Limits to Population Growth and Water Resource Adequacy in the Nile River Basin

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Abstract

The purpose of this study is to examine the potential limits to growth among selected countries within the Nile River Basin region based on actual and projected estimates of population growth and water resource adequacy between 1994 and 2100. The projected disparity between population growth and water resource adequacy within the region raises serious questions about the adequacy of water resources given current population rates and the timing of potential intra-regional conflict. This study, by employing a system dynamics model for the region, projects extreme water scarcity by mid-century with potentially catastrophic human implications. Egypt is likely to encounter a severe water crisis by mid century and as early as 2020 under conservative modeling assumptions. Averting a potential crisis in the Nile River Basin region will require the formulation and evaluation of plausible solutions to water resource issues. The impact of this crisis can be attenuated only by reducing birth rates, reducing per capita water consumption, or increasing water supply. Desalination, one method for increasing the water supply in Egypt, is not sufficient to divert this potential crisis. Future study is required to examine the internal dynamics of water and population collectively, and for each country, in the Nile River Basin.

Introduction

The world is projected to realize unprecedented population growth throughout the current century, which may exceed the resource base necessary to sustain it. One region in particular, the fertile Nile River Basin situated in northeastern Africa, is on course to double its proportion of the world's population from six to 12 percent by the end of the 21st Century. Insofar as extant water resources are already strained to sustain the current population base, continued population growth is likely to overshoot resource capacity. The problem is further compounded by the location of the region within a complex political, economic, and historical context.

The purpose of this study is to examine the potential limits to growth within the Nile River Basin based on actual and projected estimates of population size and water resource adequacy between 1994 and 2100. Our objective is to first model the dynamic relationship between population growth and water resource adequacy within the Nile River Basin in order to isolate variables that arguably influence both resource capacity and population growth. Second, we seek to anchor the problem within the political, economic, and historical context of the region in order to evaluate observed outcomes and plausible solutions in light of the stated problem. Third, we leverage this model to estimate plausible future behavior in the system and to identify future areas of study. For this project, we direct attention to the countries of Egypt, Sudan, South Sudan, and Ethiopia (Figure 1). These countries are projected to be major players in the looming crisis: Ethiopia for its position as the source of 85% of the river flow, Sudan for its position at the strategic juncture between the two flows of the Nile River, and Egypt for its position at the end of the river and its high dependence on Nile resources. Sudan and South Sudan are aggregated for modeling purposes and assumed for this paper to operate consistently as a single entity; however, the political, economic, and cultural effects of the recent split between these countries could arguably affect both population growth and behavior regarding water consumption in a manner inconsistent with this assumption.

Figure 1: Area of Study

Model development necessitates the acknowledgement of several assumptions about the nature of the Nile River Basin system. Two assumptions about our framework as a whole are important to acknowledge before undertaking the analysis. First, we assume that our model accurately incorporates the primary factors affecting population growth and resource capacity. However, to the extent that our model relies on historic data to make predictions about future outcomes, it is susceptible to "extrapolation bias." There is no guarantee that past trends will continue throughout the entire time period under study, though our model utilizes these past trends in making its predictions. In order to minimize the effects of this issue, we modify the basic assumptions of our model drastically in order to explore many of these unforeseen scenarios that are not reflected in historic data. Second, this paper assumes away the effects of internal and/or regional conflict on population growth and resource availability. Notably, while we aggregate population and water information at the country level in order to increase confidence in our model's predictions and to validate our output with well supported historical data at the country level, these assumptions make it impossible to explore dynamics that operate within countries. For example, evidence that a country as a whole has sufficient water to meet demand does not suggest that all areas of the country are without water shortages. In particular, we are unable to directly model internal forces such as changing settlement patterns, economic and industrial development, and internal water resource patterns. Instead, we must address these issues indirectly at the country level. Additionally, this paper says nothing about competing priorities within countries. To the extent that population growth exceeds the carrying capacity of available water resources in time, priorities will have to be established within countries in order to effectively address resolution of this reality; however, internal tensions and conflicts within and between the countries may limit their individual or collective ability to organize for the successful resolution of an impending regional crisis. Third, we assume that the Nile River serves as a renewable water resource within constant annual discharge rates. Fourth, we assume that changes in population do not alter current pollution levels of the Nile River. These four assumptions are incorporated as constants throughout the analysis.

We also incorporate five additional assumptions in the model: (1) that Ethiopia and Sudan adhere to the 1959 treaty; (2) that the geographical area represented by the Nile River Basin is free from drought during the 21st Century; (3) that half of the average annual rainfall collected through groundwater runoff finds its way back to the aquifers annually; (4) that the fertility rate remains constant throughout the 21st Century; and (5) that the per capita water consumption levels remain constant throughout the modeling process. While the general base model is inclusive of these additional five assumptions, we vary them to examine outcomes when these assumptions are violated.

We utilize a system dynamics approach to model limits to population growth and water resource adequacy within the Nile River Basin. System dynamics is an established method for modeling the complex interdependencies, interactions, and feedback loops found in political, economic, and social systems (Sterman 2000). This method leverages computer programs to model the inter-relationships and feedback loops embedded within the system, and updates the system after a given time step has been simulated. Our study utilizes the Vensim software platform, which is described in the methodology section that follows.

Literature Review

The purpose of this study is to examine the potential limits to growth within the Nile River Basin based on actual and projected estimates of population and water resource adequacy between 1994 and 2100. Although the Nile River Basin is fertile with a large capacity of water flow throughout the region, current population growth rates of countries comprising the basin are notably high and will, in time, place resource demands on the existing water supply. Additionally, many countries in the region are classified as failed or failing states; the resolution of their internal crises is often placed above regional concerns of water usage. The Nile River Basin is comprised of nine countries: Egypt, Ethiopia, Sudan, South Sudan, Uganda, Burundi, Democratic Republic of the Congo, Tanzania, Kenya, and Rwanda. These nine countries have economies dominated by agriculture, which is a very water intensive activity (Swain 2003, 299). Although Egypt has developed robust irrigation and water systems, the other nations of the region lag behind Egypt in this regard. Experts in the region expect this water use pattern to change, as the total population in the region increases (El- Fadel 2003: 108). Estimates suggest that the population in the region will double over the next several decades; by the end of the 21st Century, given current growth rates, conservative estimates of population growth could exceed tenfold (Brown 2009). Ethiopia, the region's most populous country and location of the largest water reserves, highlights the most dramatic case of this problem. Left out of a 1959 agreement between Egypt and Sudan that divided water resources of the Nile River solely between themselves, Ethiopia is technically not allowed to draw any water from the river within its current geographical boundaries in support of its population (a prospect that is realistically unfeasible and difficult to enforce). Increasing agricultural production in Ethiopia to meet the demands of a growing population will require that the country tap into its Nile reserves or face the prospect of severe water shortages. In drawing water from the Nile River, the downstream countries of Sudan and Egypt will be impacted. The same issue, albeit on a smaller scale, is evident in other Nile River source countries, including Uganda, Burundi, and Rwanda.

The Nile River Basin

Our research has identified four primary factors that are critical to an understanding of dynamics within the Nile River Basin. These factors include water resource capacity in the Nile River Basin, projected population growth and water resource demand, the political and legal history of water usage in the region, and the potential of regional conflict over access to water. A fifth factor, economic development, is also likely to exacerbate problems associate with water resource management in the region; however, within this paper, we will not address the potential affect of projected shifts in economic development on regional water resource management. An understanding of the complex relationship among these factors and the positioning of the corresponding stakeholders in relation to these factors is essential in developing a useful model to assess limits to population growth and water resource adequacy in the region.

Water Resource Capacity in the Nile River Basin

The Nile River Valley is essential to sustaining populations in northeastern Africa. The river flows from south to north via two primary channels, the White Nile and the Blue Nile. The White Nile begins in the Lake Victoria watershed shared among Tanzania, Burundi, Rwanda, Kenya, the Congo, and Uganda as a number of small but regular tributaries that wind together, while the Blue Nile begins at Lake Tana in the Ethiopian highlands and contains minor tributaries in a watershed shared by Eritrea (Swain 1997: 675). These two channels converge near Khartoum in central Sudan and flow through Egypt before emptying into the Mediterranean.

Although the White Nile's 5584 km span is significantly longer than the 1529 km Blue Nile, the Blue Nile contributes approximately 85% of the total water volume of the Nile itself (Elimam et al. 2008, 2). During the flood season, this average percentage increases to nearly 95% of water volume as the Blue Nile swells with flood waters and the White Nile is drained by a number of marshes and swamps that develop primarily in its upstream locations (Swain 2003: 294).

For Egypt, the river is a critical source of water. Of the approximately 57 km^3 per year of renewable water resources, only 1.8 km^3 originates from internal sources, including aquifers and groundwater absorption (Kundell 2010).[1] Approximately 0.9 km^3 per year is taken from groundwater resources from deep, nonrenewable aquifers in the Western Desert and the Sinai with the remainder coming from sporadic rainfalls (MWRI 2010). Groundwater is used as a significant source of irrigation in the fertile regions adjacent to the Nile, but this water cannot be considered as a separate water source from the river because it is recharged directly by the Nile. In Sudan, approximately 7 km^3 of groundwater is produced internally, while groundwater as a whole supplies 65 km^3 per year of the actual water used, suggesting that demand may eventually overshoot supply (Ahmed 2009). The high variability in river flows throughout Sudan necessitates water storage facilities; four main dams have been built with an estimated storage capacity of 6.9 km^3 (FAO Water Report, 2005). Ethiopia's groundwater resources are relatively uncertain due to a lack of exploration and development, though the country possesses a large number of surface sources such as tributaries, lakes, streams, and aquifers (Kundell 2008). A conservative estimate of the groundwater resources in Ethiopia are 2.86 km^3, while more optimistic researchers suggest a value as high as 13.2 km^3 (Awulachew 2007, 5; Tadesse 2004). Surface water resources that do not replenish the Nile make up approximately 62 km^3 per year (Awulachew 2007, 9).

Population Growth and Water Resource Demand in the Nile River Basin

Predictions of future water demand are uncertain, influenced partially by changes in the demand for food by extant populations (UNESCO 2012, 3). Over the past two decades, North Africa as a whole and the Nile River Basin specifically have been singled out as areas likely to experience water resource issues via unchecked population growth. The Middle East and North Africa are currently home to 6.3% of the world's population, but only 1.4% of the world's renewable water resources (Roudi-Fahimi et al. 2002). As suggested by Rijsberman (2006), water presents a particularly challenging issue when compared to more static resources such as land and fossil fuels in that it occurs in an extremely dynamic cycle of rain, runoff, and evaporation that changes with the seasons.

[1] One kilometer cubed of water(km^3) is equivalent to $2.64172052 \times 10^{11}$ US gallons or 264 billion gallons.

Although estimates differ somewhat by source, most sources agree that the population in the region will double in the next two or three decades (Roudi-Fahimi et al. 2002; Population Action International 2001).[2] Falkenmark (1990: 91) posits that Africa sits in a particularly precarious situation today, attributable in part to the harsh hydro climate that, when combined when estimated population growth in the region, may create a human disaster of unparalleled proportions during the 21st Century (1992: 1). The projected population growth in the region is likely to result in a "water-strangling effect" throughout the region. Of particular concern is the projected geographic distribution of the population growth. Current trends suggest that much of the growth will be centered in the upstream regions with gentler climates (Hurni 2005: 147). Ethiopia, currently home to the largest water supplies, is projected to experience the largest increase in population growth during the 21st Century.

While the academic community has reached near consensus on the increased likelihood of water resource constraints in the region as the population base increases, there is some debate as to how to define "water scarcity." Falkenmark is credited with developing the most widely used and simple system, known as the *Falkenmark indicator* or "*water stress index"* (Falkenmark et al. 1992). Based on estimates of household, agricultural, energy, and environmental water requirements this index proposes 1700 m^3 of renewable water resources per capita per year as the first tier known as *water stress*. Per capita supplies below 1000 m^3 represent *water scarcity*, with supplies below 500m^3 constituting *absolute scarcity*. Insofar as water resources are tied directly to population change, increases in population are likely to be associated with water scarcity. Wallace (2000) suggests that by the Falkenmark indicator, Egypt will meet the requirements for absolute scarcity by 2025, while the remaining countries comprising the Nile Basin will reach water scarcity levels by 2050.

Egypt, with a population of 65 million persons in 2000, annually consumes an estimated 1008 m^3/yr per capita (FAO Water Report, 2005), the equivalent of 266,285 gallons per person per year. Eighty-six percent of this per capita water consumption is used for agriculture, six

[2] A doubling of the population in countries comprising the region will result in a population base exceeding ten percent of the world's total population while holding water resources constant. The net result, by the Falkenmark indicator, is absolute water scarcity for countries in the Nile River Basin.

percent for industry, and eight percent for domestic use. Approximately half of the treated wastewater (2.97 km^3/yr) is used for irrigation while 4.84 km^3/yr of agricultural drainage water is returned to the river annually (FAO Water Report, 2005). Recycled water is typically used for agricultural irrigation. Sudan, with a population of 27 million persons in 2000, annually consumes an estimated 37 km^3/yr (FAO Water Report, 2005), resulting in a per capita consumption of 1367 m^3/yr or 361,117 gallons per person per year. Ninety-seven percent of this consumption is used for agriculture, 2.5 percent for domestic use, and .5 percent for industry. Most of the water consumed in Sudan is drawn from surface water (rainfall and water flow). Currently, water from the dams and aquifers are used sparingly (FAO Water Report, 2005). Ethiopia, with a population of 68 million in 2002, consumed 5.55 km^3/yr (FAO Water Report, 2005), resulting in a per capita consumption of 81 m^3/yr or 21,398 gallons per person per year.[3] Ninety-five percent of this consumption is used for agriculture, 4.5 percent for domestic use, and .5 percent for industry (FAO Water Report, 2005).

Political and Legal History of Water Usage in the Nile River Basin

Throughout the past century, various agreements have divided the critical water resources of the Nile among the countries of the region. El-Fadel et. al (2003) presents a concise history of major agreements and conflicts in the region. The two most notable treaties discussed are those between Britain and Egypt in 1929 and between Egypt and Sudan in 1959. The 1929 treaty reflected Egypt's role as a key territory in Britain's expansive plan to provide the most direct route to India via the Suez Canal. Accordingly, Britain, which sought to ensure water security in Egypt, brokered an agreement stipulating that "no irrigation or power works or measures are to be constructed or taken on the Nile River or its tributaries… in the Sudan or in countries under British administration, which would entail prejudice to the interests of Egypt" (Kendie 1999: 147). Following independence movements across the region throughout the 1950's and 1960's, many agreements adjudicated under colonial conditions were called into question under the "clean slate" doctrine of international law; this doctrine holds that a successor country should not be held liable to treaty obligations of its predecessors (Carol 1999, 278). Eager to secure their

[3] The Ethiopian per capita water consumption levels are among the lowest in the world.

claim to water resources, Sudan sought to revise the 1929 agreement. In 1959 Sudan and Egypt negotiated the "Agreement on the Full Utilization of the Nile Waters" (Elimam et al. 2008, 2). This agreement allowed for the construction of the Aswan High Dam on the border of Egypt and Sudan. The agreement, which assumes an average annual yield of water of 84 km^3 through the dam, allocated 55.5 km^3 for Egypt and 18.5 km^3 per year for Sudan as long as the flow remains constant (Carol 1999, 280). This amount translates to approximately 75% of the river's flow to Egypt and 25% to Sudan. Conspicuously absent from both agreements was Ethiopia, a country that controls the source of the majority of the water in question, and the upstream countries of the White Nile. Under the 1959 treaty, none of these countries are permitted to remove any water from the Nile for their respective populations. Recently, the upstream countries of Ethiopia, Tanzania, Uganda, and Rwanda signed the 2010 "Entebbe Agreement", which calls for a new allotment of water to each country in the basin by qualified experts (BBC 2010). Egypt and Sudan have refused to recognize this agreement as binding, with both countries contending that they will not accept any agreement that substantially decreases their allotted consumption of the Nile River.

Although approximately 40% of Africa's population lives in the Nile River Basin, the majority of the region consist of extremely arid deserts that dictate the pattern of settlement (El-Fadel et al 2003, 108). Accordingly, much of the population is clustered in the river basin. The climate and geography of Egypt presents the most extreme case, where 96% of the population lives on a narrow band of fertile land supported by the Nile (Kendie 1999, 141). Egypt is almost wholly dependent on external water resources, having nearly maximized the use of internal irrigation sources (Swain 2003, 297). Despite these limitations, Egypt dominates the region politically, economically, and militarily, evidenced in large part by the Egyptian gross domestic product (GPD); Egypt's GDP exceeds the combined GDP of the other nine riparian nations (El-Fadel et al 2003, 110). This production comes at a price, however, as Egypt uses significantly more water than the combined total of other nine nations. As a result of their dependence on the Nile, the Egyptians are fierce proponents of their rights under the 1959 agreement. President Anwar Al-Sadat of Egypt held that, "Any action that would endanger the waters of the Blue Nile will be faced with a firm reaction on the part of Egypt, even if that action should lead to war," (Kendie 1999, 156).

In response to these tensions, nine nations (Burundi, Democratic Republic of Congo, Ethiopia, Egypt, Kenya, Rwanda, Sudan, Tanzania and Uganda) created a new inter-governmental organization, the Nile Basin Initiative (NBI), which sought out partnerships and cooperation with regard to the region's water resources.[4] The NBI seeks "to achieve sustainable socio-economic development through the equitable utilization of, and benefit from, the common Nile Basin water resources" (Nile Basin Initiative 2012). While the NBI represents a critical first step in basin-wide cooperation necessary to tackle the region's looming water crisis, critics are quick to suggest that progress of the NBI has been slow. Egypt in particular has continued to develop new water projects unilaterally without input from the other riparian countries. Instead of decreasing their dependence on the Nile, the Egyptian demand is increasing rapidly (Swain 2002, 303). Additionally, the river is of varying importance to all nine nations, and some nations with minimal Nile consumption are less committed to cooperation agreements (Swain 2002, 305). Thus, while the NBI has laid the groundwork for basin wide cooperation, the situation is still dominated by the decades old rivalries between Egypt, Sudan, and Ethiopia over the river's use.

Regional Conflict over Water Access

Following the end of the Cold War, the term "water wars" was coined to suggest the potential for conflict in water stressed regions (Starr, 1991). Starr, writing during the Persian Gulf War, suggested that future water wars would be no different than Saddam Hussein's invasion of Kuwait over oil. She specifically cites problems in the Nile River Basin, where Egypt's water needs are poised to run headlong into the rapid population growth in upstream countries (Starr 1991: 20). This position is in concert with conflict prevention efforts undertaken by the United States Army Africa Command (AFRICOM), as evinced by their enhanced water engineering stability operations in the region (Albritton 2008).

The presence of several characteristics within the Nile River Basin are likely to cause water conflicts: the degree of scarcity, the extent to which the water is shared across regions and

[4] A tenth country was added to this list following the independence of South Sudan. The NBI consists of the Council of Ministers of Water Affairs of the Nile Basin, a Technical Advisory Committee and the Secretariat (Swain 2002: 301).

countries, the relative power between these actors, and the ease of access to over fresh water supplies (Gleick 1993, 84). Commonplace in water war literature is the widespread acknowledgement of statements of regional leaders such as Anwar Sadat and Boutros-Ghali who famously held that subsequent wars in the region will be over water access to Nile River (Gleick 1993: 86). Taking into account these statements and the relative balance of power in the region, the majority of scholars contend that Egypt will be the most likely country to resort to military tactics in an effort to secure water rights. When combined with their historically larger allocation of water under the 1959 treaty, the present case for water wars throughout the region becomes striking.

Significant tensions also exist within the borders of many Nile River Basin countries. Several countries have been classified as failing, failed, or collapsed, including Ethiopia, Sudan, and Uganda (Herbst, 1996; Alao 1999). Sudan is still widely considered a failed state, and the recent split between Sudan and South Sudan has only intensified problems associated with such categorization (Salman 2011). Additionally, social unrest, such as Egypt's "Arab Spring," advance regime changes that potentially undermine the predictability of the established authoritarian governments (Gause 2011).

The academic community is far from unanimous, however, on the prospect of water wars in the future. Beaumont (1994) suggests that while water may be used as a pretext for war politically, it is not likely to be the dominant cause; while people will kill to secure the water required for basic survival, once minimum thresholds are met violence is no longer a given. Similarly, Ohlsson (2000) argues that the risk of conflicts *within* countries are a more likely scenario; international conflicts typically arise out of necessity to avoid the second order effects of instability and institutional change that occur within an area affected by scarcity. In this manner, Ohlsson (2000) echoes the dangers of failing states described above. Alam (2002: 341) presents a case study of the Indus Waters Treaty, which details the cooperation on water policy between two bitter rivals in India and Pakistan. In the midst of ensuing tensions, the two sides signed an international water treaty in 1960, avoiding protracted conflict over water resources, although other social, sectarian, and political conflicts remain.

Averting a Potential Crisis

Averting a potential crisis in the Nile River Basin will require the formulation and evaluation of plausible solutions to issues associated with water resource adequacy. El-Fadel (2003: 116) presents a number of potential mitigating factors that could be introduced, some more feasible than others. These solutions include public awareness campaigns, increasing cultivation of drought and salinity resistant crops, drip irrigation, and transitioning from open drainage water delivery systems that limit evaporation. Falkenmark (1989) stresses the need for tackling the problem at the local level, especially in the underdeveloped regions of the Ethiopian plateau that form the largest source of water in the region, a sentiment echoed by Hurni et al. (2005: 148). Others cite desalination as a potential solution, especially those concerned with Egyptian dependence on foreign water resources and the resulting effects on Egyptian national security (El-Kady et al. 2001: 63; El-Sadek 2010: 876). Whittington (2004) outlines several potential policy solutions aimed at ensuring a peaceful resolution to the situation, including large scale reservoir construction administered by an intergovernmental body, economic integration of water solution efforts, and improved irrigation practices in the Ethiopian highlands.

The United Nations Taskforce on Transboundary Water and other partners have identified Integrated Water Resources Management (IWRM) as a systematic method for dealing with these challenges (UN-Water 2008: 7). The IWRM stresses creation of awareness programs, the training of water managers, and the development of new institutions to manage water in the context of the larger political, economic, and social ecosystem (Al-Radif 1999: 145). While technological and cost factors have limited the introduction of widespread desalination efforts, Egypt is reviewing such research as part of its wider Integrated Water Resources Plan (IWRP 2017; El-Sadek 2010: 878). Nonetheless, the implementation of practices suggested by IWRM has yet to produce significant results due in large part to political and cultural issues (Madema 2008: 37). IWRM alone is unlikely to ensure a successful outcome to water resource adequacy challenges; extant political, social, and technical challenges have undermined effective implementation and application of many IWRM initiatives (Madema 2008: 37).

Summary

The forecasted gap between population growth and water resource adequacy has the potential to affect the entire Nile River Basin. Previous treaties divided the flow of the Nile River between Egypt and Sudan exclusively, though the enforceability of such a treaty is suspect. Increasingly, the upstream nations led by Ethiopia and Uganda have petitioned for a share of the water in anticipation of building future capacity in support of projected population growth. In seeking a resolution, nine nations (Burundi, Democratic Republic of Congo, Egypt, Kenya, Rwanda, Sudan, South Sudan, Tanzania and Uganda) formed the Nile Basin Initiative as a forum for cooperation; however, given Egypt's high water demands and low internal water resources, there appears to be a rather pronounced likelihood of escalating conflict over water in the Nile River Basin during the 21st Century. These dynamics raise questions about the adequacy of water resources given current population rates, the likelihood and timing of conflict in the region, and potential solutions for averting crises. To investigate these questions, we develop a systems dynamics model with the hope of gaining further insight into the underlying issues and possible solutions.

Research Questions

This project seeks to address the following four research questions:

1. What is the timing and geographical location of limits to growth in the Nile River Basin?
2. What are the potential effects of water resource constraints on limits to growth in the Nile River Basin?
3. What is the timing of potential conflict as a result of water scarcity?
4. What potential courses of action may be undertaken to prevent or delay a crisis?

Methodology

Data Sources

Population, fertility and mortality estimates are drawn from the International Census Bureau databases for the years 1990-2012. Three countries were selected and modeled for analysis in this study (Ethiopia, Sudan, and Egypt) because they are located on the banks of the Nile River and have the potential to consume most of the renewable water resources from the river. By treaty, Egypt and Sudan have legal claim to water from the Nile River. Ethiopia controls the headwaters of the Blue Nile, which represents 85% of the total flow through the Nile. Seven other countries, including Burundi, the Democratic Republic of Congo, Eritrea, Kenya, Rwanda, Tanzania, and Uganda, control, to varying degrees, the headwaters of the White Nile, which represents 15% of the total flow of the Nile River. The International Census Bureau (available at http://www.census.gov/population/international/) compiled recorded data via demographers. These data estimates are drawn on surveys, census forms, and migration information, as well as data from the CIA World Fact book. Initial population conditions are presented in Table 1. Fertility and Mortality rates are derived from average crude birth and death rates per 1000 persons in the population between 1994 and 2012.

Country	Initial Population (1994)	Initial Fertility Rate	Initial Mortality Rate	Aquifer Volume (gallons)	Annual Precipitation (gallons)
Egypt	58,157,000	.020520	.0046	2.293×10^{12}	3.375×10^{12}
Ethiopia	54,030,000	.042809	.0133	9.774×10^{12}	6.185×10^{12}
Sudan	24,036,000	.034800	.0150	4.068×10^{13}	6.884×10^{13}

Table1: Initial Start Points for Data Values in the Model

Water data are drawn from the Food and Agriculture Organization of the United Nations (2010, http://www.fao.org/nr/water/aquastat/main/index.stm) and the Encyclopedia of the Earth via the water profiles on Ethiopia, Sudan, and Egypt (http://www.eoearth.org). These sources provide data on the volume of the Nile through each of these countries in addition to information on estimated volumes of aquifers and annual rainfall (Table 1). Aquifer estimates were adjusted to reflect water believed to be accessible to these countries. Annual average rainfall estimates were multiplied by a county's total landmass. Rainfall estimates reflect potential annual groundwater estimates that may replenish the aquifers. We set the initial rainfall estimate to be 50% of the total annual rainfall across the landmass, though we will evaluate the model using a variable measured on a sliding scale from 10%-50% in subsequent analyses of this study. Data were originally presented using metrics associated with either meters or kilometers cubed; we converted all of these values into gallons. The annual renewable capacity (flow) of the Blue Nile is 2.22 $x10^{13}$ gallons while the White Nile capacity is 7.32 $x10^{12}$.

Model Development

System Dynamics

Dynamics are the behavior of a system over time, which are generally complex and non-linear in nature (Forrester, 1961). This complexity is derived from feedback within the system, time delays between decisions and effects, and the learning process of the system (Sterman, 2000). Behavior of the system is described by depicting the loop as a story of the interactions within the system (Meadows, Jorgen and Meadows, 2004). Causal loop diagrams are a key element of the system dynamics approach, which are visual depictions representing the behavior of complex systems. A system will display overshoot and collapse behavior when the exponential growth of the state of the system erodes its carrying capacity to a point where the system can no longer sustain itself (Sterman, 2000).

System dynamics provides an excellent analytical tool for modeling the complex interdependencies associated with water resource adequacy in Nile River Basin. The reinforcing feedback of the population creates exponential growth until balanced by constraints on available water resources that curtail further growth. Population growth within the system places increasingly greater demands on resources until depleting the carrying capacity, which results in an overshoot of the population vice resources and a subsequent collapse of the population. Consequently, system dynamics provides an effective way to simulate the timing of growth, overextension of the carrying capacity of extant resources, and decay until reaching a sustainable equilibrium that balances population growth with available resources.

Our model is built from the Vensim software platform (Sterman 2000). Vensim is a visual modeling simulation program that allows for the conceptualization, analysis, and optimization of models of dynamic systems. It provides a simple yet powerful way to build simulation models from causal loop or stock and flow diagrams based on extant assumptions.[5] This platform enables us to combine population growth models at the country level concurrent with river flow for the region in order to develop an integrated dynamic system model.

Populations for each country (Ethiopia, Sudan, and Egypt) are estimated using models that represent the interactive dynamic between population behavior and water resource adequacy. Figure 2 presents the structure for this causal loop diagram. Although the model contains feedback loops, the underlying structure remains that of one reinforcing loop (a growth action) with two balancing loops (a slowing action) that creates the overshoot and collapse behavior (see Sterman 2000:123).

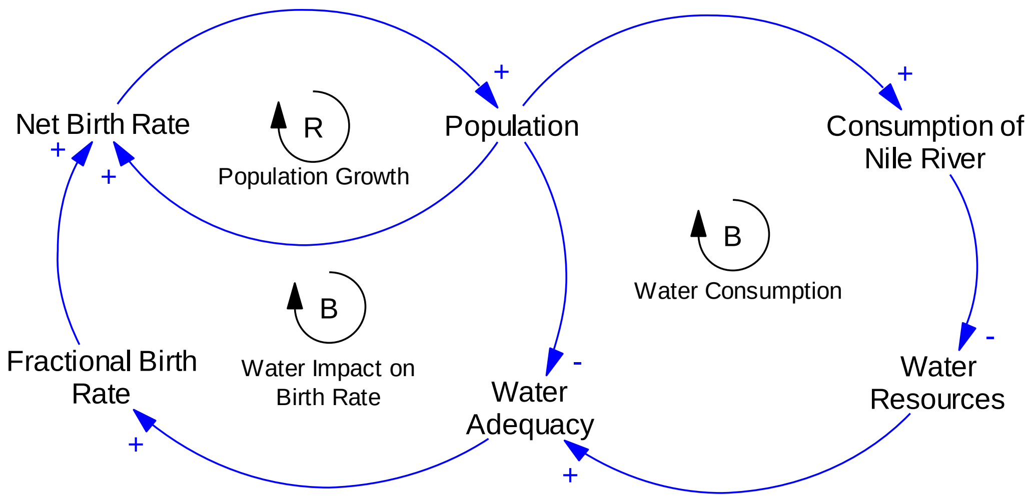

Figure 2: System Level Closed Loop Diagram

Our causal loop diagram consists of feedback loops tied together by a stock and flow diagram. Although Figure 3 presents only the model for Ethiopia, we constructed identical models for each of the three countries included in the analysis. The stock variables consist of population estimates of the three countries while the flows represent rates of change: births that increase population levels and deaths that decrease it. Stocks representing population values are

[5] Stock is an amount or quantity of some variable; flow is a rate of change or the carrying capacity of a system capable of adding or subtracting from a stock. Both the carrying capacity (replenishment or decrement) and quantity (stock) are explicitly modeled. See Sterman (2000:285-291) on system dynamics in action.

initially set at values equal to the 1994 populations.[6] Three flows affect the population: *Net Births*, *Net Deaths*, and *Net Migrations*. The *Net Births* captures the inflow of people into the population and the *Net Deaths* captures the outflow of people from the system. The *Net Migration* captures flows both in and out of the country based on the situation in the country. Migration rates are set to zero in the model unless water resource adequacy (available water divided by required water) drops below a value of 1, which indicates demand exceeds supply. The flows are influenced by the water adequacy variable, which represents the quotient of total consumption of the aquifer and Nile River to the water requirement (per *capita water consumption*population*). *Impact on death rate* is set to a value equal to (1-water resource adequacy). When sufficient capacity exists, this impact is zero; else it is something greater than zero. The larger value of either the *impact on death rate* or *initial death rate* (a constant denoted in Table 1) is selected and used as the rate of change in the model. If the water adequacy rate is less than one, the *initial death rate* is subtracted from *impact on death rate* and multiplied by a constant, where the constant is determined by the proportion of excess population targeted for elimination that is capable of migrating to a neighboring country. For Ethiopia, we estimated this rate to be approximately 5 percent because of the large proportion of the population that lives in the center of the country along the Nile River. Five percent of this excess population is by model definition permitted to migrate to Sudan, which increases the water burden on Sudan by this amount of additional persons who would likely end-up in migrant tent cities. The impact on the birth rate is set to the water adequacy ratio, which is equal to a value of one if sufficient capacity is present or less than one if insufficient. This impact rate is then multiplied by the initial fractional birth rate presented in Table 1 (a constant), which becomes the rate of change for increasing the annual population estimate. The two loops represent reinforcing (increases to quantity) and balancing (decrements to quantity) feedback into estimates of population change.

[6] The date 1994 was selected as an initial start point because it represents a year for which reliable population data is available for several Nile River Basin countries. The validity of the data before this date is potentially problematic. For example, Ethiopia did not emerge from the devastating effects of its 1975 military coup until the early 1990s, an event in which hundreds of thousands of people perished.

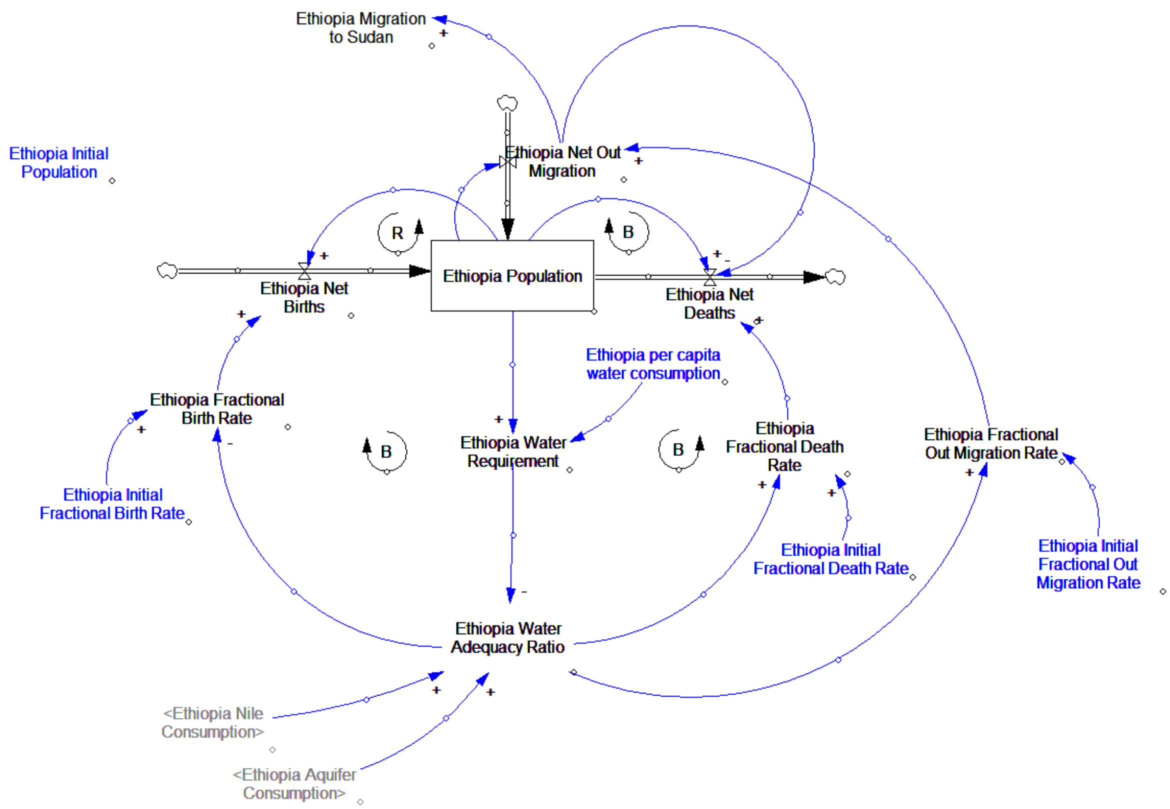

Figure 3: Population Model – Ethiopia

The regional model incorporates the per capita water requirements from the country-level models (*per capita water consumption* population*) to estimate water demand on existing water resources. We begin by modeling the annual renewable flow of the Nile River, both Blue and White portions of the river (a stock), then estimate how much water each country draws from it (a flow). Flows for the Blue and White portions of the Nile River represent the amount of water annually available at the source of each part respectively. These sources flow into stock variables simply called *Blue Nile* and *White Nile*, which shows how much water is currently in that part of the Nile. The output of these stocks is the input flow into our *Nile Sudan* stock variable. This stock represents how much water is in the Nile at the point where the Blue Nile and the White Nile come together in Sudan. As shown in Figure 4, the model of the Nile River follows the pattern of a single outflow into a single stock for each country until it finally reaches the Mediterranean Sea.

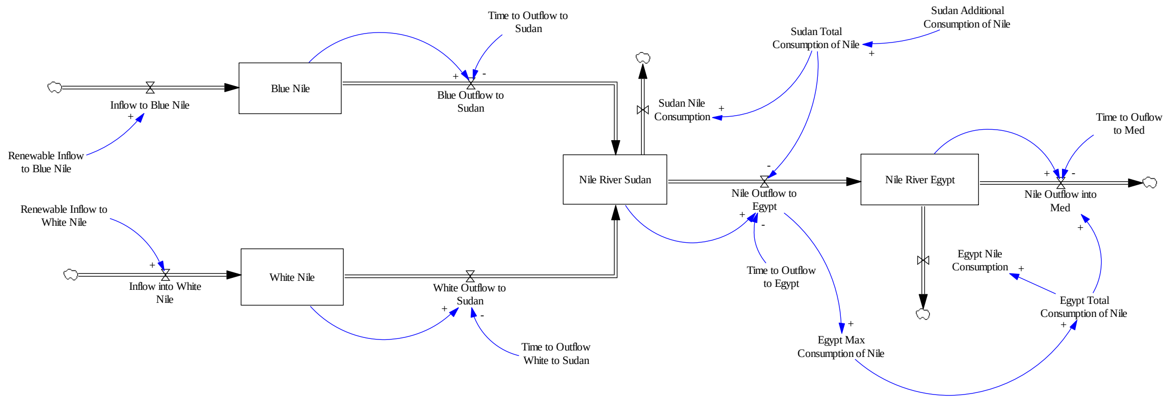

Figure 4: Nile River Model

To model the amount of water each country consumes from the Nile River, we have created loops to reflect the total water available and the total consumption permitted by treaty. Ethiopia, by definition, is not permitted to draw any water from the Nile while the Sudan is permitted to draw 25% of the total flow annually. We've included a factor, *Treaty Adherence*, which allows us to modify this assumption for both Ethiopia and Sudan. Additionally, we acknowledge that each country contains its own renewable supply of water independent of the Nile River. We account for the volume of water available in the country's respective aquifer and/or dam as part of the regional model. The water available for consumption is the sum of the water consumed from the Nile River and the aquifers and/or dam available in each country. Figure 5 illustrates this structure for Ethiopia. The model defines the aquifer as a stock and groundwater captured to replenish the aquifer, based on annual rainfall, as a flow.

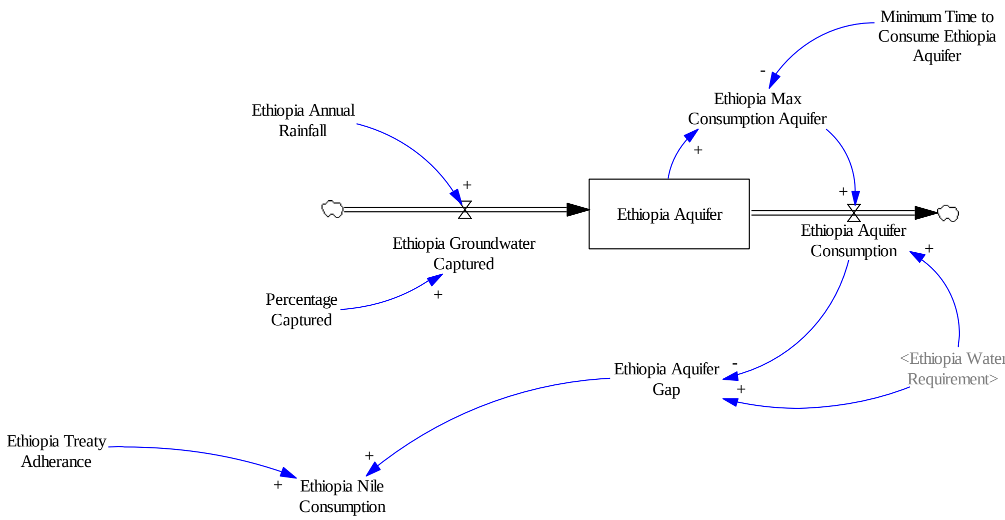

Figure 5: Ethiopia Aquifer Model

The regional model incorporates the per capita water requirements from each of the country-level models (per capita water consumption* population) to estimate water demand on existing water resources, including internal sources such as aquifers and rainfall as well as Nile River resources. The regional model is presented in Figure 6. The population model for each country is connected to the Nile River flow model via the water requirements of each country. The countries are situated within geographical proximity to one another, with Ethiopia located upstream followed by Sudan and then Egypt. Ethiopia is, by treaty, not permitted to draw any water from the Nile while Sudan is permitted to draw 25% of the total flow annually. A simple toggle in the model allows for modification of this assumption for both Ethiopia and Sudan.

To model the amount of water each country consumes from the Nile River, we designed loops to reflect the total water available and the total consumption permitted by treaty. These quantities are supplemented by the amount of internal water resources available in the country's respective aquifers and/or dams.

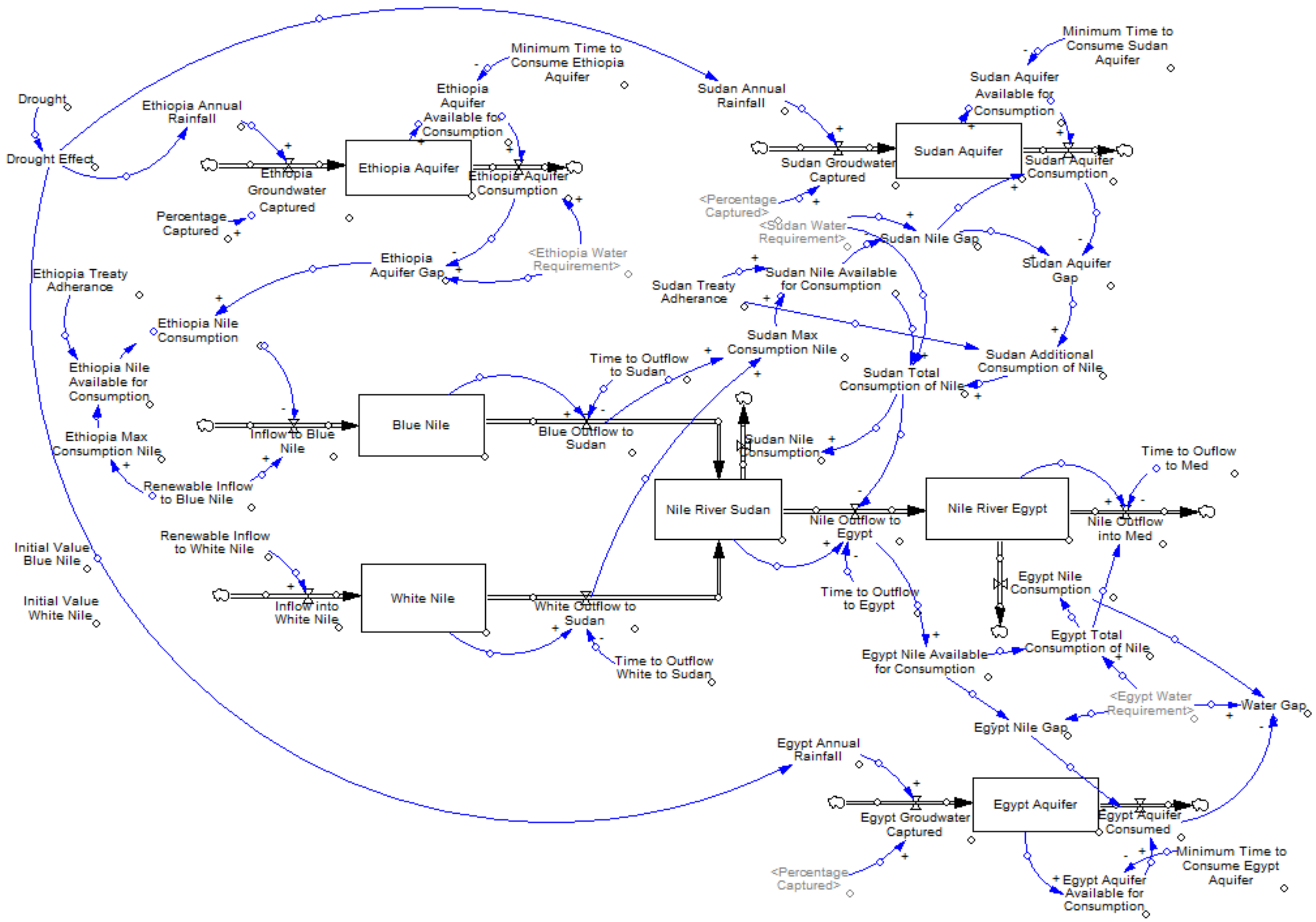

Figure 6: Complete Regional Model

Model Validation

Checks on the validity of the model were conducted in two specific ways. First, estimates generated for each variable in the model were assessed to ensure that they maintained a logical consistency in the actual data produced by the model. Toward this end, we ensured that the inflows minus consumption levels equaled the outflows. Second, we checked the estimated population data produced by the model for each country with the corresponding historical population data obtained from the Census Bureau (Table 3, Column 2), denoting the difference between the two figures for 2012. We obtained correlations and corresponding R^2 values in the .9995 range for all three countries, suggesting that variation in the estimates coincide with actual variation in the historical population data. Accordingly, we checked the population estimates for each country with the historical population data to ensure that estimates produced by the model were approximately equivalent to the actual historical data generated over the 19 year interval (1994-2012). Observed differences between actual and estimated data were comparable for Egypt and Ethiopia and somewhat less so for Sudan; however, the R^2 values were high for each set of actual and estimated population data. Overall, the model appears to accurately predict variation in population growth for the interval 1994 through 2012 (Table 3).

Country	Actual Population Differential (1994-2012)	Differential as a Proportion of 2012 Population	R^2
Egypt	8,688,000	.90	.9997
Ethiopia	10,804,000	.88	.9935
Sudan	11,293,000	.67	.9970

Table 2: Checks on the Validity of Population Estimates

Based on extant assumptions employed and tested in this model, we estimated projections for population growth and water resource adequacy from 2013 through 2100. Arguably, these projections are extrapolations that extend beyond available data. While projections are always suspect because of factors that are either unknown (i.e., the human casualties of future wars) or not correctly modelled (rates of change), we build this model on the foundation employed by Meadows et al. (1972) and Meadows et al. (1974) in their assessments of limits to growth of resource capacity and sustainability of world-level aggregations. The analysis is conducted initially with seven assumptions intact: (1) that the Nile River serves as a renewable water resource with constant discharge rates; (2) that changes in population do not alter current pollution levels of the Nile River; (3) that Ethiopia and Sudan adhere to the 1959 treaty; (4) that the geographical area represented by the Nile River Basin is free from drought during the 21st Century; (5) that half of the average annual rainfall collected through groundwater runoff finds its way back to the aquifers annually; (6) that the fertility rate remains constant throughout the 21st Century; and (7) that the per capita water consumption levels remain constant throughout the modeling process. The general model is inclusive of these seven assumptions. The model is then rerun to permit Ethiopia to violate the 1959 treaty, drawing from the Blue Nile water as is needed to meet population demand. While relaxing the 1959 treaty assumption, we then vary the amount of groundwater seepage into the aquifer from 50% (the initial assumption) to 25%. We then incorporate a factor to estimate the effects of a drought, which pulses the model for selected intervals of time (i.e., one year, five years, ten years, etc). We then examine the effects of the model when per capita water consumption levels are reduced to reflect technological advances in irrigation practices. We then examine model estimates when birth rates are attenuated to reflect implementation of growth policies comparable to China's one child per family. Finally, we examine the effects of reducing water use and supplementing water resources through desalination. The result of these separate runs provide estimates as to severity of the regional impact on the population of the three countries given different scenarios of water resource adequacy during the 21st Century. In managing successive runs of the model in this manner, we can estimate the approximate timeline when intra-national and regional crises are most likely to emerge in Nile River Basin during the 21st Century.

Results

Our model is designed to examine the interactive dynamic interplay between population growth and water resource adequacy. By examining the general model as a benchmark and the trends under each test case, we provide estimates for limits to growth in the region based on water resource constraints. The two primary base cases are presented in the body of the report, while extended results based on the relaxation of assumptions are presented in Appendix A.

Base Case 1: Adherence to 1959 Treaty

All countries modeled adhere to the requirements of the 1959 treaty. Egypt receives up to 75% of total Nile flow per year, and Sudan is allotted the remaining 25% of the flow. Ethiopia is prohibited by model definition from accessing water from the Nile River. Figure 7 shows the population output for each country from 1994-2100.

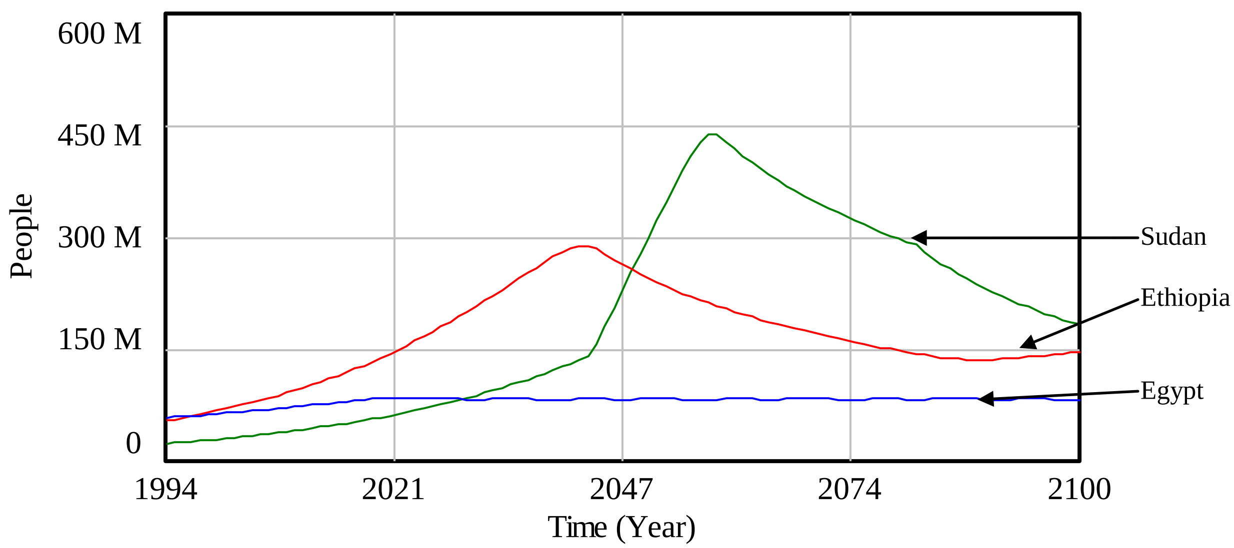

Figure 7: Simulation Based on the Treaty Adherence Assumption

Under this scenario, Ethiopia will experience a population implosion by mid-century if it adheres to the 1959 treaty requirements. Accordingly, by mid-century Ethiopia will drain the groundwater from its aquifers, thus overshooting available supply and resulting in a rapid collapse in population. The only available water on which Ethiopia can rely will be groundwater from anticipated precipitation. The model estimates catastrophic implications for Ethiopia's population beginning during the decade of 2050 with a projected decrease of nearly 150 million people by the end of the century. The population stabilizes toward the end of the decade only because we assume that 50% of rainwater per year is captured as renewable internal water resource. Sudan is unaffected during the time period studied due to large internal water resources from aquifers, which we assume to be accessible via extraction techniques. Egypt experiences water restrictions on its population in 2013, but avoids a severe population implosion. Patently, the results from this scenario are unrealistic; Ethiopia, the source of 85% of Nile River's water, would not conceivably allow upwards of 150 million of its inhabitants to perish while Egypt utilizes the Nile resources.

Base Case 2: Non-Adherence to 1959 Treaty

In the second case, we relax treaty restrictions on Ethiopia, thereby permitting them full access to the Nile River as required. Downstream countries are forced to accept this condition and receive whatever Nile resources remain (Figure 8). This scenario suggests an alternative outcome to the first model, whereby Ethiopia experiences explosive, unhindered growth throughout the 21st Century, reaching a population of approximately 800 million people by 2100. Sudan is unaffected until the latter part of the century, when its water requirements exceed its capacity. Egypt's population begins to decline around 2015 through the end of the century. Egypt's decline is slower than Ethiopia's decline in the treaty adherence model; the country loses about half of its 2015 population by the end of the century. Each year a fraction of the population is reduced due to increases in Ethiopian water use in support of their own growing population. However, both models reveal similar outcomes: water constraints at the regional level will force a reduction in population. With water levels held constant, population levels cannot grow unabated without detrimental human consequences.

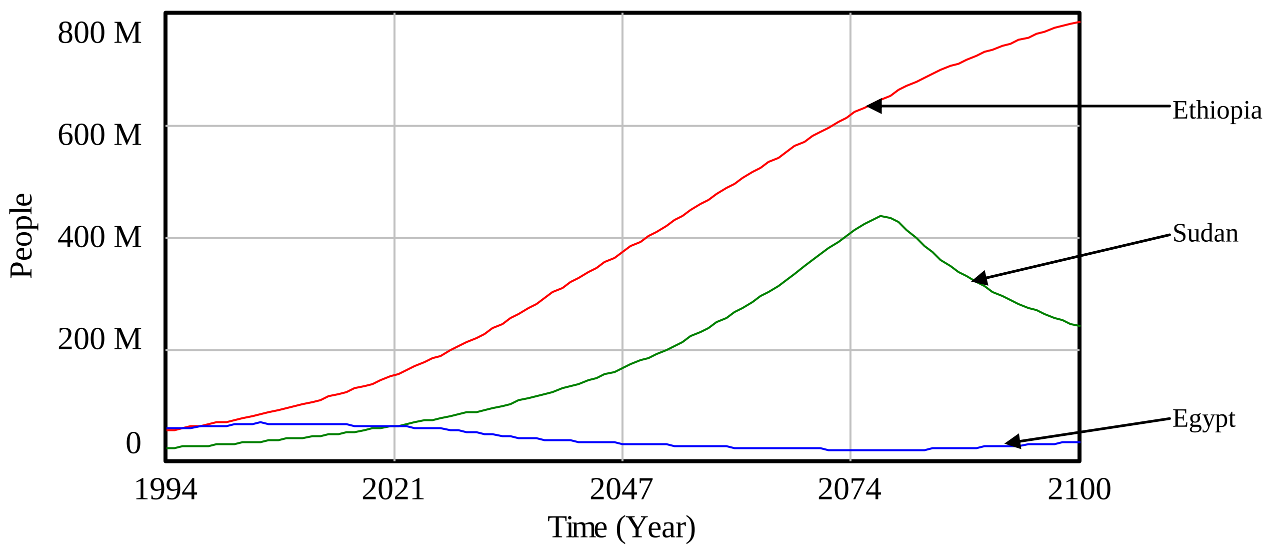

Figure 8: Simulation Based on the Relaxation of the Treaty Adherence Assumption

Relaxation of Assumptions

Following these base models, we explored a relaxation of various modeling assumptions, including aquifer recharge rates, droughts, reduced per capita water use, and the potential solution of desalination. Each of these subsequent cases is modeled on the assumption that the 1959 treaty is untenable: Ethiopia will draw water from the Nile River to support its population.

Reduction of the aquifer recharge rate significantly impacts the timing and severity of the eventual population implosion. Figure 9 illustrates the most drastic case, a reduction from the base assumption of 50% to 25% per year. This scenario reflects decreased internal water resources due to climate change and desertification in the region as well as the uncertainty in total groundwater resources and groundwater recharge in the region, which is fairly high for both Sudan and Ethiopia.

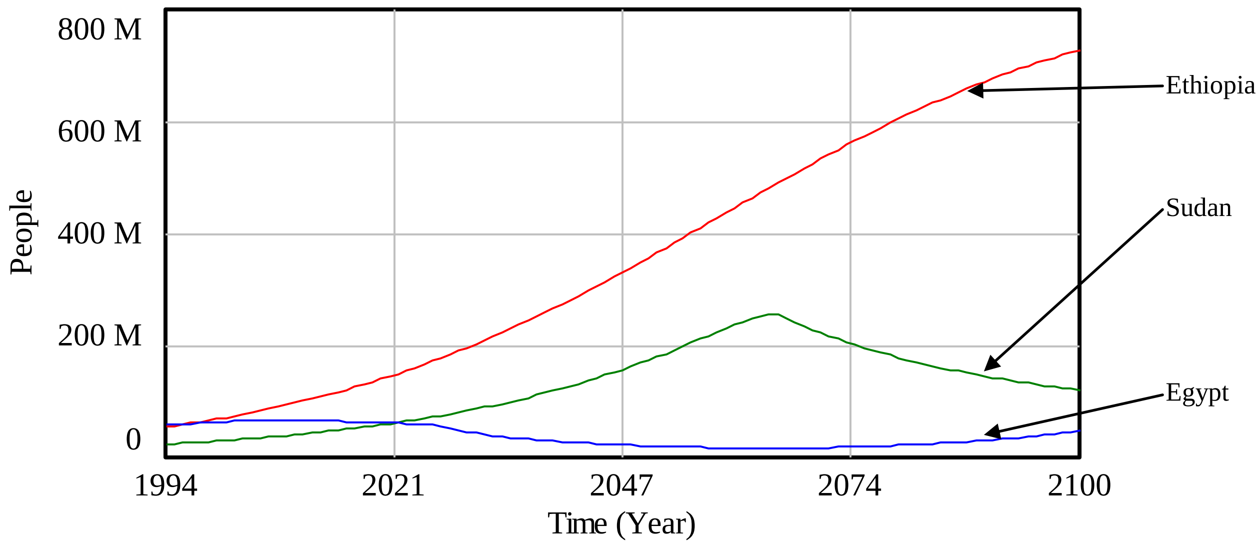

Figure 9: Aquifer Recharge Rate Assumption Reduced to 25%

Under an aquifer recharge rate of 25 percent, Egypt will face a severe population crisis in the decade of 2020 and a steady population decline collapse over the remainder of the century of nearly 50 million people. The rate of population decrease is further intensified in the 2050's when Ethiopia begins drawing from the Nile more heavily. Sudan experiences a population crisis in the 2060's. Ethiopia would consume a greater proportion of the Blue Nile as its population continues to increase. By 2060, Ethiopia's consumption of the Nile River undercuts Sudan's water requirements, which results in a situation where Sudan's water requirements exceed its capacity. At this point, Sudan's population decreases and provides Egypt with a slight increase in available water from the Nile River.

Introducing droughts has a less significant effect. The timing and severity of various drought scenarios were explored, from 33% to 50% drought and start dates from 2025 through 2045. In general, droughts were not sufficient in-an-of-themselves to cause overshoot and collapse outcomes in the model. However, when their timing coincides with the normal overshoot and collapse of a given base scenario the drought serves to severely exacerbate the problem. Figure 10 illustrates the impact of a ten-year drought beginning in 2045 with a 50% aquifer recharge rate. For example, if a drought occurred by mid-century when Egypt is experiencing a rapid initial population decrease, the drought conditions exacerbate the outcomes in the short-term.

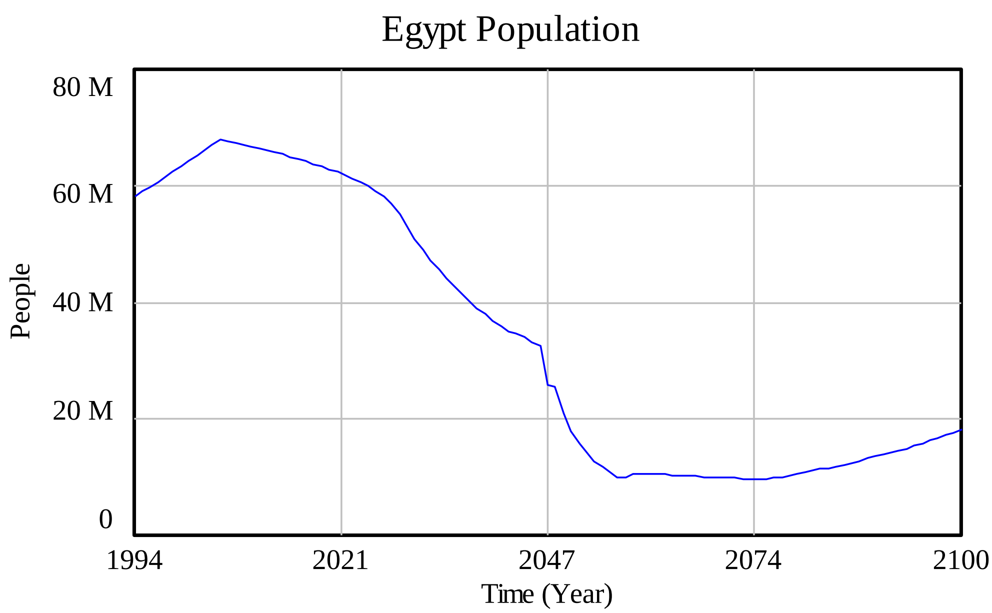

Figure 10: Drought Assumption Relaxed with a 10 Year Drought in 2045

We then explored a ten percent reduction in per capita water use for all countries. Table 2 displays these adjusted rates for each country. Although this change represents a demonstrable reduction in water use, the effects on the model were marginal. Sudan and Ethiopia were unaffected while Egypt was able to sustain its population longer (about an extra decade) before experiencing decline.

Country	Estimated Per Capita Water Consumption	Differential as a Proportion of 2012 Population
Egypt	266,285	239,657
Ethiopia	21,398	19,258
Sudan	361,117	325,005

Table 2: Adjusted Per Capita Water Use

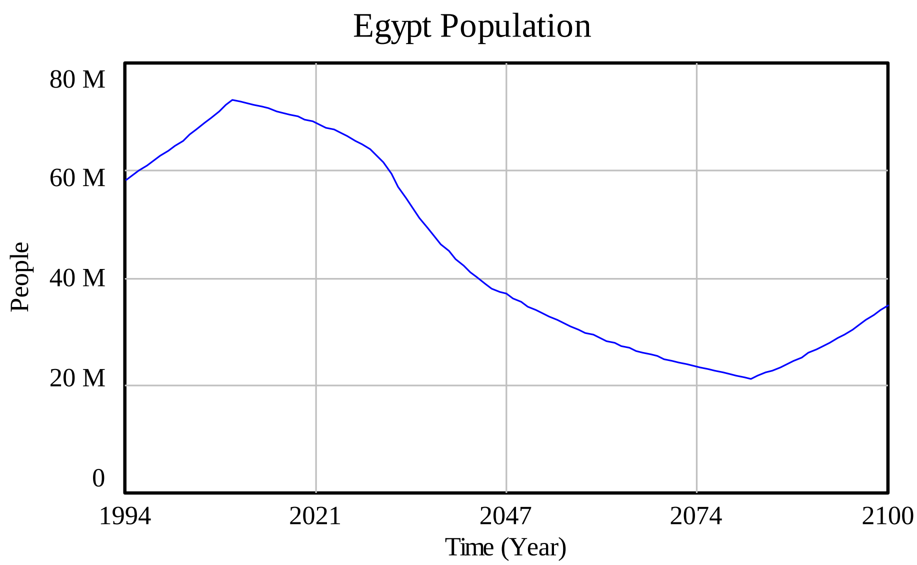

Figure 11: Per Capita Water Consumption Assumption Reduced by 10%

Few countries have successfully manipulated fertility rates in a manner that changes unconstrained population growth rates; China, with its one-child per family policy, has reduced its crude fertility rate to 12 persons per 1000 people in the population or approximately 1.5 births per woman. Canada with no such policy maintains fertility rates comparable to those of China. As a further basis of comparison, France and the United States maintain crude fertility rates of 13 births per 1000 person in the population or approximately 2 births per woman. Ethiopia, Sudan, and Egypt have crude birth rates of 43, 35, and 21 births per 1000 persons in the population or approximately 6, 4, and 3 births per woman for each country respectively. If applied to the Nile River Basin region, we observe that changes in fertility rates can alleviate much of the pressure associated with the levels of unconstrained growth depicted above.

We examined attenuation of potential constraints on water resources if these countries in the Nile River Basin were able to adjust fertility rates downward. For example, if Ethiopia and Sudan reduced fertility levels to 30 births per 1000 persons in the population by 2023, as shown in Figure 12, Ethiopia's population would be approximately 200 million persons less than that estimated by its current fertility rate Figure 8 above; ensuring greater water flow into both Sudan and Egypt. However, at 30 births per 1000 persons in the population, the general trend for all three countries remains comparable to that presented in Figure 8.

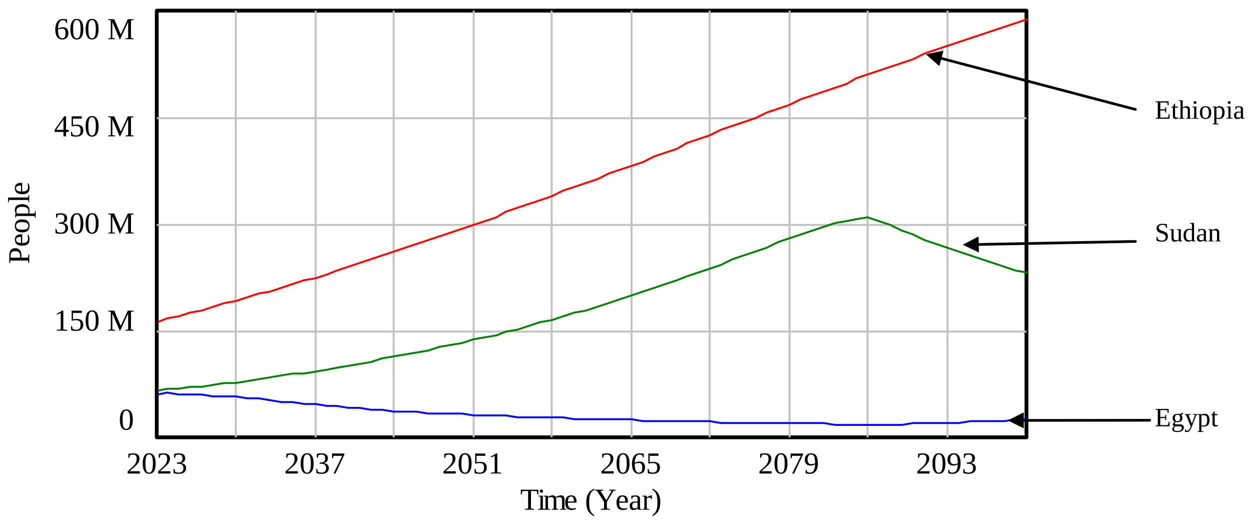

Figure 12: Ethiopia and Sudan Reduce Birth Rate to 3.0 per 1000 Persons in the Population by 2023

If, by 2043, birth rates were reduced to 20 persons per 1000 persons in the population of each the three countries, then the trend changes notably; this outcome, as shown in Figure 13, occurs primarily because Ethiopia's population growth is reduced by nearly half of that observed in Figure 8.

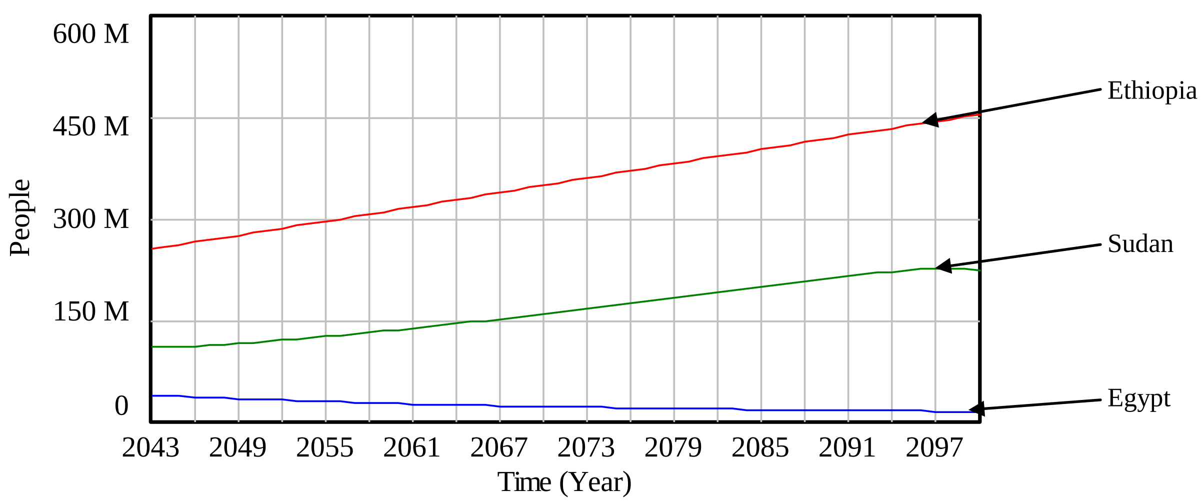

Figure 13: Ethiopia, Sudan, and Egypt Reduce Birth Rate to 2.0 Per 1000 Persons in the Population by 2043

We explored the inclusion of widespread desalination in Egypt to examine its impact on water capacity. As is evident from Figure 12, an additional inflow was added to the model to provide the possibility of using water drawn from the Mediterranean Sea after being desalinized through hypothesized facilities. Maximum plant capacity is set at 90,669,400,000 gallon per year based on estimated production of the world's largest desalination facility plant, which is currently being constructed in Saudi Arabia (Doosan, 2010). For Egypt, with a per capita water consumption level of 266,285 gallons per person, each operational desalinization plant could meet water requirements for an additional 340,500 persons. Maximum plant capacity is equivalent to this estimated value times the number of plants in operation.

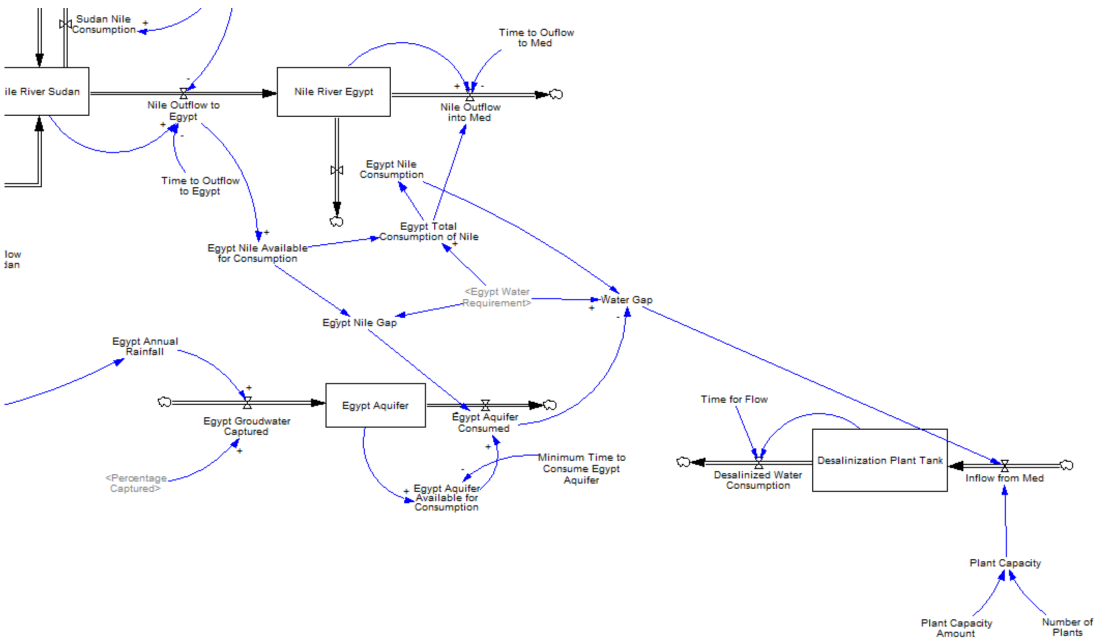

Figure 12: Modeling Desalination to Meet Projected Egyptian Population Growth

Figure 12 illustrates the required annual water capacity to meet unconstrained population growth in Egypt throughout the interval 1994 through 2100. Based on our model, Egypt would begin requiring desalinized water in 2013 with levels increasing annually. Insofar as the construction of these facilities requires several years to complete, our model indicates that Egypt is already falling behind unconstrained growth. By the end of the century, the required output would be equivalent to the maximum production of 1200 of what is today the world's largest facility; the construction cost alone to build 1200 plants will exceed approximately $1.7 trillion US dollars. This cost does not factor in estimates for the maintenance, production and energy costs associated with plant operation. The cheapest current plants produce water at roughly $2.00

per 1000 gallons. Assuming this cost held constant, by 2100 these costs would exceed $200 billion per year. Thus, without technological increases in plant output and decreases in the cost of construction and maintenance, desalination does not appear to be a feasible course of action to address constrained water resources in Egypt.

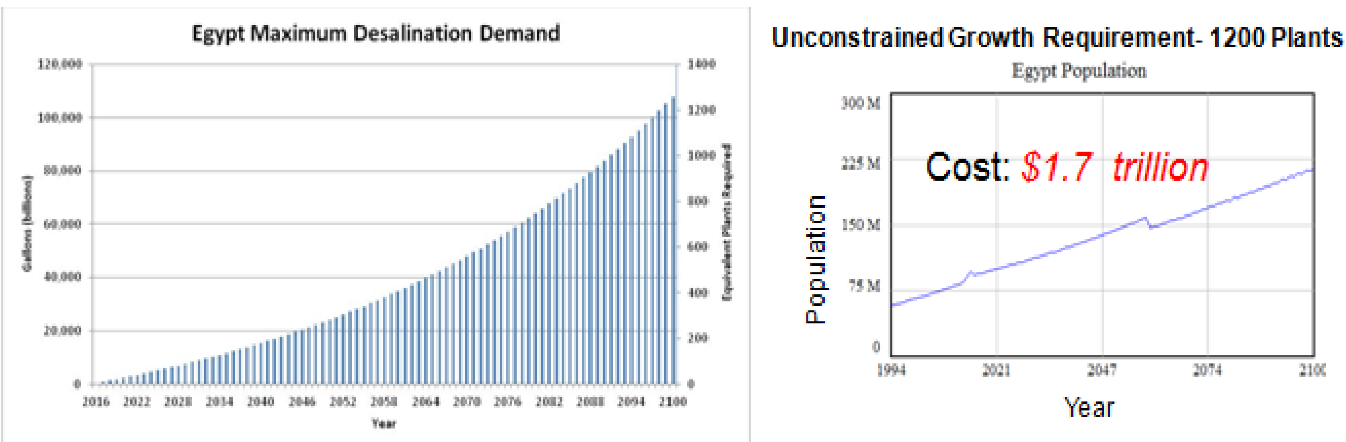

Figure 13: Desalination Requirements to Meet Projected Egyptian Population Growth

Summary of Results

In the short term, Ethiopia does not require water from the Nile River; however, long term unconstrained growth will require the use of water from the Nile water during 21st Century. Egypt faces a water shortage at current resource levels, and is extremely sensitive to upstream Nile utilization. Optimistic forecasts identify mid century as system breaking point without treaty adherence, while more conservative assumptions suggest severe issues as early as the 2020's. These results are very sensitive to groundwater resources and groundwater recharge rates, but less sensitive to reductions in per capita water use and drought conditions. Finally, desalination is not a feasible mechanism to maintain current growth rates in Egypt indefinitely given current technological constraints.

Discussion

This study was initiated to examine the potential limits to growth within the Nile River Basin based on actual and projected estimates of population size and the adequacy of water resources between 1994 and 2100. Results from this study suggest that the limits to growth in the Nile River Basin are likely to be most pronounced in Ethiopia and Egypt by the middle of the current century. Egypt, a country with few internal water resources and an extreme dependence on the Nile River, is already experiencing water resource constraints. Ethiopia will reach the limits of its internal water resources beyond the Nile River by mid-century if it adheres to the 1959 Treaty. In support of its population, it must begin to draw heavily from the Nile by mid-century, which will undermine Egypt's water resources.

The potential effects of water resource constraints on limits to growth in the Nile River Basin are extreme. Ethiopia, given current fertility rates, risks the loss of upwards of 150 million people by mid-century if it adheres to the 1959 Treaty because it will overshoot its available water resources. Consequently, we do not believe that Ethiopia will adhere to the Treaty. One example of this treaty violation is the construction of the Grand Renaissance Dam in Ethiopia along the Blue Nile, which, upon completion, is expected to profoundly change the allocation of water resources in Africa (Carlson 2013). If Ethiopia successfully draws needed water from the Nile River in support of its growing population, then Egypt will experience a gradual decline in its population throughout the remainder of the century as Ethiopia's water consumption requirements increase. Egypt faces a water shortage at current resource levels and is extremely sensitive to upstream Nile utilization.

Attenuation of the impending water crisis is an issue of demand and supply. To address it, fertility rates must decline within each of the three countries along with per capita water consumption levels while new water resources must be created to increase supply. Optimistic forecasts identify mid-century as system breaking point without treaty adherence, while the presence of droughts or increases in per capita water consumption levels could escalate the crisis as early as the 2020's. These results are very sensitive to groundwater resources and groundwater recharge rates, but less sensitive to reductions in per capita water use and drought conditions. The most promising course of action is a decline in fertility rates to levels below two children per family or one per adult. When coupled with technological advances in irrigation systems, per capita water consumption demands will decline because of fewer people and more effective irrigation systems. Desalination, under scenarios of unconstrained population growth, is not a feasible option given current technological constraints. However, the construction of desalination facilities and dams might be a feasible response to close the gap if demand is curbed through lower birth rates and per capita consumption.

Findings from our analysis suggest that water resource constraints will severely impact the limits to growth in the Nile River Basin. Indeed, Egypt is already reaching the limits to their sustainable growth. In this regard, our findings echo those originally reported by Meadows et al. (1972). Their text, *Limits to Growth*, includes a number of additional factors that are not captured in our model or are only indirectly addressed, such as pollution, climate change, and desertification. Pollution is a particularly important component, since significant levels of water pollution could have devastating impacts on the functional use of available water downstream.

It is important to note that our model results cannot be taken too exactly. Insofar as our model relies on the use of historical data and extant assumptions to make predictions about future outcomes, there is a degree of uncertainty in the exact timing of crises as a result of "extrapolation bias." Accordingly, our model is most useful as a tool for understanding the overarching behavioral tendencies of the Nile River Basin system under various assumptions as opposed to making predictions for specific years. The time interval and location of limits to growth in the region shift based on given model assumptions. Under the most plausible base scenario where Ethiopia draws water from the Nile River in support of its population demand, Egypt will experience a severe population crisis near mid-century. Under other scenarios, the timing of a potential crisis shifts forward by two or three decades; the most severe simulation predicts a significant population crisis for Egypt as early as the 2020's. Figure 10 summarizes these outcomes based on different modeling assumptions.

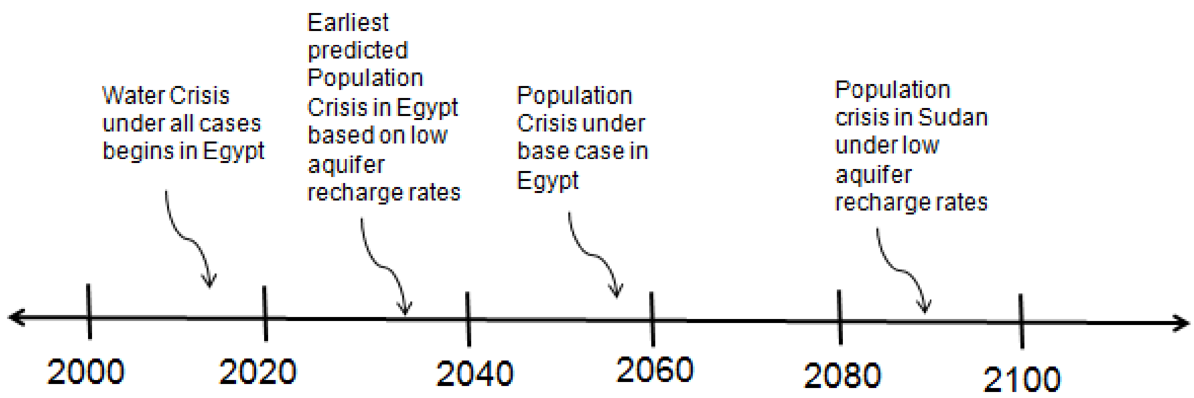

Figure 14: Crisis Timeline

Our model demonstrates that the conditions for conflict are readily apparent in the region. As a result of these crises and in light of previous rhetoric, conflict is most likely to occur between Egypt and Ethiopia. Egypt has previously asserted its historic right to most of the water resources in the Nile River. Our model highlights the precariousness of this situation; if a cooperative solution is not found, Egypt will be the likely aggressor in any conflict since they are most at risk. Sudan and Ethiopia are both likely to defend their water rights against any Egyptian aggression, whether it is militarily or diplomatically, since it is in their long term interest to do so. Additionally, the region is experiencing tremendous social and political tension within each of the three countries, thereby further kicking the proverbial can down the road until such time as the anticipated effects of the crisis cannot be modified.

Based on current technology and cost constraints, desalination alone is not the answer to Egypt's water issues, given unconstrained population growth. The construction costs required throughout the century of $1.7 trillion represent over three times the annual GDP of Egypt, and production and maintenance costs would dwarf this value over the long term. Significant technological advancement is required to make this solution feasible for unconstrained growth in the region. For example, a team of researchers at Lockheed Martin have recently developed a process they claim will significantly reduce the amount of energy needed to desalinate water (Yale E360, 2013). While this research is a promising development for the feasibility of desalination, our model predicts that Egypt is facing an immediate water crisis. It remains to be seen whether these and other future technological advances can be implemented in time to stave off conflict in the region.

One should note that the limitations of models, particularly their assumptions and selection of variables, provide only a partial understanding of system dynamics. However, simple models, such as the one presented in this study, provide a mechanism with which to simulate, under controlled conditions, the probable outcomes of an evolving dynamic process. Modifications to the environment in the form of technological advances (desalinization; irrigation), modest declines in per capita consumption, or the enactment of policies intended to reduce population growth would probably come too late to attenuate or reverse demographic or environmental degradation. However, one must acknowledge, as did Meadows et al. (1972: 87), that the extension of resource availability by one or more decades might provide time to implement remedies that are not apparent at present. One outcome is certain: the projected population growth of the Nile River Basin will most certainly overshoot the carrying capacity of its resources, notably water, by mid-century. The consequences of this overshoot and collapse process will fundamentally alter human behavior and the fabric of a stable (or predictable) social order. The challenge is to impose limits on ourselves that achieve an equilibrium state.

Conclusions

A water crisis in the Nile River Basin is inevitable. Enforcement of 1959 treaty provisions is infeasible; however, Egypt is unlikely to subsist on anything less than their current water allotment. Impact of crisis can be attenuated only by reducing birth rates, reducing per capita water consumption, or increasing water supply. Desalination does not appear to be the “magic bullet” solution touted by some experts at present. While desalination may offset Egypt’s water deficit to some degree, current technology and cost limitations may curtail overall impact without significant technological advances. As a result, regional and international influence will be essential to keeping peace in the region. If past levels of basin wide cooperation are a reliable indicator, conflict is highly likely when regional actors are left to resolve the crisis on their own. External arbitration through the United Nations or African Union is now necessary in order to keep the crisis from escalating to all out conflict. A nonviolent solution to this dilemma is possible by manipulating three possible factors: declines in population growth rates, declines in per capita water consumption, and/or increases in additional water sources.

Recommendations for Future Study

Our model contains a number of assumptions and limitations that provide several plausible avenues for future study. First, due to a high degree of sensitivity with regard to internal aquifer resources and aquifer recharge rates, more thorough assessments and planning are required to evaluate, monitor, and manage the allocation of internal regional resources. While we forecast that Sudan is potentially capable of sustaining itself largely on internal resources alone, its poor infrastructure throughout the country erodes the predictability of internal water resource estimates. Additionally, intra-national dynamics such as settlement patterns, distribution of water sources, and infrastructure must be modeled to assess water resource adequacy with more fidelity, especially when discussing potential courses of action. Plausible solutions that can be assessed at this level include better irrigation practices, land use practices, water transport, and reservoir development, which do little to alleviate the impending crisis unless fertility rates are dramatically reduced. Extending the model to an intra-national level would allow much more robust and accurate predictions than exist at present; however care must be exercised to ensure that model complexity does so excessive that the power of the model is diluted. There is a need to develop value metrics to better assess these and other courses of action in order to draw more tangible solutions for action. In sum, the impending limits to growth problem in the Nile River Basin will not go away without being addressed; significant work remains to be done in order to avert a potential crisis.

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