WSDP) of 2002, which reflects the Ethiopian master plans by the Ministry of Water Resources (MoWR), has identified 560 irrigation potential sites on the major river basins. According to the WSDP (2002), approximately 200,000 hectares of crop area are currently being irrigated in Ethiopia, accounting for just over 2 percent of all cropland. They plan to double the current investment in irrigation. They estimated the total potential irrigable land in Ethiopia to be around 3.7 million hectares. The irrigation targets for 2002-2016 are stated as 126,000 ha more for the development of small-scale irrigation systems and 148,000 ha for medium and large-scale irrigation (MoWR, 2002). The expansion of the irrigation program may be a first step for Ethiopia to adapt to climate change. With the adequate storage infrastructure, Ethiopia may be more prepared for increased frequency of flood and drought events. Infrastructure that can contribute to both irrigation and flood control may be beneficial. It would help decouple its dependence on rain for agriculture and ensure more reliability. Controlling river runoff has the additional benefits of flood control and preventing siltation in the downstream reservoirs. Storage then is a higher priority, particularly multifunctional reservoirs. Since irrigation is a consumptive use of water, Egypt sees any development of irrigation by Ethiopia as a claim on water that has already been legally allocated.

The WSDP also highlighted that Ethiopia has 144,710 GW hours per year of potential hydroelectric power. Only a small fraction of this potential has, thus far, been harnessed. Ethiopia has a comparative advantage for producing and selling hydroelectric power. The nations could engage in power trade agreements so that Ethiopia could sell power to its neighbors, including Sudan and Egypt. Ethiopia has already begun plans to construct hydropower dams. Projects such as hydropower dams, which are non-consumptive, may be more acceptable for Sudan and Egypt but, ultimately Ethiopia will have to develop irrigation to meet its food security needs.

2.3.7 Value of Cooperation

It would be beneficial if large projects on the Nile basin were managed cooperatively in order to have more integration. Whittington et al. (2005) used a model proposed by Thomas and Ravelle (1966) and expanded by Guariso and Whittington (1987) to quantify the economic value of cooperation in the Nile using different scenarios. They cite one of the main problems with economic optimization of the Nile Basin is that the demand for irrigation water is unknown and changes with time (This thesis will try to elucidate this irrigation demand for the UBN in Ethiopia). Still, they make some simplifying assumptions: that all riparian states value the water equally at about 5 cents per m3 of water and 8 cents per kWh of hydropower and that all riparian states have perfect horizontal demand curves. They compared the status quo with full cooperation (all proposed infrastructure projects like Blue Nile reservoirs, wetland conservation and White Nile power projects). They find that the economic value of cooperation is US $4.94 billion annual and varies in a small range (4.7-5.5 billion annually) when the value of water for irrigation varies from 2-8 cents per m3 (Table 3).

Table 3: The Value of Cooperation in the Nile Basin

	Status Quo	Full Cooperation	Economic Value of Cooperation
Ethiopia	**50**	**3010**	
Sudan	**723**	**513**	
Egypt	**3204**	**4313**	
Others	**186**	**1272**	
Total	**4164**	**9167**	**4943**

(Source: Whittington et al., 2005)

The model allocates water to irrigation or hydropower based on the price, thus, it does not promote water use for irrigation in the highlands region of Ethiopia because abstracting water would result in significant losses in the hydropower along the Blue Nile gorge. Once it passes the highlands and the hydropower potential is caputred, it does not matter if water is withdrawn for irrigatin in Sudan, Egypt or lowlands of Ethiopia.

Despite the benefits to cooperation, currently Egypt and Sudan maintain their allocation of the resource and hold back from establishing legal and institutional frameworks that may negatively alter these. The power balance in the Nile is unusual as downstream states developed first. Egypt in essence holds the power, but is not a pure hegemon. Egypt has been able to make its interests prevail by allying with Sudan and implicitly thwarting Ethiopia. The Egypto-Sudanese alliance, however, is not one between equals; Egypt sees itself as the Sudan's patron and protector and in order to maintain the stability of this dyad, Sudan has made a great number of compromises, which can provoke private resentment (Waterbury, 2002). In this position, the wealthier, more powerful downstream countries can exert pressure on Ethiopia. Ethiopia holds the position that Egypt and Sudan have monopolized the Nile (Arsano and Tamarat, 2005). Although the countries would like to engage in multi-lateral projects, this has not prevented the nations from pursuing projects within their own borders. It is in essence a rush to claim waters.

2.3.8 Nile Basin Initiative

The Nile Basin presents an example of the political nature of water at the national and international level. The Nile Basin Initiative was officially established in 1999. The Nile Basin Initiative (NBI) is an inter-governmental organization dedicated to equitable and sustainable management and development of the shared water resources of the Nile Basin to achieve water security and avert conflicts over water resources. The organizational structure is composed of the Nile COM, the council of ministers whose members are the ministers of water resources of the basin countries, and Nile TAC, which is the Nile technical advisory committee and is composed of two members from each country. The Nile Basin Initiative divides its investments into two main areas::

- **The Nile Equatorial Lakes Subsidiary Action Program (NELSAP)** whose member countries include Burundi, DR Congo (DRC), Egypt, Kenya, Rwanda, Sudan, Tanzania, and Uganda. It oversees the implementation of the jointly identified projects and promotes cooperative inter-country and in country investment projects related to the common use of the Nile Basin water resources.
- **The Eastern Nile Subsidiary Action Program (ENSAP)** is implemented by three NBI Member States: Egypt, Ethiopia and Sudan. Among others, ENSAP's objective is to ensure cooperation and joint action between Eastern Nile countries seeking win-win gains. (NBI, 2010)

In November 2000, Ethiopia, Sudan and Egypt presented their respective proposed projects summarized in Table 4. From the number and types of projects, a general pattern is visible. Ethiopia proposed 46 projects focusing primarily on large infrastructure within its own borders. In contrast, Egypt proposed 5 projects that involved information and conservation outside of its borders. According to the FAO (2006) this is a general pattern for riparian states: first unilaterally develop projects within their borders. Then at some point, the regional power will implement projects, which impact at least one neighbor. This might be in order to continue to meet existing uses. This was the case of Egypt and the Aswan high dam.

Table 4: Development Projects Proposed by Egypt, Sudan and Ethiopia in 2000

Ethiopia	Sudan	Egypt
13 hydroelectric power projects, 8 irrigation development projects 25 watershed management projects	4 hydroelectric power projects, 1 flood early warning project, 1 pilot watershed management 2 irrigation development projects	1 simulation modeling project 1 water conservation project 1 hydropower and flood control 1 power transmission study project 1 siltation study

(Source: Arsano and Tamarat, 2005)

The Nile Basin Initiative is aimed at improving cooperation for development projects in the region. In particular, the focus has been on drafting a legally binding "Cooperative Framework Agreement" (CFA). Often, the problem with treaties and agreements is that they do not make provision for the dynamic nature of economic, climatic, and political states. In the Nile basin, the particular conflict is over the legal language of article 14b: "(...) the Nile Basin states, therefore, agree in a spirit of cooperation, to work together to ensure that all states achieve and sustain water security and not to..." Ethiopia argues the next phrase should be "***significantly*** affect the water security of any other Nile Basin Sates," while Egypt and Sudan agree it should be "***adversely*** affect the water security ***and*** current use and rights of any other Nile Basin Sates." (Grey, 2012)

2.3.9 Water Law

The current disagreement in the language in the search for a Cooperative Framework Agreement in the Nile Basin points to a conflict of the guiding principles in water law. There are generally two recognized principles in water law: "significant harm and equitable use." The first is the concept of "significant harm." This principle has been recognized in several important international cases, but its application is highly controversial (FAO, 2006). While it is clear that one state may not intentionally cause harm to another through, for example, flooding or deliberate releases of toxic pollution, there is dispute about whether one state's use that reduces the available supply in another state is prohibited by this norm. Egypt and Sudan espouse the principle of "significant harm" and believe a reduction in supply does constitute harm.

If reduction in supply did constitute harm, a later-developing upstream state would be prevented from developing. Ethiopia argues that downstream states can cause significant harm to upstream states by creating new projects that use significant amounts of water. Egypt's action in the New Valley, for example, would preempt Ethiopia's rights to harness the Nile water since Egypt would have made a claim first. Ethiopia will have to forgo projects of its own in order to protect Egypt's rights in the New Valley. Ethiopia will suffer appreciable harm in order not to cause harm to Egypt. Similarly, inefficient use of water in one part of a watershed can provide benefits for users further downstream. Efficiency then may cause harm. This principle has several contradictions and, it becomes important to understand what is meant.

The second principle is that of "equitable utilization." Ethiopia would prefer this principle to form part of the CFA. Each riparian should have equitable rights. Although it may seem like the UN Convention supports this principle when it comes into conflict with the principle of harm, in practice it is more feasible to ascertain harm than to promote equity. "Damage can be measured, but fairness is in the eye of the beholder" (FAO, 2006). All nations could make a claim for equity: If equity were defined as protecting the water supply for poor populations that rely heavily upon it, South Sudan and Ethiopia have a strong claim. If equity depended on the nations' dependence on the resource or availability of alternative water resources, then Egypt, with no other freshwater source but the Nile and over 90% of its population near the Nile, might have a strong claim. If equity depended on the potential for development, Sudan would have the strong claim (Waterbury, 2002).

All parties can make claims on either principle but those countries that are upstream and downstream have to protect themselves from the inconstancy of the having absolute territorial sovereignty but being a victim to another nations' development. Egypt is a pure downstream state with all surface waters coming from outside its borders. It can afford to adhere to the principle of significant or appreciable harm. Similarly Ethiopia is pure upstream, and can adhere to equitable use. Sudan, which is both upstream and downstream, must help in designing a system that protects it from the inconsistencies in these principles.

Chapter 3

Study Area: Upper Blue Nile

With a general understanding of the region and the context of the problem, we can turn to the thesis question: what is the maximum irrigation water that Ethiopia could consume in the Nile basin. A better understanding of the maximum water demand of Ethiopia may elucidate the perceptions and motivation in the Nile Basin, reduce political mistrust, and may enhance the policy discussion regarding investments in irrigation projects and complementary investment policies to minimize any economic losses. For purposes of this study, we limit the scope of the project; the modeling is done over the Upper Blue Nile (Figure 18), a sub-catchment of the Nile basin in Ethiopia that can provide important insight in addressing the thesis question. By analyzing the irrigation potential of this sub-basin, and understanding the maximum water use for irrigation, we can determine how this might affect the Nile basin flow downstream and what this might mean for Egypt in trying to secure water resources.

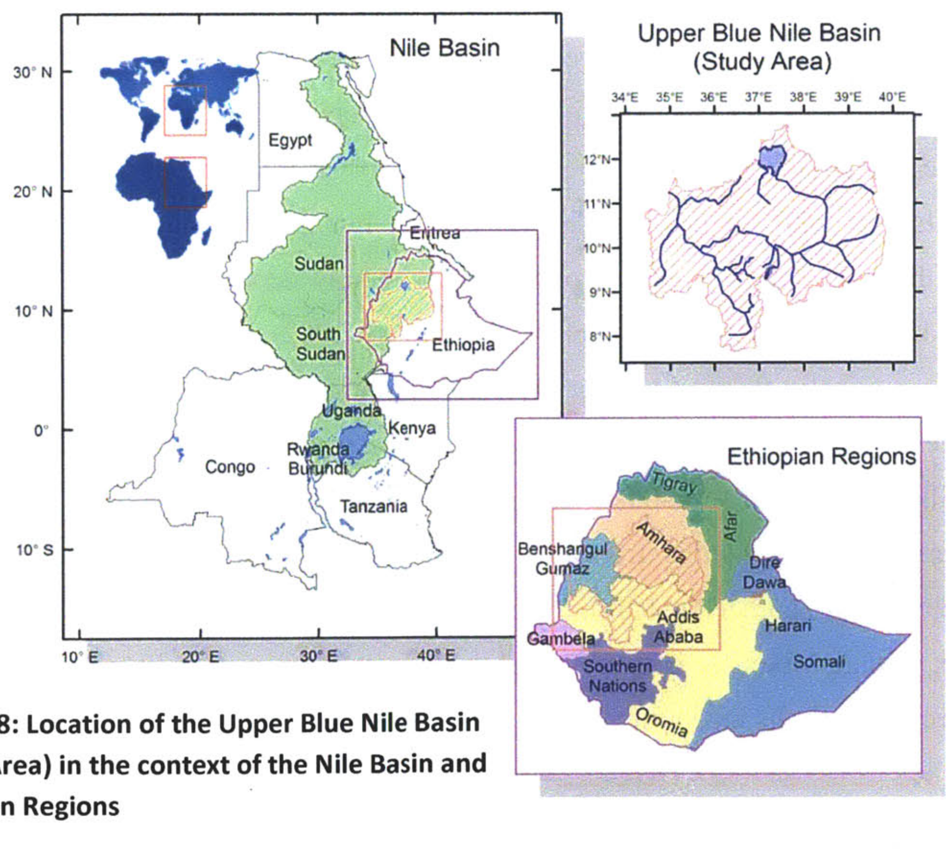

Figure 18: Location of the Upper Blue Nile Basin (Study Area) in the context of the Nile Basin and Ethiopian Regions

3.1 Description of the Upper Blue Nile

The Upper Blue Nile basin is selected because it is the basin that provides the largest contribution to the Nile's annual flow. The Blue Nile basin is shared by Ethiopia and Sudan but the Upper Blue Nile is within the borders of Ethiopia (Figure 18), the nation that is trying to spur the most change to the status quo in the Nile Basin.

Ethiopia is divided into eleven administrative regions as shown in Figure 18. The Upper Blue Nile basin is located in the northwestern part of the Ethiopian Plateau from 7 degrees north to 13 degrees north and 34 degrees east to 40 degrees east, covering areas of the Amhara, Benshanguil-Gumaz and Oromia regions. The Upper Blue Nile basin's remoteness, limited data and underdeveloped water resources has led to it being called the "great unknown" in the Nile Basin (Waterbury, 1988). It has an area of 177,000 square kilometers, representing about 16% of Ethiopia's land. It is the largest basin in Ethiopia in terms of discharge and second largest in terms of area (Conway, 2000).

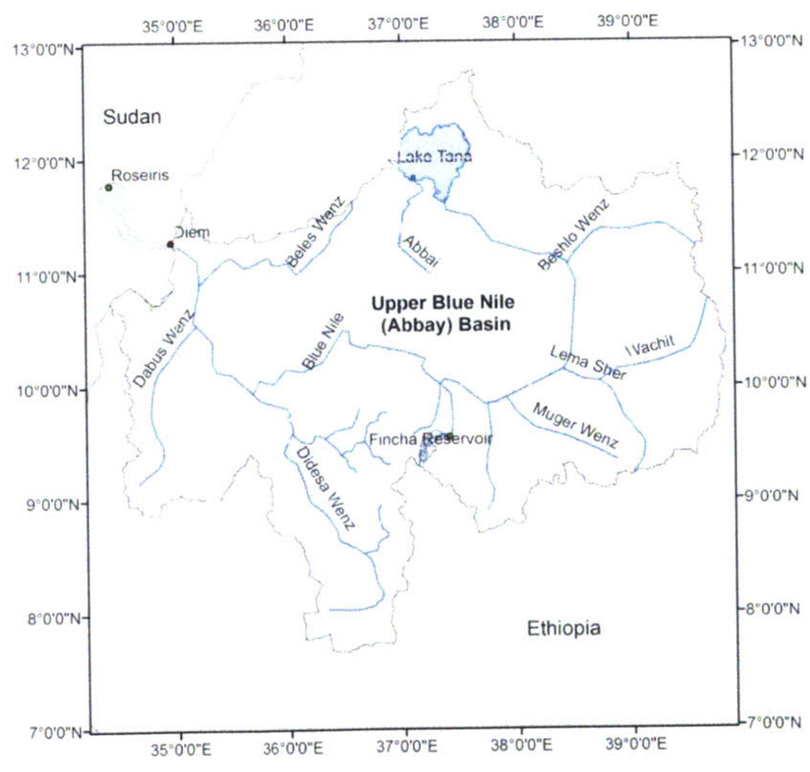

Figure 19: Upper Blue Nile Basin and Major Tributary Rivers

The Blue Nile river has several headwaters and tributaries including Lake Tana and the rivers Dabus, Didessa, Finchae, Guder, Muger, Beshio, Beles, and Jema as shown in Figure 19. Individual discharges of these tributaries range from 2-13 bcm per year. As measured at Diem, the average runoff over the basin is 46 bcm per year. The Blue Nile river headwaters begin at Lake Tana at around 1830 m above sea level and flows about 850 km (Block et al., 2007) westward towards the main Nile. The Nile River, called the Abbay in Ethiopia, falls about 1200 m in its course from Lake Tana in the plateau region to the low lands near the Ethiopian-Sudanese Border.

3.1.1 A note on projections

To portray geographic data on a flat map, a map projection is needed. Every projection has advantages and disadvantages and the choice is determined by the needs of the user. For our purposes and in the study area of the Nile Basin and Upper Blue Nile, an Africa Albers Equal Area Conic projection was used (specifications can be found in the Appendix A2). All areas on the map are proportional to areas on Earth, directions are reasonably accurate and distances are true on the standard parallels. The maps however are non-conformal or equidistant (USGS, 2008). ESRI and the USGS provide a discussion on projections. The projection was chosen in order to calculate accurately arable land areas.

3.1.2 Elevations and Land cover in the Upper Blue Nile Basin

The UBN region is considered highland since a large part of the basin is above 1000 m. Using the elevation map based on SRTM (see Figure 20) we can trace contour lines every 500 m and we see that there is a wide elevation range (500 to 4000m). Notice that the western side of the basin has a higher grade. Several climatic properties are driven by the topography and follow this east-west division.

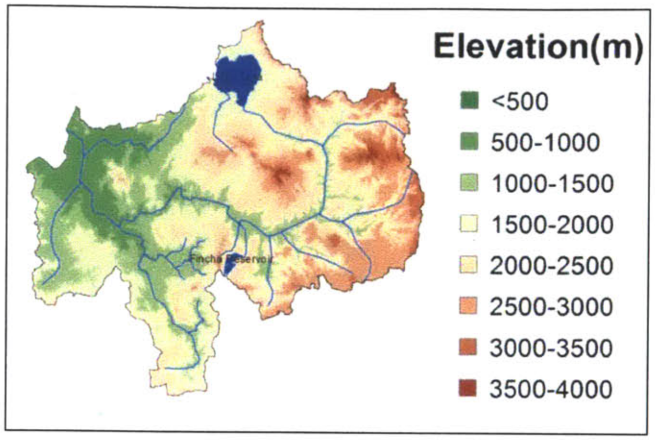

Figure 20: Elevations in the Upper Blue Nile Basin in Ethiopia.

At elevations above 1000 m, most of the Upper Blue Nile is considered highland. (Source: SRTM, Farr et al., 2007)

When the SRTM DEM is combined with a land cover map derived from the Advanced Very High Resolution Radiometer (AVHRR) the figures shows that the mountainous regions of elevations between 1500-3000 meters are classified as wooded grasslands and tend to be wet, lush and green (Block et al., 2007). The lowlands are classified mainly as woodland. About 55,000 square km (about 30% of the basin) is classified as cropland (Figure 21). Using data from Monfreda et al. (2008), Figure 22 shows the percent of a 5-minute pixel (84 square km) that in the year 2000 was being used by cropland. These are concentrated on the eastern side of the basin and total about 23,700 square kilometers of cropland. These are combined irrigation and rainfed systems.

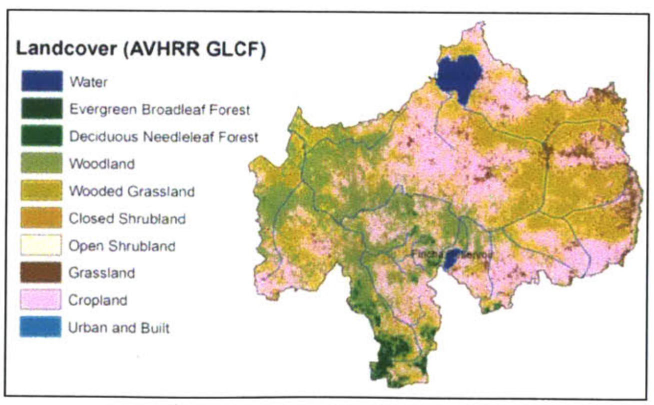

Figure 21: Land cover in the Upper Blue Nile Basin.

The land of the Upper Blue Nile basin is characterized by wooded grasslands, cropland and woodland. (Source: AVHRR GCLF Hansen, et al., 1998)

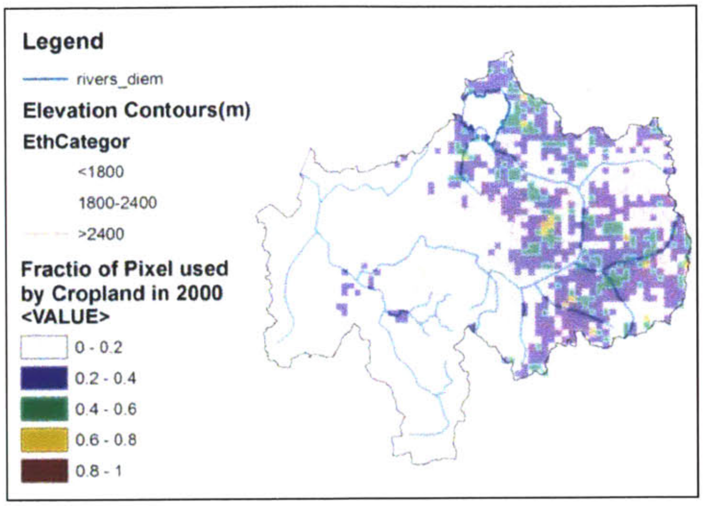

Figure 22: Cropland in 2000 in the Upper Blue Nile Basin (23,700 sq. km) (Source: Monfreda et al., 2008)

3.1.3 Soil Types in the Upper Blue Nile Basin

The western side of the Upper Blue Nile basin consists primarily of soils classified as Nitisols (NTu) as shown in Figure 23. Nitisols are generally considered "fertile" soils although they sometimes have low phosphorus and low base saturation. It refers to well-drained, red, tropical soils with more than 30% clay. In fact, the UBN basin as a whole is made up primarily of clays. Nitisols are strongly weathered soils but are considered far more productive than most other red tropical soils. More than half of all Nitisols in the world are found in the highlands (>1000m) of Ethiopia and tropical Africa. Nitisols are quite productive; the stable structure of the soil permits deep rooting and makes it more resistant to erosion. The good workability, internal drainage, water holding capacity and chemical properties make it a favorable soil. These soils are suited to plantation crops such as cocoa, coffee, and rubber as well as food crop production (FAO, 2011). This suggests that there may be available cropland in which to expand. Since clay has a slow infiltration rate, the large presence of clayey soils may explain the high runoff coefficient of the basin during intense precipitation events.

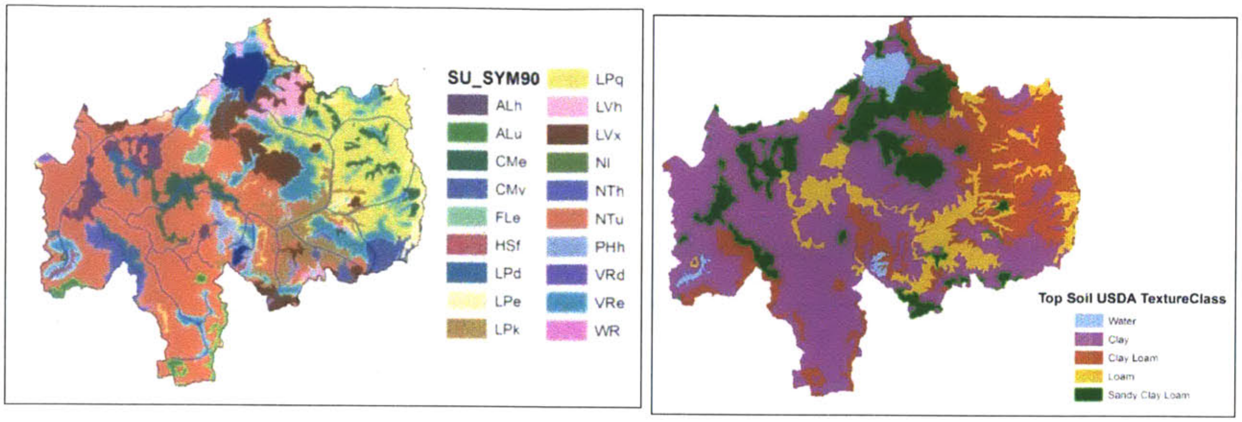

Figure 23: Major Soil Types in Upper Blue Nile Basin.

Nitisols (NTu) classified as clay make up a large portion of the lower lands in the Upper Blue Nile Basin. This Soil Type is characterized as highly fertile. (Source: FAO et al., 2012)

3.1.4 Hydrology and Climatic Conditions in the Upper Blue Nile

3.1.4.1 Temperature

Using temperature data from the Climate Research Unit (CRU) and averaging the long term record from 1901-2006 gives the mean annual spatial temperature distribution in the basin which is shown in Figure 24.

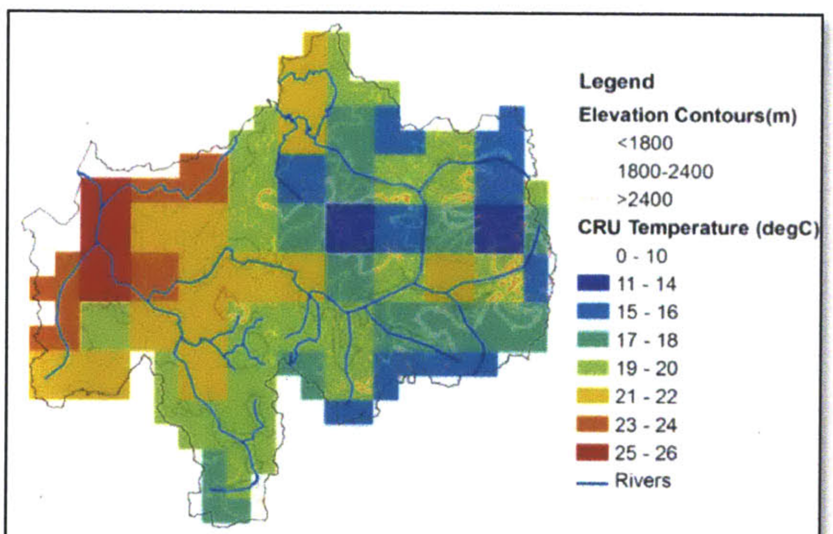

Figure 24: Spatial Distribution of Mean Annual CRU Temperature in the UBN 1901-2006

The traditional Ethiopian classification of climate is based on elevation. Three temperature zones are recognized shown in Figure 24 and displayed in Table 5. The majority of the population lives in the cooler upper zones.

Table 5: Ethiopian Classification of Climate Zones based on Elevation

Climate Zone	Elevation (m)	Temperature (°C)
Kolla	<1800m	20-28
Woina Dega	1800-2400m	16-20
Dega	>2400m	6-16

Temperature ranges from 13 degrees Celsius to 25 degrees Celsius and follows the topography, with the lowlands being hotter. According to Conway (2000), on average temperature falls 5.3 degrees Celsius for every 1,000 meters. Temperature does not vary much throughout the year with a range of about 4 degrees from17.5 to 21.5 degrees Celsius as shown in Figure 25. The coolest month is in December and the warmest is April right before the rainy season. During July, the temperatures are reduced due to the rainfalls and clouds. The mean maximum and mean minimum temperatures are favorable for cultivation since many crops have operating temperatures between 10 and 30 degrees Celsius.

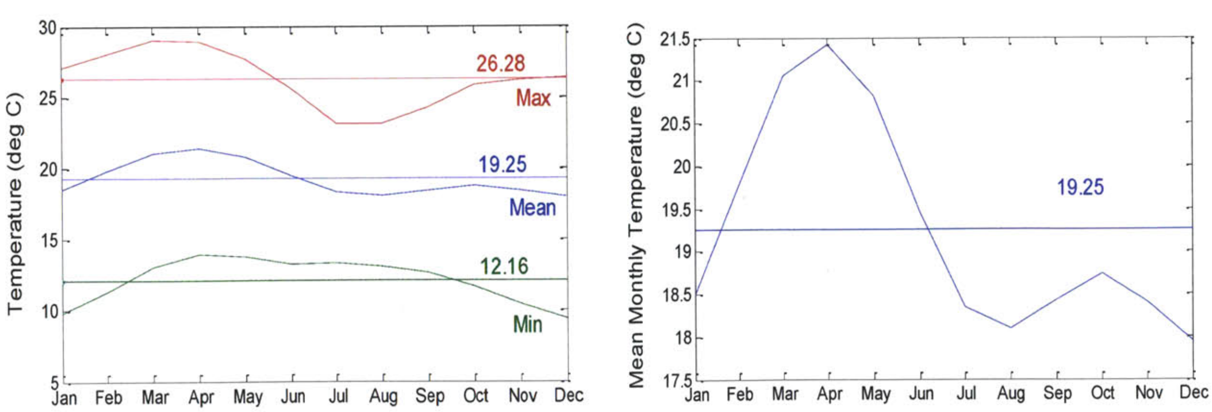

Figure 25: Maximum, Minimum and Mean Monthly CRU Temperature (C) in the UBN

3.1.4.2 Precipitation

The annual precipitation for the entire Upper Blue Nile basin using satellite data available from the Tropical Rainfall Monitoring Mission (TRMM) from 1998-2010 is 970 mm with a range of 600-1,400 mm per year. Figure 26 shows the spatial distribution of the annual precipitation. In general TRMM shows a lower precipitation than what other data sets suggest such as CRU and Conway (2000). These latter two sets are longer than TRMM; CRU is available from 1901-2006 and Conway uses eleven gauges to construct a data set from 1900-1998. Conway suggests that the rainfall ranges from 1,000 to over 2,000mm. The discrepancy with CRU is covered in Chapter 4. In all the datasets the precipitation tends to decrease from south-west to north-east. The topography has strong influence on precipitation and the high spatial variability in the Ethiopian Highlands (Nicholson, 1986).

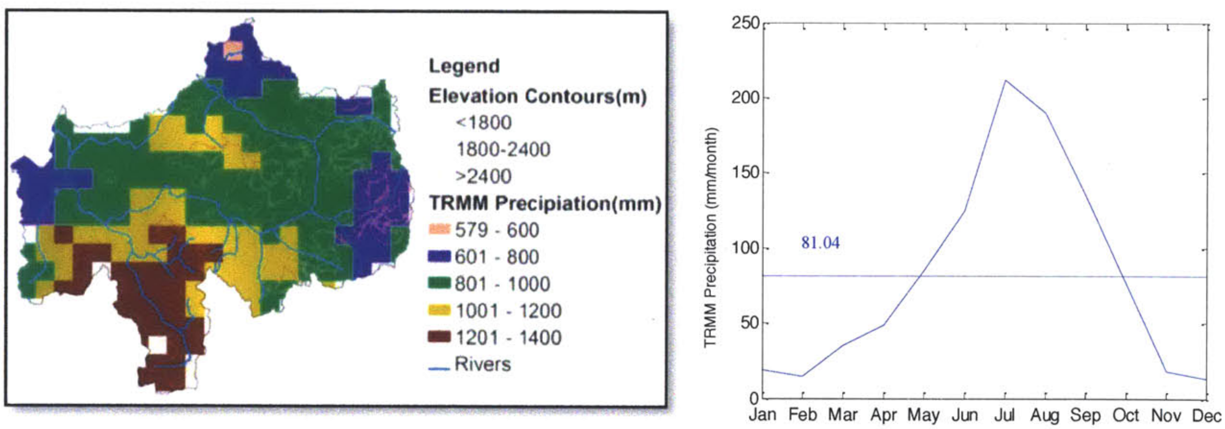

Figure 26: Annual Spatial (mm/yr.) and Monthly Temporal (mm/month) Distribution of TRMM Precipitation in UBN

Precipitation also has a strong seasonality (Figure 26). The main rains occur in the summer, between June and August known as the "Kirmet" or "Meher" (heavy rainfall) season. The rest of the seasons constitute the "Belg" encompassing March, April and May and having occasional showers. September, October and November make up the "Tseday" and are typically the harvest season. December January and February are the "Bega" (dry season).

The causes of rainfall in Ethiopia are described by Griffiths (1972), Gamachu (1977) and Conway (2000). The rainfall mechanisms are 1) Summer Monsoon (ITCZ movement) 2) tropical upper easterlies and 3) local convergence in the Red Sea coastal zone. In December, during the

"Bega", the ITCZ is south of Ethiopia and rainfall occurs only along the Red Sea coast. In March, the ITCZ moves up bringing rain to the southern, central and eastern part of the country. In May, a high pressure zone over Egypt become strong, the cool airstream from the desert prevents further upward movement of the ITCZ and creates a short dry season before the "Kirmet". Then in June the ITCZ moves north bringing high rains to the country. It should be noted that inter-annual variability in rainfall is considerable, and several consecutive years with below average rainfall is not uncommon.

3.1.4.3 Potential Evapotranspiration

Evaporation is the process of converting water from liquid state in oceans, over land or from wet vegetation to a vapor state. This process depends strongly on temperature and requires latent heat (energy). Evapotranspiration (ET) reflects the loss of water vapor from land surface, oceans, wet vegetation, as well as from the leaf cells of plants, which use the water for biophysical process. Soil water is taken up by plant roots and lost to the atmosphere through the leaves, mainly during the day. Several factors affect ET including temperature, relative humidity, wind, soil moisture, and plant type. The potential evapotranspiration refers to evapotranspiration that occurs from a specified reference crop if water is not a limiting factor. Growing crops, may result in evapotranspiration greater than the reference crop ET if they consume more water than the reference crop. Using the Willmott and Matsuura dataset, the total annual potential evapotranspiration over the basin is 870 mm.

Potential evapotranspiration follows the topography and increases from east to west with the highest rates in the lowlands. Since potential evapotranspiration depends highly on temperature, it follows the temperature closely decreasing during the rainy season of June to September (see Figure 27)

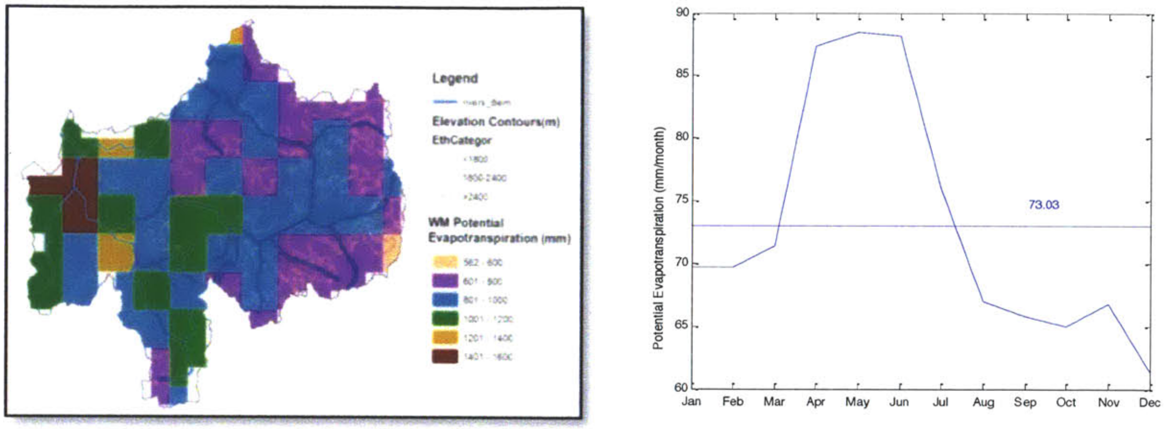

Figure 27: Annual Spatial (mm/yr.) and Monthly Temporal (mm/month) distribution of the Potential Evapotranspiration in the UBN (Source: Willmott and Matsuura, 2001)

3.1.4.4 Runoff

In this thesis, runoff describes the ways in which rainfall is converted to stream flow. The water that moves through the landscape includes both surface and ground water runoff. Runoff is inferred via stream gauges, which measure direct runoff from overland flow as well as baseflow from groundwater discharge. The fractional contribution from base flow is often greater near the bottom of the basin and it accounts for all of the stream flow in a prolonged dry period. Similar to precipitation, runoff varies in time (season) and with geography. There is very little published stream flow data from gauges in the Upper Blue Nile basin. Although the Ministry of Water Resources in Ethiopia may have these, they are currently unavailable. The USBR report provides short term data (less than 4 years) but the quality of these data is unknown. We use for this study a set of unpublished data with daily readings at "El Diem" located on the Blue Nile at the border between Ethiopia and Sudan. Annually, the UBN basin discharges 46.4 bcm of water. Due to the high seasonal variability in rainfall in the Ethiopian plateau, the flow of the Abbay River varies considerably. The peak discharge occurs in August (14.7 bcm) and is 35 times greater than the minimum flow of 0.42 in March. The peak discharge lags the peak rainfall by one month (Figure 28).

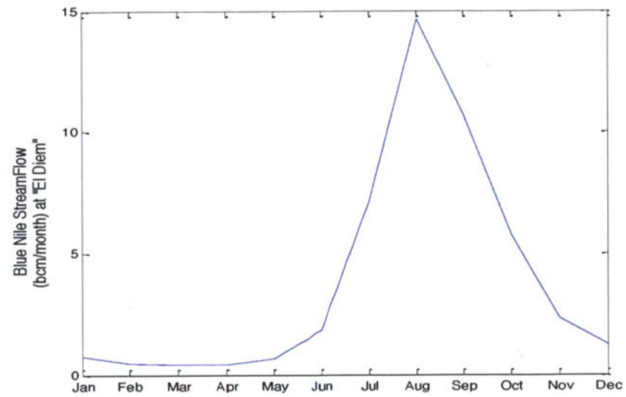

Figure 28: Monthly River Flow (bcm/month) Measured at "El Diem"

In order to understand how average precipitation partitions into average runoff and average evapotranspiration we can apply the Budyko curve. Budyko's 1974 enduring framework helps link climate to catchment runoff and ET. The assumptions, in order to use this framework, are: steady-state, large catchments (larger than 10,000 km2) and long-term averages (greater than 1 year). The data presented so far for the Upper Blue Nile basin fits these categories. Deviations from the theoretical relationship observed by Budyko have been explained by several scholars attributing them to variability and seasonality in climate (Milly, 1994; Koster and Suarez, 1999; Potter et al., 2005), to soil characteristics and to the scales of analyses (Milly, 1994; Zhang et al., 2001; Porporato et al., 2004; Donohue et al., 2006).

In arid and semi-arid regions, evapotranspiration dominates the partitioning of the rainfall and determines how much of the precipitation become runoff. The ratio of actual evapotranspiration (AET) to potential evapotranspiration (PET) is low in arid areas, and, thus, are water limited. The AET to PET ratio is close to one in areas that are energy limited. In the UBN, using the WM actual evapotranspiration data and the TRMM precipitation data, the AET normalized by the precipitation (P) is 0.76 and the PET normalized by the P is 0.98. Budyko's prediction expected a PET to P ratio of 1.2. There is about a 20% discrepancy. Still, the UBN falls within the framework and seems to be more energy limited than water limited.

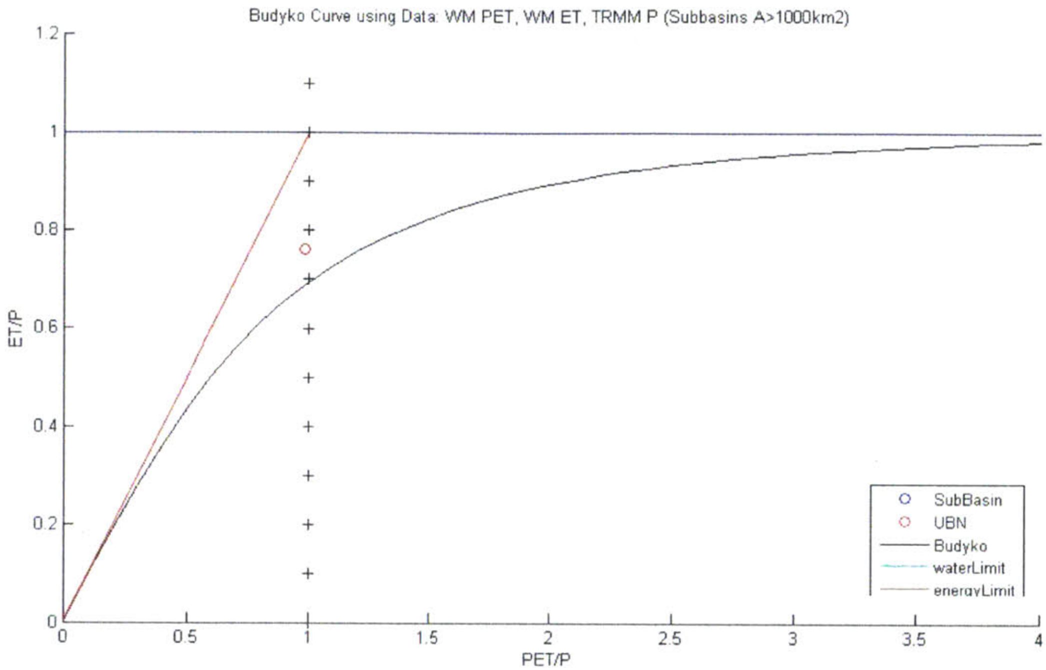

Figure 29: Ratio of annual evapotranspiration to precipitation as a function of aridity index (PET/P) for the UBN Basin Relative To Budyko Curve

Chapter 4

Modeling Approach and Data Sets

This chapter describes in detail the modeling framework, necessary data sets, and approach to answer the questions: What is the maximum volume of irrigation water that Ethiopia could use and what is the hydrologic effect downstream? The research method selected is the application of an optimization model.

Modeling studies can be useful in representing hydrological processes at various scales, but their reliability depends entirely on the uncertainties related to the model input. In any modeling effort there is a choice of either using sophisticated models with approximate or imperfect input data or using a simpler conceptualization of a model with less stringent data requirements. The advantage of a model with less stringent data requirements is the ability to be used by non-professionals that want a general understanding of the processes being modeled which is useful when addressing a policy-maker.

For the thesis, we develop a conceptual grid based model that uses remotely sensed data. A water balance is the guiding physical principle that is modeled. According to Conway and Hulme (1996), a physically based (conceptual) water balance model is perhaps the most appropriate method for simulating Blue Nile river flow. A simple grid based water balance model with limited data input requirements on a monthly timescale can be integrated with Global Climate Models and can use remotely sensed data. There have been few attempts to use remotely sensed data for the UBN and the Nile as a whole (Conway, 1996). Many of the available remotely sensed data are still being verified and compared to ground truth observations, thus the selection of input data is crucial as it can affect the outcome.

4.1 Water Balance

A water balance consists of the principle of conservation of mass applied to water. The transport of water is described in mathematical terms by the continuity equation:

Equation 1 $$\frac{dS}{dt} = I(t) - Q(t)$$

This states that any change in storage in the area is equal to the difference between water inflows and water outflows. Applying this equation to a control volume as shown in Figure 30 and using the processes of the water cycle, yields the following equation:

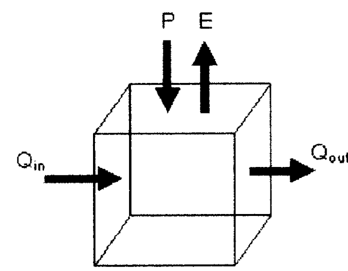

Figure 30: Sample Control Volume for a Water Mass Balance

Equation 2 $$\frac{dS}{dt} = Q_{in} + P - E - Q_{out}$$

Where inflows consist of precipitation (P) and surface or river runoff into the volume (Qin); outflows consist of any diversions, surface water, groundwater, river outflow (Qin), and evaporation (E). The change in storage refers to soil moisture, channel storage, and groundwater storage. Applying this in a long time frame (or for stead-state conditions), the change in storage would be negligible. This means that for an upstream control volume with no inflows, the difference between precipitation (P) and evaporation (E) should equal the outflow (Qout) or runoff.

4.2 General Framework

Since we are interested in irrigation, we opted for a grid-based distributed model run at a monthly time scale over a singlet year. We used a typical average year but the model can be expanded to account for differences from year to year. The monthly conceptual water balance model simulates the mean annual hydrology by looking at each grid cell as a storage unit on which rain falls, runoff flows, and evaporation occurs. The controlling equations ensure that the water balance is satisfied.

The method selected consists of 3 phases: first, a determination of arable lands using geographic information systems (GIS); second, a data assimilation procedure to capture the current hydrology; and third, the application of a water-consumptive land use model. The outputs of the first two phases are intended to be inputs into the third phase. Figure 31 shows the inputs necessary for each phase. Yellow boxes represent soil and topography inputs. Blue boxes represent climatological inputs; in this case, runoff data, precipitation data and actual evapotranspiration data. The red box symbolizes crop specific data.

Phase 1 requires soil properties, temperature, topography, and crop specific data in order to find arable areas that are suitable for irrigation. Phase 2 requires precipitation and actual evapotranspiration data. Phase 3 requires the arable land from Phase1, the modified precipitation and actual evapotranspiration from Phase 2, crop coefficients and growing period lengths and the potential evapotranspiration data. The data sources used are shown in Table 6 and are described in section 4.3. Each phase of the methodological framework is described in an independent chapter encompassing Chapters 5, 6 and 7.

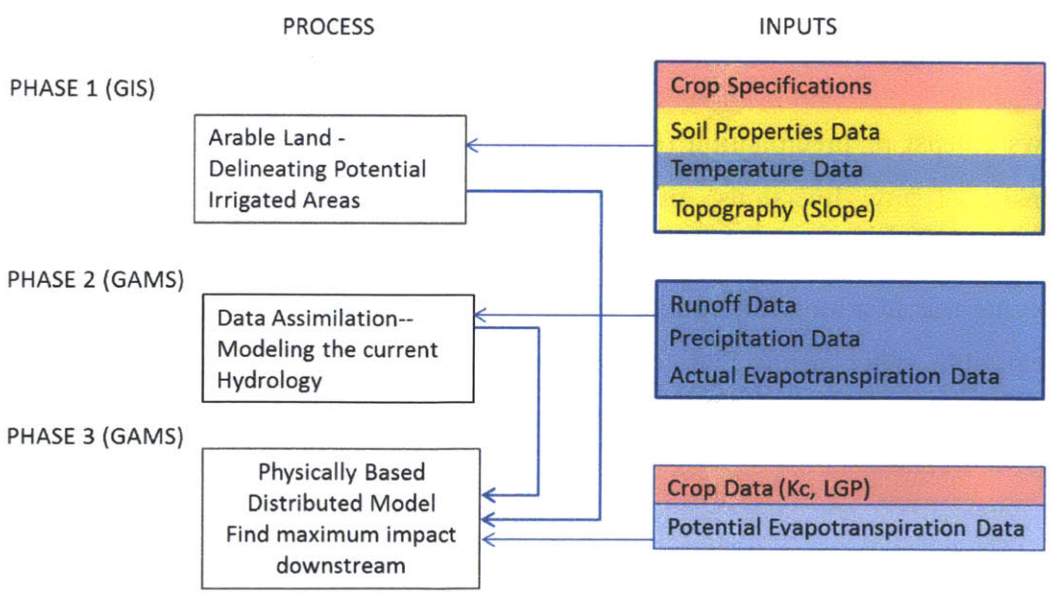

Figure 31: Conceptual Framework of Method

Table 6: Summary of Datasets Needed and Considered in the Modeling Framework

	Source Abbreviation	Center/University	Time Period	Spatial Resolution	Temporal Resolution
Topography Data					
Digital Elevation	SRTM	Shuttle Radar Topography Mission - Nasa Jet Propulsion Lab	-	3 arcsec (~90m)	-
Soil	HWSD	Harmonized World Soil Database - IIASA	-	30 arcsec (~1km)	-
Crop Data					
Crop Coefficients	kc	FAO			
Crop Requirements		FAO, C. sys			
Climate Data					
Temperature	CRU TS 3	Climatic Research Unit, University of East Anglia	1901-2006	0.5 deg global	Monthly
Precipitation	CRU TS 3	Climatic Research Unit, University of East Anglia	1901-2006	0.5 deg global	Monthly
	TRMM 3b43	Tropical Rainfall Measuring Mission, NASA and the Japan Aerospace Exploration Agency	1998-2010	0.25 deg global	Monthly
Evapotranspiration	Willmott-Matsuura	Center for Climatic Research, University of Delaware	1900-2008	0.5 deg global	Monthly
	UMT -NTSG	Numerical Terradynamic Simulation Group, University of Montana	1983-2006	0.5 deg global	Monthly
Potential Evapotranspiration	Willmott-Matsuura	Center for Climatic Research, University of Delaware	1900-2008		Monthly
Flow Direction (Dominant River Tracing)	UMT-NTSG	Numerical Terradynamic Simulation Group, University of Montana	-	0.25 deg global	-
Runoff	Unpublished source		1965-2009	-	Daily aggregated to monthly
	SAGE	Center for Sustainabilit and the Global Environment, University of Wisconsin-Madison	Varies per station	-	Monthly

4.3 Description of Data Sources

4.3.1 Topography

4.3.1.1 Shuttle Radar Topography Mission (SRTM) Digital Elevation Maps[1]

The SRTM is an international dataset managed by the National Geospatial-Intelligence Agency (NGA) and the National Aeronautics and Space Administration (NASA). The mission used a shuttle to obtain elevation data at a global scale using radar interferometry at a 90 m. (3 arc sec) resolution. SRTM data is in a raster grid format and is delivered in individual tiles, each covering one degree by one degree in latitude and longitude. The SRTM DEM can be added to ESRI's GIS software, Arc Map, and clipped to the study area. At 90 m., the processing time for any spatial analysis is quite high so the 90m SRTM was resampled to 250 m. using ESRI's cubic convolution. A similar result is obtained with the bilinear interpolation. Descriptions of these two methods are found in ESRI's Arc Map Desktop Help. An alternative source for DEM is the Hydro1k but at a resolution of 1km, it was too coarse for the purpose of this research.

4.3.1.2 Harmonized World Soil Database (HWSD)[2]

The HWSD is a 30 arc-second raster database with over 16,000 different soil mapping units that combines existing regional and national updates of soil information worldwide (SOTER, ESD, Soil Map of China, WISE) with the information contained within the 1:5,000,000 scale FAO-UNESCO Soil Map of the World (FAO et al., 2011).

Using ESRI's Arc Map, the data is read and converted from a ".bil" to a raster format. This process is described in the HWSD report. The resulting raster database consists of 21,600 rows and 43,200 columns, which are linked to the harmonized soil property data. The data contains several parameters for each unit, including the following: organic carbon, pH, water storage capacity, soil depth, cation exchange capacity of the soil and the clay fraction, total

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[1] The raw SRTM data may be obtained through this URL: http://dds.cr.usgs.gov/srtm/

[2] The raw HWSD data and manual can be obtained through this URL: http://www.iiasa.ac.at/Research/LUC/External-World-soil-database/HTML/

exchangeable nutrients, lime and gypsum contents, sodium exchange percentage, salinity, textural class and granulometry. The use of a standardized structure allows for the linking of the attribute data with the raster map to display or query the map in terms of soil units and the characterization of selected soil parameters.

Reliability of the information contained in the database is variable: the parts of the database that still make use of the Soil Map of the World such as North America, Australia, West Africa and South Asia are considered less reliable, while most of the areas covered by SOTER databases are considered to have the highest reliability (Central and Southern Africa, Latin America and the Caribbean, Central and Eastern Europe).

4.3.2 Crop Data

4.3.2.1 Crop Coefficients, "kc"

In order to simulate the water required by the plants to grow, it is necessary to calculate the crop evapotranspiration. The FAO (1998) Irrigation and Drainage Paper 56[3] describes the typical method of multiplying a reference crop evapotranspiration (ETo) by a crop coefficient (kc). The ETo reflects evapotranspiration rate from a reference surface that is not water limited. In the analysis, the potential evapotranspiration will be used.

Equation 3 $$ET_{crop} = k_c * PET$$

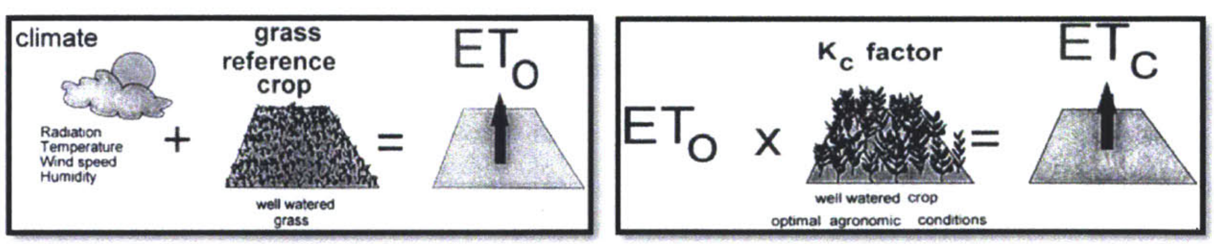

Figure 32: FAO Method for Calculating Crop Evapotranspiration

(Source: FAO, 1998)

[3] The FAO paper and data for kc values can be obtained through this URL: http://www.fao.org/docrep/X0490E/X0490E00.htm

The crop coefficient incorporates information about the crop type, crop development and crop phenology. The FAO outlines two approaches for calculating crop coefficients: the single crop coefficient or the dual crop coefficient. The single crop coefficient approach is used for most applications related to irrigation planning, design, and management. The dual crop coefficient approach is used in real time irrigation scheduling applications or water quality modeling. The thesis methodology applies the single crop coefficient.

For a selected list of crops, the FAO tables provides three values for kc: initial stage (kc_{ini}), the mid-season stage (kc_{mid}) and at the end of the late season stage (kc_{end}). FAO also tabulates the number of days a crop spends in the initial stage, crop development stage, mid-season stage and late season stage. The lengths are average lengths for the regions and periods specified and serve as a guide. Local information would be preferred but in its absence the FAO values are used. With this information, a crop coefficient curve like the one shown in Figure 33 can be constructed for each crop and the kc for any day can be interpolated.

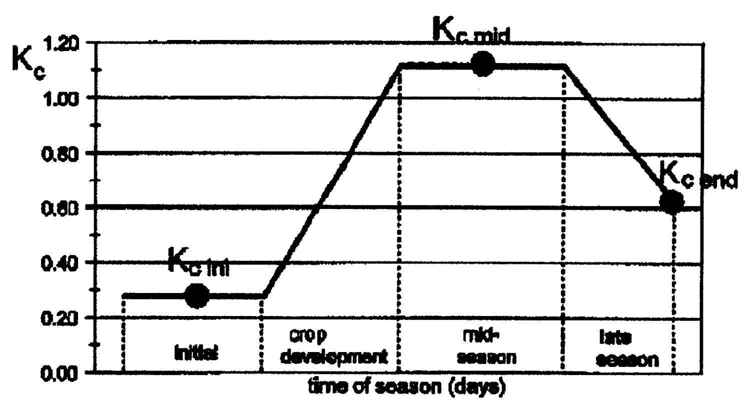

Figure 33: Typical Crop Coefficient Curve

Crop coefficient curves capture how water requirements of plants vary throughout the season. (Source: FAO, 1998)

4.3.2.2 Crop Soil Requirements

In order to assess the suitability of soils for crop production, the soil requirements of a crop must be known. Meeting the soil requirements does not guarantee that a crop can grow since there are other factors, such as landforms and climate. Nonetheless, the basic soil requirements of plants are needed and have been summarized for several crops by Professor C.

Sys (1991) The books written by Dr. Sys outline the conditions required to grow rainfed crops. The data on growing conditions requires only slight modifications to be used for irrigated crops. The dominant feature that limits irrigation is the terrain slope, which can be obtained from a digital elevation map. In ArcGIS a "slope" can be calculated as a percentage or an absolute number. For the thesis percent slopes are calculated as specified in Dr. Sys' books.

4.3.3 Temperature Data

4.3.3.1 Climatic Research Unit (CRU) Temperature Data [4]

Temperature is needed to ensure that the crops are within an operative temperature range. This parameter is necessary for a basin wide analysis. For the study area, the temperature is typically suitable for most crops. The British Atmospheric Data Center holds the Climatic Research Unit (CRU) Time Series 3.0 dataset for 1901-2006. (TS3.1, a newer version to 2009 is now available). The data are provided as a high-resolution 0.5 by 0.5 degree gridded dataset. It includes monthly mean, maximum, and minimum temperatures. The data are collected by 4,000 weather stations around the world. The data are available in ASCII and NetCDF format.

4.3.4 Precipitation Data

4.3.4.1 CRU

The Climatic Research Unit (CRU) Time Series 3.0 dataset for 1901-2006 at a resolution of 0.5 by 0.5 degrees provides monthly precipitation collected by ground stations. The CRU data suggests an annual precipitation range over the UBN study area of 1,200-1,800 mm per year, but care must be taken. In 2011, the UK Met Office reviewed observation climate data available over Africa. For CRU, the recommendation is to interpret the data with regard to the station density information because over Africa, the scarcity of *in situ* data is still a problem. The Met office suggests that in mountainous areas like East Africa, it may take more than 20 gauges per 2.5° grid box to have a monthly gauge error of less than 10 percent. They also mention that "bull's eye" is an

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[4] The CRU data can be obtained through this URL: http://badc.nerc.ac.uk

artifact of interpolation. Over the study area, there are only about 30 stations for a 5° grid box as shown in Figure 34. The Met office recommends using gauge-satellite or satellite based measurements for these areas with sparse data.

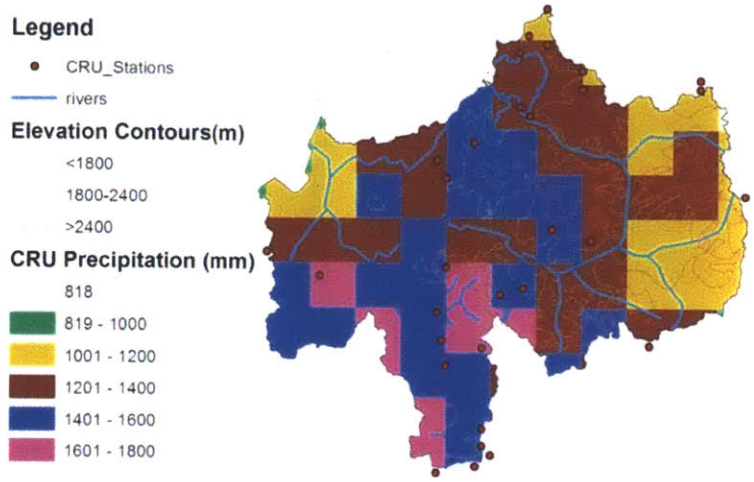

Figure 34 CRU Precipitation Data and Location of CRU Stations

The Met Office recommends more than 20 gauges for a 2.5 by 2.5 degree grid box. The CRU stations in the UBN do not meet this criterion and are quite sparse.

4.3.4.2 Tropical Rainfall Measuring Mission (TRMM)[5]

The Tropical Rainfall Measuring Mission (TRMM) is a joint mission between NASA and the Japan Aerospace Exploration Agency (JAXA) designed to monitor and study tropical rainfall. It has a sampling range between 50°N and 50°S. TRMM offers rainfall rates (mm/hour) for 0.25 degree grid boxes. The data must be converted to total monthly precipitation to use in the model. All TRMM products are archived and distributed by the Goddard Distributed Active Archive Center (GES DISC DAAC). The TRMM combination monthly product is a combination of the 3-hourly TRMM 3B 42 precipitation estimates and gauge analyses from the GPCC and Climate Assessment and Monitoring System (CAMS). The gauge data are used first to bias-correct the satellite data fields and then, during merging with the satellite data, to provide the final product using inverse error variance weighting. Fekete and Vörösmarty (2003) compared

[5] The TRMM data can be obtained through this URL: ftp://pps.gsfc.nasa.gov/pub/trmmdata/

six monthly precipitation datasets—Climate Research Unit of University of East Anglia (CRU), Willmott–Matsuura (WM), Global Precipitation Climate Center (GPCC), Global Precipitation Climatology Project (GPCP), Tropical Rainfall Measuring Mission (TRMM), and the Department of Energy's (DOE) Atmospheric Model Inter-comparison Project (AMIP-II) Reanalysis (NCEP-2) They showed that in comparison to many of the other data sets, TRMM had a global low bias. This is a known deficiency, acknowledged by TRMM data sources and still being checked. Currently TRMM is being validated with selected gauges data, ground based radar and GPCP.

In comparing CRU to TRMM, it is evident that TRMM is much lower. The mean monthly precipitation for CRU is 110 mm/month, 40% higher than TRMM (79mm/month). Both data products have recognized deficiencies as discussed in the previous sections. (For the interested reader, an alternative product is the GPCP).

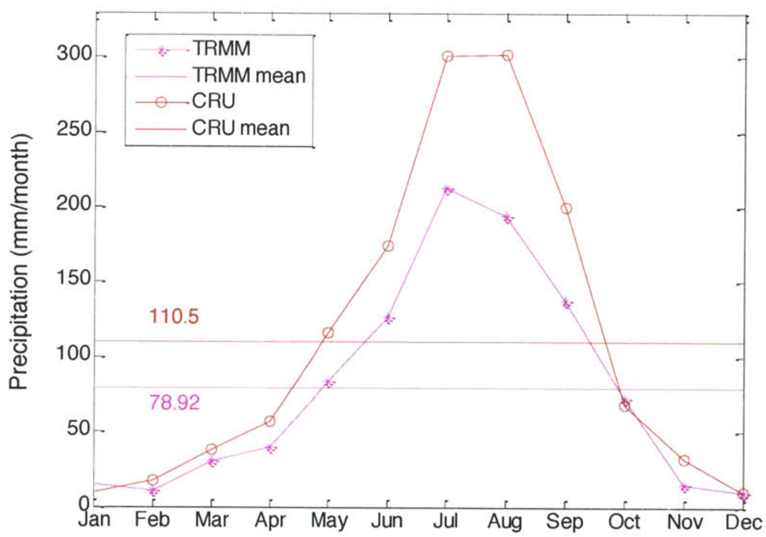

Figure 35: Comparing CRU and TRMM Monthly Mean Precipitation (mm/month) Datasets over UBN

4.3.5 Evapotranspiration Data

4.3.5.1 Numerical Terra Simulation Group (NTSG) - Global Evapotranspiration (ET)[6]

The Numerical Terra Simulation Group at University of Montana provides global terrestrial ET data from 1983 to 2006 that was estimated using a satellite remote sensing–based evapotranspiration (ET) algorithm. The algorithm quantifies canopy transpiration and soil evaporation using a modified Penman-Monteith approach and information from normalized difference vegetation index (NDVI). It quantifies open water evaporation using a Priestley-Taylor approach. These algorithms were applied using advanced very high resolution radiometer (AVHRR). The global ET results capture observed spatial and temporal variations at the global scale and the authors show how these compare favorably with ET inferred from basin-scale water balance calculations for 261 basins covering 61%of the global vegetated area.

4.3.5.2 Willmott and Matsuura (WM)—Global PET, ET

Average-monthly water-balance fields including ET and PET were estimated from the gridded average-monthly temperature and precipitation fields according to Willmott et al.'s (1985b) modified version of the Thornthwaite water-balance procedure. The computational algorithm was derived from Willmott (1977). These 0.5-degree resolution water-balance estimates are based on semi-empirical relationships between observed average monthly precipitation and an estimated average monthly potential evapotranspiration (Eo), derived from an average monthly temperature. Soil water-holding capacity (w*) was held constant, i.e. at 150 mm.

In comparing NTSG and WM ET, the variation is not too large (notice the scale of the y-axis). The mean monthly ET with NTSG data is about 65 mm/month, about 8% higher than the mean monthly WM ET (60mm/month). The seasonality, however presents some differences with NTSG having a peak ET in October and the WM ET having a peak in May.

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[6] The NTSG data can be obtained through this URL: http://www.ntsg.umt.edu/data

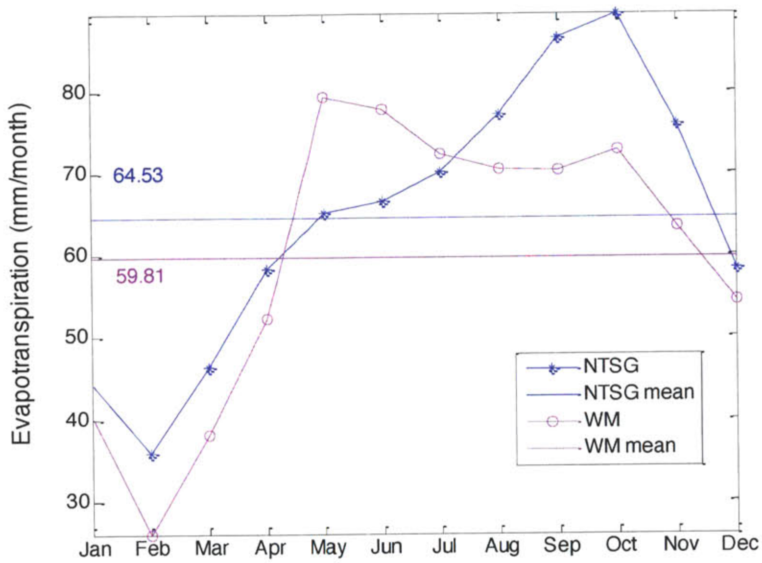


Figure 36: Comparing NTSG and WM Monthly Mean Evapotranspiration (mm/month) Datasets in the UBN Basin

4.3.6 Selecting Precipitation and Evapotranspiration Data Sets

Given the differences and limitations of the datasets explained, all the combinations of precipitation and ET were compared in order to select which data sets to use in the model. At the yearly scale, precipitation minus evapotranspiration is expected to equal the runoff. This means the (P-E)/R ratio should be close to 1. The yearly runoff of the UBN is about 46 bcm or about 260 mm expressed as a depth over the 177,000 square km area. As shown in Table 7 and Table 8, using the TRMM precipitation and the WM evapotranspiration results in the ratio closest to 1. Consequently TRMM was selected for precipitation and WM for evapotranspiration for the application over the UBN basin.

Table 7: Combination of Precipitation and Evapotranspiration Datasets

	Precipitation (P)		Evapotranspiration (E)	
Units	**TRMM**	**CRU**	**WM**	**NTSG**
mm/day	2.59	3.63	1.97	2.12
mm/month	79	110	60	65
mm/year	947	1327	718	774
Percent different	40%		8%	

Table 8: Selecting Datasets by Comparing the Ratio of Precipitation minus Evapotranspiration to Runoff

mm/year	P-E	Runoff Data	Perc. Diff	Ratio (P-E)/R
TRMM-NTSG	173	263	-34%	0.66
TRMM-WM	229	263	-13%	0.87
CRU-NTSG	553	263	110%	2.10
CRU-WM	609	263	132%	2.32

4.3.7 Runoff Data

4.3.7.1 Discharge Data

SAGE provides a compilation of monthly mean river discharge data (m3/s) for over 3,500 sites worldwide. The data sources are RivDis2.0, the United States Geological Survey, Brazilian National Department of Water and Electrical Energy, and HYDAT-Environment Canada. The period of record for each station is variable, from 3 years to greater than 100. For the study area, the station is "Sudanborder" with pointID 12 located at a latitude and longitude of 11.15 N and 35.15 East. This data source had only 5 years of usable data so it was opted not to use this data and instead rely on unpublished data with a long record from 1965 to 2009 for 13stations along the Nile River provided by Professor Eltahir.

4.3.8 Flow Direction Data

4.3.8.1 NTSG - DRT

Since we opted for a distributed grid-based model, a water balance is applied at each grid box. It is then necessary to have a flow-routing scheme to know how (i.e. in which direction) the water travels to go from one grid box to another and in this way extract the surface channel network. The resolution of the grid box becomes quite important; due to the computational demands, it is often necessary to upscale physical processes, including the flow routing, to a reasonable grid size. Several methods exist to find flow direction including D8, D-inf, multi-flow direction and Demon (Figure 37). The choice of flow routing algorithm is important because it affects the flow accumulation and the upslope contributing area. The methods listed apply for square grid DEMs and use a 3x3 moving window. The D8 method treats the water as point source (non-dimensional) and guides it in the direction of maximum descent restricting the flow to one of eight possible directions. D-inf allows for only one direction but has infinite possibilities. The multi-flow direction is more realistic, particularly at tops of mountains where the water can flow in several directions but it is more complicated to calculate. The Demon method uses an aspect angle and partition the catchment into irregular shapes.

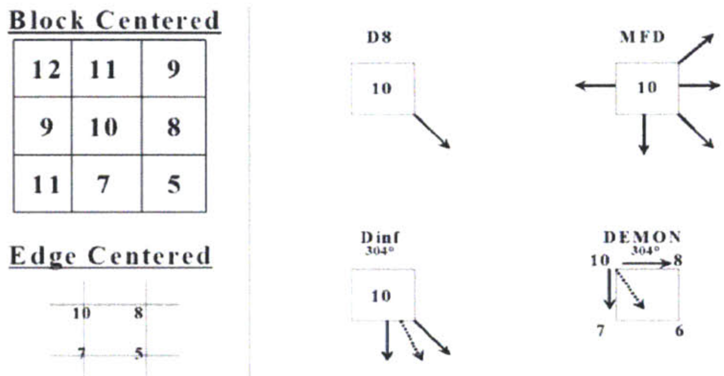


Figure 37: Flow Routing Methods for Determining Flow Direction

(Endreny and Wood, 2001)

In selecting the flow direction the following were considered: using existing global data from the Total Runoff Integrating Pathways (TRIPS) method by Oki and Sud (1998), using existing global data from the Dominant River Tracing (DRT) method by Wu et al. (2011), or using the built in Arc Map flow direction calculator. The Arc Map flow direction calculator will propagate any errors in the DEM and may have problems with sinks in the DEM; it however, has the advantage of allowing the user to find flow direction at any resolution desired instead of relying on the resolution that is provided by other scholars. On the other hand, using the provided datasets and published methods ensures quality control since these have been compared with river directions and validated accordingly.

The method and data chosen is the DRT algorithm described by Wu et al. (2011). It uses a D8 method, the Hydro1k DEM and an automated extraction and spatial up-scaling algorithm to provide basin flow directions at resolutions of 1/16, 0.25, 0.5 and 2 degrees. In contrast with previous up-scaling methods, the DRT algorithm utilizes information on global and local drainage patterns from baseline fine scale hydrography to determine up-scaled information.

Selecting the DRT data as a reasonable input means that in our model, the available DRT data set resolutions dictate the resolution to which all other data sets must be scaled.

Figure 38 shows the flow direction from the DRT dataset at the chosen resolution of 0.25 degrees over the UBN; this is a coarse resolution but is similar to what is used in climate change models making future integration with climate change models much easier. From the DRT data, it is possible to read which neighboring pixel contributes to a specified pixel. Our model however requires a set of all the tributaries contributing to the pixel. The Matlab and Python codes developed to make tributary list files are found in Appendix A5 and A6. These codes read the DRT dataset by Wu et al. (2011) and re-format it in a way that is usable by our model.

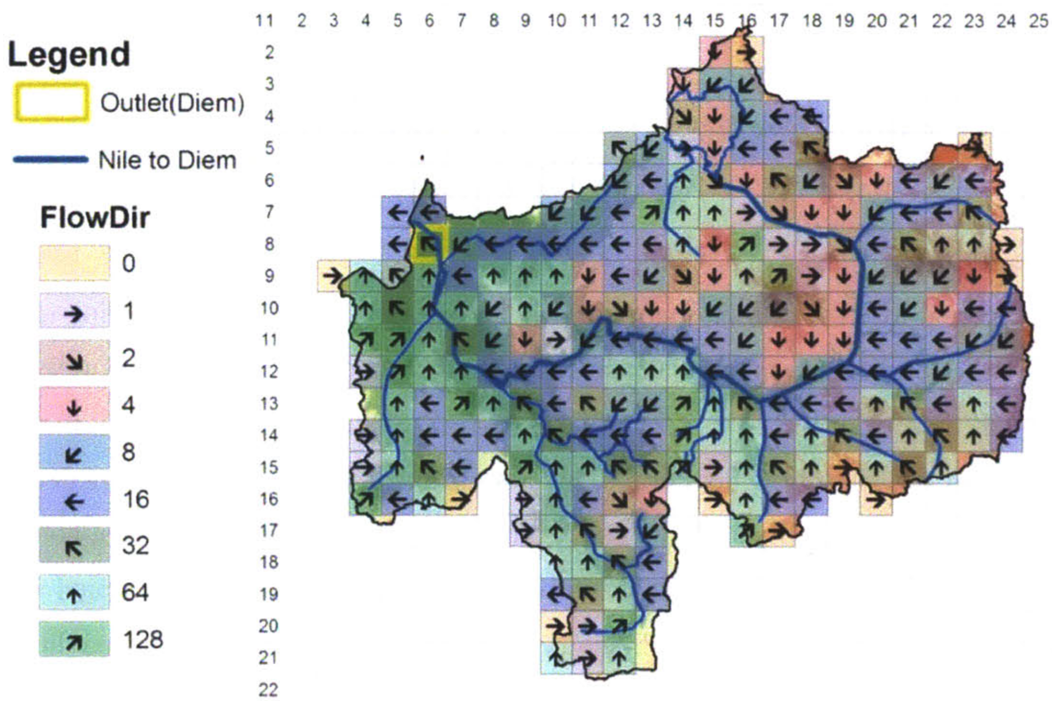


Figure 38: D8 Flow Direction by Wu et al. (2011) over the UBN at the chosen resolution of 0.25 degrees

The water flows from Lake Tana to the outlet at "El Diem." This is a course resolution since it implies channel widths of about 25 km, but this resolution reduces computational processing time and is a common resolution for climate change models making future integration with these easier.

Chapter 5

Phase 1: Delineating Irrigable Arable Lands

In order to quantify the maximum irrigation water that can be used over the Upper Blue Nile, the first step is to determine the land areas that can be irrigated. We are concerned with determining suitable areas for crop irrigation depending upon the soil, slope and temperature conditions. Since we are considering irrigation potential and not rainfed potential, the local availability of water is not considered during this first phase. The model created is intended to be descriptive to identify the favorable irrigable agricultural locations in the UBN.

5.1 Crop Choice

According to the International Food Policy Research Institute, (IFPRI), five major cereals (teff, wheat, maize, sorghum and barley) account for 14 percent of the GDP and 64 percent of calories consumed in Ethiopia (Tafesse et al., 2011). Figure 39 shows the farming system classification; cereal based cultivation dominates cropped lands with single, double and shifting cropping cycles (Awulachew et al., 2010).

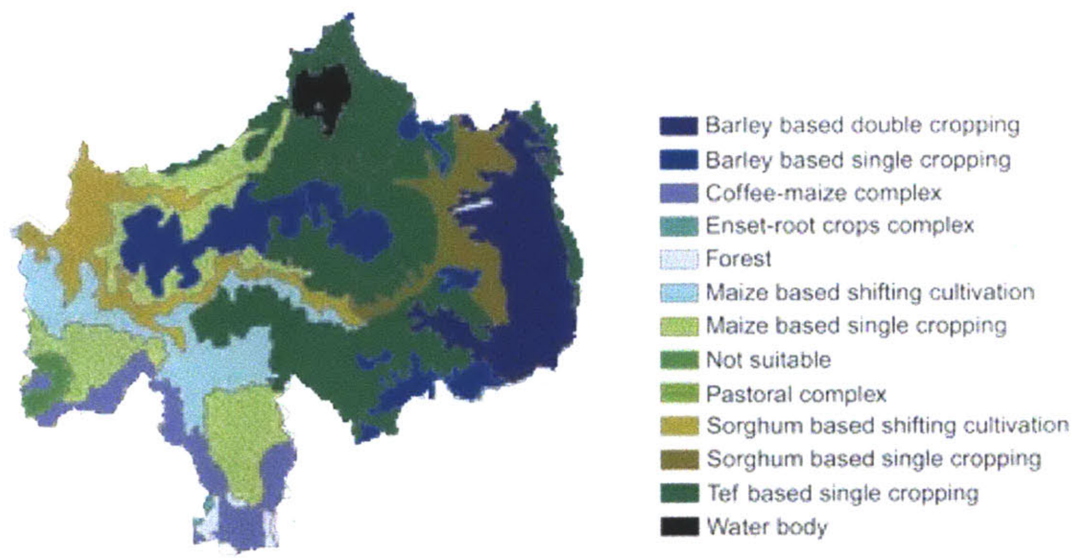


Figure 39: Classification of Farming Systems in the Upper Blue Nile

Source: (Awulachew et al., 2010)

To select the crops for analysis, we examined crop production in Ethiopia as published in FAOstat. As shown in Table 9, maize, wheat, sorghum, sugar cane, barley, beans, millet, potatoes, sweet potatoes and papayas are the top ten crops produced by weight.

Table 9: Top Ten Crops Produced in Ethiopia by Weight Ranked by Five-Year Average (2005-2009)

Selected for Analysis		Production (Million Tonnes)					
Item		**2005**	**2006**	**2007**	**2008**	**2009**	**Average**
Y	**Maize**	**3.91**	**4.03**	**3.34**	**3.78**	**3.93**	**3.80**
Y	**Wheat**	**2.31**	**2.78**	**2.22**	**2.46**	**2.54**	**2.46**
Y	**Sorghum**	**2.20**	**2.31**	**2.17**	**2.32**	**2.80**	**2.36**
-	**Sugar cane**	**2.45**	**2.50**	**2.20**	**2.30**	**1.10**	**2.11**
Y	**Barley**	**1.40**	**1.41**	**1.27**	**1.35**	**1.52**	**1.39**
-	**Beans**	**0.52**	**0.60**	**0.58**	**0.69**	**-**	**0.60**
Y	**Millet**	**0.40**	**0.50**	**0.40**	**0.48**	**0.56**	**0.47**
Y	**Potatoes**	**0.45**	**0.45**	**0.53**	**0.40**	**0.38**	**0.44**
Y	**Sweet potatoes**	**0.41**	**0.39**	**0.39**	**0.53**	**0.26**	**0.40**
-	**Papayas**	**0.26**	**0.26**	**0.26**	**0.26**	**-**	**0.26**

(Source: FAOstat, 2012)

From the top ten crops produced in Ethiopia, the cereals and tubers were selected. Sugarcane and beans were dropped from the analysis due to a software data corruption. Cassava, cotton, sesame and groundnut were added to the list. Investigation showed these are main subsistence local crops and some can be grown in high elevations. Allowing for crops that seem to have large suitability but are currently not the top in production helps expand the potential irrigable areas and makes the analysis more appropriate for finding a potential maximum. For this study the extended list of crops used include maize, wheat, sorghum, barley, millet, potatoes, sweet potatoes, cassava, cotton, sesame and groundnut.

5.2 Soil Conditions

After selecting the list of crops, the next step is to ascertain where these crops can grow. The FAO evaluation framework (Sys, 1991) is utilized to identify suitable land for each crop. The FAO Framework is fundamentally a classification system. In the FAO method, all land is divided into two suitability orders: suitable (S) or not suitable (N). These orders are further divided into suitability classes: 'S1' for suitable, 'S2' for moderately suitable, 'S3' for marginally suitable, 'N1' for unsuitable areas due to economic reasons but otherwise marginally suitable, and 'N2' for unsuitable areas due to physical reasons. N2 implies limitations that cannot be corrected at any cost within the context of the land utilization type. In general FAO practice, S1 corresponds to 80-100 percent of optimum crop yield, S2 corresponds to 40-80 percent, and the S3/N1 corresponds to 20-40 percent (Rossiter, 1994). In this analysis, land is considered suitable for the crop if it meets the requirements of S1 or S2. To find the overall rating of suitability, land qualities are compared with the requirements of each crop. The land characteristics and land qualities are measurable properties of the physical environment (Sys, 1991).

5.2.1 Land Qualities

The following includes a brief description of the land qualities considered in the soil analysis. The soil data comes from the HWSD at a resolution of 30 arc seconds. HWSD has data for topsoil (0-30cm) and subsoil (30-100cm). Since topsoil is very critical for crop production, in the analysis only the topsoil was considered. Figure 40 shows the selected soil qualities in the Upper Blue Nile and they are subsequently described.

Drainage: Removing excess water from the soil with surface ditches or conduits, is necessary to maintain a suitable soil structure, conserve soil nitrogen and prevent waterlogging, leaching and salinization. Favorable drainage conditions will depend on the depth and quality of the groundwater table. The classifications consist of poorly, imperfectly, moderately, excessively and well-drained. The Upper Blue Nile basin has soils that drain moderately well in the lower eastern lands and drain poorly and imperfectly in the higher western mountainous region. However if drainage is limiting, it can usually be improved, so for the analysis all drainage classes were accepted

U.S Department of Agriculture (USDA) Texture Class: coarse textured soils can lack both nutrient and water holding capacities. Fine-textured soils often have structural and infiltration problems. The UBN consists primarily of fine soils in the lowlands and medium textured soils in the highlands. The soils in the lowlands are classified primarily as light clays, the soils in the highland are loam and clay loam, and soils near Lake Tana are sandy clay loam.

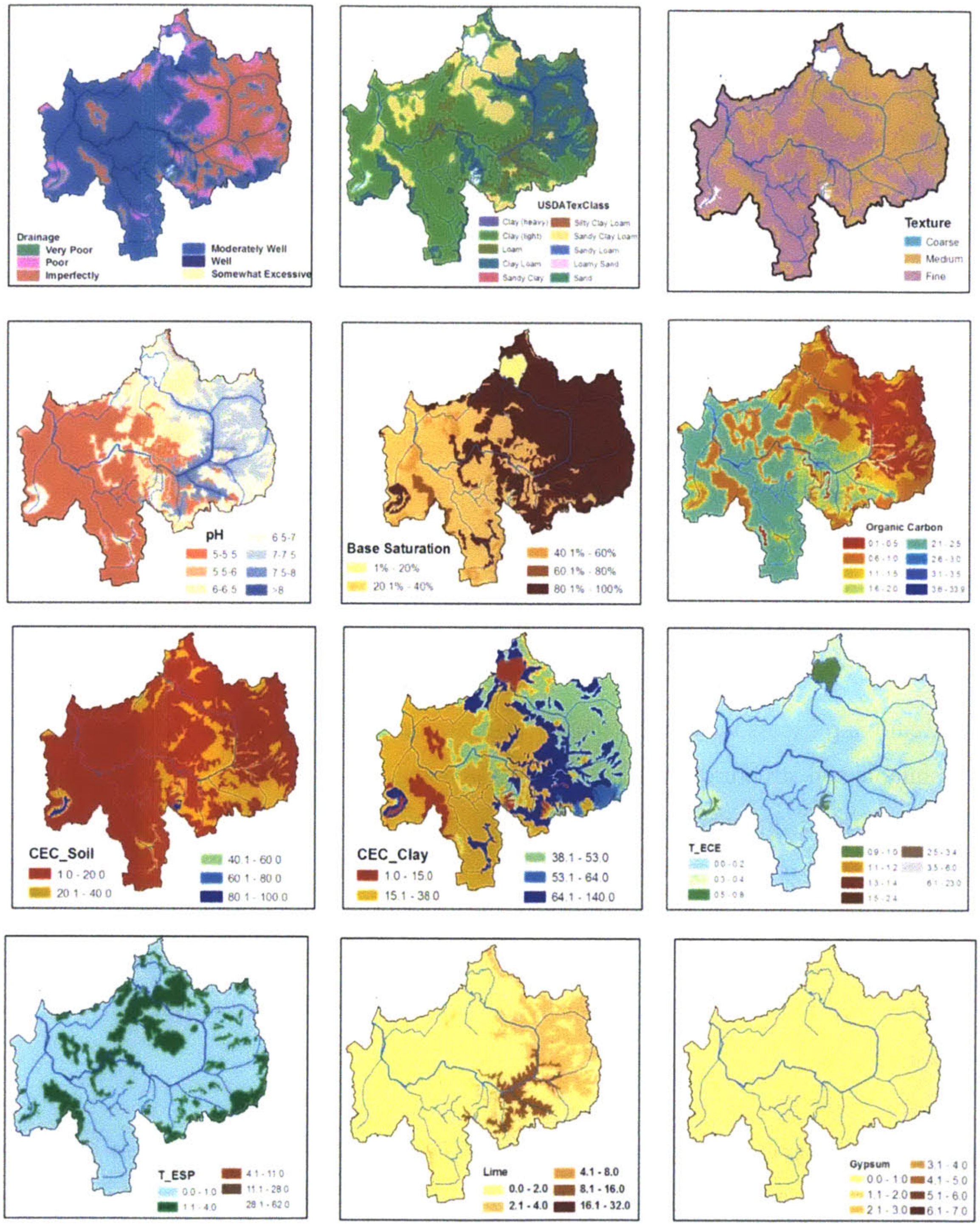


Figure 40: HWSD Soil and Land Qualities for the Upper Blue Nile

Organic Carbon (percent by weight) and pH: Together these serve as a simple indicator of the health status of the soil. Moderate to high organic carbons indicate fertile soils with good structure. Soils that are very poor in organic carbon may require organic fertilizers. The organic carbon also follows the topography. The highlands have lower organic carbon with less than one percent by weight, while the lowlands have slightly higher organic carbon with more than two percent by weight. The pH controls the form in which a nutrient will be present. The lowland areas have lower pH values in the range five to six while the highlands are more basic with a pH of seven to eight.

Topsoil Calcium Carbonate (CaCO3 percent weight): Commonly called limestone, CaCO3 is important to reduce the possibility of the soil becoming too acidic. Most of the basin has low levels of lime but in the southeast, near Finchae reservoir, the calcium carbonate can reach 16 percent by weight.

Topsoil Calcium Sulfate (CaSO4 percent weight): Commonly called gypsum, often two percent in the soil favors plant growth, but more than 25 percent can cause substantial reduction in yields (FAO, 1990). The Upper Blue Nile has very small amounts gypsum by weight so it does not inhibit plan growth.

Cation Exchange Capacity (cmol/kg): Represents the total cations that a soil is capable of holding at a given pH for exchange with soil solution. Soils with low CEC have little resilience and cannot build up stores of nutrients.

Base Saturation (percent): Measures the calcium, magnesium, potassium, and sodium in a soil. The percentage of each of these cations is added to determine the base saturation. The higher the base saturation, the more available these nutrients are for the crop. The western mountainous region of the UBN is nutrient rich. In fact, many of these nutrient-rich soils erode, get carried by the Nile River and are deposited in the lower lands in Sudan and Egypt making these fields fertile.

Salinity (ECE, ds/m) and Soil Sodicity (ESP, percent): Soil salinity can be a beneficial soil property as it allows the soils to aggregate and helps with stabilization and soil aeration. On the other hand, when salinity is too high, generally if their ECE is greater than 2 to 4 deci-Siemens per meter (dS/m), the salts will accumulate in the plant root zone and the plants can be negatively affected as they cannot absorb water from the soil. Barley, wheat, cotton and sorghum are considered salt tolerant while sugar cane and maize are not (NRW, 2007). Sodicity measures the sodium content. Sodium has the opposite effect of salinity on soil stabilization since it causes dispersion but this may lead to less infiltration, lower hydraulic conductivities and increased soil crusting. The UBN sodicity is primarily less than one percent, although, there are areas where it ranges from one to four percent. Less than fifteen percent results in no hazard to the plant. Thus, sodicity is not the main limiting factor.

The FAO's framework allows for a "simple limitation method" which consists of matching tables for each crop. For each suitability class, the tables describe land quality criteria that must be satisfied in order to be suitable for the crop. For example, to find land that is suitable for growing wheat, the top soil must have lime availability of up to 40 percent by weight, gypsum of up to 10 percent by weight, a base saturation of more than 35 percent, a pH between 5.6 and 8.3, more than 0.5 percent organic carbon, salinity of less than 5 ds/m, sodicity of less than 35 percent, and a CEC of more than 3.5 cmol/kg. The matching tables are assembled in Part 3 of Land Evaluation by C. Sys (1991) and describe crop requirements. The synthesized land quality criteria used for the selected list of crops can be found in Appendix A3. An ArcGIS query was created using python scripts to do the matching automatically. These codes can be found in Appendix A4. For many crops, the major limitations are the pH, organic carbon and base saturation. Figure 41 shows the areas with S2 suitability for each crop after applying the matching query.

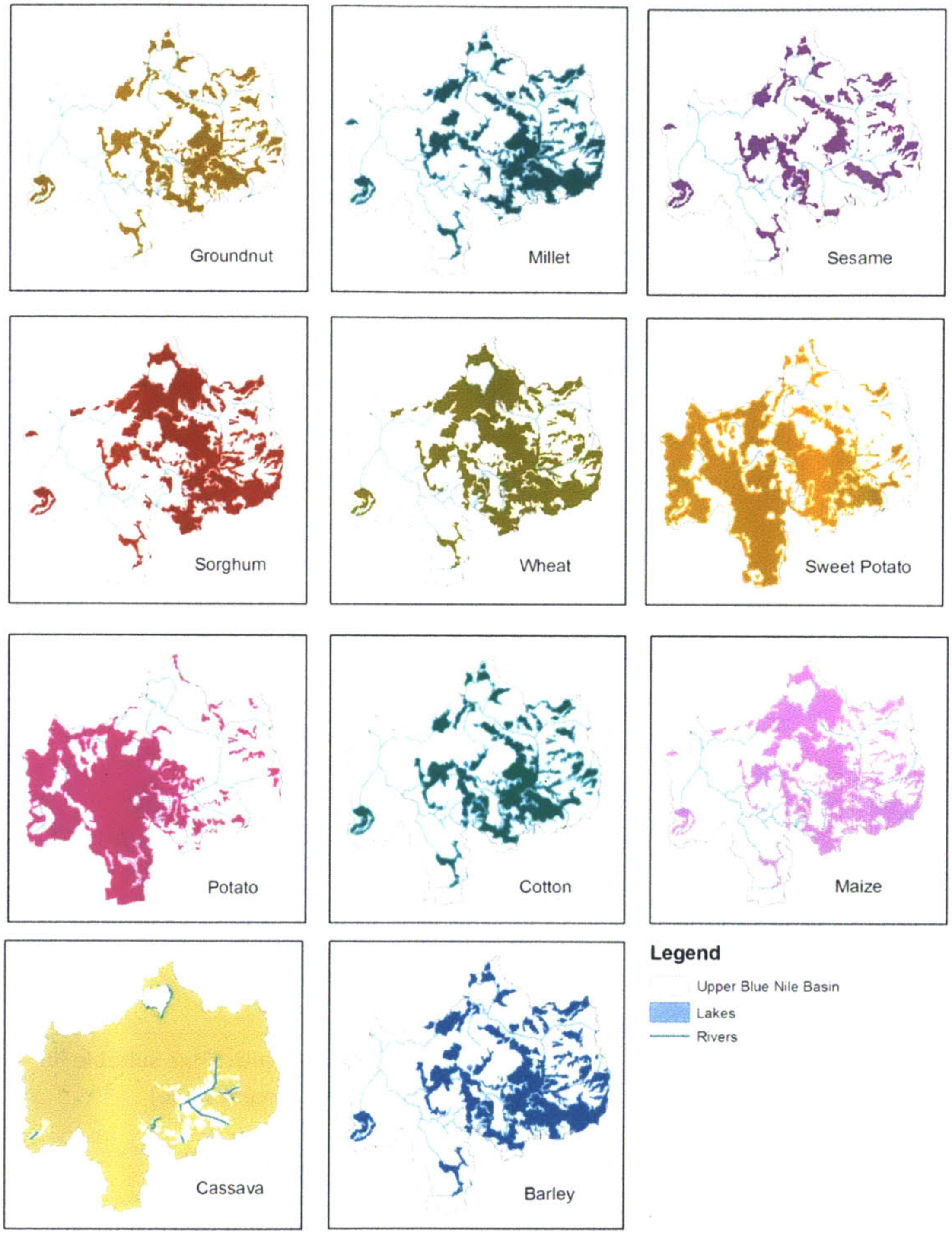


Figure 41: Areas with at least 'S2' Soil Suitability for Selected Crops

Several of the crops can be grown in the same areas. The cereals and tubers, however, complement each other. Nearly the entire UBN is suitable for at least one crop.

5.3 Slope Conditions

Slope plays an important role in mechanization for agricultural purposes. According to Dr. C. Sys (1991), slopes greater than twenty percent make mechanization impossible. For gravity irrigation, zero to two percent slopes is unconstrained while two to five percent show slight constrain. Slopes of zero to four percent are optimal for sprinkler irrigation or annual arable land farming. Sloping terrain is more difficult to cultivate than flatland because slopping lands are subject to higher rates of water runoff and soil erosion. When the slope is too great, planting large areas can be detrimental to the topsoil. For this analysis, a slope criterion of zero to four percent, as shown in Table 10, was considered as suitable for the selected list of crop irrigation. Figure 42 shows areas in the UBN where the slope is 0-4 percent, and is, therefore, unconstrained for irrigation. About 48,220 square km or 27 percent of the UBN basin area fits this criterion.

Table 10 : Optimal and Marginal Slope Criteria for Irrigation Schemes and Land Use Types

	Slope Classes in %	
Utilization Types	**Optimal**	**Marginal**
Surface Irrigation		
-flush	<0.2	0.5
-furrow	<1	4-6
Sprinkler Irrigation	0-2	16-25
Annual arable land	0-4	16-26
Perennial crops and grassland	0-8	25-30
Forest (exploitable)	0-16	25-30

(Source: C. Sys, 1990)

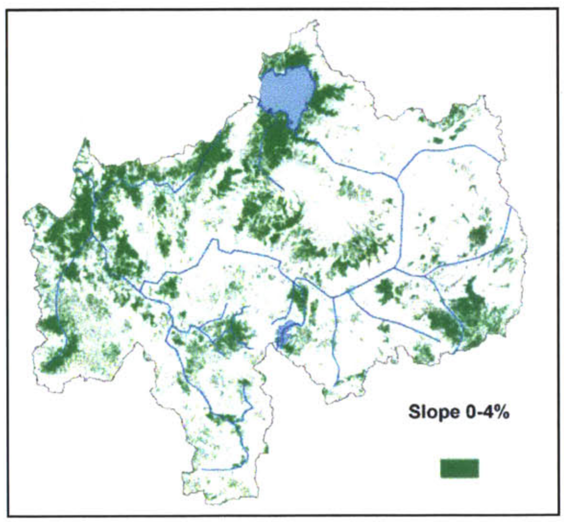


Figure 42: Areas with Slope suitable for irrigation (0-4 percent slope)

5.4 Temperature

Temperature determines the rate of growth of the plant as it dictates the photosynthesis and phenology. Many procedures use the "Growing Degree Days" (GDD) method. We use mean monthly temperatures at 0.5-degree spatial resolution provided by CRU. The temperature at a specific pixel is checked to see if it falls within the operative range for the selected crops (Table 11) for that month. This is a coarse method of accounting for the crop phenology. The underlying implicit assumption is that temperature and crop development are linearly related so that temperature can be accrued in the growing period. This relies on the same linearity assumption of the GDD method.

Table 11: Optimum and Operative Temperature (degrees Celsius) for selected crops

Temperature (degrees C)	Optimum		Operative	
Barley	15	20	5	30
Cassava	25	30	12	35
Cotton	24	34	18	40
Groundnut	22	28	10	38
Maize	30	35	15	45
Millet	30	35	15	45
Potato	15	20	5	30
Sesame	21	32	15	45
Sorghum	30	35	15	45
Sweet Potato	22	32	16	40
Wheat	15	20	5	30

Source: Adapted from FAO, 1985)

The length of the growing period and planting date is obtained from the FAO Drainage Paper 56. The temperature at each pixel is checked and if the month is successful (i.e. the pixel temperature is within the operative range for the crop) that pixel is marked with a one for the month (zero is used for unsuccessful months). The binary values are averaged for the growing season, giving a fraction of the total season that presented operative mean temperatures. The year of the 106-year time series is marked as a successful year if the temperature were operative for 80% of the season (arbitrary threshold). The 106 years are averaged to give a fraction of success. This process was done in Matlab to identify areas where the temperature would meet necessary conditions for the crop. The Matlab codes for the temperature check can be found in the Appendix A8. Except for cotton, most crops are not strongly limited by the temperature for the selected growing season. Figure 43 shows areas in gray that had success of less than 70 percent in the 106 year time series. White areas were successful more than 70 percent of the time and are suited for crop growth.

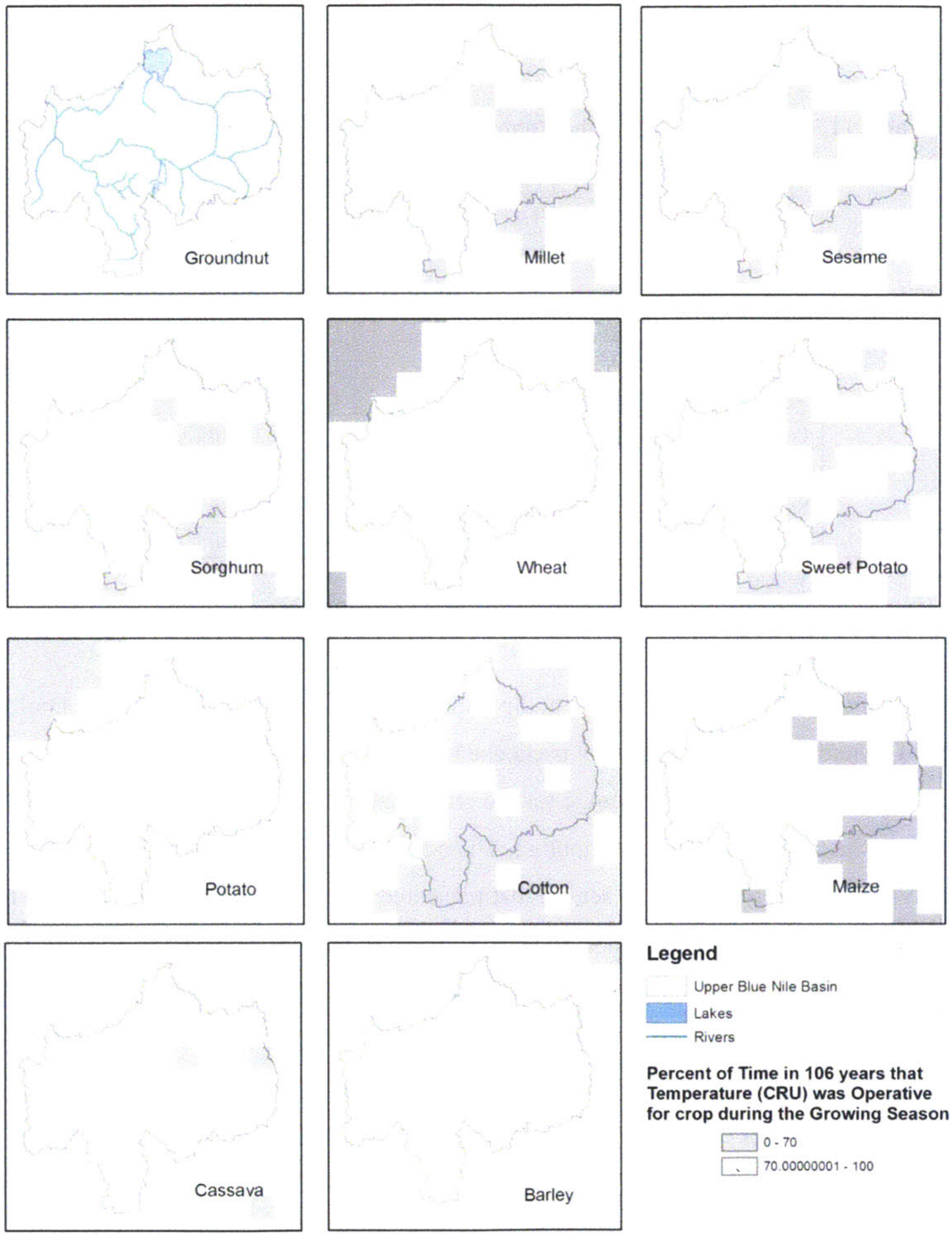


Figure 43: Areas That Are Suitable (white) And Unsuitable (gray) For The Crop Due To Temperature

5.5 Combining Slope, Soil and Temperature

For each crop the areas with suitable soil, slope and temperature are intersected to identify areas where all three conditions are favorable for the growth of the crop. The codes to this can be found in Appendix A7. Figure 44 shows a graphical illustration of the process. The results and area calculations for each crop are show in Figure 45. Notice the best irrigable land for cereals lie around Lake Tana and for roots and tubers, near the border with Sudan at lower altitudes. Also notice that cassava has the largest area that is arable (54,700 square kilometers) but it is not part of the top Ethiopian crop productions or main dietary crop.

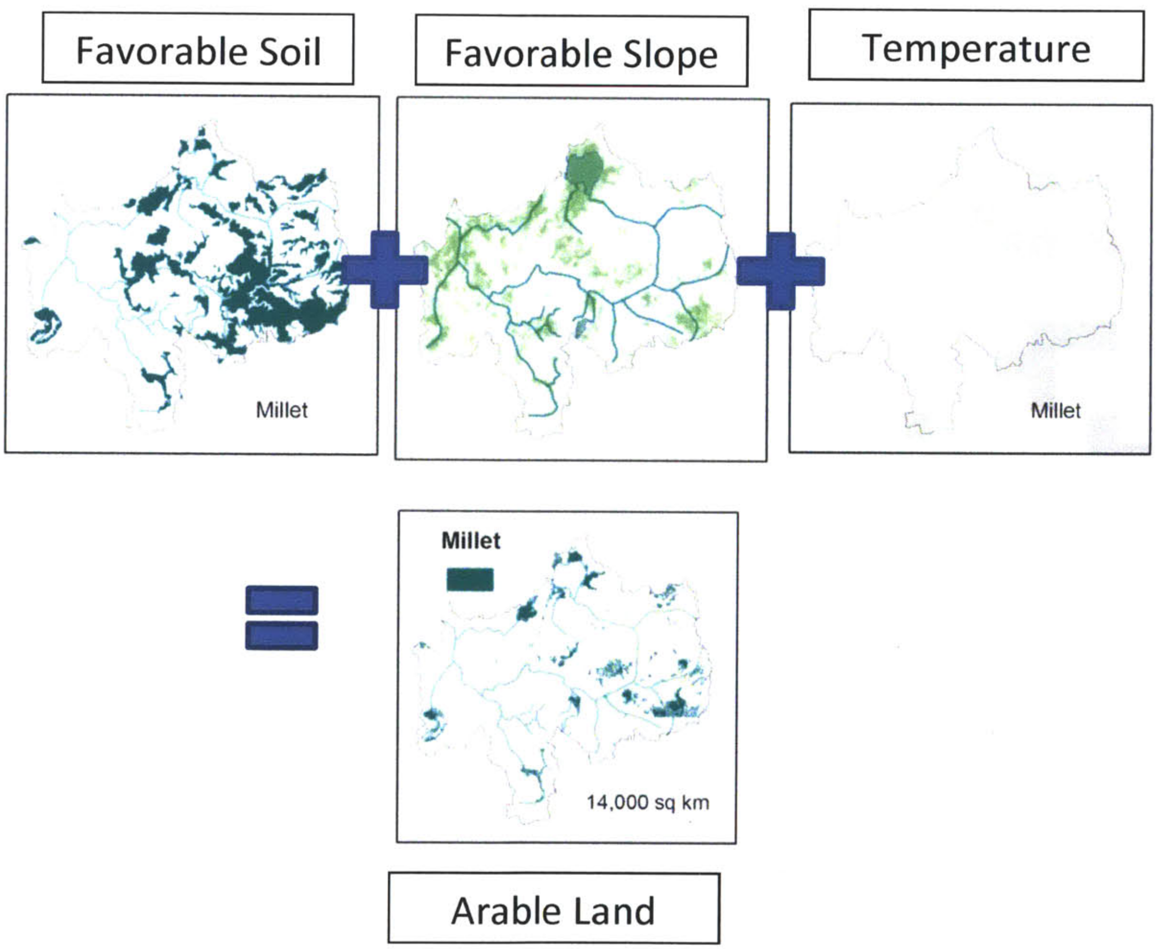


Figure 44: Graphical Example for Millet of how Arable Land is Defined and Identified

Favorable soils encompass specific land qualities, particularly nutrient availability (teal color); favorable slope limit the areas to where irrigation and mechanization could occur (green) and favorable temperatures ensure that the crop will have enough heat (white). All together, the areas become more limiting.

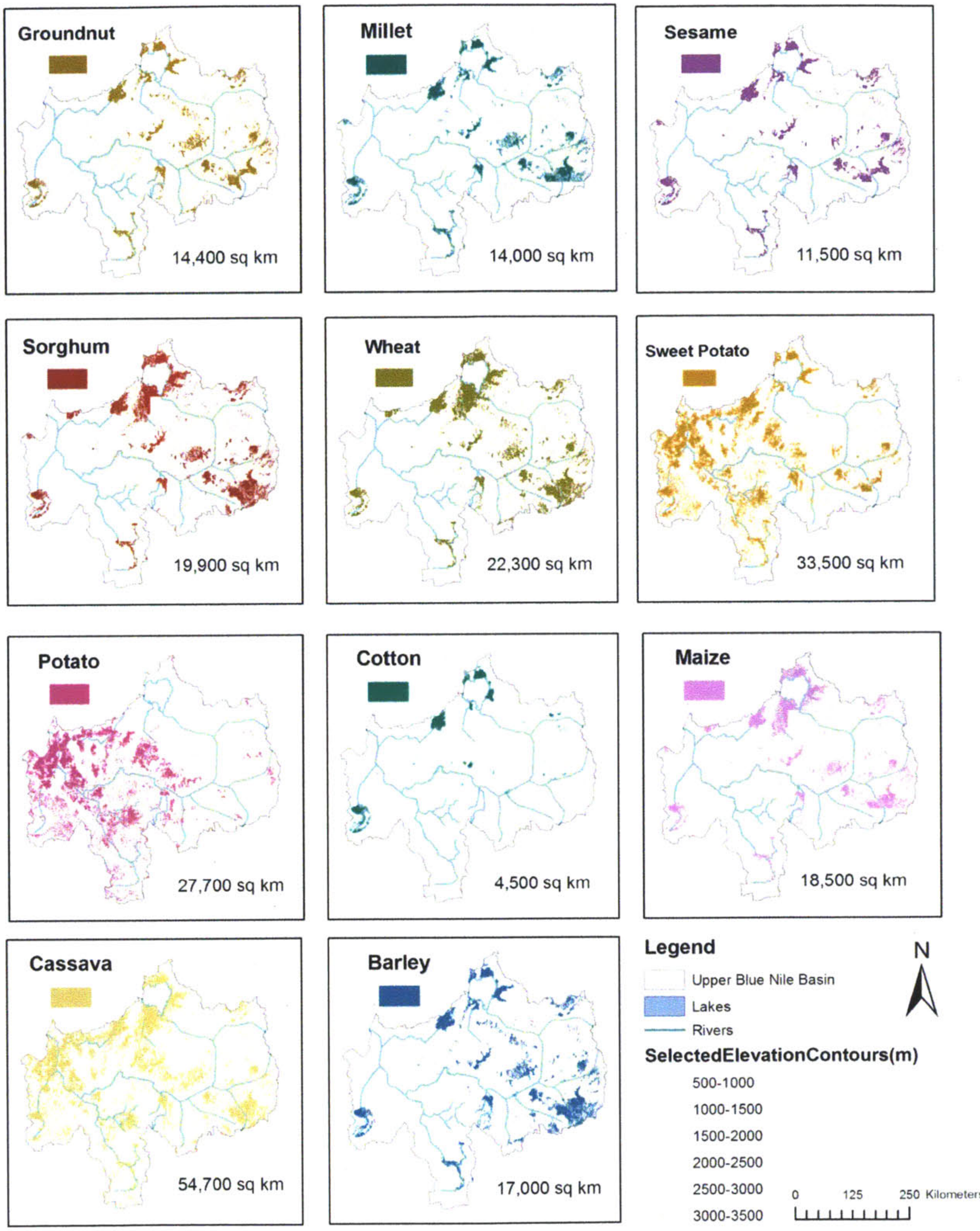


Figure 45: Arable Land Areas for Selected Crops

5.5.1 A note on resolution and combinatorial problems

The spatial resolution of the analysis becomes very important when working with several data sets. Temperature from CRU is at 0.5 degrees (50km), soil from HWSD is at 30 arc second (~1km) and slope from the resampled SRTM is at 250m.The arable land that was calculated uses the smallest resolution of input layers, that is, 250m. This however, is much smaller than the selected analysis resolution of 0.25 degrees (25km). With this arable land, we are able to identify what percent of a 25 km by 25 km grid box is arable but this poses a combinatorial problem. In each grid box, multiple crops may be grown and the arable areas may overlap. Take the example in Figure 46 with two crops, maize and cassava.

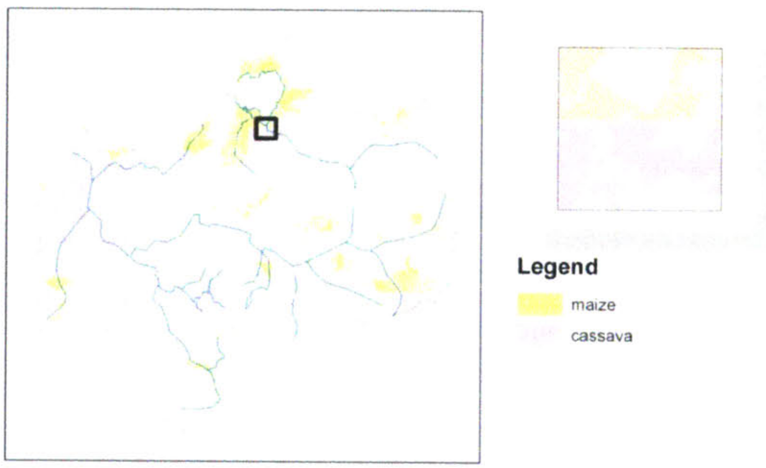


Figure 46: Maize and Cassava Example to Illustrate a Combinatorial Problem

The following equation is a mathematical representation of where each crop is located; L is the arable land:

Equation 4 $$L_{maize} + L_{cassava} + L_{noncrop} - \cap(L_{maize} + L_{cassava}) = \boldsymbol{Pixel\ Area}$$

This must be done in every pixel for every crop combination. This becomes a combinatorial problem with the selected list of 11 crops or elements that must be distributed into groups from one to eleven. This becomes computationally difficult and mathematically cumbersome. We can however simplify this in two possible ways. The first is to average all the properties (soil, slope, temperature) inside the 0.25 degrees and then intersect the layers. The second is to use the fine resolution arable land and calculate what percentage of the grid box is arable and apply a cutoff. If the percentage exceeds the cutoff, the entire square is deemed arable. This would allow the intersection in equation 4 to be eliminated since the arable lands are now 0 or 1 for each grid box. When attempting the first method, we noticed a large loss of information, particularly when up scaling the slope. Consequently we opted for the second method. A cutoff could be applied to each crop or one cutoff for all crops. The latter approach, a cutoff for all crops was chosen to avoid computational complexity. It must be noted that applying a cutoff to each crop would yield more accurate results. For our study the difference would have been marginal. To select the cutoff percent, the goal was to maintain the total area of the crops as close to the actual values. This could be achieved by minimizing the mean squared error between the actual areas and the areas with a cutoff. Figure 47 shows the mean squared error versus the cutoffs and the least square error occur with a cutoff between 0.3 and 0.4 Figure 55 shows how the areas would differ for each crop if these cutoffs were applied. Using goals seek in excel, a cutoff of 0.34 maintained the total area as close to actual area as possible. Figure 48 shows grid boxes that become arable for each crop using a cutoff of 0.34. The arable area is comparable to the actual areas. This arable land area becomes an input into the third phase.

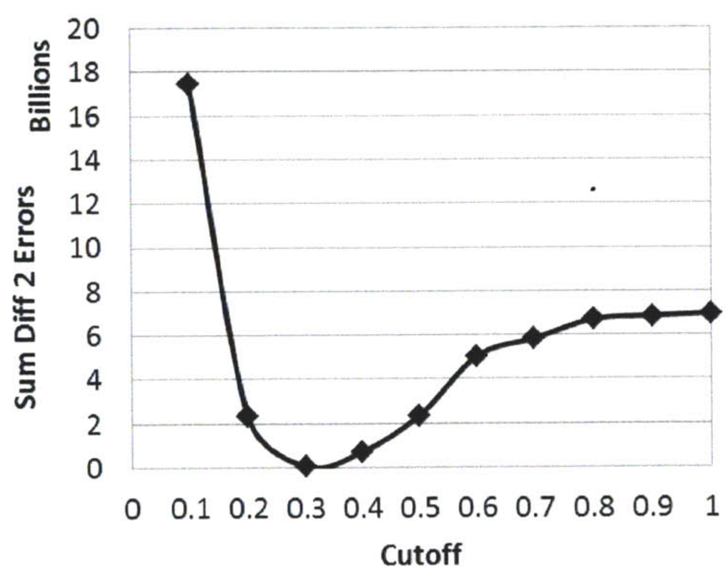


Figure 47: Cutoff that Minimizes The Sum of the Squared Error

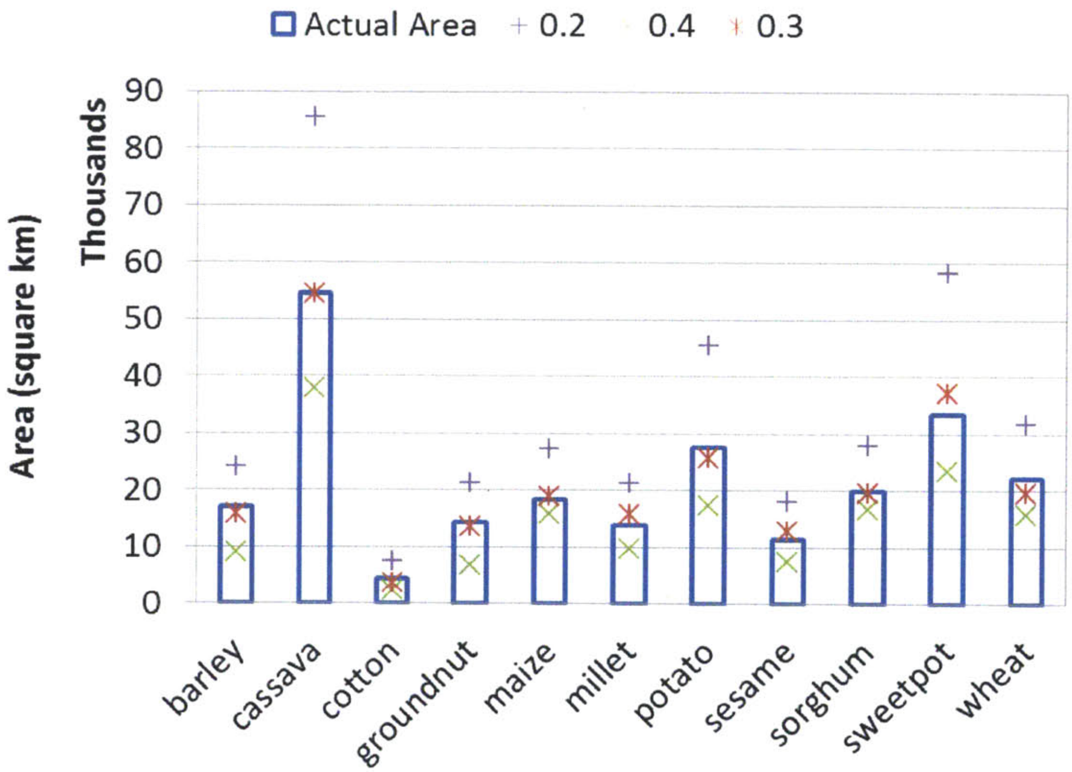


Figure 48: Actual Areas versus Areas with Cutoffs of 0.2, 0.3, 0.4

5.6 Phase 1 Arable Land Results

Figure 49 shows the0 0.25 degree grid boxes that are considered arable after applying the cutoff of 34 percent and compares it to the finer scale areas that are considered arable. Although the difference in areas is minimized, it is evident that small patches that area arable are lost in in the upscaling and other's are gained. Over all, nearly 44,300 sq. km of the basin's land is arable, about 25% of the basin, for at least one of the crops selected considering suitable soil, irrigation slope, and temperature conditions.

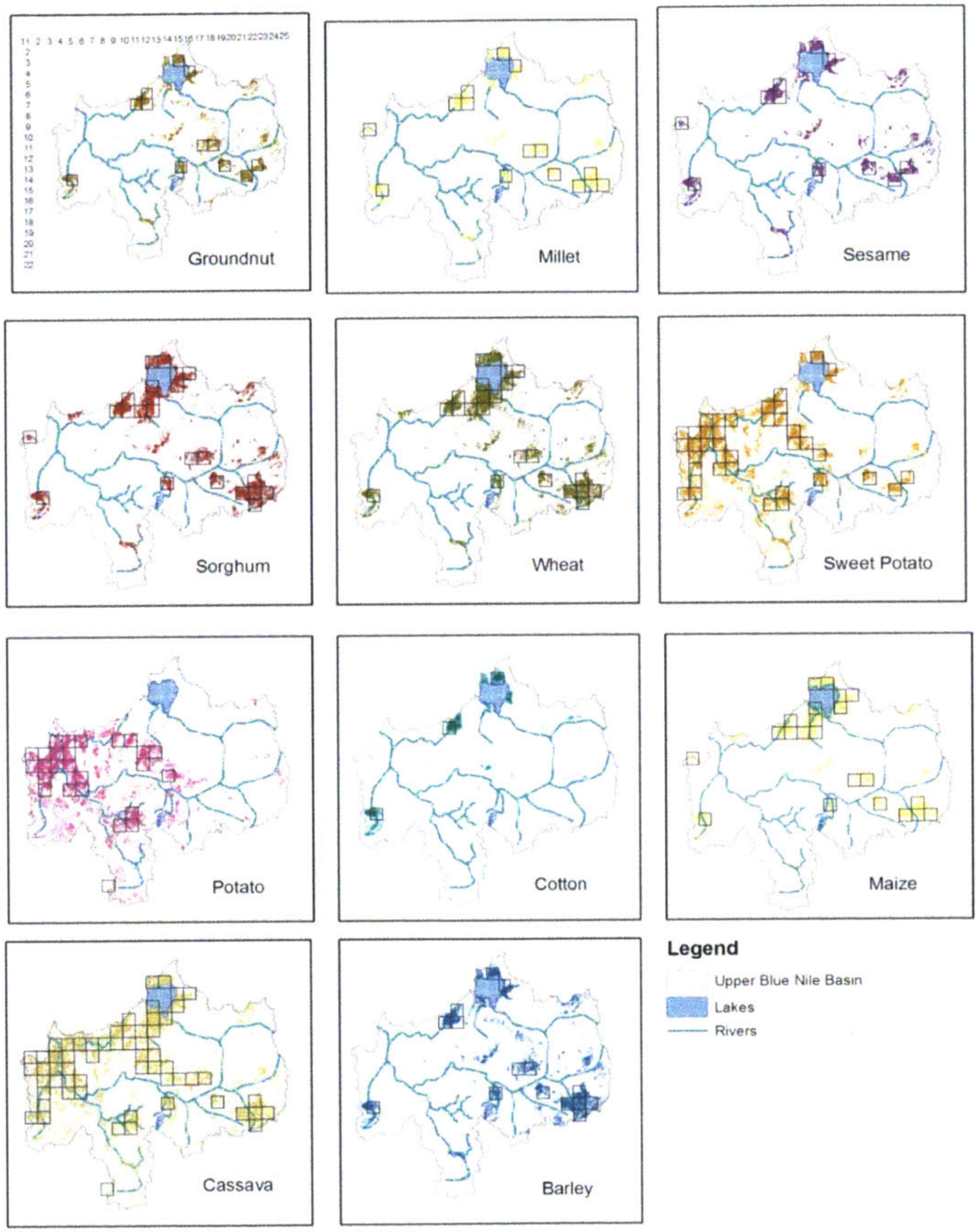


Figure 49: Grid Boxes are Arable for the Crop After applying a 0.34 Cutoff

Notice there are patches that are arable at small scales that are lost with this cutoff and areas that are not arable that are gained. Overall, however, the total area is maintained.

Chapter 6

Phase 2: Data Assimilation of current Hydrology

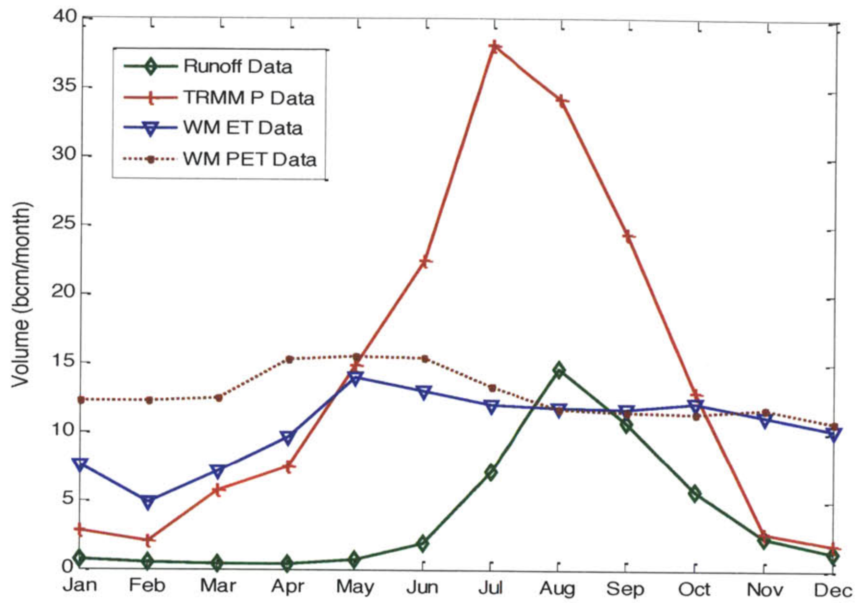
This chapter describes Phase 2 of the analysis and explains a data assimilation process. In this phase we provide measured precipitation, evapotranspiration and runoff, which may contain errors[7] and are inconsistent, and we obtain adjusted precipitation, adjusted actual evapotranspiration, adjusted runoff, and estimates for change in storage which are physically consistent with the water balance principle described in Chapter 4.

6.1 Purpose of the Data Assimilation

As mentioned in Chapter 4, the TRMM precipitation and Willmott Matsuura evapotranspiration data sets are selected because they have the best agreement with the theoretical water balance when compared to NTSG or CRU. At the annual scale the difference between precipitation and evapotranspiration should equal the runoff; TRMM and WM have a 5 percent error

Figure 50). Many environmental models are nonlinear and thus an initial error will propagate and augment nonlinearly. This impinges on the predictability of the model. Minimizing the errors in the inputs is, thus, an essential step. We are modeling the water balance as a linear model and the error margin between TRMM and WM is within an acceptable error margin, thus, the data assimilation for u, has another purpose in addition to reducing the error and ensuring physical consistency. Through a data assimilation process we can obtain reasonable estimates for the change in storage, which is a necessary parameter in the water balance. Furthermore, it allows us to capture the movement of water without having to define water velocities as water moves from one pixel to another.

[7] These errors may be instrument errors, sampling errors, environmental noise or interpolation errors. Error estimation and error modeling are central to the concept of data assimilation (Robinson and Lermusiaux, 2000)



	bcm/yr.
P	169.3
E	125
P-E	44.25
R	46.4

At the annual level, TRMM Precipitation minus WM Evapotranspiration has a 5% error from the Runoff Data.

Figure 50: Plotting TRMM Precipitation, WM Evapotranspiration and Potential Evapotranspiration, and Runoff Data sets.

Data assimilation schemes are meant to combine available knowledge such as dynamical models (i.e. a water balance) and measured observations to derive more accurate estimates of the current or future state of the system along with the uncertainty in the estimated states. Data assimilation can be used to control predictability of forecasting models and also to infer the underlying dynamical processes. Often it is used for parameter estimation to develop forecasts. We use the data assimilation to combine data and dynamics in order to make the different data sets conform to the expected model of nature: a water balance. The goal of the data assimilation is to adjust the inputs in order to correctly capture the water balance and to adjust state variables like storage to correctly capture lags. These are shown graphically in Figure 51.

The data assimilation works by looking at each pixel during each time interval and making adjustments (time-space adjustments) in order to match observed data. We used the weighted mean squared error as the cost function. This penalizes misfits between the model predictions and the measured observations under a set of constraints.

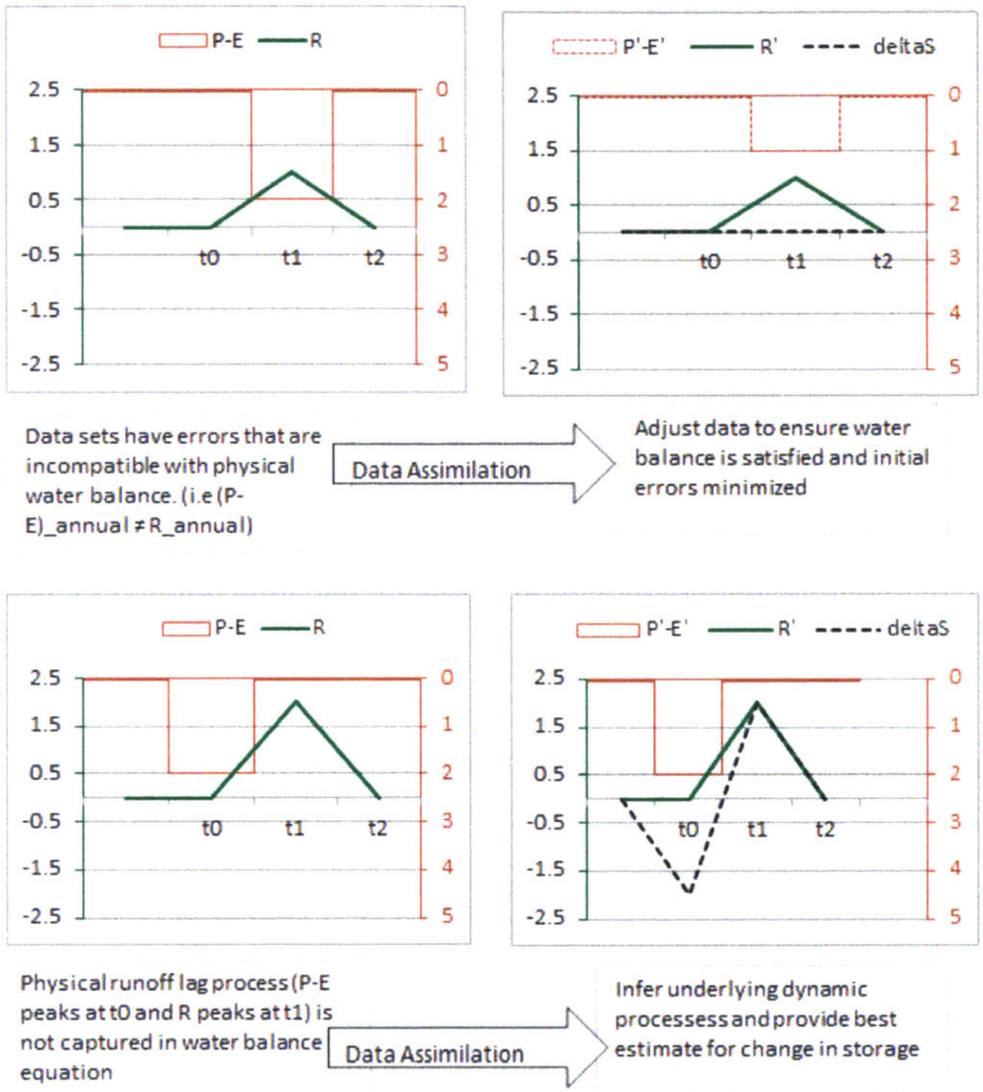


Figure 51: Illustrative Example of Two-Fold Purpose of Data Assimilation: Ensuring Input Data Meets Water Balance and estimated change in storage

The objective of the data assimilation is to minimize the cost function. We made adjustments using the entire time data (past, present and future data), a data smoothing process. If we were to make adjustments using only past and present information, then it would be a filtering process. The data serve as a priori estimates of the modeled values. Two types of constraints are used, "strong" and "weak." Strong constraints cannot be violated and are enforced with Lagrange multipliers as suggested in the literature. Physical principles should be enforced with strong constraints. Weak constraints add penalties to the cost function; these constraints can be infringed but at a cost in the objective. The cost depends on weighing factors and the relative magnitude of the error (Robinson and Lermusiaux, 2000).

6.1.1 A note on optimization

The General Algebraic Modeling System (GAMS) is used to solve the cost function minimization problem. Several methods exist including a line search in the direction of steepest local descent. Descent methods are sensitive to the initial conditions. A rational choice for the weights is also important. The weights act as "regularization" terms that dampen the sensitivity of the solution to errors and ensure that all the units are comparable. The data assimilation problem we formulated is a quadratic program: convex linearly constrained optimization problem with a quadratic objective function. The math behind the program is explained in the next section.

6.2 Mathematical Representation of the Data Assimilation

The algebraic representation of this problem is as follows:

Indices:

n = pixel number[8]

m = months[9]

g = river gauge location

end = pixel where river discharge data is measured

Domain = list of pixels in domain

---

[8] Pixel numbers conform to a grid and are written in a two-part format of "row.column"

[9] Months are listed in water cycle order.

Given Data:

$trib_{n,np}$= list of pixels, np, tributary to pixel n.[10]

$A_{n,}$ = Area for pixel n (m^2) [11]

$P'_{n,m}$= observed TRMM precipitation data in pixel n in month m (mm/month)

$ET'_{n,m}$= observed WM evapotranspiration data in pixel n in month m (mm/month)

$R'_{g,m}$= observed river discharge data at gauge, g, and month m (bcm/month)

$PET'_{n,m}$= observed WM potential evapotranspiration data (mm/month)

W_P =weight for precipitation data

W_{ET} = weight for evapotranspiration data

W_R = weight for runoff data

StoreThreshold= maximum storage level threshold (bcm) representing soil storage

$\Delta Smax$= maximum increase in storage (bcm)

$\Delta Smin$= maximum decrease in storage (bcm)

The weights such as WP, WET, WR, are calculated based on the possible error, x, of the data sets. The discharge data is the most reliable and is expected to ha have a 10% error or less. The TRMM precipitation data set could have a 50% error, and the WM ET data set could have a 90% error. The absolute values for the expected error are not important; it is the relative magnitude of these errors that matters for the solution. The weights are calculated using the following scheme where Xi is the expected percent error for data set i:

Equation 5

$$W_i = \frac{\left(\frac{1}{X_i}\right)^2}{Num\ Observations}$$

[10] A description of how to obtain a tributary pixels list for the UBN study area is provided in Chapter 4. The codes can be found in the Appendix A4 and A5.

[11] Areas were calculated using ArcGIS and albers projection for 0.25x0.25 degree pixels.

StoreThreshold is estimated using the HWSD database information for water holding capacity of the soil in the region. One value was chosen for the whole basin but it should be noted that slight modifications in the code could make this a parameter that is applied at each pixel. The storage threshold was an average of 150 mm/month per pixel or about 0.12 bcm per pixel. The change in storage can represent an infiltration rate and was chosen at +/-0.10 bcm per pixel or about 130 mm/month, this would translate to 4 mm per day.

Calculated Scalars:

$BasinArea = \sum_{n \in Domain} A_n$

$\bar{P}$ =Mean precipitation over the year in the domain

$\overline{ET}$ =Mean evapotranspiration over the year in the domain

$\bar{R}$ =Mean river discharge over the year in the gauge location

Decision Variables:

$\boldsymbol{P}_{n,m}$ = Assimilated (modeled) precipitation in pixel n in month m

$\boldsymbol{ET}_{n,m}$ =Assimilated (modeled) evapotranspiration in pixel n in month m

$\boldsymbol{R}_{m,g}$ =Assimilated (modeled) runoff at gauge location g in month m (bcm/month)

$\boldsymbol{Qout}_{n,m}$ =Outflow from pixel n in month m (bcm/month)

$\boldsymbol{Qin}_{n,m}$ =Inflow to pixel n in month m (bcm/month)

$\boldsymbol{S}_{n,m,}$ =Water storage in pixel n in month m

$\Delta\boldsymbol{S}_{n,m}$ = change in storage in pixel n in month m

Objective Function: Minimize the Regularized Least Squares Error (RLSE):

Equation 6

$$\sum_{n \in Domain} \sum_{m} W_P * (\frac{\varepsilon_{P\,n,m}}{\bar{P}})^2 + \sum_{n \in Domain} \sum_{m} W_{ET} * (\frac{\varepsilon_{ET\,n,m}}{\overline{ET}})^2 + \sum_{m} W_R * (\frac{\varepsilon_{R\,m,g}}{\bar{R}})^2$$

Where the errors for each pixel, n, in the domain and each month, m, are defined as follows:

Equation 7 Precipitation misfit: $\epsilon_{P\,n,m} = \boldsymbol{P}_{n,m} - P'_{n,m}$

Equation 8 Evapotranspiration misfit: $\epsilon_{ET\,n,m} = \boldsymbol{ET}_{n,m} - ET'_{n,m}$

Equation 9 Runoff misfit: $\epsilon_{R\,m,g} = \boldsymbol{R}_{m,g} - R'_{m,g}$

Constraints:

Non-negativity of physical parameters:

Equation 10 $\boldsymbol{P}_{n,m}, \boldsymbol{R}_{m,g}, \boldsymbol{ET}_{n,m}, \boldsymbol{S}_{n,m}, \boldsymbol{Qout}_{n,m}, \boldsymbol{Qin}_{n,m} \geq \boldsymbol{0}$

Monthly Pixel Water Balance for $n \in Domain$

Equation 11 $\boldsymbol{Qout}_{n,m} = \boldsymbol{Qin}_{n,m} + \boldsymbol{P}_{n,m} - \boldsymbol{ET}_{n,m} - \Delta\boldsymbol{S}_{n,m}$

Since a monthly pixel water balance is satisfied, the monthly basin water balance ($\boldsymbol{R}_{m,g} = \sum_n(\boldsymbol{P}_{n,m} - \boldsymbol{ET}_{n,m} - \Delta\boldsymbol{S}_{n,m})$) and the annual basin balances ($\sum \boldsymbol{R}_{m,g} = \sum_m \sum_n(\boldsymbol{P}_{n,m} - \boldsymbol{ET}_{n,m} - \Delta\boldsymbol{S}_{n,m})$) in the domain are also satisfied. (Over the long term the change in storage is negligible, $\sum_m \Delta\boldsymbol{S}_{n,m} = 0$)

Tributary Flow for $n \in Domain$

Equation 12 $\boldsymbol{Qin}_{n,m} = \sum_{trib(n,np)}(\boldsymbol{P}_{np,m} - \boldsymbol{ET}_{np,m} - \Delta\boldsymbol{S}_{np,m})$

This strong constraint characterizes the flow routing as it describes how and how much water moves from pixel to pixel.

Monthly Basin Runoff for $n \in Domain$

Equation 13 $$R_{m,g} = Qout_{end,m}.$$

The outflows, Qout are accumulated flows. This outflow must be compared to the measured river discharge at the location where the river discharge is measured ("end"). The constraint imposes that the outflow at the outlet point should equal the river discharge. This will help capture the current underlying dynamic processes.

Change in Storage for $n \in Domain$

Equation 14 $$\Delta S_{n,m} = S_{n,m++1} - S_{n,m}$$

The "++1" is a feature of the GAMS language, which allows a cyclical lag. Since we are working with a typical year and are interested in the variability within a year, this condition allows the change in storage to cycle back to the beginning of the year. This implies that the storage in month 1 and the storage in the non-existent month 13 are the same. In essence it allows the year to repeat. For hydrological purposes this is a convenient feature since many physical phenomena are cyclical and have seasonality. This yearly cycle, for example, follows the idea of a water year.

First Storage for $n \in Domain$

Equation 15 $$S_{n,'Apr'} = 0$$

This follows the water year and assumes that at the end of the dry season (right before the rainy season) the soil moisture has been depleted by evaporation.

Max Storage for $\boldsymbol{n} \in \boldsymbol{Domain}$

Equation 16 $$S_{n,m} \leq StoreThreshold$$

Equation 17 $$\Delta Smin \leq \Delta S_{n,m} \leq \Delta Smax$$

6.3 Phase 2 Data Assimilation Results

After running the model, we can plot the effect of the data assimilation versus the observed data on a basin wide, monthly level as shown in **Error! Reference source not found.**. These figures show the necessary aggregate changes in order to make the observed data consistent with the physical principles of a water balance. In order to ensure the water balance, the precipitation must be lowered during the rainy season and increased during the dry season as shown in Figure 52.The ET has the opposite adjustment as it is increased during the rainy season and decreased during the dry season.

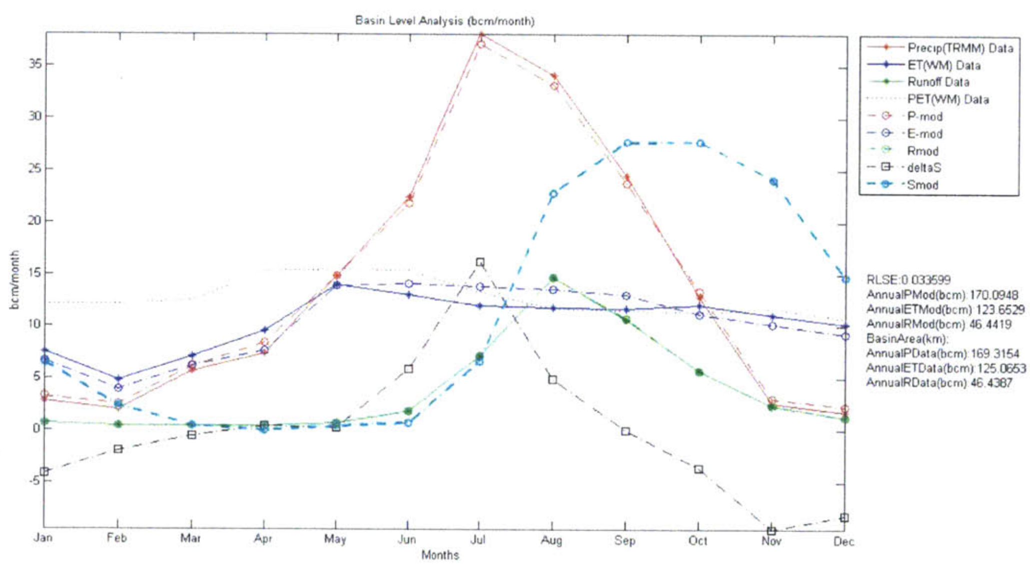


Figure 52: Data Assimilation versus Observed Data on Basin Level, Monthly Timescale (bcm/month)

This data assimilation adjustment causes the ET to be greater than the PET during July-October (Figure 53). The original ET data exceeded PET from Aug-Oct but at a much smaller magnitude. One aspect that is changed is the decrease in ET during the rainy season. Physically, increased cloud cover, higher humidity and lower temperatures can explain a lower ET during the wet months during June, July and August. This physical decrease is much less pronounced in the modeled ET. The percent change between the measured and the data assimilation for precipitation and evapotranspiration is shown in Figure 53. The monthly ET values are changed in a range of 0.2-27.5% with an average of 11.4%. The monthly P values are changed in a range of 0.2-27.5% with an average of 10.5%. The runoff is matched quite well, with differences in a range of 0.02-0.5% and average of 0.2%.

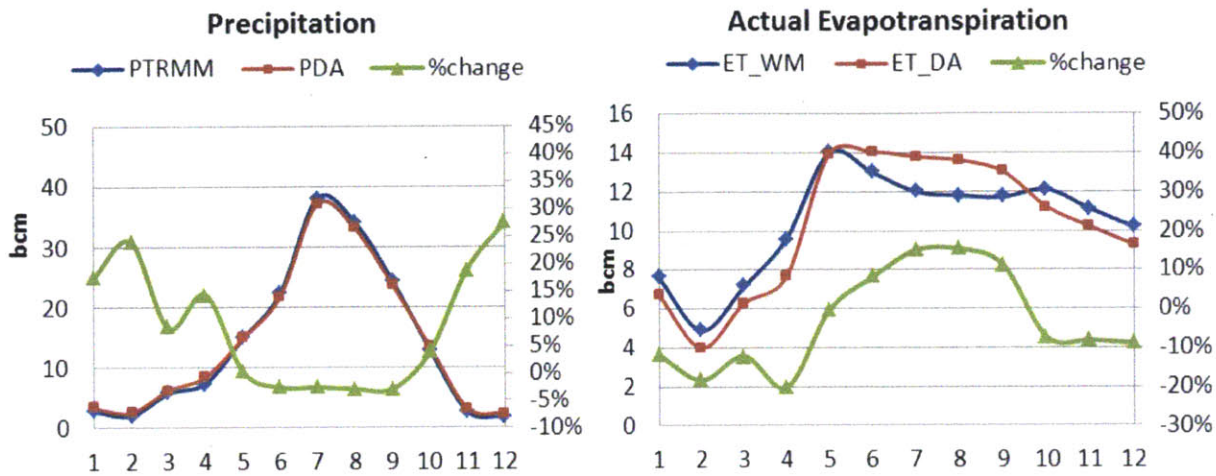


Figure 53: Percent Change in Data Assimilation Adjustments to Precipitation and Evapotranspiration

The results from the data assimilation are the best approximation to what is currently happening, thus they become the baseline for the next phase. The modeled evapotranspiration ($\boldsymbol{ET}_{n,m}$) and modeled precipitation ($\boldsymbol{P}_{n,m}$) from the data assimilation will become input parameters in Phase 3. The modeled soil storage ($\boldsymbol{S}_{n,m,}$), change in soil storage ($\Delta \boldsymbol{S}_{n,m}$) as well as all the flow fluxes ($\boldsymbol{Qout}_{n,m}, \boldsymbol{Qin}_{n,m}$) will be the initial values or first guess for the Phase 3 Land and Water Allocation.

Chapter 7

Phase 3: Land-Water Allocation

In this chapter, we describe Phase 3 of the analysis, where we explain how we estimate Ethiopia's maximum irrigation potential and its hydrologic impact downstream. The problem of maximizing the irrigation water use in the basin can be rephrased as minimizing the outflow from the UBN. By minimizing the flow out of the Upper Blue Nile basin given a set of constraints we bound the impact that expanded irrigation can have downstream. To keep the problem tractable, we reformulate the complex optimization problem as a convex minimization problem. In this stage it is essential to keep the mathematical formulation of the model as a convex[12] problem because in optimization theory, this ensures that any local optimum is also a global optimum. A convex problem can have linear constraints and a linear or quadratic objective.

Figure 54 summarizes the inputs and outputs of the Land-Water Allocation problem. The model is developed in GAMS and takes as input the arable land results from Phase 1, the modified precipitation, evapotranspiration, runoff, storage, change in storage, and flow fluxes from Phase 2. The required potential evapotranspiration data comes from WM. Additionally, the model requires crop data, particularly crop coefficients and lengths of growing periods which come from the FAO as described in Chapter 4.

[12] A convex problem has a convex function over a convex set or feasible region. The objective function is convex if it is twice continuously differentiable and this second derivative (or the Hessian Matrix) is greater than or equal to zero. A convex set occurs when the boundaries of the constraints create a space in which every pair of points can be connected with a line that falls entirely in the space (no interior angle is greater than 180 degrees)

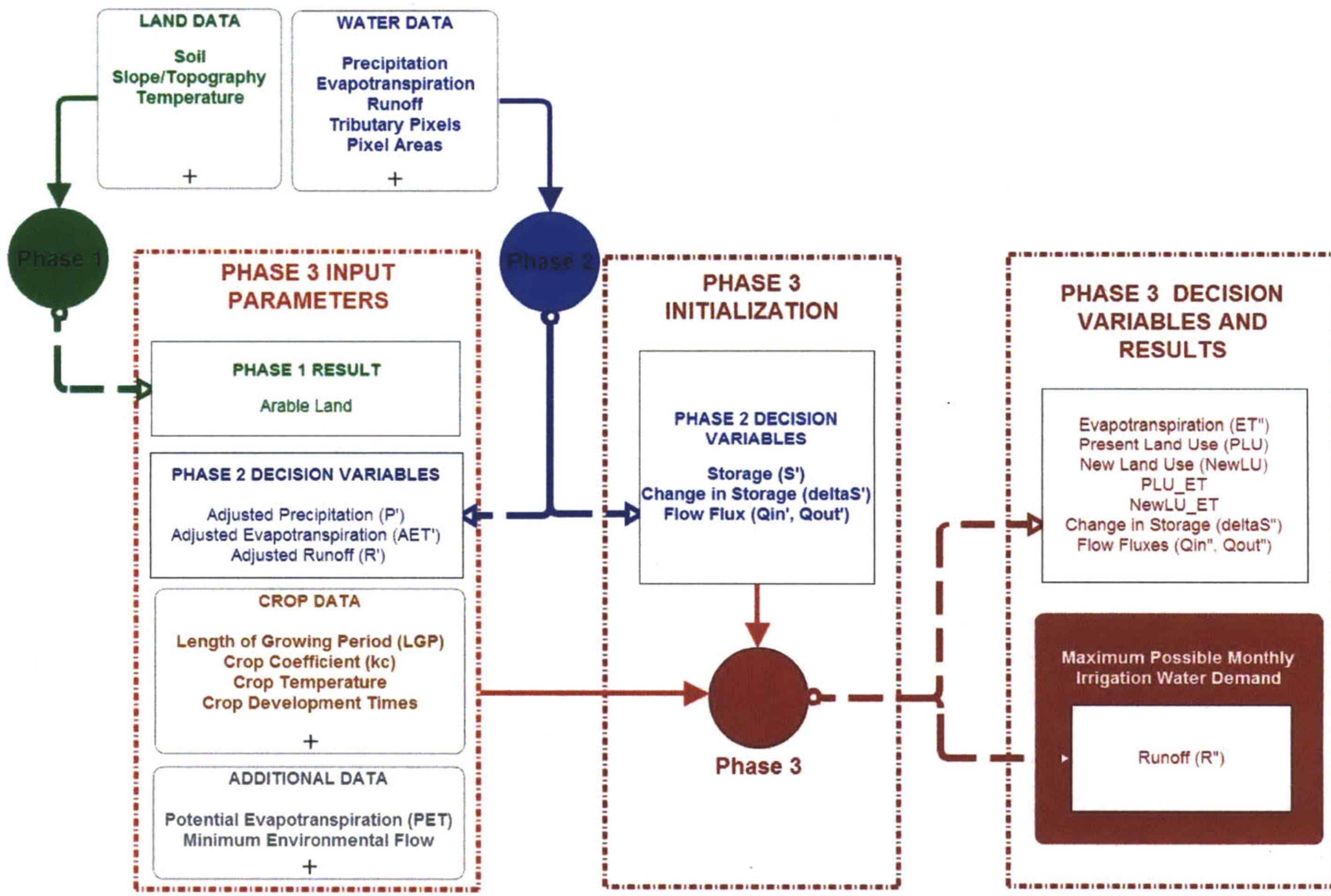


Figure 54: Inputs and Output of Land and Water Allocation (Basin Runoff Minimization) Problem

7.1 Data Inputs

7.1.1 Arable Land (Phase 1) and Data Assimilation (Phase 2) Inputs

The inputs that come from Phase 1 and Phase 2, arable land and data assimilated inputs respectively are described in detail in Chapters 5 and 6. The arable land input is in a binary format (from Phase 1). It is one if the pixel is arable for a specific crop and zero otherwise. It depends only on the pixel number and crop and is entered as a text file.[13] The outputs from the data assimilation are also inputs into Phase 3. All values are entered in units of volume (bcm/month) and are included as gdx files.[14] A graph of the output from the data assimilation program can be found in Appendix A11.

7.1.2 Crop Coefficients and LGP

Crop coefficient (kc), length of growing periods (LGP) and plant growth information is obtained from the FAO (1998) drainage paper 56. The values for the selected crops are summarized in Appendix A9. With the three "kc" points and development times, a monthly "kc" curve was developed (Figure 55) and used as an input for Phase 3. The codes used to create the monthly "kc" curves and the plant month used can be found in the Appendix A10.

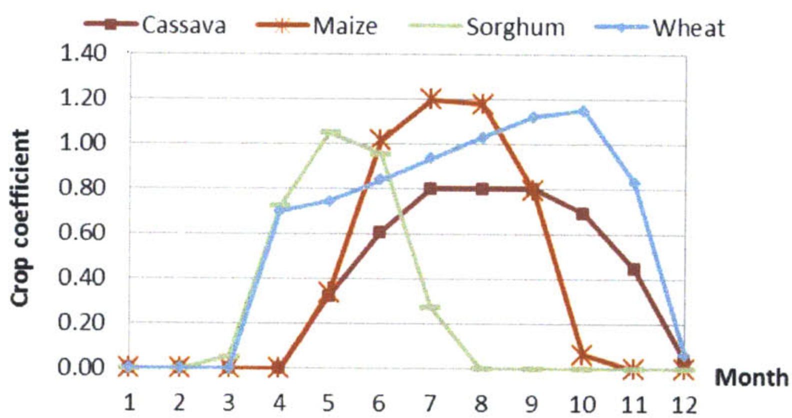


Figure 55: Example of Interpolated Crop Coefficient Curves using FAO kc Data

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[13] ArcGIS shapefiles can be converted to ASCII textfiles in a format readable by the GAMS parameter and $include commands.

[14] The results from the data assimilation can be exported to a gdx file which can be read into the new GAMS program.

The purpose of water storage and irrigation capacity is to help decouple food production from dependence on rain. Stored water can be provided where and when needed, the crop plant dates are not restricted to starting right before the rainy season. To account for this and get an upper bound on the possible irrigation water consumed, we created crops with the crop curve shifted as shown in Figure 56. Wheat01 refers to the wheat crop that can be planted in month 1 and so on. This opens the possibility of planting the crops at any time. The model will determine if there is enough water to plant it and grow it during the growing season. It also enables multi-cropping. If two or more seasons of a crop can be fit in the year, the optimization model may choose to use that combination. In the end, with this model, crops are allocated in arable pixels in the way that minimizes the runoff or, in other words, uses the most water within the basin.

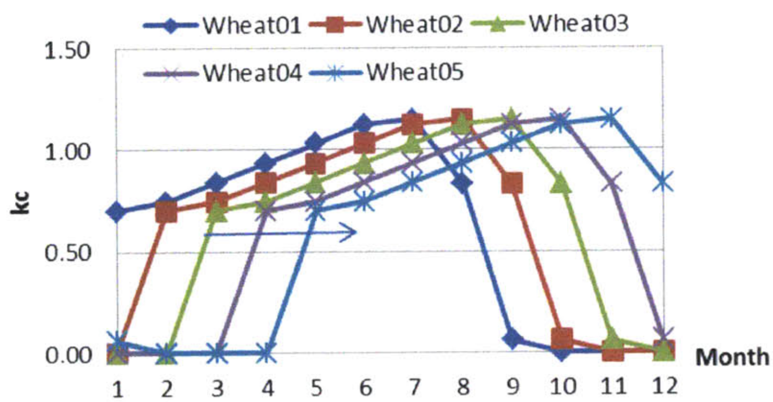

Figure 56: Shifting the Monthly Crop Coefficient Curve to enable Multi-Cropping

7.1.3 Minimum Environmental Flow

A minimum environmental flow is imposed to ensure that the stream-flow is not stored completely within the basin, and is not allowed to run dry in some months. An assessment of environmental flows necessary downstream of "El Diem" has not been published in the literature. However, such an analysis was performed for the reach downstream of Lake Tana. McCartney et al., (2009) use a more ecological-based approach to determine environmental flow downstream of the Chara Chara weir, located at the mouth of Lake Tana, on the main stem of the Upper Blue Nile (Abbay) River. McCartney et al. state that reduced inter-seasonal variability (the goal of storage) can adversely impact the ecology as it impacts species that are adapted to the seasonal cycle. The maintenance flow they suggest accounts for this. We use the ratio of maintenance flow to observed runoff from the Chara Chara weir and McCartney et al, paper and translate it to "El Diem" to serve as a rough approximation for environmental flows. Using this ratio method ensures that there is a slight seasonal cycle. It results in an annual minimum flow requirement of 9.42 bcm.

Table 12: Minimum Environmental Flow (bcm/month)

	Source: McCartney et al. (2009)				
	Mean observed Runoff @ Chara Chara Weir 1960-1995	Maintenance Flow	Ratio	Runoff @ "El Diem" Data Assimilation 1965-2009	MinFlow
	bcm	bcm	bcm	bcm	bcm
Jan	0.217	0.068	0.31	0.73	0.23
Feb	0.135	0.056	0.41	0.46	0.19
Mar	0.097	0.042	0.43	0.42	0.18
Apr	0.058	0.028	0.48	0.42	0.20
May	0.042	0.022	0.52	0.68	0.35
Jun	0.044	0.021	0.48	1.87	0.90
Jul	0.18	0.039	0.22	7.14	1.57
Aug	0.59	0.083	0.14	14.67	2.05
Sep	0.946	0.192	0.2	10.70	2.14
Oct	0.839	0.117	0.14	5.76	0.81
Nov	0.526	0.109	0.21	2.36	0.50
Dec	0.345	0.086	0.25	1.24	0.31
ANNUAL	**4.02**	**0.86**	-	**46.44**	**9.42**

7.2 Mathematical Representation of the Land-Water Allocation

7.2.1 Water Constraints

The model can be viewed as having an objective and two sections of constraints; a section dealing with water constraint and another section dealing with land constraints. These two sections are connected through the evapotranspiration. The water constraints are similar to those in Phase 2 described in Chapter 6, including Equation 11 and Equation 12, however there are a few changes: 1) The Land Water Allocation problem is expressed in terms of change in storage ($\Delta S_{n,m}$) and not absolute storage. In Phase 2, storage referred to the soil water holding capacity but in this phase storage implies the ability to store water in ponds, dams, or other storage units and release it when needed. It is unbounded to ensure that the only constraints on irrigation potential are physical constraints. The cyclical constraint is replaced with a "Change in Storage" (Equation 18) constraint that ensures that the sum of the change in storage across the months is negligible (zero). 2) Since we are not trying to approximate the current hydrology, but instead analyzing the effects of new land use, the monthly basin runoff does not have to equal the measured runoff; instead it must be greater than a minimum environmental flow (Equation 19). For n in the domain, the water constraint equations can be written as follows:

(Equation 11) Monthly Pixel Water Balance:

$$\boldsymbol{Qout}_{n,m} = \boldsymbol{Qin}_{n,m} + P_{n,m} - \boldsymbol{ET}_{n,m} - \Delta \boldsymbol{S}_{n,m}$$

(Equation 12) Tributary Flow:

$$\boldsymbol{Qin}_{n,m} = \sum_{trib(n,np)} (P_{np,m} - \boldsymbol{ET}_{np,m} - \Delta \boldsymbol{S}_{np,m})$$

Equation 18 Change in Storage: $\sum_m \Delta \boldsymbol{S}_{n,m} = \boldsymbol{0}$

Equation 19 Min. Environmental Flow: $\boldsymbol{Qout}_{end,m\cdot} \geq \boldsymbol{MinFlow}_{m,g}$

7.2.2 Land Constraints

The New Land Use Fraction (NewLU_Frac) and the Present Land Use Fraction, (PLU_Frac), must sum to one. Land can only be devoted to the current land use or the new land use which consists of a combination of the selected list of crops.

Fraction of Land, Total for $n \in Domain$

Equation 20 $\sum_{crops} \boldsymbol{NewLU\_Frac}_{n,crop,m} + \boldsymbol{PLU\_Frac}_{n,m} = \boldsymbol{1}$

PLU refers to the present or existing land conditions. The existing land conditions may have crops but they represent what is currently in place and becomes the baseline. The program will change the land use from present conditions to a crop in the list if this change will ultimately allow for a more water consumptive basin. This means a particular pixel may actually become less water consumptive to allow water to flow downstream where it will be available for a more water consumptive crop. Ultimately, the basin runoff (not the pixel runoff) must be minimized. Fractions are used instead of absolute areas in order to maintain the constraints at values near 1. Optimization in GAMS works better and computes more easily if the constraints are properly scaled to values near 1.

Fraction of Land, Arable for $n \in Domain$

Equation 21 $\boldsymbol{NewLU\_Frac_{n,crop,m} \leq ArableLand_{n,crop}}$ if kc_crop, m >0

Fraction of Land, Arable2 for $n \in Domain$

Equation 22 $\boldsymbol{NewLU\_Frac_{n,crop,m} = 0}$ if kc_crop, m = 0

The kc represents the growing period. If kc is greater than zero, the crop is demanding water and the month is part of the growing season of the crop. During a crops growing season, the land devoted to the crop can be any fraction up to a full pixel. The program could devote the entire pixel to a crop, but it can also choose to devote only a fraction (Equation 21). Each pixel can have several crops in it as long as the pixel is arable for those crops. The kc will be equal to zero if the crop is not in its growing season and it will demand no water. Therefore, outside of the crop growing period, no land must be devoted that crop (Equation 22).

Fraction of Land in Time for $n \in Domain$

Equation 23 $\boldsymbol{NewLU_{n,crop,m++1} = NewLU_{n,crop,m}}$

if kc_crop, m>0 and not endMonthLGP_crop,m

In determining the fraction of land that is devoted to the crops in the list, this fraction must remain unchanged during the length of the growing period. This ensures that if an area is chosen to be cropland it is seen through from plant date to harvest without changing the crop in the middle of the season. It prevents the optimization program from gaining an unrealistic advantage by switching crops when a crop demands less water or from changing the size of the plot devoted to cropland.

7.2.3 Evapotranspiration: Connecting Land and Water Constraints

A few more constraints are needed to connect the water and land constraints together. This is achieved through the evapotranspiration since physically this connects the water and soil moisture in the water balance to the land devoted to a specific crop.

Evaporation volume for $n \in Domain$

Equation 24 $$ET_{n,m} = NewLU\_ET_{n,m} + PLU\_ET_{n,m}$$

Where

Equation 25 $$PLU\_ET_{n,m} = AET_{n,m} * PLU\_Frac_{n,m} * A_n * conv$$

Equation 26 $$NewLU\_ET_{n,m} = \sum_{crop} kc_{crop,m} * PET_{n,m} * NewLU\_Frac_{n,m} * A_n * conv$$

The PLU_ET represents the evapotranspiration from the baseline or present conditions. The best estimate we have for the evapotranspiration from existing conditions is the adjusted ET from the data assimilation (Phase 2). This adjusted ET is referred to as the AET in Equation 25 in units of depth. The NewLU_ET is calculated using the method outlined by the FAO and described in Chapter 4 in which a crop coefficient, "kc" is multiplied by the potential evapotranspiration (PET). The PET comes directly from WM with no data assimilation adjustments and is expressed in units of depth.

7.2.4 Objective Function

A short discussion of the choice of objective is valuable in understanding the formulation. A convex objective can be attained through a linear or quadratic function. In developing the model, we learned that the choice of the objective is actually significant. Initially, we formulated the problem as a linear program where the objective was to minimize the basin runoff (min $\sum_{end,m} Qout_{n,m}$). This objective, however, is not linearly independent as it can be obtained from a linear combination of the constraints. Running the model with this objective showed that although the annual basin runoff value itself remained the same (42.7 bcm/year), there were an infinite land allocations and resulting hydrographs that could achieve the minimum basin runoff. In other words, the solution with a linear objective is not unique. This means the resulting hydrograph becomes quite sensitive to the initialization as shown in Figure 57 and is unrealistic as it stores all the water and releases the majority in one month.

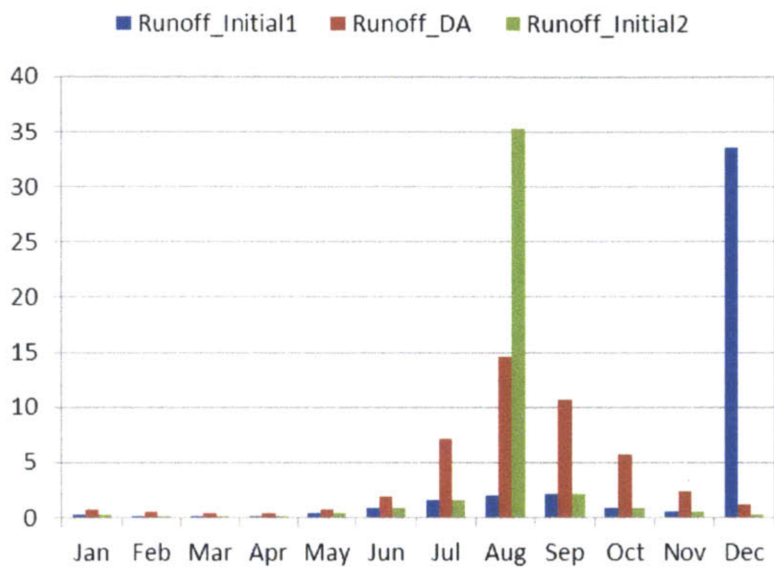

Figure 57: Resulting Hydrograph for Land Water Allocation Problem Using Linear Objective and Different Initializations

This figure shows that a linear objective that is parallel to the constraints has a non-unique solution.

We considered two ways to make the problem linearly independent and ensure uniqueness. First, we could multiply each monthly outflow, Qout, by a parameter alpha, α_m, however, this would require calibration and criteria for the choice of alphas. We opted for the second method: add a quadratic term to the objective that acts as a weak constraint and tries to keep the runoff similar to the current hydrograph.[15] The objective is expressed mathematically in Equation 27and Equation 28.

[15] Changing the objective to a quadratic function instead of a linear function to ensure uniqueness is consistent with optimization theory since the second derivative (Hessian Matrix) of a least-squares is strictly positive definite, if there are at least as many unknowns as measurements, while the second derivative of a linear function is exactly equal to zero and therefore can be both concave or convex.

Objective Function: Minimize the basin runoff and maintain the shape of the current hydrograph:

Equation 27 $$\sum_m \boldsymbol{Qout_{end,m}} + \boldsymbol{W_R} * \sum_m \left(\frac{\varepsilon_{H\ end,m}}{\bar{R}}\right)^2$$

Equation 28 $$\epsilon_{H\ end,m} = \boldsymbol{Qout_{end,m}} - \boldsymbol{Runoff_{DA_{g,m}}}$$

This is a reasonable weak constraint since it implies that the land use changes that lead to a more consumptive water basin will be gradual changes. The annual basin runoff is still the same (42.7 bcm/year) but the hydrograph is more physically realistic. Furthermore, the hydrograph is not sensitive to the weight, WR or to the initialization. The solution is unique. The disadvantage of making the objective quadratic instead of linear is that it increases the computation time required to solve the problem by sixteen times from a magnitude of about 25 minutes to over 4 hours.

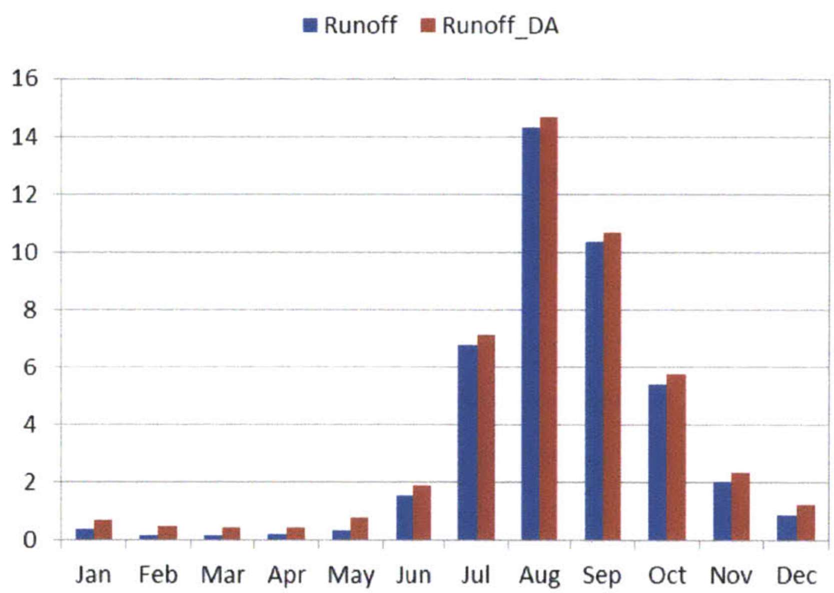

Figure 58: Resulting Hydrograph of Land Water Allocation Problem using a Quadratic Objective

This quadratic objective tries to maintain a realistic hydrograph

Chapter 8

Conclusion

With the model in place, it is now possible to run the program and estimate the maximum irrigation water that Ethiopia could reasonably use. The problem has been formulated to ensure that any optimum is the global optimum. The model provides a single optimal solution. The results and policy implications are presented in this section.

8.1 Results

The Upper Blue Nile basin in Ethiopia faces physical land and water limitations that constrain the irrigation potential. Approximately 44,296 sq. km or 25 percent of the basin's land is arable for at least one of the crops selected considering suitable soil, irrigation slope, and temperature conditions. Our result is 20% higher than the Ethiopian Ministry of Water Resources (MoWR) estimate of 37,000 sq. km irrigable land in all of Ethiopia but it is unclear how MoWR calculated its estimate. The most limiting factor in our calculation is the irrigation slope.

When water constraints are also considered, the annual average, of the new land use cropped area decreases to 18,790 sq. km or 11 percent of the basin(

Figure 59). As mentioned in Chapter 2, the MoWR has plans to expand irrigation in Ethiopia by about 2,750 sq. km by 2016. This would be 15 percent of the estimated irrigable area.

The results of the "Land Water Allocation" model also show how much area is devoted to the new crop land use in each month. On a monthly scale, the results from our model suggest that the new cropped land area ranges from 1,620 sq. km in August to 31,790 sq. km in February and March. Wheat planted in November and potatoes planted in December make up the biggest cropped fraction area. Wheat and potato both have a wide operative temperature range (5-30 degrees Celsius as shown in Table 11) which contains the mean maximum and mean minimum temperatures of the basin, so these crops could be suitably planted in these months[16];

[16] Several studies in the literature focus on identifying the genotypes that will provide the best yield for crops grown in the dry season under irrigation. For example Mohammed, J., 1994. "Performance of Wheat Genotypes under Irrgation in Awash Valley, Ethiopia." African Crop Science Journal. http://www.bioline.org.br/request?cs94022

nonetheless, the way temperature is included in the analysis should be refined in future works. Other crops that are planted are maize, cassava, cotton, sweet potato and sesame.

The present land use may include crops too but a change from present conditions to a crop on our list implies a more consumptive water basin than the present one at the annual scale. A comparison of the spatial distribution of the solutions' cropped land use in July and February as estimated by the model can be found in the Appendix A12.

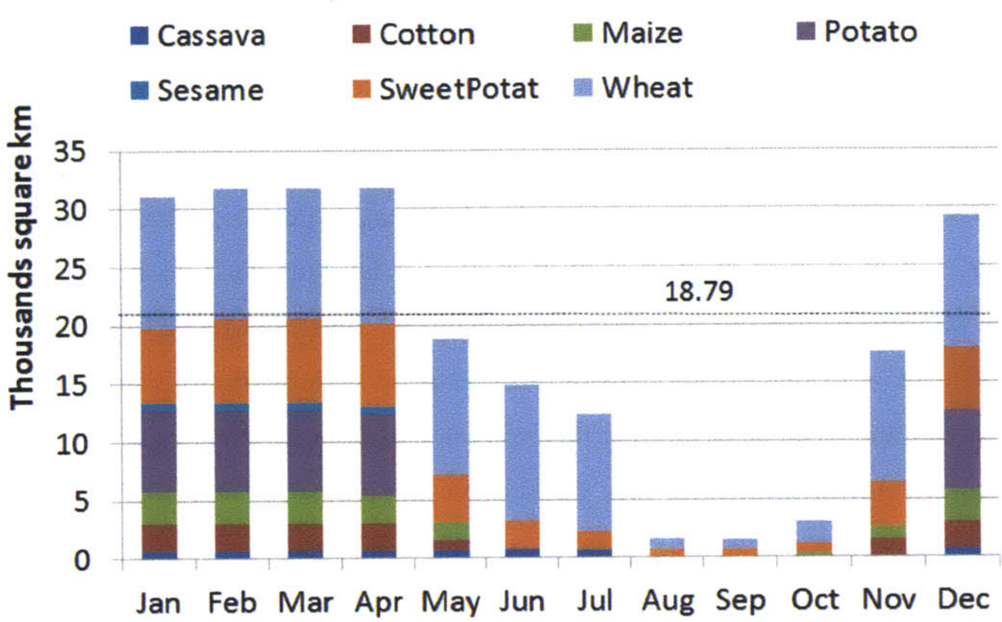

Figure 59: Resulting Basin Wide Land Use that Consumes 3.75 bcm more water than Present Land Use and Keeps Hydrograph Similar to Current hydrograph

Most of the crops are planted and grown in the dry months in order to use the most irrigation water. Notice that not all the possible arable land in our model is cropped. This occurs because there is no gain in water use. Whether to change from present land use to a new land use is dictated by the evapotranspiration for the relative land uses, which in turn depend on the AET and PET respectively. An arable pixel will use more water than the present land use if the crop coefficient curve is above the AET/PET curve (Figure 60).

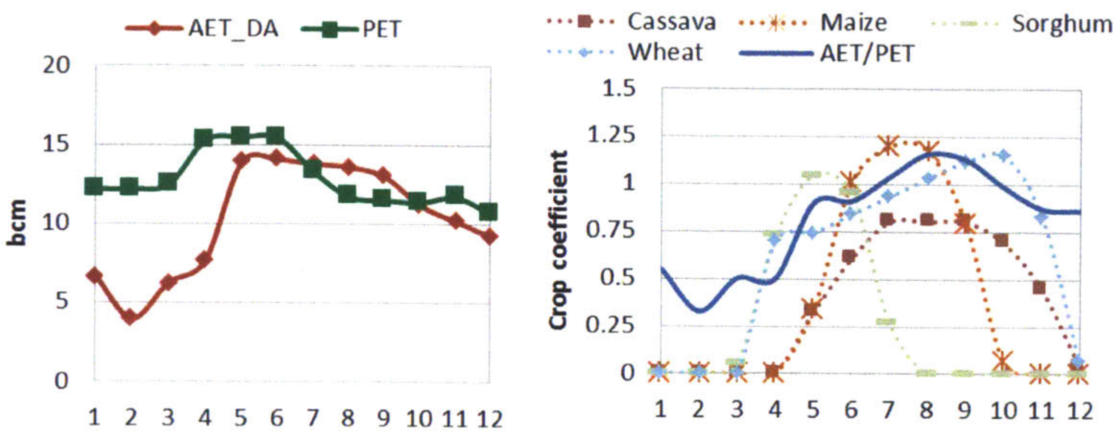

Figure 60: AET vs. PET and Crop Coefficients vs. AET/PET curve.

AET and PET drive the Evapotranspiration. A pixel is more water consumptive if the crop coefficient is above the AET/ PET curve.

There is no reason to irrigate during the rainy season (July to September), so reasonably, most of the pixels are cropped in the dry season. The few pixels that are cropped during the rainy season are primarily meant to reduce water use in those months to facilitate use in a dry month with a more water consumptive crop. The cropped area does not reach the full arable land which suggests that changing land use to a crop on the list might result in less water than present conditions or that there is not enough water to see the crops from plant date to harvest date.

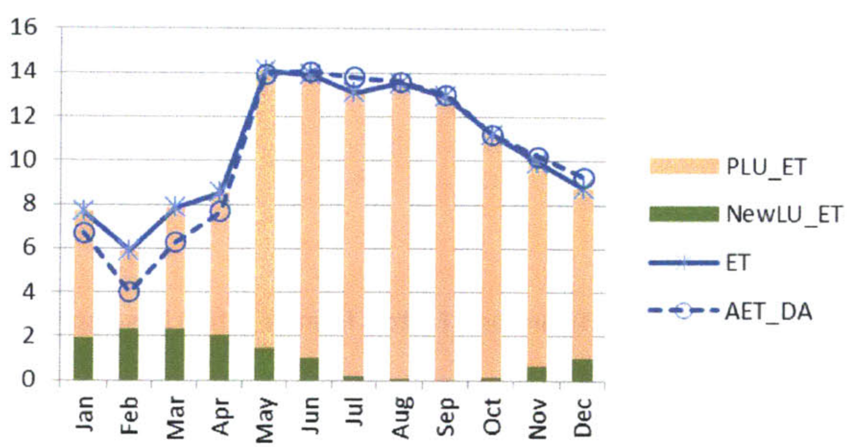

Figure 61: Evapotranspiration corresponding to New and Present Land Use

Figure 62 compares the model results with potential irrigation to the current hydrology from the data assimilation. The total annual discharge for the model runs is 42.70 bcm compared to the existing discharge of 46.4 bcm/ year. This means, in a typical year, 3.75 bcm of water can be used for irrigation purposes while keeping the hydrograph with the same seasonality. This estimate for irrigation water is lower than the 6 bcm estimate by Javonvic (2009) and presented in Figure 17. Ethiopia does not need to divert substantial quantities of water to obtain agricultural benefits. As discussed in Chapter 2 currently, Ethiopia as a whole withdraws 5 bcm of water for irrigation. By changing the land use in the UBN and implementing storage capacity, the results suggest that Ethiopia could increase agricultural water withdrawal to 8.75 representing nearly a 70% increase. The largest irrigation water use occurs between January and May with a 1.89 bcm of the 3.75 used in February.

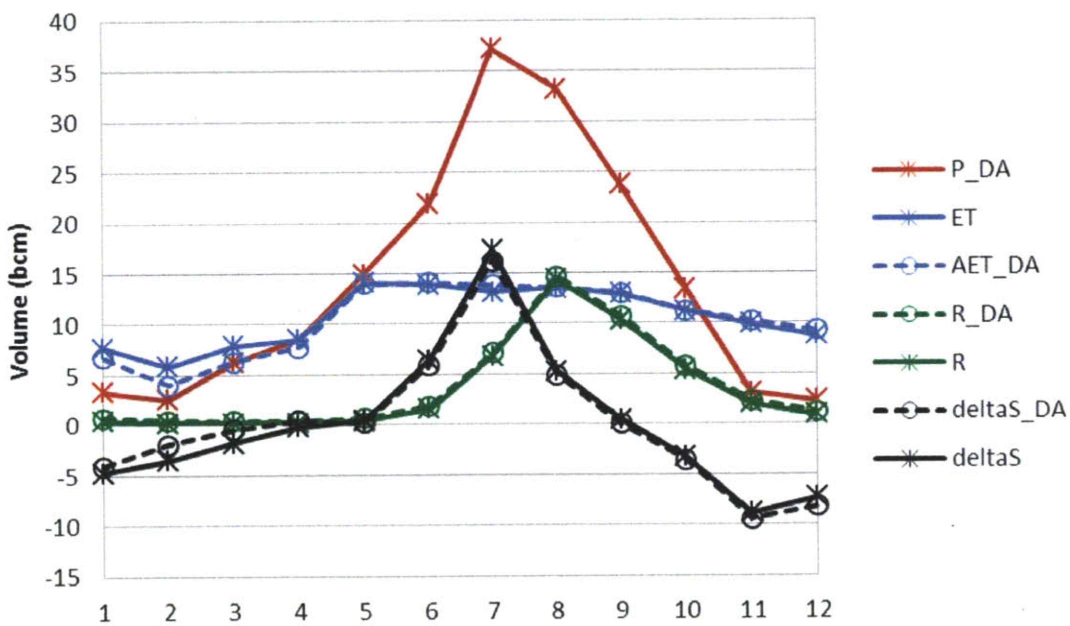

Figure 62: Resulting Hydrologic Factors from Irrigation Development

8.2 Policy Implications Downstream

In terms of policy planning for Ethiopia, the tradeoff is that the lowlands are less populated since it is much hotter, however, the highlands are not suitable for irrigation due to the steep slopes. Careful planning of irrigation schemes, particularly around Lake Tana, could help balance these two.

The effect of this irrigation development in the upper Blue Nile would be an 8% reduction in annual flow at El Diem. The results show that the shape of the current hydrograph can be maintained and the largest reductions in flow would occur in the dry months with up to a 60% reduction, and less than 10% reduction in the wet months. But what does 3.75 bcm/year of possible irrigation water for Ethiopia mean to Egypt? Ethiopia's irrigation potential is similar in magnitude to the amount of water that Egypt hoped to gain from the Jonglei Canal Project. The primary objective of the canal was to increase Nile water yield by 4.7 bcm to be divided equally between Sudan and Egypt (Waterbury and Whittington, 1998).

Currently Egypt is planning to pump 5-10 bcm of water per year from the HAD to the New Valley Project which, when completed, may have an additional 3,000-5,000 sq. km of irrigated land (Waterbury and Whittington, 1998). What is evident is that the nations have not foregone the nationalistic self-interest and despite negotiations and talks, they have not adopted a regional perspective. Ana Cascao (2009) describes how changing power dynamics and access to outside funding has led to an increase in unilateral projects. Each country is rushing to make claims on water revealing that they have not committed to a regional effort. In fact, the countries in the Nile region seem to be trying to derive benefits from both unilateral and multilateral strategies without acknowledging that these may clash.

Each country is establishing water claims but is not realizing that the supply is insufficient. Ethiopia has plans to double irrigated land, Egypt has plans to develop the New Valley (0.5M acres) and Sudan is planning the Rahad and Kenana Projects (1.7M acres). Mr. Ayalew Negussie, project coordinator of the Irrigation and Drainage project of the NBIC makes it clear that unilateral projects such as these are colliding with basin wide approaches and the NBI vision. "The three countries have unilaterally planned ambitious irrigation expansion. If you add all the water requirements of the planned irrigation expansion of the three countries together, it emerges that the total demand is beyond the capacity of the Eastern Nile to provide." (NBI, 2011)

The 3.75 bcm of water that Ethiopia could withdraw for irrigation, is only 7 percent of the 59 bcm of water that Egypt currently withdraws for irrigation. Although in an arid country "every drop counts," Egypt's fear is likely not the absolute amount of water that Ethiopia could use but more likely the impact that consenting to the development might have. From an Egyptian perspective, agreeing to a cooperative framework and renegotiating water allocation may open a "Pandora's box" that would be followed by irrigation development in other countries with much higher irrigation potential such as Sudan. Nevertheless, as the downstream country, Egypt should have an inherent desire to participate in cooperative frameworks in order to have a voice in the implementation of projects; otherwise it will foreclose its future options and may have to use hard power. Sudan and Ethiopia are among the poorest states in the world. Egypt is surrounded by extreme poverty which decreases national security. As the whole region lifts out of poverty and has improved health, it would open new markets for Egypt and increase their security. These are the benefits that Egypt will receive. Simply because the benefits are in different realms or of different "amounts" does not mean the process is inequitable. Ultimately trust develops as the links between the nations strengthen; the "benefits beyond the river" as described by Grey and Sadoff (2002) must be expanded.

8.3 Future Work

The development of the model has set a foundation to ask more complex questions. The thesis necessarily focused on the natural and physical constraints on irrigation. It would be useful to expand and include other factors such as human, social and economic constraints. Integrating crop yield information, in the model, to ensure not only more water use but also yields above rainfed agriculture would be useful in developing policies for better food security. The model was run for a typical year but it can be used to analyze a much longer time series with inter year variability focusing perhaps on low flow and drought years. This could also be useful to understand how climate change might affect the results. If a wider domain is modeled to include the Nile basin in Sudan and Egypt, it may be possible to overlay facilities and projects and see the benefits to the region and to the individual countries.

In developing the model, several simplifying assumptions were made that can now be refined including the treatment of temperature, the use of crop specific cutoffs to solve the combinatorial problem and the choice of resolution. The temperature in the analysis was included as part of the arable land calculation but it will be more useful if it can be incorporated directly in the model in order to check whether a crop can actually grow in any growing season. To simplify, it is assumed that temperature is not limiting. Currently the way we regard temperature has two effects: 1) spatially it limits some land which might be available for crops in other months, this could result in an underestimate to the water use but 2) temporally we assume all growing seasons are possible in the arable pixels which might result in an overestimate of water use. The two effects offset each other but the ultimate effect could be an overestimate or an underestimate. Improving the temperature treatment would require removing the temperature from the arable land, recalculating the new arable land, including pixel based temperature data and adding a section of temperature constraints to the model.

Currently the cutoff calculation, which resolves the combinatorial problem explained in Chapter 5, is performed outside of the GAMS model but it would be quite valuable to incorporate it into the model. This would make the model more flexible when making any changes that might affect arable land. The cutoffs could also be crop-specific.

The thesis was primarily concerned with water use from expanding irrigation potential, but to understand how much water Ethiopia could use by simply expanding agriculture, it would be interesting to include rainfed agriculture to this analysis.

The choice of resolution was 0.25 degrees in order to connect different data sets and keep the problem computationally tractable as we developed the model. Now that the framework is in place, it may be possible to use a finer resolution. This may require more time to solve, but may have physical features that are more reasonable (currently channels are 25 km wide pixels).

Ultimately, the model should be used to understand how Ethiopia, Sudan and Egypt can manage hydrologic variability and to decrease economic vulnerability. All countries share this goal and in planning policies or development projects they should remember that water is not an end in itself, but a means towards agricultural production, poverty reduction, economic robustness, energy, and food security.

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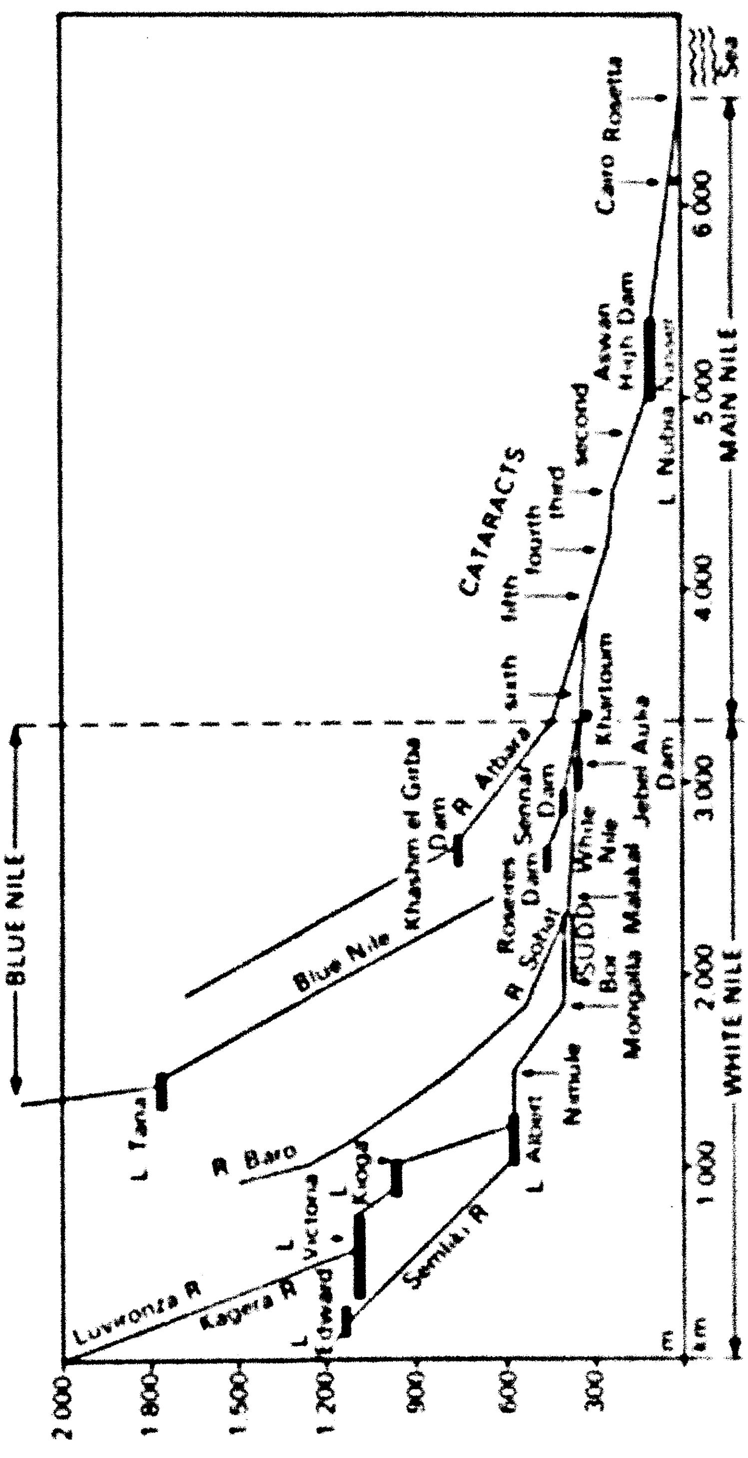
Appendix

A1. Profile of Nile River



A2. Africa Albers Equal Area Conic Projection Specifications

Projection

Africa Albers Equal Area Conic Projection: Albers
False Easting: 0.000000
False Northing: 0.000000
Central Meridian: 34.000000
Standard Parallel 1: 28.000000
Standard Parallel 2: 8.000000
Latitude Of Origin: 0.000000
Linear Unit: Meter
Geographic Coordinate System WGS 1984
Datum: D WGS 1984

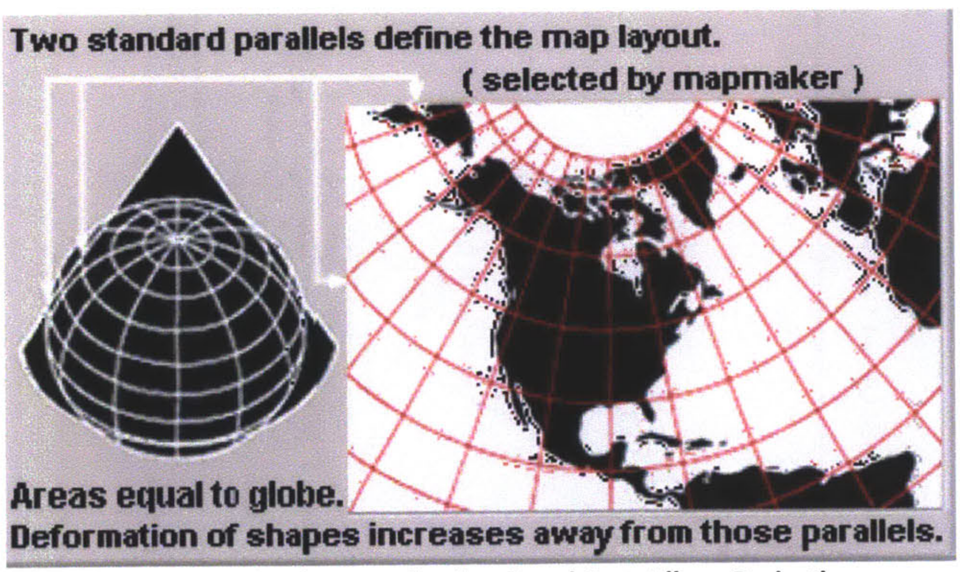


Figure A 1: Simple Example of an Equal Area Albers Projection

A3. S2 Soil Suitability Land Quality Criteria

CropName	T_CACO3	DRAINAGE		T_CASO4	T_CEC_CLAY	T_BS	T_CEC_SOIL	T_PH_H2O		T_OC	T_ECE	T_ESP
Potatoes	< 15	> 1	< 7	NoData	> 0	< 100	> 2	> 5.2	< 8.0	> 0.8	< 5	< 35
Maize	< 25	> 1	< 7	< 10	> 0	> 35	> 3.5	> 5.5	< 8.2	> 0.5	< 6	< 20
Wheat	< 40	> 1	< 7	< 10	> 0	> 35	> 3.5	> 5.6	< 8.3	> 0.5	< 5	< 35
Sorghum	< 45	> 1	< 7	< 10	> 0	> 15	> 2	> 5.3	< 8.3	> 0	< 12	< 28
Tomatoes	< 10	> 1	< 7	< 3	> 0	> 20	> 2	> 5.5	< 8.0	> 0.8	< 8	< 25
Millet	< 35	> 1	< 7	< 10	> 0	> 15	> 2	> 5.4	< 8.0	> 0	< 6	< 35
Barley	< 40	> 1	< 7	< 10	> 0	> 35	> 3.5	> 5.8	< 8.2	> 0.4	< 16	< 35
Arabica Coffee	< 2	> 1	< 7	< 2	> 0	> 35	> 2.8	> 5.4	< 7.4	> 0.8	< 0.5	< 100
Banana	< 10	> 1	< 7	< 4	> 0	> 20	> 2.8	> 5.2	< 8.0	> 0.8	< 4	< 8
Cassava	< 5	NoData	< 7	< 1	> 0	> 0	> 0	> 4.8	< 7.6	> 0	< 3	< 100
Cotton	<30	> 1	< 7	< 10	> 0	> 35	> 2.8	> 5.6	< 8.0	> 0.8	< 12	< 30
Groundnuts	< 35	> 1	< 7	< 10	> 0	> 0	> 1.6	> 5.6	< 8.0	> 0.8	< 6	< 15
Sugar Cane	< 30	> 1	< 7	< 12	> 0	> 35	> 3.5	> 5.0	< 8.0	> 0.6	< 8	< 15
Beans	< 20	> 1	< 7	< 1	> 0	> 20	> 2	> 5.4	< 8.0	> 0.8	< 1.5	< 8
Mango	< 10	NoData	< 7	< 3	> 0	> 20	> 1.6	> 5.0	< 8.0	> 0.8	< 6	< 20
Sweet Potato	< 25	> 1	< 7	< 10	> 0	> 20	> 2	> 4.8	< 8.4	> 1	< 6	< 20
Sesame	<9999	> 1	< 7	NoData	> 0	> 35	> 5.5	> 5.5	< 7.5	> 0.8	< 6	< 100

Appendix Figure 1: Synthesized Land Quality Criteria for at least S2 Suitability for Selected Crops

A4. Python Codes to Query the HWSD and determine Soil Suitability for Crop

```
# --------------------------------------------------------------------------
# Soils_Model_FINAL_script.py

# Created on: Thu Mar 31 2011 04:48:05 PM
#   Last modified on 7/27/2011 <<<<<<<<<<<<<<<<< PLEASE CHANGE IF MODIFY
#   by Anjuli Jain Figueroa ajainf@mit.edu
# --------------------------------------------------------------------------
# In general this code goes through a text file, creates a list of conditions
# and selects areas of a polygon by attributes that match the requirements.

# The purpose of this code is to give ARCGIS a polygon of the Harmonized
World
# Soil Database and find the areas where all soil conditions ("All
conditions")
# as tabulated in Land Evaluation part 3 by Dr. C Sys are true. The soil
conditions
# are written in a specified comma value separated text file following a
specific
# format. This code checks the ArcGIS polygon's attribute tables and matches
# it with the required soil conditions.
# --------------------------------------------------------------------------

# Import system modules
import sys, string, os, arcgisscripting

# Create the Geoprocessor object
gp = arcgisscripting.create()

# Load required toolboxes...
gp.AddToolbox("C:/Program Files (x86)/ArcGIS/ArcToolbox/Toolboxes/Data
Management Tools.tbx")

#gp.workspace = "D:\\Research_GIS\\shapfiles"

# Setting OverWriteOutput to True allows geoprocessing tools to overwrite
#    the output if it already exists.
gp.OverWriteOutput = 0

#---------------------------------------------------------------------------
# Local variables...
Input_Layer_Name = "D:\\Research_GIS\\shapfiles\\hwsd1_polygon_final.shp"
# <<<<<<<<<< CAN CHANGE THIS (HWSD polygon path)

FilePathOut = 'D:\\Research_GIS\\CROPS\\Crops_py\\Crops_ThirdRun\\'
# <<<<<<<<<<<<<<< CAN CHANGE THIS (where you want to save file path)

# Filename of .csv that has soil conditions as tabulated by "Land Evaluation
# Part 3" by Dr. C Ss 1993 University of Ghent

FileIN = 'S2_All_2_061611'
FilePathIn ='D:\\Research_GIS\\SoilConditions\\' + FileIN + '.csv'
# <<<<<<<<<<<<<<< CAN CHANGE THIS (Land Quality Criteria)

#---------------------------------------------------------------------------
```

```
n1 = 0
n2 = 6 # number of characters of FileIN to display in output name

fileName = open(FilePathIn)

# Read first Line - These are the headers of the conditions (ie "pH",
"texture class"...)
headers = fileName.readline()
h = headers.split(',')
endRow = len(h)

#Read Second Line - These are the operators of the conditions (ie "AND",
"OR")
operator = fileName.readline()
op = operator.split(',')

# Hardcode the number of crops from FileIN
numcrops = 18
for cropNum in range(1,numcrops):
    all_conditions = ""
    crops = fileName.readline() # Reads the next line c[0] is the crop name
(ie Wheat) c[i] is the conditions (ie "<5")
    if len(crops) == 0:
        break
    c = crops.split(',')

    for i in range(1,endRow-2): # Use (endRow-2) because last 2 rows are 1)
number of columns with conditions and 2) word "end"
        cropName = c[0]

        if i == float(c[endRow-2]):
            condition = h[i]+c[i]
        else:
            condition = h[i]+c[i]+" "+op[i]

        if c[i] <> "NoData":
            all_conditions = all_conditions + ' ' + condition

    Output_Layer_Name = cropName

    Output_Feature_Class = FilePathOut + FileIN[n1:n2] + '_' +
Output_Layer_Name + '.shp'

    print Output_Layer_Name

    Temp_Layer = "lyr_" + cropName

    # Make a layer from the feature class
    gp.MakeFeatureLayer(Input_Layer_Name,Temp_Layer, "#"
,"D:\Research_GIS\shapfiles")
    #<<<<<<<<<<<<<<<<< CHANGE THIS (path of input )

    # Process: Select Layer By Attribute...
    gp.SelectLayerByAttribute_management(Temp_Layer, "NEW_SELECTION",
all_conditions)

    # Process: Copy Features...
```

```
    gp.CopyFeatures_management(Temp_Layer, Output_Feature_Class, "", "0",
"0", "0")

    del Temp_Layer

    #print c[0]
    #print all_conditions
    #print ""

fileName.close()
print 'done'
```

A5. Matlab Code to read DRT Flow Direction

```
%Read DRT and create a list of neighboring pixels for each pixel

%function [Runoff] =
FlowTributaryToTable(PrecipMatrix,ETMatrix,FlowDirectionMatrix,pixelArea)
% Written by Anjuli Jain
% Last modified 10/18/2011

%fid =
fopen('D:\Matlab_Scripts\Global_Codes\RFpot_MainFunctions\IrrigationFiles\Tri
butary\drt_ubn_qd_fdr.txt') %FlowDirectionMatrix

%Flow Direction Key
E = 1; SE = 2; S = 4; SW = 8; W = 16; NW = 32; N = 64; NE = 128;

latmax = size(FlowDirectionMatrix,1);
longmax = size(FlowDirectionMatrix,2);

D = padarray(FlowDirectionMatrix,[1 1]);
FDM = FlowDirectionMatrix;

BalanceMatrix =zeros(latmax,longmax);
tribarray = struct('pixel',[],'trib',[]);

count =0;
i=0;

while(any(D(:) ~= 0))
    for lat = 1:latmax
        for long = 1:longmax
        i=i+1;
        j=1;

tribarray(i).pixel=str2double(strcat(num2str(lat),'.',num2str(long)));

        % As long as it is not the boundary

        if (long ~=1) % Not the side edge
            if(FDM(lat,long-1)==E)

tribarray(i).trib(j)=str2double(strcat(num2str(lat),'.',num2str(long-1)));
                j=j+1;
            end
        end

        if (long ~=1 && lat ~=1) % Not the top left corner
            if(FDM(lat-1,long-1)==SE)
                  tribarray(i).trib(j)=str2double(strcat(num2str(lat-
                  1),'.',num2str(long-1)));
                j=j+1;
            end
        end

        if (lat ~=1) % Not the top edge
            if(FDM(lat-1,long)==S)
```

```
                tribarray(i).trib(j)=str2double(strcat(num2str(lat-
                1),'.',num2str(long)));
             j=j+1;
          end
        end

        if (lat ~=1 && long ~=longmax) % Not the top right corner
            if(FDM(lat-1,long+1)==SW)
                tribarray(i).trib(j)=str2double(strcat(num2str(lat-
                1),'.',num2str(long+1)));
              j=j+1;
            end
        end

        if (long ~=longmax) % Not the left edge
            if(FDM(lat,long+1)==W)
                tribarray(i).trib(j)=str2double(strcat(num2str(lat),'.',num
                2str(long+1)));
              j=j+1;
            end
        end

        if(lat ~=latmax && long ~=longmax) % Not the bottom right corner
            if(FDM(lat+1,long+1)==NW)
                tribarray(i).trib(j)=str2double(strcat(num2str(lat+1),'.',n
                um2str(long+1)));
              j=j+1;
            end
        end

        if (lat ~=latmax) % Not the bottom edge
            if(FDM(lat+1,long)==N)

                tribarray(i).trib(j)=str2double(strcat(num2str(lat+1),'.',n
                um2str(long));
              j=j+1;
            end
        end

        if(long ~=1 && lat ~=latmax) % Not the bottom left corner
            if(FDM(lat+1,long-1)==NE)

tribarray(i).trib(j)=str2double(strcat(num2str(lat+1),'.',num2str(long-1)));
              j=j+1;
            end
        end

        %Check that cell has no inputs(only outgoing flow directions)

        row = lat+1;
        col = long+1;

            if( D(row-1,col-1)~=SE && D(row-1,col)~= S && D(row-1,col+1)~=SW
            && D(row, col-1) ~=E && D(row,col+1) ~=W && D(row+1,col-1)~=NE &&
            D(row+1,col) ~=N && D(row+1,col+1)~=NW);
            tribarray(i).trib(j)= 0;
            D(row,col)=0;
```

```
            count = count+1;
            j=j+1;
        end

        end
    end
    %waitbar((count/(latmax*latmax*longmax)),h)
end

count
Runoff = BalanceMatrix;
tribarray

%save('Runoff.mat', 'Runoff');

% open the file with write permission
fid =
fopen('D:\Matlab_Scripts\Global_Codes\RFpot_MainFunctions\IrrigationFiles\Tri
butary\UBNTrib.txt', 'w');
fprintf('Neighboring Tribs List\n')
fprintf('pixel,Num tribs, Tributaries')
for k=1:size(tribarray,2)
%fprintf(fid, 'trib to %s are %s\n',
num2str(tribarray(k).pixel),num2str(tribarray(k).trib));
fprintf(fid, '%s, %s, %s\n', num2str(tribarray(k).pixel),
num2str(size(tribarray(k).trib,2)));  %,num2str(tribarray(k).trib));
for j = 1:size(tribarray(k).trib,2)
fprintf(fid, '%s,', num2str(tribarray(k).trib(j)));
end
fprintf(fid, '\n');
end
fclose(fid);

% view the contents of the file
type UBNTrib.txt
'done'
```

A6. Python Code to create Tributary Pixel File for GAMS

```
# Python—Read neighboring pixels output file from matlab and produce text
# file with a list of all tributary pixels to each pixel in the proper GAMS
# format
# Jan 31 2012

###-----------------------------------------------------------------------------
#### Recursive Function to print ALL tributaries
###-----------------------------------------------------------------------------

def printUpstreamNodes(nodes, Allneighbors, trib_dict, memo, memokey):
    a=1;
    for j in range(0,len(Allneighbors)):
        if Allneighbors[j] == '0':
            memo.setdefault(memokey, [])
            return
        if a == 'None':
            return
        else:
            newNode = Allneighbors[j]
            newNeighbors = trib_dict[newNode]
            memo.setdefault(memokey, []).append(newNode)
            a = printUpstreamNodes(newNode, newNeighbors, trib_dict, memo,
memokey)
    return

#------------------------------------------------------------------------------
##                                        MAIN
#------------------------------------------------------------------------------

FilePath = 'D:\\Research_GIS\\PythonScripts\\'
#'D:\\Matlab_Scripts\\Global_Codes\\RFpot_MainFunctions\\IrrigationFiles\\Tri
butary\\'

FileIN = 'tribTest.txt'
#'UBNTrib_021312.txt'
FileOut = 'tribTestOut'
#'UBNTribGAMSNoUpLeadZero_021312.txt'

ReadFile = FilePath+FileIN
WriteFile= FilePath+FileOut

numct = 2; # number of digits needed for GAMS format 001 or 01 or 1 (3, 2, 1)
import re

#------------------------------------------------------------------------------
#Create Dictionary of Neighboring Tributaries from Matlab file
#------------------------------------------------------------------------------

fileName = open(ReadFile)
trib_dict={} # define a "dictionary" or lookup table

for line in fileName:
```

```
    line = line.strip('\n')      # remove new line character
    line = line.replace(' ','') # remove white spaces in middle
    linesep = line.split(',')   # linesep is a list object; line is a string
    endRow = len(linesep)
    name = linesep[0]
    numtribs = linesep[1]
    trib = linesep[2:endRow-1]
    trib_dict[name]=trib

#print trib_dict
fileName.close

TribList = zip(trib_dict.keys(),trib_dict.values())
#print TribList

#-----------------------------------------------------------------------------
#Create Dictionary of ALL Tributaries
#-----------------------------------------------------------------------------

memo = {}
ALLnodes = trib_dict.keys()

for i in range(0,len(ALLnodes)):
    node = str(ALLnodes[i])
    memokey = node
    #print node
    ALLneighbors = trib_dict[node] # list object
    printUpstreamNodes(node, ALLneighbors, trib_dict, memo, memokey)

#print memo

#-----------------------------------------------------------------------------
# Write to file in the GAMS format
#-----------------------------------------------------------------------------

fout = open(WriteFile, "w")

for i in range(0,len(ALLnodes)):
    k = str(ALLnodes[i]) # k, for "dictionary key", represents the node that
water flows into
    hasDupes = memo[k] # tributaries may be repeated so the duplicates must
be removed
    noDupes =[]
    [noDupes.append(i)for i in hasDupes if not noDupes.count(i)] #remove
duplicates
    a = str(noDupes)
    #a = str(memo[ALLnodes[i]])
    a = a.replace("',","),") #use special GAMS formatting rules
    a = a.replace("']",")")
    a = a.replace("'",'(')
    a = a.replace(']','')
    a = a.replace('[','')
    a = a.strip('\n')
    a = a.replace(", 0",'')
    if len(a)==0:
        b =''
        fout.write(b)
```

```
    else:
        b = "("+k+")."+ "("+ a +")" +"\n" # tributary list but does not have
leading zeros

        #print b
        #pickle.dump(b,fout)

        #---------------------------
        # Add leading zeros-- necessary for GAMS
        #---------------------------
        nodeNum2 = str()
        temp = str()
        num_list = re.findall(r"\d+",b) # finds only the digits in b
        fin = len(num_list)-1
        for i in range(0,fin+1):
            num_list[i]=num_list[i].zfill(numct) # fills in number of zeros

        nodeNum1 = '('+str(num_list[0])+'.'+str(num_list[1])+').('
        nodeNum3= '('+str(num_list[fin-1])+'.'+str(num_list[fin])+')'

        for j in range(3,fin-1,2):
            nodeNum2 = nodeNum2 +'(' +str(num_list[j-1]) +'.'
+str(num_list[j]) +'),'
        temp = nodeNum1 + nodeNum2 +nodeNum3 +')'+"\n"
        print temp # tributary list with leading zeros, no duplicates,
correct formatting
        fout.write(temp)

print "done"
```

A7. Python Codes to Intersect Soil, Slope, and Temperature

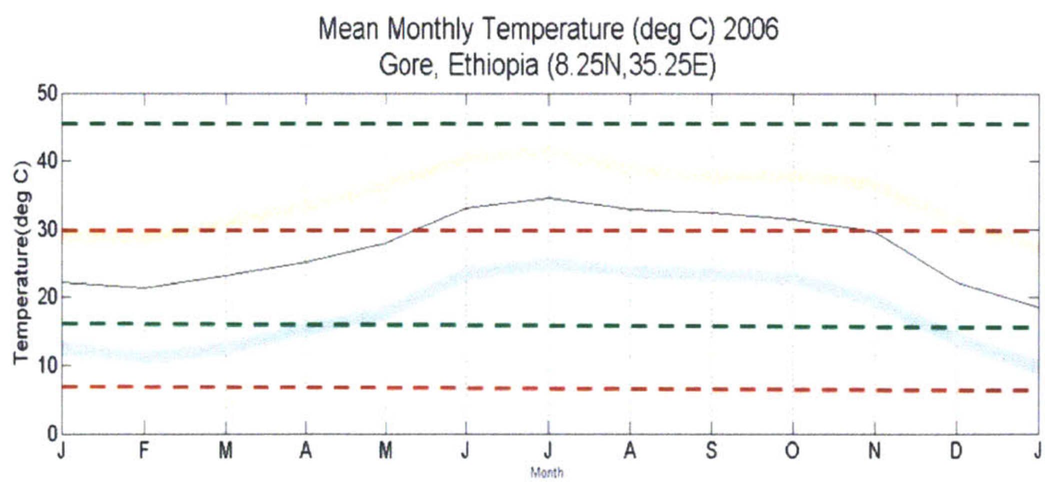
```
# ---------------------------------------------------------------------------
# Conditional SOMA.py
# by Anjuli Jain Figueroa
# 9/15/2011
# 1/19/2012
# ---------------------------------------------------------------------------
# This code intersects the favorable soil + slope raster with a favorable
climate raster (irrigation or rainfed)

# slope is 0-4%; slope and climate are crop specific

# ---------------------------------------------------------------------------
# Import system modules
import sys, string, os, arcgisscripting

# Create the Geoprocessor object
gp = arcgisscripting.create()

# Check out any necessary licenses
gp.CheckOutExtension("spatial")

# Load required toolboxes...
gp.AddToolbox("C:/Program Files (x86)/ArcGIS/ArcToolbox/Toolboxes/Spatial
Analyst Tools.tbx")

# Allow the geoprocessing tools to overwrite the output if it exists
gp.OverWriteOutput = 1

Input_Coordinate_System =
"GEOGCS['GCS_WGS_1984',DATUM['D_WGS_1984',SPHEROID['WGS_1984',6378137.0,298.2
57223563]],PRIMEM['Greenwich',0.0],UNIT['Degree',0.0174532925199433]]"
Output_Coordinate_System =
"PROJCS['Africa_Albers_Equal_Area_Conic',GEOGCS['GCS_WGS_1984',DATUM['D_WGS_1
984',SPHEROID['WGS_1984',6378137.0,298.257223563]],PRIMEM['Greenwich',0.0],UN
IT['Degree',0.0174532925199433]],PROJECTION['Albers'],PARAMETER['False_Eastin
g',0.0],PARAMETER['False_Northing',0.0],PARAMETER['Central_Meridian',34.0],PA
RAMETER['Standard_Parallel_1',28.0],PARAMETER['Standard_Parallel_2',8.0],PARA
METER['Latitude_Of_Origin',0.0],UNIT['Meter',1.0]]"

InRaster = 'D:\\EmailEsri\\slope_folder\\slope_250ccc' #_0_4'
#'D:\\Research_GIS\\SRTM_DEM\\SRTM_grid\\SRTM_DEM_FILES\\Slop250cc_0_4'
pixelsize = gp.GetRasterProperties (InRaster, "CELLSIZEX")
gp.CellSize = pixelsize

#Set extent
#dsc = gp.Describe('D:\\Research_GIS\\shapfiles\\Nile_Cntry.shp')
gp.extent = "-1306335.01 377220.612 1540657.07 3530040.68"
#'D:\\Research_GIS\\SRTM_DEM\\SRTM_grid\\SRTM_DEM_FILES\\Slop250cc_0_4'
#
#"XMIN YMIN XMAX YMAX"


# ---------------------------------------------------------------------------
```

```
# User can change the following variables:

# Set Workspace
gp.workspace =
"D:\\Research_GIS\\Suitability_Calcs\\Suitability_Folders\\slope_soil_irr\\"

# File with CropList
FileIN = 'CropList2_short'
FilePathIn ='D:\\EmailEsri\\' + FileIN + '.csv'

# Local variables...

path ='D:\\Research_GIS\\Suitability_Calcs\\Suitability_Folders\\'

slope_AND_soil_folder = path + 'slopeANDsoil_suitability'
climate_folder = path + 'irrig_suitability'

File_out_folder = path + 'slope_soil_irr'

# Conditions
climate_con1 = " >= 70 " # Arbitrary condition where climate is favorable
more than 70% of time (1900-2006)
slope_AND_soil_con1 = " ==1 " # Ensure the slope condition is true for slope
between 0 and 4 percent

# ---------------------------------------------------------------------------

fileName = open(FilePathIn) # List of Crops

try:
    for i in range (0,2): # Hardcode number of crops in list
       cropName = fileName.readline()

       # Check lenght of string name and ensure it is less than max_pos, 9;
Raster names can only be 13 characters
       s = cropName
       length = len(s)
       max_pos = 9

       if length >= max_pos:
           cropName = s[0:max_pos]
       else:
           cropName = s.strip() # remove end of line character to allow
proper running of gp

       #----------------------------------Project Climate Raster-------------
       RasterLayerIn = climate_folder + cropName.strip()
       Projected_Raster =climate +"_pj"

       # Process: Project Raster...
       gp.ProjectRaster_management(RasterLayerIn, Projected_Raster,
Output_Coordinate_System, "NEAREST", "56525.527271", "", "",
Input_Coordinate_System)
       print "projected raster"

       climate = climate_folder + Projected_Raster.strip()
```

```
        slope_AND_soil = slope_AND_soil_folder + cropName.strip()

        #----------------Single Output Map Algebra: Overlap 2 Conditions

        InExpression = "CON (" + climate + climate_con1 + " && " +
slope_AND_soil + slope_AND_soil_con1 + ",1)"
        print InExpression

        # User can change outfile locations
        #D:\Research_GIS\SOMA\SRTM_dem_90m
        fileout_SOMA = File_Out_folder + 'som_' + cropName.strip() #

        print cropName

        # Process: Single Output Map Algebra (Conditional)
        gp.SingleOutputMapAlgebra_sa(InExpression, fileout_SOMA, "")
        print "SOMA"


except:
    # If an error occurred while running a tool, then print the messages.
    print gp.GetMessages()
    print "Had error"

print 'Done with ' + str(i+1) + ' crops'
```

A8. Matlab Codes to check Temperature Suitability

Example of Temperature check at one location. Crops with an operative range of 15-45 deg (green dottedlines) ,such as maize, millet, sesame sorghum could be grown here. To check if this location is suitable for wheat with operating range of 5-30 degree celsius, the temperature time series for each year is checked. The Length of Growin Period is 8 months and plant date is in April. The temperature is checked and only 3 of the 8 months are within the operable range. This is only 37.5% of the growing season, thus for this year, the temperature does not meet the 80% threshold and gets a 0. The process is repeated for all years in the time series. These 0,1 values are averaged yielding the percent of time that the temperature was suitable for that crop.



```
function Irrigation2(FilenameToSave, num_crops)

% This code gives the Irrigation potential at each pixel during each year
% by checking if the temperatures for each crop are operative for the LGP

% Import and Calculate Climatology Data ---------------------------------
% Spatial Scale: 0.5x0.5 deg, Temporal Scale = monthly

Pixel_TempMean = importdata('D:\Matlab_Scripts\Temp\TempMP_CRUTS3.mat');

% Format Crop Data -------------------------------------------------------
% Crop Coefficients, Development Stages, Length of Growing Period, Crop
% Operative Temperature Ranges from FAO and various sources
% Put all data into a structure

crop = CreateCropStructInput2; %%Function to Create a Data Structure

%% VARIABLES to Change
num_yrs = 106;
longmax = 56;
latmax = 58;

%% Determine Variables
IRRpot2Map = zeros(longmax,latmax,num_crops);

Irr_mnth_binary = zeros(1,1);
IRR_binary = zeros(num_crops,num_yrs);
IrrMean_var = zeros(num_crops,num_yrs);

timer = 0;
h = waitbar(0,'Please wait...');

for c = 1: num_crops

    for long = 1:longmax

        for lat = 1:latmax

              for yr = 1:num_yrs

                 % IRRIGATION -- temperature is ok but water is missing
                 OptTemp = crop(c).TempOpt{1};
                 startmonth = str2num(crop(c).plantDate{1});
                 endmonth = startmonth+crop(c).LGP{1};

                 i = 1;
                 for m = startmonth:endmonth
                     t3 = (yr-1)*12+m;
                     if (t3>12*num_yrs)
                         break
                     end
                     if (Pixel_TempMean(long,lat,t3)<=crop(c).TempMx{1} &&
 Pixel_TempMean(long,lat,t3)>=crop(c).TempMn{1})
                         if (Pixel_TempMean(long,lat,t3)>= OptTemp(1) &&
 Pixel_TempMean(long,lat,t3)<= OptTemp(2))
                             T ='temp optimal';
```

```
                        Irr_mnth_binary(1,i)= 1;
                    else
                        Irr_mnth_binary(1,i)= 1; %can write a formula
that varies between zero and 1
                        T ='temp operative';
                    end
                else
                    Irr_mnth_binary(1,i)= 0; %
                    T = 'temp bad';
                end
                i = i+1;
                %t3 = t3+1;
            end

            IrrMean_var(c,yr) = mean(Irr_mnth_binary(1,:),2);

            % Ensure temperature is ok for long part of the year to
            % ensure plant growth
            if IrrMean_var(c,yr)>0.8 % 0.8 is arbitrary threshold but
ensures that smalles LGP is not less than 70 days which some sources say is
too small for plant growth
                IRR_binary(c,yr)= 1;
            else
                IRR_binary(c,yr)= 0;
            end

        end %yr

        IRRpot2Map(long,lat,c) = mean(IRR_binary(c,:),2);
        counter = [c,lat,long, IRRpot2Map(long,lat,c)]
        waitbar(timer/(latmax*longmax*num_crops),h)

    timer = timer+1;
    end %lat
timer = timer+1;
end %long
timer = timer+1;
end %crop

IRRpot2Map100 = IRRpot2Map*100;
filevar = 'IRRpot2Map100';
save(FileNameToSave, filevar);

Q = 'done'
```

A9. Length of Growing Period, Crop Coefficient and Planting Dates from FAO

Table A 1: Crop Planting Months

	FAO Region	FAO Plant Date	FAO Plant Month	Crop Map Region	Crop Map Plant Month	Plant Month Used	Notes
Barley	East Africa	Oct	10	Ethiopia	4	4	
Cassava	Tropical regions	Rainy	6	Ethiopia	fill: 3	5	
Cotton	Egypt; Pakistan;	Mar-May	3, 4, 5	Ethiopia	5	5	*dry crop
Groundnut	West Africa	Dry	1	Ethiopia	5	1	
Maize	East Africa (alt.)	Apr	4	Ethiopia	fill: 2	4	
Millet	Pakistan	Jun	6	Ethiopia	4	4	
Potato	(Semi)Arid Climate	Jan/Nov	11, 12, 1	Ethiopia	5	11	*dry crop
Sesame	China	Jun	6	Ethiopia	NoData	6	
Sorghum	Arid Region	Mar/Apr	3, 4	Ethiopia	3	3	
Sweet Potato	Mediterranean	April	4	Ethiopia	5	5	
Wheat	Mediterranean	Nov	11	Ethiopia	4	4	

Table A 2: Length of crop devvelopment stages for various planting periods and climatic regions (days)

Crop	Init. (Lini) (days)	Dev. (Ldev) (days)	Mid (Lmid) (days)	Late (Llate) (days)	Total (days)	LGP (month)
Barley	15.00	30.00	65.00	40.00	150	5
Cassava	20.00	40.00	90.00	60.00	210	7
Cotton	30.00	50.00	60.00	55.00	195	7
Groundnut	25.00	35.00	45.00	25.00	130	4
Maize	30.00	50.00	60.00	40.00	180	6
Millet	15.00	25.00	40.00	25.00	105	4
Potato	25.00	30.00	30/45	30.00	115/130	4
Sesame	20.00	30.00	40.00	20.00	100	3
Sorghum	20.00	35.00	45.00	30.00	140	5
Sweet Potato	20.00	30.00	60.00	40.00	150	5
Wheat	30.00	140.00	40.00	30.00	240	8

(Source: FAO, 1998)

Table A 3: Single (time-averaged) crop coefficients, Kc, and mean maximum plant heights

Crop	K_{cini}	$K_{c\ mid}$	$K_{c\ end}$	Maximum Crop Height (m)
Barley	0.3	1.15	0.25	1
Cassava	0.3	0.803	0.3	1
Cotton	0	1.15-1.20	0.70-0.50	1.2-1.5
Groundnut	0	1.15	0.6	0.4
Maize	0	1.2	0.60-0.3511	2
Millet	0	1	0.3	1.5
Potato	0	1.15	0.754	0.6
Sesame	0	1.1	0.25	1
Sorghum	0	1.00-1.10	0.55	1.0-2.0
Sweet Potato	0	1.15	0.65	0.4
Wheat	0.7	1.15	0.25-0.410	No Data

(Source: FAO, 1998)

A10. Python Code to Derive Monthly Crop Coefficient Curve

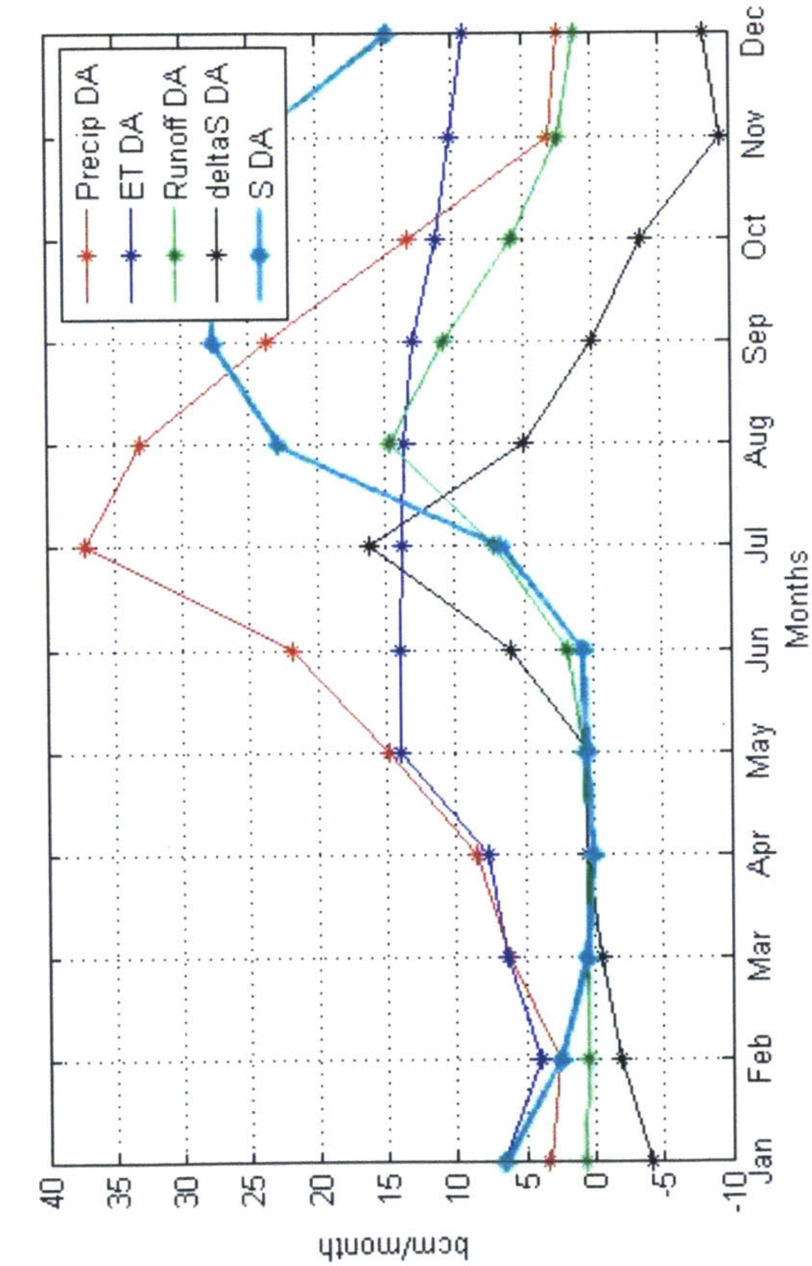
The crop planting month, the lengths of the gowing period in days and the crop coefficients from FAO or other crop calendar datasets is an input into the code.

```
% function X = InterpolCropCoeff2Monthly_v2_04172012(plantmonth,kc,num_crops)

% The purpose of this code is to take 5 step kc values and interpolate
% into a 365 day matrix and aggregate into a 12 month matrix

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% Section 1. Input Data from FAO Tables
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

Name = {'Barley';'Cassava';'Cotton';'Groundnut';'Maize';
       'Millet';'Potato';'Sesame';'Sorghum';'SweetPotato';'Wheat'    };
%----------------------------
plantDate = {'04/01';'05/01';'05/01'; '01/01';'04/01';
             '04/01';'11/01';'06/01';'03/01'; '04/01';'04/01'        };
%----------------------------
devTime = { %in days
            [15 30 65 40],  %Barely
            [20 40 90 60],  %Cassava
            [30 50 60 55],  %Cotton
            [25 35 45 25],  %Groundnuts
            [30 50 60 40],  %Maize
            [15 25 40 25],  %Millet
            [25 30 40 30],  %Potato
            [20 30 40 20],  %Sesame
            [20 35 45 30],  %Sorghum
            [20 30 60 40],  %Sweet Potato
            [30 140 40 30,  %Wheat
         };
%----------------------------
 coeff = {
            [0.3 0.3 1.15 1.15 0.25],   %Barley
            [0.3 0.3 0.803 0.803 0.3],  %Cassava
            [0 0 1.175 1.175 0.6],      %Cotton
            [0 0 1.15 1.15 0.6],        %Groundnut
            [0 0 1.2 1.2 0.47555],      %Maize
            [0 0 1 1 0.3],              %Millet
            [0 0 1.15 1.15 0.754],      %Potato
            [0 0 1.1 1.1 0.25],         %Sesame
            [0 0 1.05 1.05 0.55],       %Sorghum
            [0 0 1.15 1.15 0.65],       %Sweet Potato
            [0.7 0.7 1.15 1.15 0.33],   %Wheat
      };

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% Section 2. Create Crop Structure
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

```
num_crops =length(name);
crop(1,num_crops)= struct('name',[],'plantDate',[],'coeff',[],'devTime',[]);

for d = 1:num_crops;
    crop(d).name = name(d);
    crop(d).plantDate = plantDate(d);
    crop(d).coeff = coeff(d);
    crop(d).devTime = devTime(d);
end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% Section 3. Create kc Structure
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

for d = 1:num_crops;
i=1; % Start at stage i=1

    %store Name
    kc.name(d) = crop(d).name;

    time = crop(d).plantDate;
    kc.time(d,i) = datenum(datestr(time,'mm/dd/yy'));

    % Store Dates
    for i = 2:5
    date_offset = time;
    time = datestr(addtodate(datenum(date_offset),crop(d).devTime{1,1}(i-
1),'day'),'mm/dd/yy');
    kc.time(d,i)= datenum(time);
    end

    % Store Crop Coeff
    for j =1:5
    coeff = crop(d).coeff{1,1}(j);
    kc.coeff(d,j)=coeff;
    end

end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% Section 4. Interpolate
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

MonthVector = [1:1:12];
num_months = length(MonthVector);

NDM = [31 28 31 30 31 30 31 31 30 31 30 31];

kc_monthly_matrix2 = zeros(num_crops,num_months);

for d = 1:num_crops
    KcDailyVector = zeros(1,365);
    Y = interp1(kc.time(d,:), kc.coeff(d,:),kc.time(d,1):kc.time(d,5)); %
Interpolated kc values

    for j = 1:length(Y)
           KcDailyVector(j)= Y(j);
```

```
    end

    i = month(crop(d).plantDate);
    MonthAvgKc = zeros(1,num_months);
    NDMcum1 = 1;
    for k = 1:12

        NDMcum2 = NDM(i)+NDMcum1 - 1;
        MonthAvgKc(i) = sum(KcDailyVector(NDMcum1:NDMcum2))./NDM(i);
        i=i+1;
        NDMcum1 = NDMcum2;

        if i >12;
            i=1;
        end
    end

kc_monthly_matrix2(d,:) = MonthAvgKc;
end

kc4GAMS= struct('name',[],'kc',[]);

    kc4GAMS.name = name;
    kc4GAMS.kc = kc_monthly_matrix2;

save('kcValuesforGams.mat','kc4GAMS')
```

A11. Output from Data Assimilation



Appendix Figure 2: Output from the Data Assimilation becomes Initialization for Water and Land Allocation

A12. Spatial Distribution of Crops In a Water Consumptive Basin in February and July