

Estimating the Effect of Climate Change on the Hydrology of the Nile River in the 21st Century

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Abstract

The purpose of our study is to examine the impact of environmental and human factors on the carrying capacity (streamflow) of the Nile River throughout the 21st Century. We employ estimates from 33 General Circulation Models (GCM), inclusive of Representative Concentration Pathways (RCP) 4.5 and 8.5, within a Vensim model in order to model the dynamic interplay between climate change and streamflow for the Nile River Basin. We subdivided the time periods into 30-year intervals for 2010-2039 (early century), 2040-2069 (mid century), and 2070-2099 (late century). Using this model, we estimate the potential effect of the proposed reservoir fill rate of the Grand Ethiopian Renaissance Dam on streamflow for downstream countries. We offer four key findings. First, temperature is projected to increase continuously in all assessed regions of the Nile River Basin through the 21st Century. Second, precipitation is projected to increase water capacity (i.e., streamflow) in source countries (Regions 3 and 4), maintain a moderately constant capacity in Region 2 (Sudan), and declining streamflow in Region 1 (Egypt), particularly after 2050. Third, a reservoir fill rate of 10 to 15%, given projected increases in streamflow within the Blue Nile region, would build hydroelectric capacity in Ethiopia while concurrently ensuring a constant level of streamflow throughout Sudan and Egypt. Fourth, increasing population throughout the Basin during the 21st Century will further strain water capacity. Implications of these findings are discussed in the context of a comprehensive water management system.

Introduction

Four key sources of uncertainty persist about future climate change key sources of uncertainty persist about future climate (Knutti and Sedláček, 2013). First, what is the level of greenhouse gas emissions? Second, what are the concentrations of those emissions in the atmosphere? Third, how does the presence of greenhouse gas concentrations affect the balance of energy in the atmosphere (i.e., radiative forcing)? Fourth, how does the climate respond to changes in the atmospheric concentrations of greenhouse gasses? This paper focuses primarily on the fourth issue, notably on the dynamic processes connecting climate change outcomes to the sustainability of human systems. By using two scenarios of future greenhouse gas concentrations (RCPs 4.5 and 8.5) and 33 climate models, we acknowledge the complexity of climate impacts and explore a range of possible scenarios for streamflow outcomes in the Nile River Basin.

Considerable evidence supports the contention that climate change will increase average temperatures throughout the Nile River Basin (Di Baldasserre et al. 2011; El-Din 2013; Chen 2012). As shown by the Clausius-Clapeyron equation, in high temperature regions such as the Nile River Basin, even a small increase in temperature can yield a large increase in potential evaporation; large increases in precipitation would be required to simply maintain the existing water balance. There is less certainty about how precipitation may change in the basin, but such changes are likely to create the potential for either inundation of arable land through enhanced precipitation levels or droughts through the attenuation of such levels. Thus, climate change is likely to increase competition for water in the region.

With the rapid growth of population coupled with episodic food insecurity, the Nile River Basin is a potential flash point for conflict over water. We use the well-documented strong relationship between

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1) temperature and streamflow, and 2) precipitation and streamflow to explore a potential added stressor for the region; climate change. This study represents an initial effort to begin to quantify the extent of climate effects on streamflow in the Nile River Basin. Additionally, in assessing the estimated effects of climate change on streamflow, we consider the additive effect of water diversion necessary to fill the reservoir of the Grand Ethiopian Renaissance Dam on the Basin's water capacity. The purpose of our study is to examine the impact of environmental and human factors on the carrying capacity (streamflow) of the Nile River throughout the 21st Century.

Methodology

Data Sources

Four regions were included in this analysis. Collectively, these regions span the Nile River Basin. Regions 1 and 2 are aligned with Egypt and Sudan/South Sudan respectively. Region 3 includes most of Ethiopia while Region 4 represents the Lake Victoria area. Ethiopia is the source of the headwaters of the Blue Nile and Atbara Rivers, which represents approximately 85% of the total volume of the Nile River. 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. These regions were selected because of hydrological features (Elshamy 2006), approximate administrative boundaries of nations, and the presence of at least one weather station to support historical validation of the model (Figure 1).

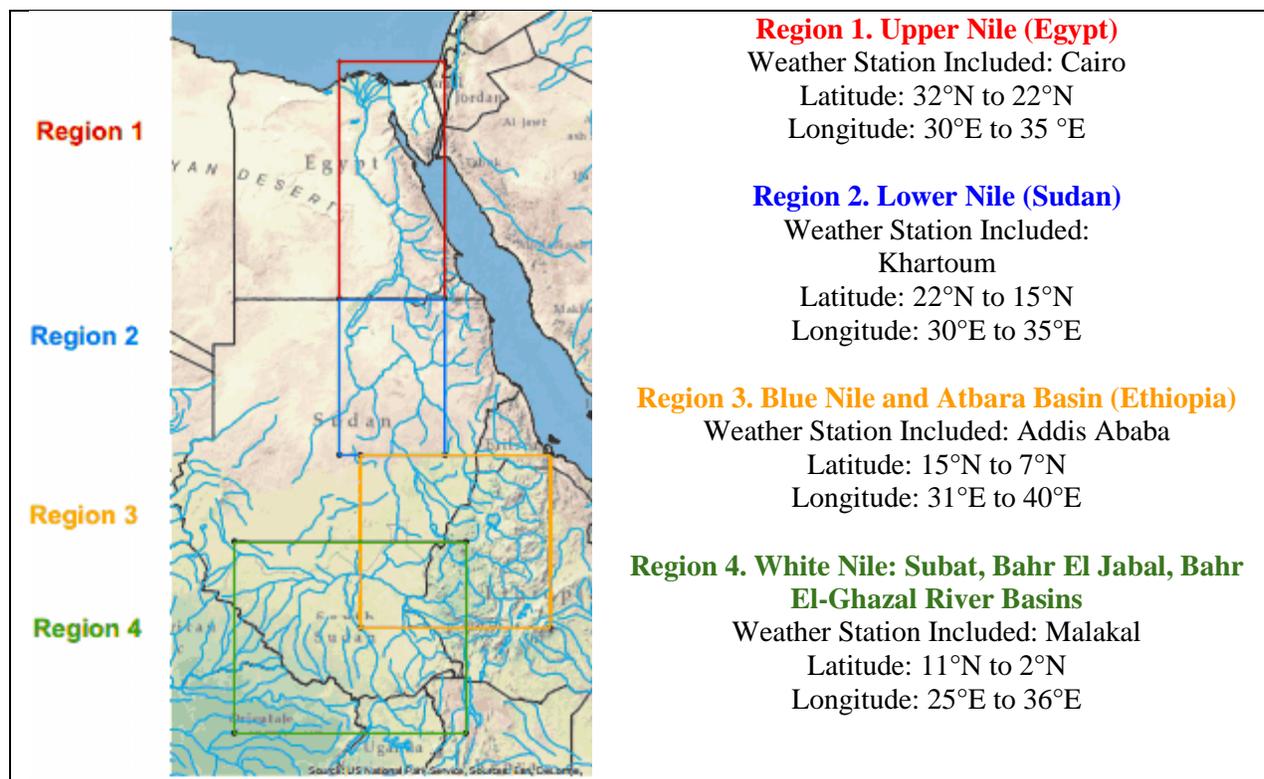


Figure 1: Nile River Basin Regions

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 in each of the three countries in addition to information on estimated volumes of

aquifers and annual rainfall. Additional sources were used to validate these figures (Awulachew, 2008; Ahmed, 2007). Historical estimates for precipitation were drawn from Beck et al. (2005) for the years 1970-2000. Historical gridded observation data on temperature were obtained from the University of Delaware based on NOAA data. Estimates of temperature and precipitation in each of these four regions were drawn from 33 independent General Circulation Models (GCMs) and two Representative Concentration Pathways (RCPs) were drawn from NOAA/OAR/ESRL Physical Science Division (see Taylor et al. 2012).⁴ Detailed information on each of these 33 GCMs is presented in Appendix A.

Model Development

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.

a. Modeling Streamflow

Our hydrology model is a simple representation of the Nile River inclusive of its major tributaries: Blue Nile and Atbara in Ethiopia and the White Nile from Lake Victoria (Figure 2). We converted all water data into U.S. gallons, which was originally presented using metrics associated with either millimeters per day or kilometers cubed. We assume that the Nile and its major tributaries are regenerated annually by rainfall; accordingly, average annual precipitation for Region 3 is $2.68477e+014$ (FAO Aquastat data base) while that for Region 4 is set at $7.9146e+012$ (FAO 2005; Ismail 2010). Annual renewable surface water produced internally within Region 3 feeds both the Blue Nile and Atbara recharge. Calculation of recharge rates for Region 3 required a two-step process. First, we summed reported measures of surface and groundwater produced internally using FAO Aquastat data (<http://www.fao.org/nr/wate/aquastat/data/query/results.html>), subtracting the overlap between surface and groundwater from this sum; this figure was then divided by the long-term average precipitation figure reported by Aquastat. These calculations produced a rainfall recharge rate for Ethiopia of 0.13029. Second, the estimated annual streamflow, drawn from Ahmed (2008) and Awulachew (2007), were used as estimates for the Blue ($1.28659e+013$ gallons), White ($7.9146e+012$ gallons), and Atbara ($2.99449e+012$ gallons) Rivers. Values for the Blue and Atbara Rivers were divided by the sum of Region 3's annual average precipitation and .13029, resulting in an annual estimated recharge rate for these tributaries; estimates for these recharge rates are .36895 and .085061 for the Blue Nile and Atbara respectively. Thus, the overall estimated recharge rate from total annual average precipitation in Region 3 is .0481 for the Blue Nile and .0111 for the Atbara River. Precipitation changes for Regions 1 and 2 are entered later in the model when taking into account climate change.

⁴ We acknowledge the World Climate Research Program's Working Group on Coupled Modeling, which is responsible for CMIP, and thank the climate modeling groups (listed in Appendix A of this paper) for producing and making available their model output.

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) on system dynamics in action.

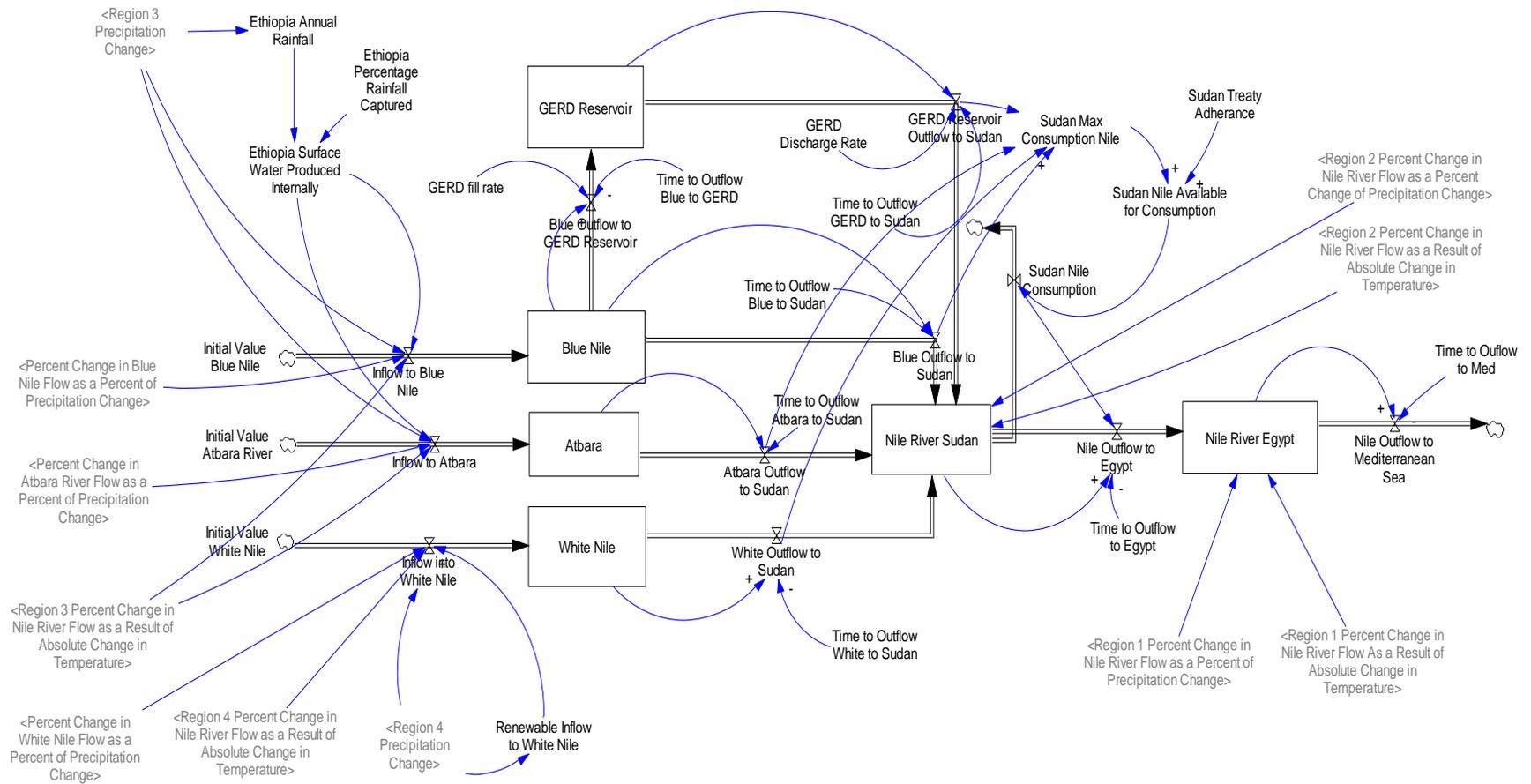


Figure 2: Hydrology Model

Prior to the introduction of climate change factors, the hydrology model assumes a constant level of precipitation, which results in no variation in the hydrology of the river from one year to the next (Figure 3). The three primary tributaries of the Nile River (White, Blue, and Atbara) transport water from Lake Victoria in Uganda and the Ethiopian Highlands until the three rivers merge together to form the Nile River near Khartoum, Sudan. Near this location, the river volume is approximately 94.5km^3 or 2.4964e^{13} gallons (Ahmed 2008). Egypt and Sudan, via a 1959 treaty on the utilization of the Nile waters, prohibited the source countries from consuming any water from the Nile (Elimam et al. 2008). This treaty, which was not ratified by the other countries in the Nile River Basin, divides with approximately 75% of the river's flow to Egypt and 25% to Sudan (Carroll 1999). Our model diverts approximately 12% of the water for Sudanese consumption with the rest flowing into Egypt. The value of "time to outflow" is set at 1 because all streamflow estimates are aggregated as annual averages, with each streamflow value representing a single year.

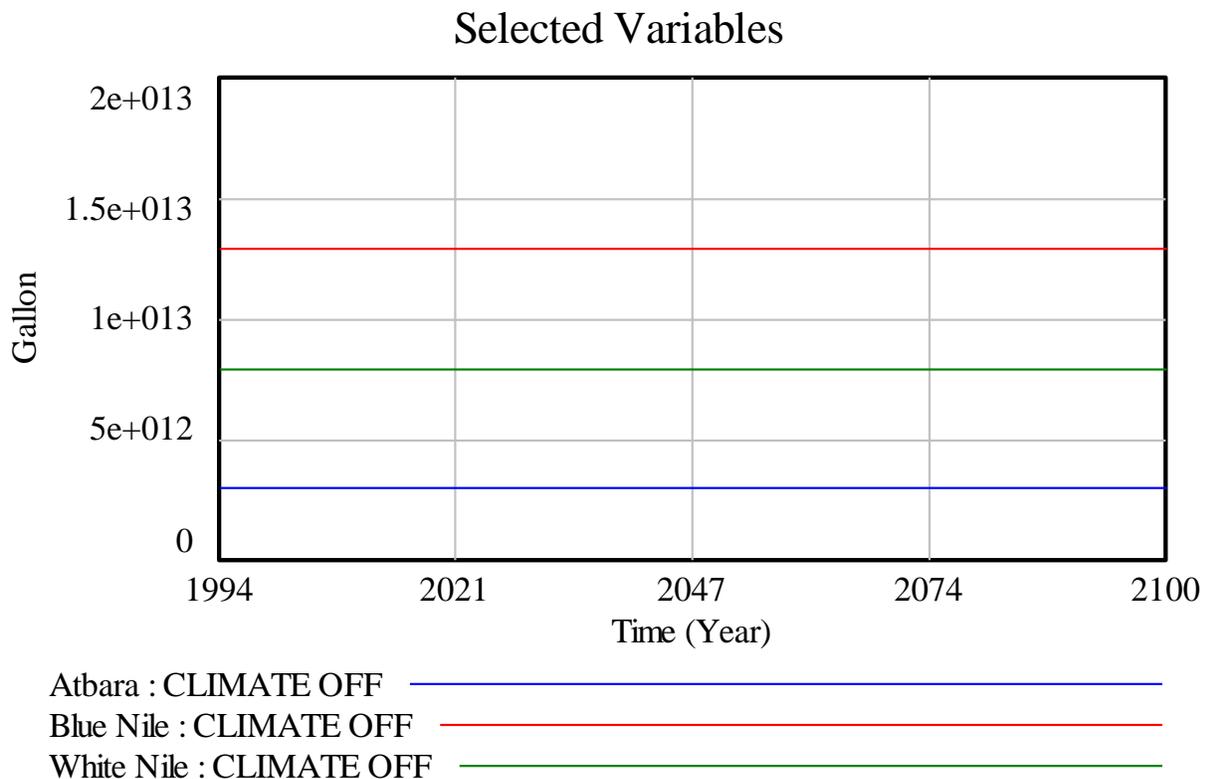


Figure 3: Hydrology Estimates for the Nile River Tributaries in the absence of Climate Variation.

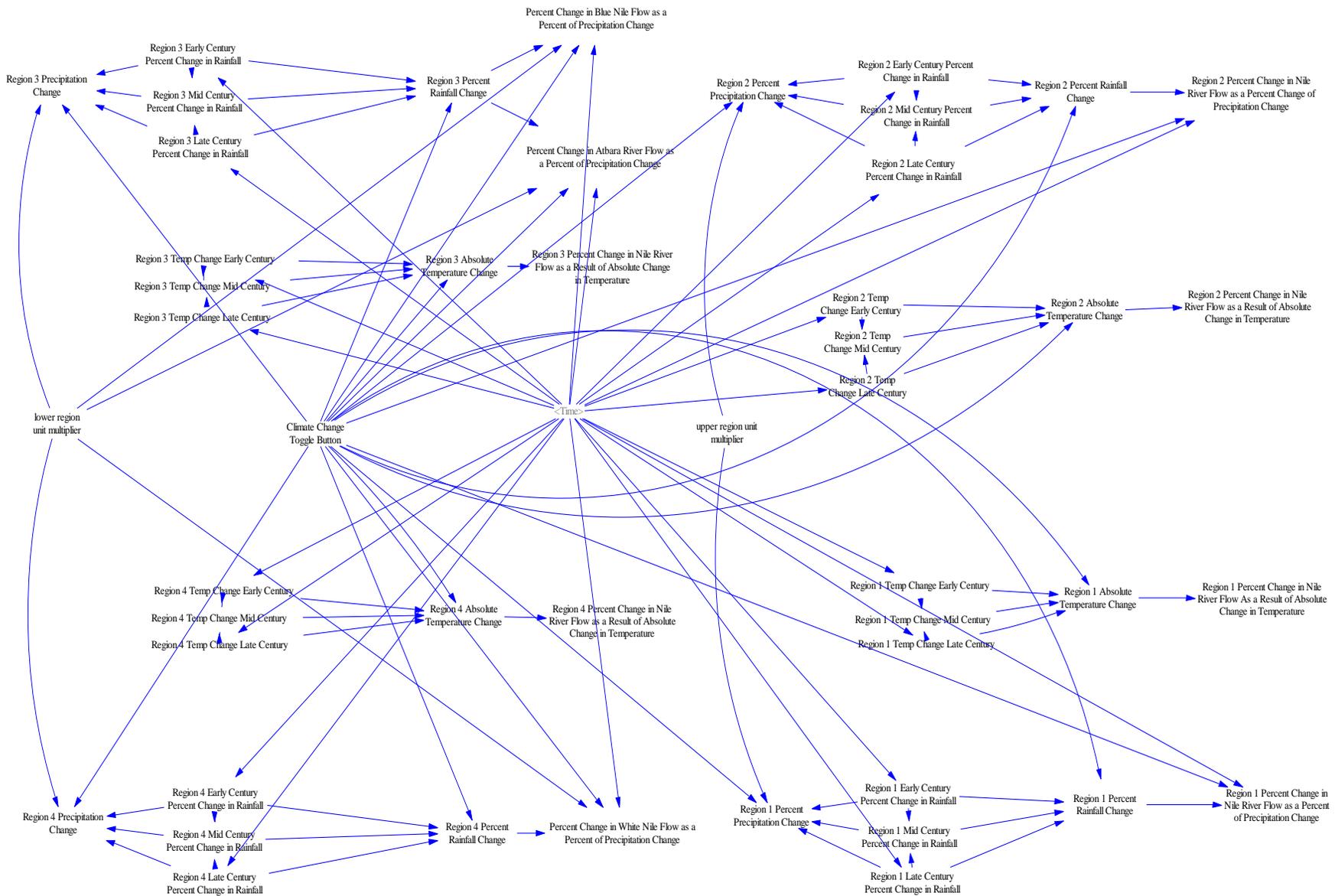


Figure 4: Climate Change Model

b. Modeling Climate Change

The 33 General Circulation Models (GCM), which are used in our analysis and described in Appendix A, were run for Representative Concentration Pathways (RCP) 4.5 and 8.5. RCPs are emission scenarios reflective of greenhouse gas concentrations with 450 and 850 parts per million of greenhouse gases such as CO₂ and methane. RCP 4.5 represents a pathway requiring significant emissions cuts and multilateral policy commitments, while RCP 8.5 represents a “status quo” business as usual scenario. All 33 GCMs were run with both RCP scenarios, producing 66 estimates per year for each of the four regions under investigation. Estimates for precipitation and temperature were generated for the years 2010 through 2100. We subdivided the time periods into 30-year intervals for 2010-2029 (early century), 2040-2069 (mid century), and 2070-2100 (late century). Baseline data, generated by each of the 33 GCMs for 1970-2000, was used to measure change in precipitation and temperature over time. This strategy was employed instead of using historical weather station data because (1) the availability of historic data is not consistently available and (2) the model baseline data from which percent change and absolute differences are calculated are unique to the specific set of variables incorporated in each of the GCMs; the historical data are used solely for purposes of model validation as discussed in more detail below. Means, standard deviations, minimum and maximum values, and percentiles are presented in Appendix B. While this paper presents the average across the 33 GCM models and two RCP scenarios, additional analyses may be undertaken in the future to examine variations among the 33 models and the RCP scenarios.

Calculations for climate change data were generated for absolute temperature change and percentage change in precipitation to remain consistent with the extant literature. These inputs were then entered into the Vensim model by region (Figure 4). Our goal was to build variables that were capable of assessing the potential effect of precipitation and temperature change on the water volume of the Nile River or its associated tributaries. Each quadrant of Figure 4 represents one of four regions. Variables for each region were constructed in an identical manner from temperature and precipitation data drawn from Appendix B. We'll illustrate this procedure and the rationale behind the construction of the variables from Region 3, one of the four regions in the model. Variable constructions for the remaining three regions are presented in Appendix C.

In calculating variables for temperature, our initial step is to generate estimates in Vensim based on incorporation of a random normal function that uses the minimum and maximum values as well as the mean and standard deviation for each of the three time intervals. Accordingly, calculated variables for precipitation and temperature change were developed as follows for Region 3.

Region 3 Temp Change Early Century = IF THEN ELSE (Time <2040, RANDOM NORMAL (0.416988,1.67915,1.07567,0.283738,1),0)

Region 3 Temp Change Mid Century = IF THEN ELSE (Region 3 Temp Change Early Century+Region 3 Temp Change Late Century=0, RANDOM NORMAL (0.739661,3.52847,2.20132,0.617205,1),0)

Region 3 Temp Change Late Century = IF THEN ELSE (Time >=2070, RANDOM NORMAL (0.712064,5.79721,3.28753,1.24337,1),0)

The variables are constructed in this manner to ensure that each iteration of the Vensim model produces only one estimate, which corresponds to the appropriate time interval. For example, if estimates were organized in an Excel spreadsheet with variables in the columns and time points (fractions of years) in the rows, each cell would contain either a value of 0 or an estimate so that summing across these four variables (columns) produces a single estimate for absolute temperature change. The climate change toggle button is simply a dichotomous variable, coded as either 0 or 1, that permits us to activate or deactivate the effects of climate change on the hydrology model.

Region 3 Absolute Temperature Change = Climate Change Toggle Button * (Region 3 Temp Change Early Century + Region 3 Temp Change Mid Century + Region 3 Temp Change Late Century)

To estimate the effect of absolute temperature change on water volume, we draw on the findings of Elshamy, Seierstad, and Sorteberg (2009). They report, from an analysis of 17 GCMs in the Nile River Basin, a one degree increase in temperature (Celsius) corresponds to a 3.75 percent reduction in the volume of the Nile River. Accordingly, we multiply the temperature change estimate by -.0375. Because the observed outcome is non-linear, with larger temperature changes associated with a slightly larger attenuated effect, we calculate the effect exponentially as follows:

Region 3 Percent Change in Nile River Flow as a Result of Absolute Change in Temperature = $-(1.0375^{\text{Region 3 Absolute Temperature Change}} - 1)$

Estimating the effects of precipitation change on water volume is also calculated through a series of incremental steps. We first generate estimates in exactly the same manner described above for temperature, except that precipitation is equal to percentage change instead of absolute change.

Region 3 Early Century Percent Change in Rainfall = IF THEN ELSE (Time < 2040, RANDOM NORMAL (-4.93148, 23.515, 5.17864, 5.84869, 1), 0)

Region 3 Mid Century Percent Change in Rainfall = IF THEN ELSE (Region 3 Early Century Percent Change in Rainfall + Region 3 Late Century Percent Change in Rainfall = 0, RANDOM NORMAL (-9.41894, 42.5032, 7.97624, 10.3675, 1), 0)

Region 3 Late Century Percent Change in Rainfall = IF THEN ELSE (Time >= 2070, RANDOM NORMAL (-8.17837, 71.3365, 12.9634, 15.7283, 1), 0)

Elsaeed (2012:339) provides data on the association between changes (as a percent) in precipitation and the corresponding water volume in the Nile River. Elsaheed acknowledges, the range of sensitivity of river volume to precipitation differs by region. Using these data reported by Elsaheed (2012), we ran some regression analyses, presented in Figure 6 below, to determine the equation best represented by each distribution based on corresponding R^2 values. These equations were incorporated in variables in the Vensim model to capture this range of sensitivity.

To illustrate, we incorporated the regression equations for the Blue Nile (El Diem) and Atbara in the following manner. The region unit multipliers (lower and higher) are simply used to change the specification of units from dimensionless to gallons per year.

Percent Change in Blue Nile Flow as a Percent of Precipitation Change = IF THEN ELSE (Time >= 1994, $(-0.0001 * (\text{Region 3 Percent Rainfall Change}^3)) + (0.014 * (\text{Region 3 Percent Rainfall Change}^2)) + (2.8626 * \text{Region 3 Percent Rainfall Change}) + 1.1369$), 0) * lower region unit multiplier * Climate Change Toggle Button

Percent Change in Atbara River Flow as a Percent of Precipitation Change = IF THEN ELSE (Time >= 2010, $(0.0178 * (\text{Region 3 Percent Rainfall Change}^2)) + (2.8186 * \text{Region 3 Percent Rainfall Change}) + 2.1885$), 0) * lower region unit multiplier * Climate Change Toggle Button

Atbara (Ethiopia)		Blue Nile (El Diem, Ethiopia)		Blue Nile (Khartoum, Sudan)		Lake Victoria (Jinja, Uganda)		White Nile (Malakal, Sudan)		Nile Main (Dongla, Sudan)	
Percent Change in Rainfall	Percent Change in Water Volume	Percent Change in Rainfall	Percent Change in Water Volume	Percent Change in Rainfall	Percent Change in Water Volume	Percent Change in Rainfall	Percent Change in Water Volume	Percent Change in Rainfall	Percent Change in Water Volume	Percent Change in Rainfall	Percent Change in Water Volume
-50	-93	-50	-92	-50	-98	-50	-20	-50	-41	-50	-85
-25	-60	-25	-62	-25	-77	-25	-11	-25	-28	-25	-63
-10	-24	-10	-24	-10	-31	-10	-4	-10	-11	-10	-25
10	34	10	32	10	36	10	6	10	19	10	30
25	84	25	78	25	89	25	14	25	48	25	74
50	187	50	165	50	149	50	33	50	63	50	130
Atbara (Ethiopia)				$y = 0.0178x^2 + 2.8186x + 2.1885$ $R^2 = 0.9997$							
Blue Nile (El Diem, Ethiopia)				$y = -0.0001x^3 + 0.014x^2 + 2.8626x + 1.1369$ $R^2 = 0.9997$							
Blue Nile (Khartoum, Sudan)				$y = -0.0004x^3 + 0.0098x^2 + 3.5578x + 0.7986$ $R^2 = 0.9998$							
Lake Victoria (Jinja, Uganda)				$y = -.00005x^3 + 0.0024x^2 + 0.4918x + 0.4296$ $R^2 = 0.9997$							
White Nile (Malakal, Sudan)				$y = -0.0002x^3 + 0.0023x^2 + 1.6462x + 5.8769$ $R^2 = 0.9968$							
Nile Main (Dongla, Sudan)				$y = -0.0003x^3 + 0.0085x^2 + 2.9027x + 0.9994$ $R^2 = 0.9998$							

Table 1: Modeling Precipitation Change on Streamflow for Selected Locations

Modeling Assumptions

Our model incorporates the following modeling assumptions:

1. Water hydrology in the Nile River occurs exclusively through an interaction between precipitation and temperature.
2. The Nile and its major tributaries are regenerated annually by rainfall.
3. Ethiopia will adhere to the treaty with the sole exception of drawing water from the Blue Nile to fill the dam's reservoir. All other upstream countries will adhere to the treaty and draw no water from the White Nile River.
4. In accordance with treaty adherence, Sudan will draw not more than 25 percent of the total streamflow from the Nile River Sudan.
5. Per capita water consumption will remain constant throughout the century.
6. Technology will remain constant such that innovations in irrigation systems, desalinization, and/or farming practices will have no discernible effect on water utilization.

Results

Average estimates taken across the 33 GCM models and two RCP levels suggest that three of the four regions will experience a net increase in precipitation throughout the 21st Century while one (Region 1—Egypt) may experience a net decrease in rainfall (Figure 5). For example, Region 4, source of the White Nile, may experience an average precipitation increase of around 35%. Region 3, source of the Blue Nile, may experience an average increase of 30%. Region 2, Sudan, may see an average increase of approximately 15% during the century.

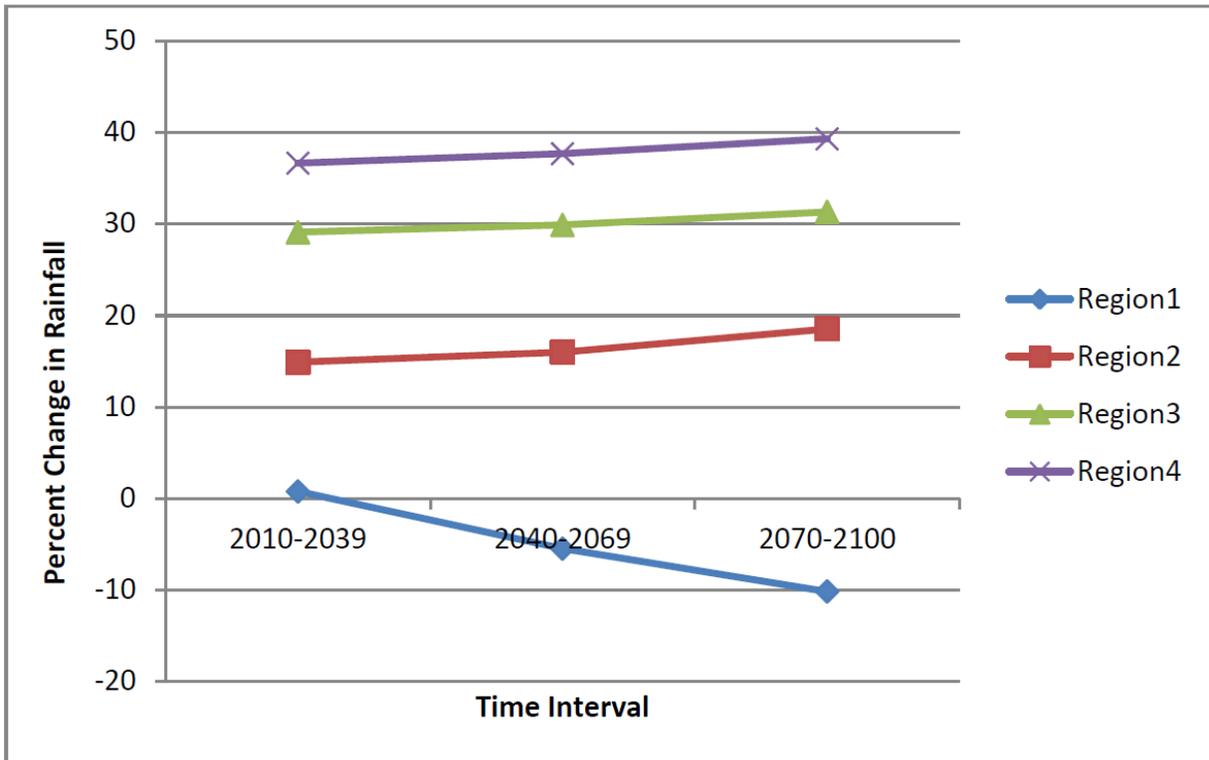


Figure 5: Nile River Basin Rainfall Change in the 21st Century

Similarly, the average estimated temperature value across the 33 GCM models suggests that all four of the regions will experience a net increase in temperature throughout the 21st Century (Figure 6). Region 2 (Sudan) may experience the greatest net increase in temperature, an average of six or seven degrees by mid-century. Region 4, source of the White Nile, may experience an average increase in temperature of around four degrees Celsius by mid-century. Regions 3 (Ethiopia) and 1 (Egypt) may experience an average increase in temperature of around two degrees Celsius by mid-century. However, insofar as these estimates are only annual averages reflecting aggregations across months, RCP levels, and the 33 GCMs, it must be acknowledged that the minimum and maximum estimates suggest the possibility of a rather wide interval.

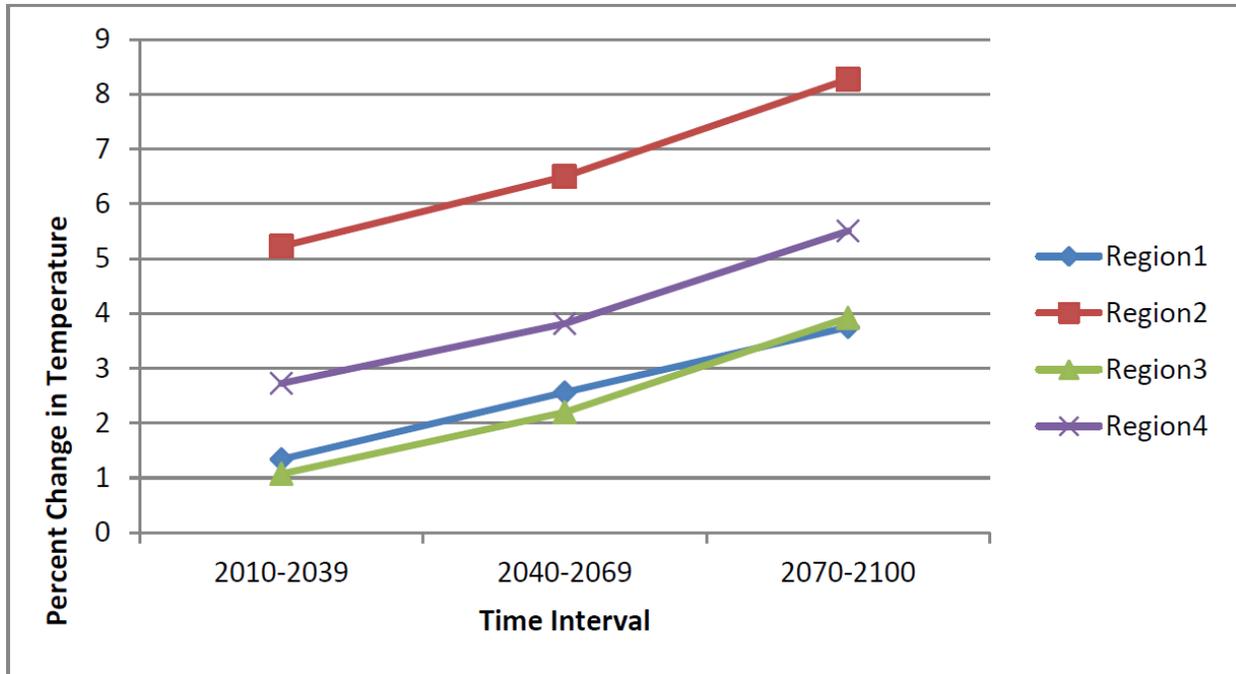


Figure 6: Temperature Change in the 21st Century

These results suggest that, on average, the Nile River Basin may experience both increases in precipitation and temperature throughout the 21st Century. Such outcomes posit differential effects on the Nile River. The big question is to what extent these effects, if observed, will change the volume of the Nile River.

Figure 7 presents a visual depiction of the estimated effect of climate change on the Nile River at selected locations. We are particularly interested in the observed trends and not the estimates for any given year. These trends suggest that streamflow in the Blue Nile (Ethiopia) may actually increase, perhaps by as much as 20 to 25 percent. Similarly, the other two tributaries of the Nile River, the Atbara (Ethiopia) and the White Nile (Uganda) may witness increases in the average annual volume by as much as 13 to 18 percent. The Nile River as it flows through Sudan (Region 2) may increase by as much as eight percent on average. Indeed, its decreased volume may have been estimated to be greater were it not for the greater volume in the Blue Nile. The overall effect of climate change on Egypt (Region 1) may be a net decrease of upwards of 17 percent of its current carrying capacity.

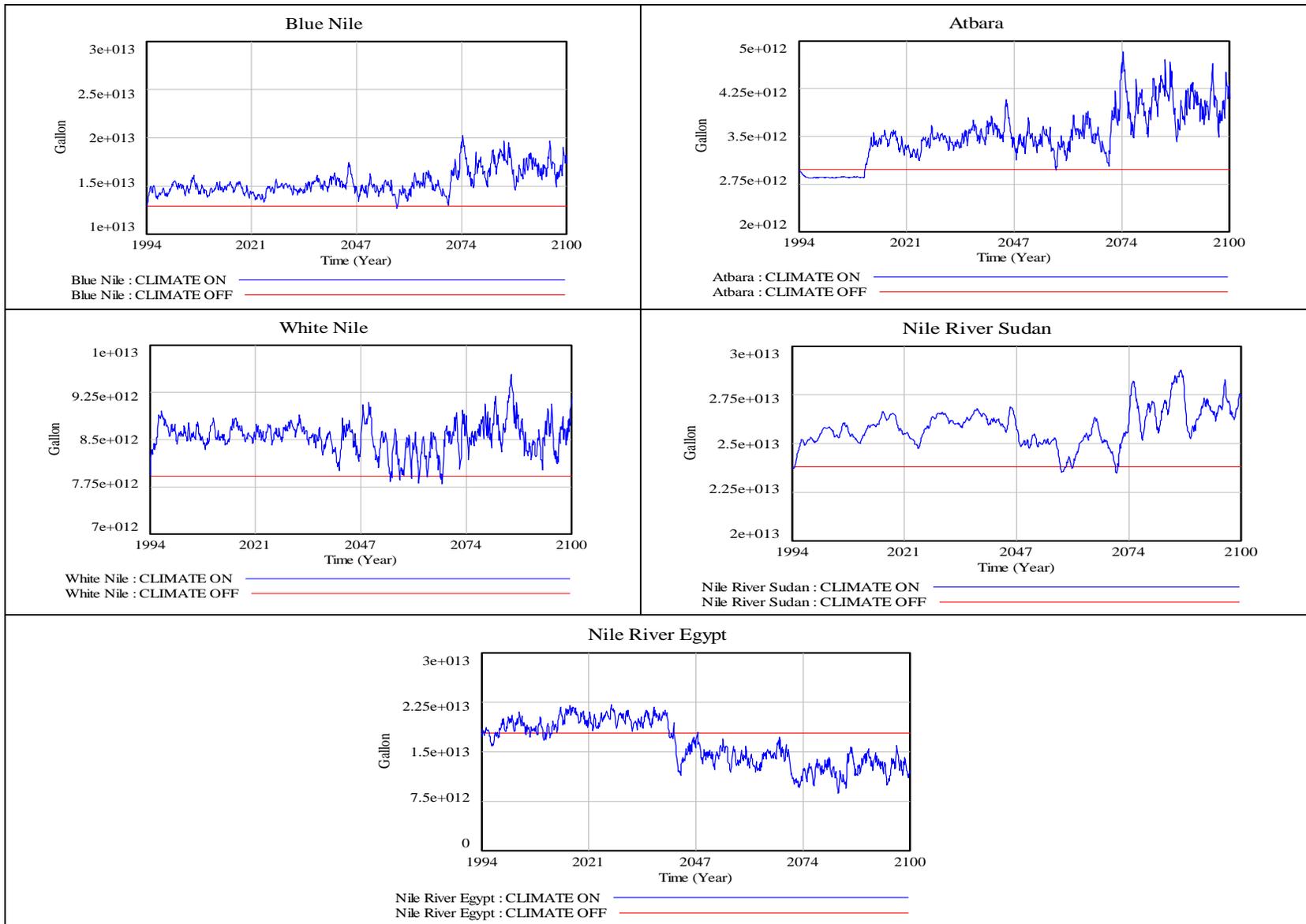


Figure 7: Effects of Climate Change on Streamflow of Nile River at Selected Locations

Impact of the Grand Renaissance Dam

One of the main goals of this study is to assess the impact of the Grand Ethiopian Renaissance Dam on downstream countries. To date, little demonstrable analysis has been conducted in a manner that might inform discussions about the dam's effect on streamflow for downstream countries – an area which presents a cause for concern for the stability of the region. With the dam expected to be completed in 2017, the rate at which the dam's reservoir is filled could exacerbate tensions in the region. The dam's reservoir, which will have a capacity of 50 billion cubic meters upon completion, could require the diversion of a significant portion of the Blue Nile depending upon the reservoir's fill rate and predicted climate impacts (King 2013). For example, as is evident from Figure 8, a rate of 25% will fill the reservoir in four years while a rate of 5 percent will require upwards of 20 years.

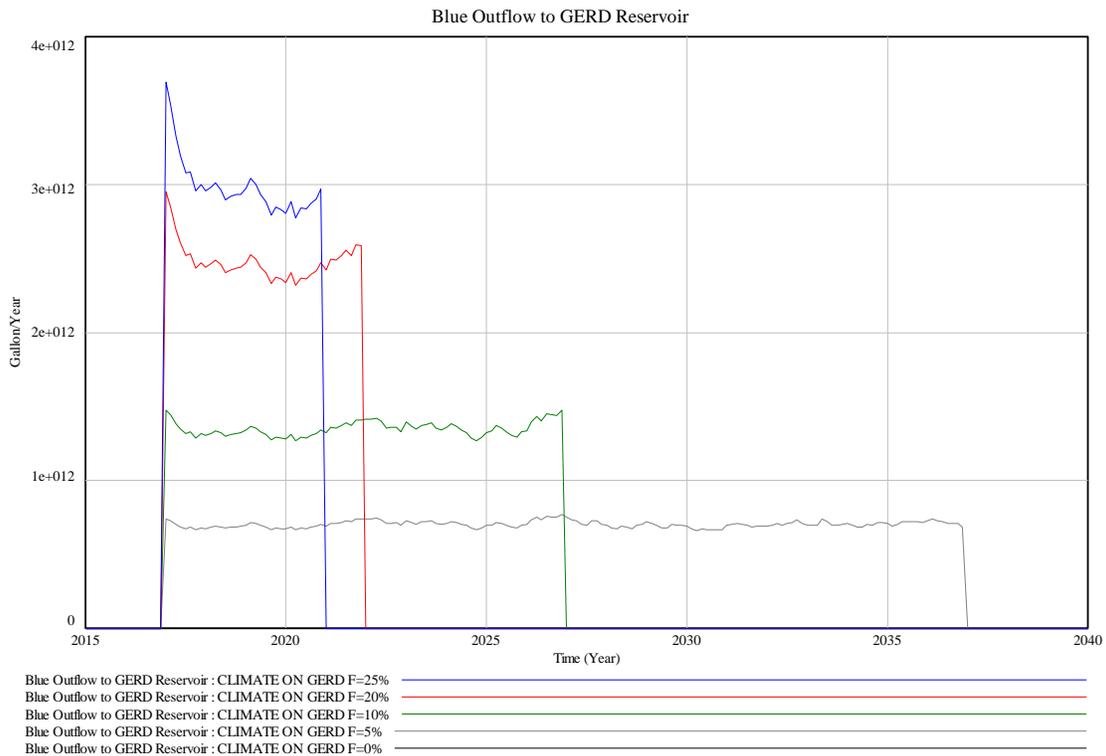


Figure 8: Effects of GERD Fill Rate on Outflow to GERD Reservoir

Egypt and Ethiopia obviously have competing interests with reference to the dam's reservoir fill rate. Previously published reports suggest that the Ethiopian government may attempt to fill the reservoir quickly, say within four years in order to maximize the dam's operational hydroelectric capacity; only a portion of the dam's turbines can run without completely filling the dam. Four -years corresponds with a reservoir fill rate of 25% (King 2013). As is evident from Table 3, a lower fill rate spreads the attenuation in streamflow across a longer time interval, producing something analogous to a long-term stressor rather than an immediate system shock of a shorter duration. For example, a 25% fill rate might reduce streamflow by 21% and 5% respectively in the Blue Nile and Nile Egypt; conversely, a 5% fill rate might result in a four and two percent reduction in streamflow in the Blue Nile and Nile Egypt respectively.

GERD Fill Rate	Years to fill	Average Blue Nile Flow (gallons)	Estimated Percent Reduction to Blue Nile	Average Streamflow in Egypt (gallons)	Estimated Percent Reduction to Nile in Egypt
0%	N/A	1.4025E+13	0	2.5253E+13	0
5%	2017-2037	1.3434E+13	-4.22	2.4839E+13	-1.64
10%	2017-2027	1.2795E+13	-8.77	2.4348E+13	-3.58
15%	2017-2024	1.2180E+13	-13.15	2.4098E+13	-4.57
20%	2017-2022	1.1644E+13	-16.98	2.4043E+13	-4.79
25%	2017-2021	1.1119E+13	-20.72	2.3982E+13	-5.03

Table 2: The Impact of the Grand Ethiopian Renaissance Dam

Estimated effects are illustrated graphically in Figure 9. When accounting for climate change impacts, utilization of higher fill rates will create larger short-term systemic shocks that deplete Blue Nile streamflow more rapidly; conversely, lower fill rates, when stretched over a longer duration, create long-term stressors that may be somewhat more manageable overall to stakeholders throughout the Nile River Basin. Of course, lower fill rates may attenuate hydroelectric capacity attributable to Ethiopia.

Blue Nile

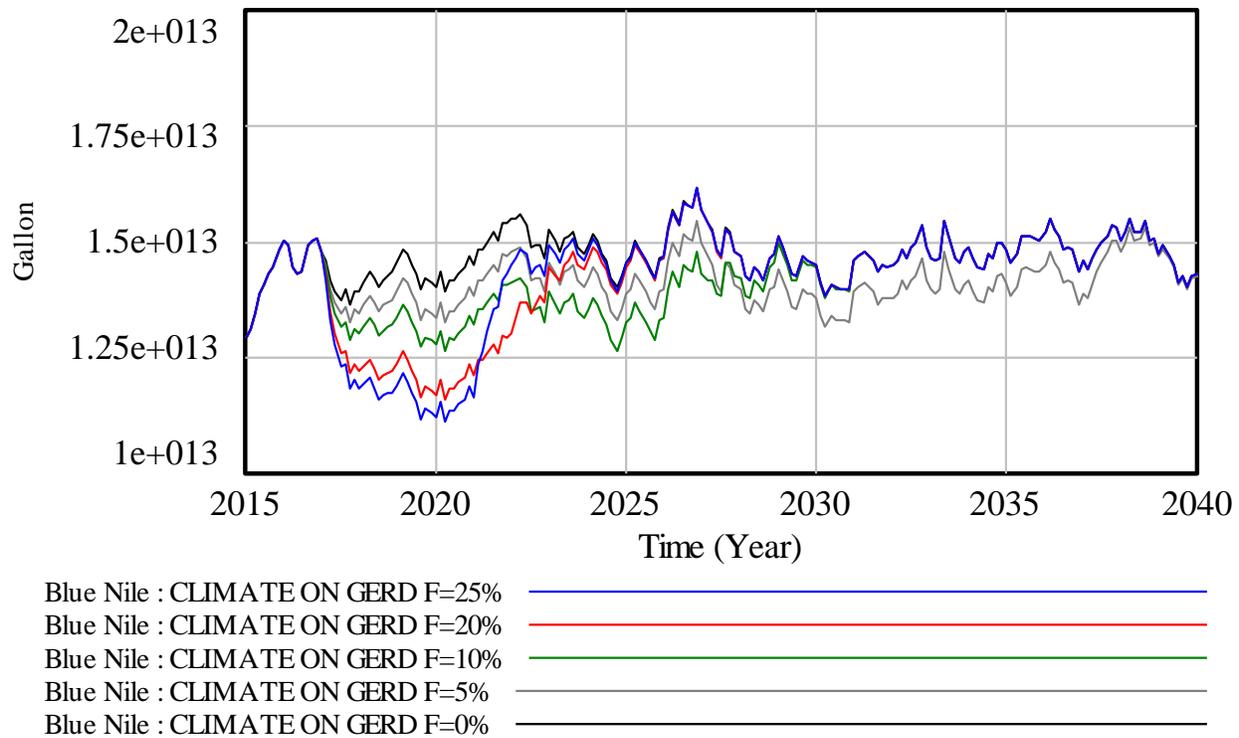


Figure 9: Effects of GERD Fill Rate on Streamflow in the Blue Nile River

Based on an average Egyptian per capita water consumption of 266,285 gallons, a reservoir fill rate of 25% equates to the water reduction equivalent to 4,773,000 people. Egypt already consumes approximately 97% of its internal renewable water resources, so this additional strain on resources could have devastating effects on the country's population (Degefu, 167). Insofar as 94% of Egypt's per capita water consumption is used for irrigation in support of crop production, high reservoir fill rates could create systemic shocks in Egypt's agricultural economy.

Another way to approach the problem is by examining fill rates in the context of projected climate change outcomes. Results from our study suggest that precipitation levels in source countries will increase at rates that exceed detrimental effects from higher predicted temperatures. This finding suggests that there will be more water, and perhaps considerably greater streamflow, than previously existed.⁶ Greater streamflow will create problems with inundation, possibly resulting in episodic flooding of arable lands, which may result in a reduction in crop yields. To reduce the negative consequences of inundation, one possible strategy is to systematically divert projected excess water beyond the channel to an area analogous to a large hole in the ground. The GERD's reservoir certainly satisfies this condition. Thus, what is needed is an evaluation of projected excess water brought about by climate change that is assessed against a baseline to determine what fill rate(s) might retain constancy in streamflows while diverting excess water. Essentially, we need a controlled water optimization model that considers fill rates in the context of projected climate change outcomes.

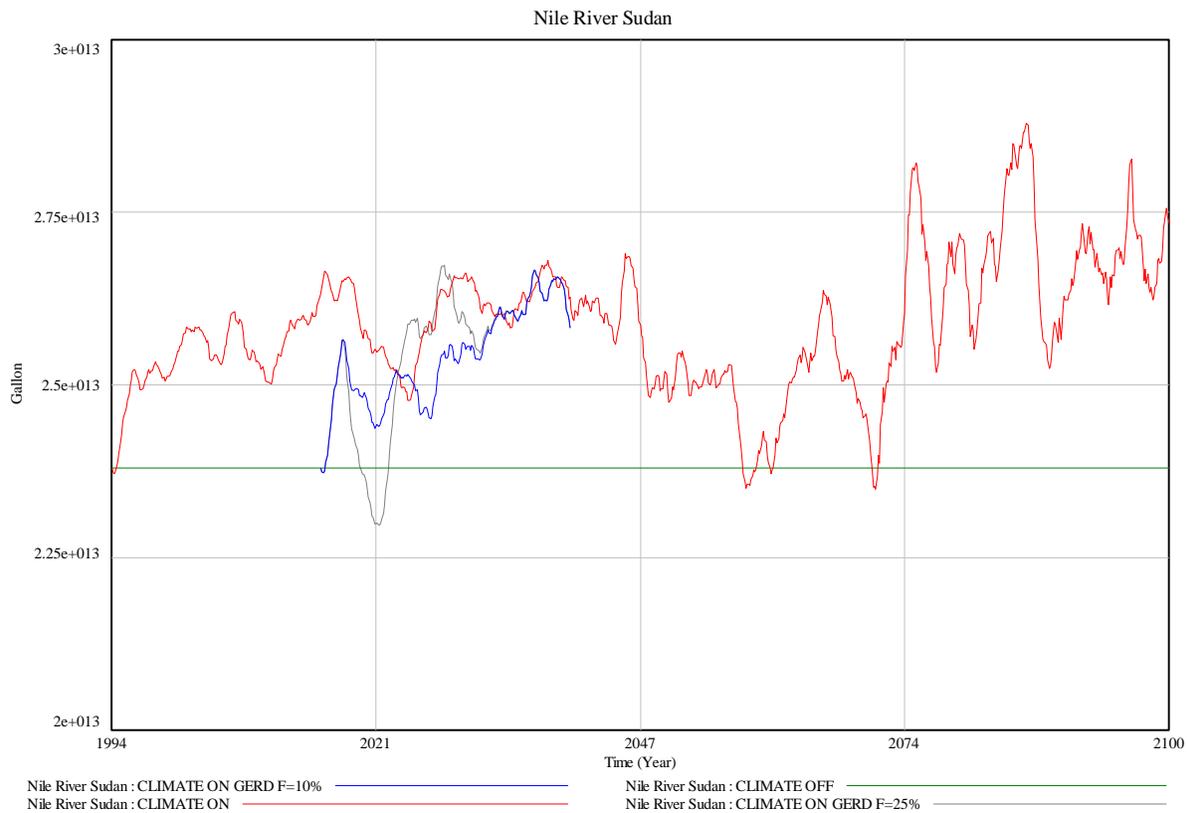


Figure 10: Effects of GERD Fill Rate on Streamflow in the Nile River Sudan

Figure 10 illustrates variation in fill rates while taking into account the estimated effects of climate change on streamflow in the Nile River. The green line portrays the baseline streamflow for the Nile River Sudan without taking into climate change into consideration while the red line portrays the estimated level of streamflow when accounting for climate change. The difference between these two lines is the water differential, in this case, a net positive increase in streamflow. The blue and gray lines

⁶ This scenario is, of course, only one of several potential scenario based on averages across RCPs and GCMs. It is entirely possible that other scenarios, such as selection of most plausible model (i.e., selecting one or two GCMs instead of the average over all 33 of them) or considering a low versus high RCP level, may lead to different interpretations. Certainly, the minimum and maximum values presented in Appendix B suggest the potential for considerable variability in outcomes.

represent two extreme fill rates at 10% and 25% respectively.⁷ Evident from Figure 11 is the finding that a fill rate of 25% reduces streamflow below the baseline (i.e., current level) while a rate of 10% is well above the baseline. The optimal fill rate from our model is found to be in the interval of 12% and 15%.⁸

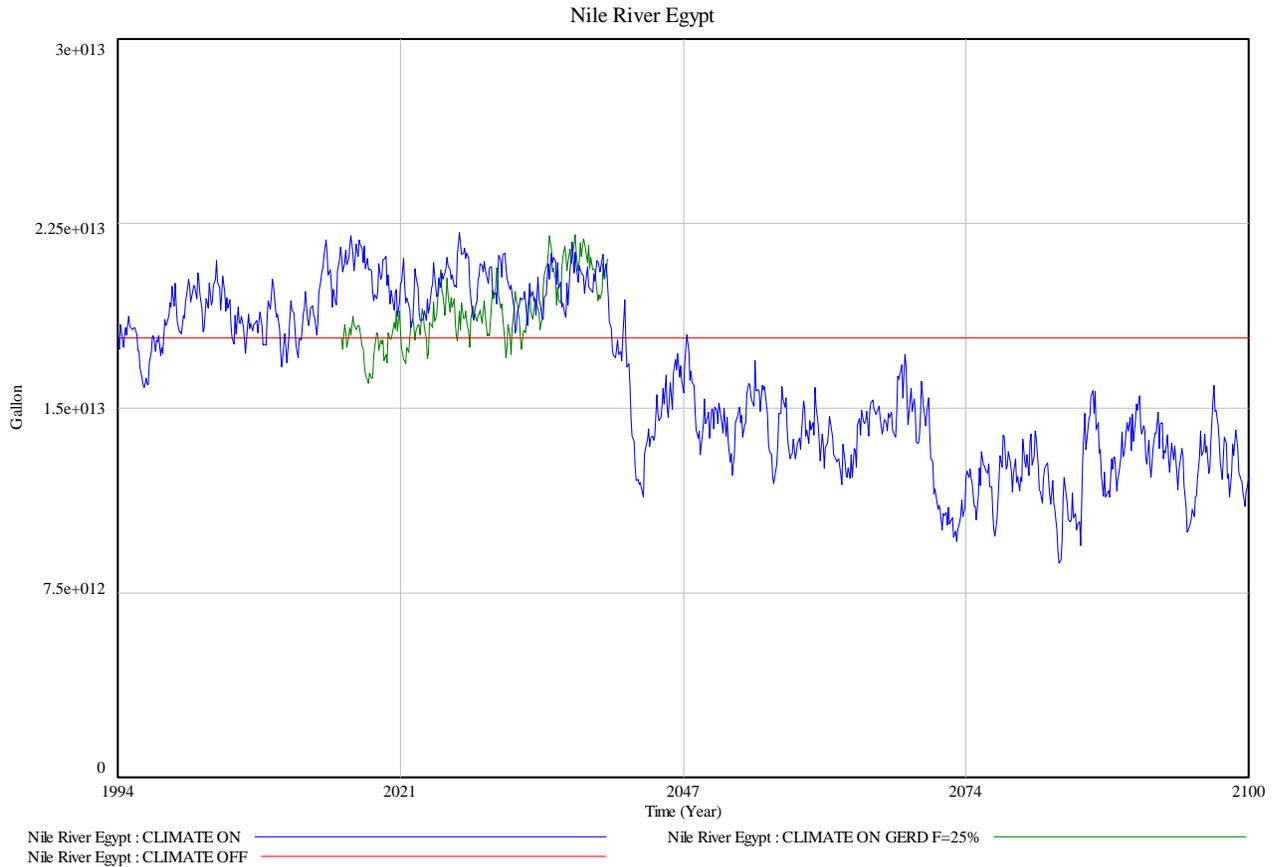


Figure 11: Effects of GERD Fill Rate on Streamflow in the Nile River Egypt

Figure 11 presents streamflow in the Nile River Egypt. Evident from this graph is the finding that a fill rate of 25% reduces streamflow below the baseline. The optimal fill rate for the Nile River Egypt that minimizes disruption to streamflow in the context of projected climate change is closer to 10%. Our model suggests that a fill rate of 10% will ensure that the GERD’s reservoir is operating at full capacity within ten years.

Discussion

The purpose of our study is to examine the impact of environmental and human factors on the carrying capacity (streamflow) of the Nile River throughout the 21st Century. By incorporating river hydrology, climate change, and the fill rate of the GERD reservoir within our model, we have sought to develop a refined understanding of the dynamic interaction between climate change, water use, and water capacity.

⁷ A fill rate denoted by zero is depicted by the red line.

⁸ As suggested in footnote #5 above, inundation at a gradual rate is certainly not guaranteed; extreme events (i.e., floods) are most often rapid and frequently cause more destruction unless the infrastructure was specifically designed to divert effects of inundation.

Our results suggest a few key findings. First, climate change presents a relatively mixed picture of the future water capacity of the Nile River Basin. While rainfall in many of the Basin's regions is expected to increase, concurrent increases in temperature will attenuate Nile River streamflow. The net result is a projected increase in water capacity throughout the 21st Century in source countries (Regions 3 and 4), a moderately constant capacity, on average, in Sudan, and declining streamflow in Egypt, particularly post 2050. Throughout the Basin, streamflow in first half of the century is likely to be at levels equal to or higher than present, while declining in Sudan and particularly Egypt during the second half of the century. The anticipated reservoir fill rate of the Grand Ethiopian Renaissance Dam could present problems; clearly a high fill rate will reduce streamflow and water capacity in downstream countries. Though, when coupled with projected effects of climate change, the anticipated increases in streamflow in source countries, particularly before 2050, may provide strategic opportunities with which to simultaneously provide Ethiopia with a planned capacity to fill the reservoir while minimizing the potential impact on Egypt. We estimated that a fill rate of 10 to 15 %, given projected increases in streamflow within the Blue Nile region, would build hydroelectric capacity in Ethiopia while concurrently ensuring a constant level of streamflow throughout Sudan and Egypt. Additionally, diverting the anticipated increase in streamflow, particularly in Ethiopia, may reduce problems associated inundation and subsequent flooding of arable land in the vicinity of the Blue Nile.

These findings are bounded by several assumptions. First, climate change is assumed to operate exclusively through precipitation and temperature. This assumption implies that the observed effects of climate change will be largely incrementally monotonic rather than episodic and sporadic. The problem with incorporating this assumption in the model is that it is less likely capable of capturing the sudden and extreme volatility resulting from dramatic changes in the climate. For example, a flood, when smoothed over time, is indicative of higher precipitation that occurs gradually; when experienced at a particular point in time, a sudden shock can devastate an area and undermine other systems that can dramatically and exponentially deplete resource capacity within the system, such as agricultural production. Incorporation of this assumption potentially minimizes the actual effect of climate change because of the potential absence in the model of these interaction effects. Second, we assume that The Nile and its major tributaries are regenerated annually by rainfall. This assumption does not capture the extant groundwater present in various aquifers throughout the region. For example, Ethiopia and Sudan draw water from aquifers that can offset any observed attenuation in streamflow in the Nile River. Indeed, some sources suggest that Sudan may have tremendous yet untapped potential in the size and scope of its extant aquifers. Conversely, while most sources seem to agree that Egypt has relatively few aquifers, thereby maximizing its dependence on Nile river streamflow, it is developing desalinization plants along the Mediterranean and Red Seas that might offset some of the anticipated declines in streamflow attributable to climate change. Third, we assume that Ethiopia will adhere to the 1959 water treaty with the sole exception of drawing water from the Blue Nile to fill the GERD's reservoir. All other upstream countries are assumed to adhere to the treaty and draw no water from the White Nile River. This assumption is rather dicey and probably untenable. As population increases throughout the region, demands on water for both agricultural and domestic consumption are likely to increase. Such increased demand will most certainly challenge inequity issues associated with the treaty, as is already been seen through discussions of the Nile River Basin Initiative. Thus, a fourth assumption is also problematic, namely that per capita water consumption will remain constant throughout the 21st Century. Fifth, our model assumes that technology will remain constant such that innovations in irrigation systems, desalinization, and/or farming practices will have no discernible effect on water utilization. Clearly, this assumption is untenable; technological innovations will occur, though their effect on water utilization is very difficult to assess.

The net effect of these assumptions on our model estimates, though difficult to assess, appear to be, on average, negligible.⁹ For example, in smoothing shocks, we assume water capacity is more continuous, than it will most certainly be in reality, thereby, via assumption, providing for more water capacity to the Basin than it is likely to receive continuously throughout the year. The same is true when assuming that all countries will adhere to the treaty; this assumption probably provides for more streamflow, particularly for downstream countries, than is likely to exist. Similarly, in assuming that per capita water consumption remains constant in the face of a much larger population, we are artificially providing for more water capacity than will be present. Taken together, these three assumptions provide a net positive effect on streamflow (i.e., includes more water than would probably exist). Conversely, our assumption that other water sources, such as aquifers, do not contribute to water capacity artificially lowers the actual capacity than that estimated by the model. Similarly, in assuming that technology will not change streamflow, we artificially eliminate capacity that will certainly evolve throughout the century. Thus, taken together, we believe the net gains and losses assumed by the model will probably result in an overall capacity that is comparable to that presented in this report.

Climate change observations are based on a large number of estimates that were generated by a large number of GCMs and RCPs. Each of the 33 GCMs in our analysis represent very distinct mental models on how climate change affects the environment. The value of these models is that, while many are quite distinct from one another, collectively they represent an indication as to what may happen in the future given the articulation of a set of assumptions about how climate change operates. In utilizing averages from this large set of GCMs, our analysis is able to offer insights into what may happen with respect to temperature and precipitation in the Nile River Basin. Additionally, our analysis is able to integrate climate change estimates to Nile River streamflow in order to forecast what types of trends may be most pronounced throughout the current century.

While trends, as presented in this paper, corroborate findings from other sources (Elsaeed 2012; Nawaz et al. 2010), namely that the Nile River is sensitive to fluctuations in precipitation and/or temperature attributable to climate change, our study would benefit from a deeper exploration of greenhouse gas concentrations (RCP 4.5 vs. RCP 8.5) and the corresponding variation in outcomes for the Nile River. Additionally, our study could provide a deeper examination of variation among the 33 GCMs and what types of trends might be present from a deconstruction of these various models. Therefore, separate assessments of RCP concentrations, individual assessments of selected GCMs, and extreme events probably warrant further analysis. Although our model includes streamflow estimates, given changes in climate, it remains unclear on changes in streamflow might affect extant flood plains and people living within those flood plains, i.e., the effects of river hydrology on human populations.

Model Validation

In assuming that our modeling assumptions, both positive and negative, are likely to create a net zero effect on streamflow, the next question concerns validity of our actual findings with historical observations. Certainly, confidence derived from one's observed outcomes is dependent in part on the extent to which they align with historical observations, else the model risks being disconnected from any

⁹ Although we've smoothed streamflow through aggregation and averaging, we, of course, acknowledge that impacts from streamflow variability, particularly in the presence of extreme climate events, is not likely to be negligible. Our point is that streamflow, given our modeling assumptions, is not likely to be, on average, any more or less than what we've reported because the assumptions, when taken as a set, are likely to balance inputs and outputs to streamflow that we've omitted by assumption.

realistic anchor. Toward that end, through the Columbia University team, we obtained data from Paul Block at the University of Wisconsin on historic streamflow data from 1912 through 1993 from the weather station at the Roseires Dam on the Blue Nile River. While these data would appear to be sufficient in number to provide some validation efforts, the number of historic data points available for comparison against estimates generated by our model is very limited. Recall that estimates from our model are based on the estimates generated by 33 GCMs over RCP 4.5 and 8.5; recall also that we averaged these models to essentially create averaged distributions using mean, standard deviation, minimum, and maximum values. Additionally, our baseline for the assessment of changes in precipitation and temperature was drawn from estimates generated by the GCMs for years 1970-2009; each of the successive time points, i.e., 2010-2039, 2040-2069, 2070-2100, were assessed as changes against this baseline. To validate estimates generated by our model against the historic data from the Roseires Dam requires us to split the baseline into decades (1970s, 1980s, and 1990s), create distributions for each decade reflective of the averages of the GCM models, and input these estimates into a revised Vensim model for the Blue Nile River.

We first ran multiple time steps to check for consistency among the outputs, essentially selecting a time step that was fairly robust in comparison to other time steps. Insofar as system dynamic models are a set of differential equations, the time step represents the number of integrations generated per time interval. Our time interval is year, so a time step of 1 is equivalent to one integration per year, .50 is two per year, while .125 is roughly eight integrations per time step. We found that time steps at .50, .125, and .0625 produced results that were moderately to strongly correlated with one another; we ultimately selected .125 because it appeared to be the most robust time step.

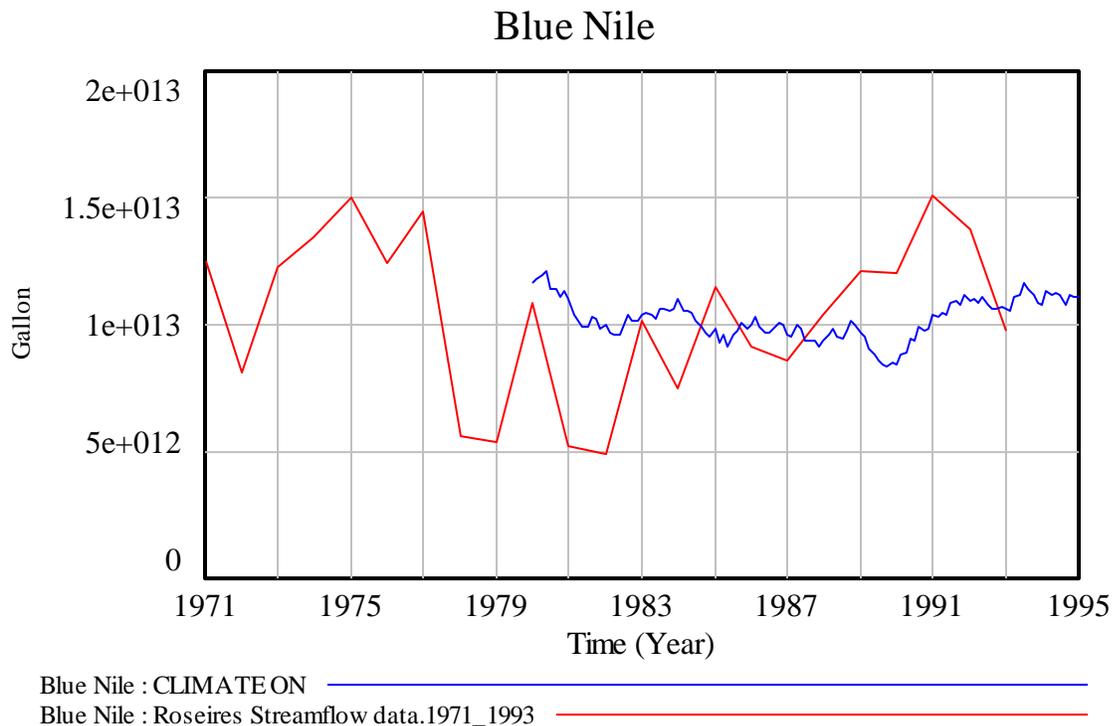


Figure 12: Validation Comparison Between Historic and Estimated Values

Our validation analysis produced the distributions between historic and estimated values presented in Figure 12. These two distributions, limited to 14 years within the time interval 1980-1993, are not significantly correlated. Evident from Figure 12 is the observation that our model produces estimates that are smoother than the historical distribution. Essentially, our model, based on estimates

generated by a set of normal distributions, tends to generate estimates that regress toward the mean; while the model does not accurately capture the extreme volatility apparent in the historic data, it does a decent job of following an average trend line that one might expect to generate based on the manner in which the climate change variables were constructed. Hence, while our model is not particularly good at capturing the actual volatility of streamflow, either drought or inundation, it does reflect the general trend of the streamflow over time. Consequently, we might conclude, based on this observation, that the trend line generated by our model most likely accurately reflects the general direction of future trends.

A comparison of other studies using multiple methods finds similar outcomes for estimated changes in temperature while acknowledging considerable variation in precipitation. For example, the Egyptian Environmental Affairs Agency (1996), based on an analysis of several GCM models, reports increases in both precipitation and temperature over the next century, with the net overall effect being probable decreases in streamflow. Such changes could attenuate streamflow in the Nile River through Egypt by as much as 10 to 90 percent (El Saeed 2012:30). While nearly all GCM experiments project a temperature rise in the 21st Century, the range of estimates in streamflow throughout the Basin varies significantly. Yates and Strzepek (1998) found that three of four GCM models project an increase in streamflow at Answan of more than 50%; conversely. Sayed (2004) predicted considerable variation in streamflow, ranging between -14 and 32%, with a net positive average increase. El Shamy (2009), in examining 15 GCMs, predicts variation ranging between -15 to +14% precipitation changes and temperature increases of between 2 and 5 degrees Celsius in the Blue Nile Basin by Century's end.

Toward the Evolution of a Water Management System

Our study finds, much like other studies on the Nile River Basin, that temperature will increase throughout the Basin during the 21st Century. The net effect of higher temperatures, *ceteris paribus*, is lower streamflow. However, source regions of the Nile River might be projected to experience a net increase in precipitation at levels sufficient to provide these regions with a net increase in streamflow. Sudan, and particularly Egypt, are likely to see less precipitation throughout the century, particularly post 2050, resulting in attenuation of streamflow. Hydroelectric power will become increasingly important to the Basin, particularly as countries shift to a greater reliance on renewable energy sources. Based on our projections, the time to invest in hydroelectric energy via dams is early in the century, before the detrimental effects of climate change become pronounced, particularly for Egypt. Sufficient evidence now exists that Egypt is likely to witness diminished streamflow, particularly post 2050.

The Nile River Basin is comprised of ten countries: Egypt, Ethiopia, Sudan, South Sudan, Uganda, Burundi, Democratic Republic of the Congo, Tanzania, Kenya, and Rwanda. These ten countries have economies dominated predominately 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 expect to see changes in the water use patterns throughout the region as the population in the region increases (El-Fadel 2003:108). Such water use patterns will depend on changes in the volume of the Nile River during the current century.

Demographic estimates also suggest that the population in the region may 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 a river that is largely generated within its current geographical boundaries. Increasing agricultural and industrial (i.e., energy) production throughout Ethiopia to meet the demands of a growing population may require the country to tap into its Nile reserves or face the prospect of severe water shortages. The timing of such action, if undertaken,

may reduce the river's streamflow to the downstream countries of Sudan and Egypt. The same issue, albeit on a smaller scale, is evident in other Nile River source countries.

These ten countries of the Nile River Basin are linked together by a common factor: water. Sustainability of the Basin will depend on the willingness of these countries to form cooperative agreements around the management of water that are capable of enhancing the viability of the entire region. The current treaty, forged in 1959 between Egypt and Sudan, which allocates the entire Nile River to these two countries, is not tenable. Upstream countries, though their precipitation levels are projected to increase throughout the century, will require access to waters from the tributaries of the Nile for purposes that develop their countries. However, projections suggest that Egypt and Sudan will experience decreases in streamflow post 2050. Climate change, particularly with respect to water shortages, exacerbates the potential for conflict (Barnett and Adger 2007).

Avoidance of conflict within the region during the 21st Century will require attention to the development of a comprehensive water management system. This system will have to account for utilization of water for enhanced energy capacity in the Basin as well as an equitable distribution of water based on changes in the water capacity of the region. Insofar as the vast majority of water used annually is earmarked for agricultural production, anticipated changes in population will have to be regulated and managed within the Basin's water system. Moreover, insofar as evidence from this study, as well as others, suggests that precipitation will likely increase in upstream countries prior to 2050, systemic management of streamflow will be critical in order to divert water into meaningful uses in order to avoid the negative effects of inundation. Utilization of this water might best be directed toward the strategically planned diversion toward the GERD reservoir.

The Nile River Basin Initiative, as a regional forum established for the purpose of managing resources, has taken an active role in the development of future policy initiatives for the Basin. This group will be critical in the evolution of a water management system for the Basin. Essential to this group, are policies capable of managing the allocation and utilization of water in a manner that is equitable and supportive of all ten countries. Such policies will need to focus on issues associated with the dynamic association between water, crop yield, and population growth in the contextual realities associated with climate change. Without the presence of an association that can both establish regional policy around intra-country water consumption and assess water utilization, the region is likely to become mired in conflicts associated with winner-take-all strategies. Such actions will most certainly undermine the Basin's developmental capacity.

Consumption is always juxtaposed to carrying capacity. Presently, the Nile River Basin is on course to overshoot its water capacity. This scenario will likely intensify over the next 15-20 years with the potential for increased regional tension by mid-century. Avoidance of conflict within the Basin will require prompt attention to the development of a comprehensive water management system. This system must account for utilization of water for enhanced energy capacity in the Basin while maintaining an equitable distribution of water based on anticipated regional changes in the water capacity of the region. Post 2050, the systemic management of streamflow will be critical in order to divert water into meaningful uses in order to avoid the concurrent negative effects of inundation and drought throughout the Basin. Future work needs to assess plausible scenarios for sustainable water management systems within the Basin that are capable of incorporating both agricultural and energy production and the creation of new water sources including desalinization in light of tremendous population growth.

Conclusion

The purpose of our study is to examine the impact of environmental and human factors on the carrying capacity (streamflow) of the Nile River throughout the 21st Century. We offer three key

findings. First, temperature is projected to increase continuously in all assessed regions of the Nile River Basin through the 21st Century. Second, precipitation is projected to increase streamflow capacity in source countries (Regions 3 and 4), maintain a moderately constant capacity in Region 2 (Sudan), and decrease streamflow in Region 1 (Egypt), particularly post 2050. Third, a reservoir fill rate of 10 to 15%, given projected increases in streamflow within the Blue Nile region, would build hydroelectric capacity in Ethiopia while concurrently ensuring a constant level of streamflow throughout Sudan and Egypt.

Presently, the Nile River Basin is on course to overshoot its water capacity. This scenario will likely intensify over the next 15-20 years with the potential for increased regional tension by mid-century. Avoidance of conflict within the Basin will require prompt attention to the development of a comprehensive water management system. This system must account for utilization of water for enhanced energy capacity in the Basin while maintaining an equitable distribution of water based on anticipated regional changes in the water capacity of the region. Post 2050, the systemic management of streamflow will be critical in order to divert water into meaningful uses in order to avoid the concurrent negative effects of inundation and drought throughout the Basin. Future work needs to assess plausible scenarios for sustainable water management systems within the Basin that are capable of incorporating both agricultural and energy production and the creation of new water sources including desalinization in light of tremendous population growth.

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Appendix A: General Circulation Models Employed By Study

Modeling Center (or Group)	Institute ID	Country	Model Name
Commonwealth Scientific and industrial research organization (CSIRO) and Bureau of Meteorology (BOM), Australia	CSIRO-BOM	Australia	ACCESS 1.0 ACCESS 1.3
Beijing Climate Center, China Meteorological Administration	BCC	China	BCC-CSM1.1 BCC-CSM1.1(m)
College of Global Change and Earth System Science, Beijing Normal University	GCESS	China	BNU-ESM
Canadian Centre for Climate Modelling Analysis	CCCMA	Canada	CanESM2
National Center for Atmospheric Research	NCAR	United States	CCSM4
Community Earth System Model Contributors	NSF-DOE-NCAR	United States	CESM1 (BGC) CESM1 (CAM5)
Centro Euro-Mediterraneo per i Cambiamenti Climatici	CMCC	Italy	CMCC-CM
Centre National de Recherches Météorologiques/ Centre Européen de Recherche et Formation Avancée en Calcul Scientifique	NRM-CERFACS	France	CNRM-CM5
Commonwealth Scientific and Industrial Research Organization in collaboration with Queensland Climate Change Centre of Excellence	CSIRO-QCCCE	Australia	CSIRO-Mk3.6.0
LASG, Institute of Atmospheric Physics, Chinese Academy of Sciences and CESS, Tsinghua University	LASG-CESS	China	FGOALS-g2
The First Institute of Oceanography, SOA, China	FIO	China	FIO-ESM
NOAA Geophysical Fluid Dynamics Laboratory	NOAA GFDL	United States	GFDL-CM3 GFDL-ESM2G GFDL-ESM2M
NASA Goddard Institute for Space Studies	NASA GISS	United States	GISS-E2-R
National Institute of Meteorological Research/Korea Meteorological Administration	NIMR/KMA	Korea	HadGEM2-AO
Met Office Hadley Centre (additional HadGEM2-ES realizations contributed by Instituto Nacional de Pesquisas Espaciais)	MOHC (additional realizations by INPE)	United Kingdom, Brazil	HadGEM2-CC HadGEM2-ES
Institute for Numerical Mathematics	INM	Russia	INM-CM4
Institut Pierre-Simon Laplace	IPSL	France	IPSL-CM5A-LR IPSL-CM5A-MR IPSL-CM58-LR
Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies	MIROC	Japan	MIROC-ESM MIROC-ESM-CHEM
Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology	MIROC	Japan	MIROC5
Max-Planck-Institut für Meteorologie (Max Planck Institute for Meteorology)	MPI-M	Germany	MPI-ESM-MR MPI-ESM-LR
Norwegian Climate Centre	NCC	Norway	NorESM1-M NorESM1-ME

Appendix B: GCM Estimates for Precipitation and Temperature by Baseline and Time Interval.

Region 1

Temperature Celsius (absolute change)	Mean	SD	Min	Max
Baseline (1970-2000) Degrees Celsius	23.51247	0.063135	23.39227	23.63616
2010-2039	1.339714	0.336522	0.615538	2.156777
2040-2069	2.55795	0.682266	0.989572	4.196116
2070-2099	3.754007	1.386669	1.154784	6.580904
Precipitation (pct change as per baseline)				
Baseline (1970-2000) avg mm per day	0.083676	0.004094	0.075392	0.091388
2010-2039	0.76817	9.464448	-15.0666	34.08161
2040-2069	-5.4842	13.44645	-30.1275	42.49581
2070-2099	-10.1646	16.48913	-51.3757	19.87096

Region 2

Temperature (absolute change)	Mean	SD	Min	Max
Baseline (1970-2000) Degrees Celsius	28.6879	0.07509	28.50042	28.81471
2010-2039	1.320741	0.290089	0.770276	2.218633
2040-2069	2.593155	0.633309	1.29757	4.176803
2070-2099	3.796322	1.3836	1.42838	6.797748
Precipitation (pct change as per baseline)				
Baseline (1970-2000) avg mm per day	0.173843	0.01184	0.153503	0.202482
2010-2039	20.0027	27.20607	-29.4655	92.70388
2040-2069	25.77937	42.21757	-27.6254	165.421
2070-2099	38.59188	69.47413	-43.0666	283.3779

Region 3

Temperature Celsius (absolute change)	Mean	SD	Min	Max
Baseline (1970-2000) Degrees Celsius	24.78143	0.076027	24.61589	24.89654
2010-2039	1.075666	0.283738	0.416988	1.67915
2040-2069	2.201316	0.617205	0.739661	3.528473
2070-2099	3.287525	1.243371	0.712064	5.79721
Precipitation (pct change as per baseline)				
Baseline (1970-2000) avg mm per day	2.387648	0.0247	2.33719	2.450391
2010-2039	5.178637	5.848689	-4.93148	23.51502
2040-2069	7.976245	10.36755	-9.41894	42.50315
2070-2099	12.96343	15.72835	-8.17837	71.33646

Region 4

Temperature Celsius (absolute change)	Mean	SD	Min	Max
Baseline (1970-2000) Degrees Celsius	26.46385	0.090793	26.2789	26.61994
2010-2039	1.044355	0.260522	0.488399	1.558883
2040-2069	2.134654	0.607395	0.836587	3.466959
2070-2099	3.191658	1.213483	0.878914	5.591757
Precipitation (pct change as per baseline)				
Baseline (1970-2000) avg mm per day	3.031168	0.032878	2.955664	3.078317
2010-2039	3.69223	4.564066	-5.24352	15.69697
2040-2069	6.538865	7.98511	-12.3754	30.62573
2070-2099	11.00625	11.0403	-10.821	44.96045

Appendix C: Regional Climate Change Calculations

Calculations for the other three regions were generated in a manner identical to the steps provided for Region 3. We provide these estimates below for purposes of replication.

Region 4:

Region 4 Temp Change Early Century = IF THEN ELSE (Time <2040, RANDOM NORMAL (0.488399,1.55888,1.04436,0.260522,1),0)

Region 4 Temp Change Mid Century = IF THEN ELSE (Region 4 Temp Change Early Century+Region 4 Temp Change Late Century=0, RANDOM NORMAL (0.836587,3.46696,2.13465,0.607395,1),0)

Region 4 Temp Change Late Century = IF THEN ELSE (Time >=2070, RANDOM NORMAL (0.878914,5.59176,3.19166,1.21348,1),0)

Region 4 Absolute Temperature Change = Climate Change Toggle Button*(Region 4 Temp Change Early Century+Region 4 Temp Change Mid Century+Region 4 Temp Change Late Century)

Region 4 Percent Change in Nile River Flow as a Result of Absolute Change in Temperature = $-(1.0375^{\text{Region 4 Absolute Temperature Change}}-1)$

Region 4 Early Century Percent Change in Rainfall = IF THEN ELSE (Time <2040, RANDOM NORMAL (-5.24352,15.697,3.69223,4.56407,1),0)

Region 4 Mid Century Percent Change in Rainfall = IF THEN ELSE (Region 4 Early Century Percent Change in Rainfall+Region 4 Late Century Percent Change in Rainfall=0, RANDOM NORMAL (-12.3754,30.6257,6.53887,7.98511,1),0)

Region 4 Late Century Percent Change in Rainfall = IF THEN ELSE (Time >=2070, RANDOM NORMAL (-10.821,44.9604,11.0063,11.0403,1),0)

Region 4 Percent Rainfall Change = Climate Change Toggle Button*((Region 4 Early Century Percent Change in Rainfall+Region 4 Mid Century Percent Change in Rainfall+Region 4 Late Century Percent Change in Rainfall))

Percent Change in White Nile Flow as a Percent of Precipitation Change = IF THEN ELSE (Time>=1994,((-0.0002*(Region 4 Percent Rainfall Change^3))+0.0023*(Region 4 Percent Rainfall Change^2))+1.6462*Region 4 Percent Rainfall Change)+5.8769)*0.01,0)*lower region unit multiplier*Climate Change Toggle Button

Region 2:

Region 2 Temp Change Early Century = IF THEN ELSE (Time <2040, RANDOM NORMAL (0.770276,2.21863,1.32074,0.290089,1),0)

Region 2 Temp Change Mid Century = IF THEN ELSE(Region 2 Temp Change Early Century+Region 2 Temp Change Late Century=0, RANDOM NORMAL (1.29757,4.1768,2.59315,0.633309,1),0)

Region 2 Temp Change Late Century = IF THEN ELSE (Time >=2070, RANDOM NORMAL (1.42838,6.79775,3.79632,1.3836,1),0)

Region 2 Absolute Temperature Change = Climate Change Toggle Button*(Region 2 Temp Change Early Century+Region 2 Temp Change Mid Century+Region 2 Temp Change Late Century)

Region 2 Percent Change in Nile River Flow as a Result of Absolute Change in Temperature = $-(1.0375^{\text{Region 2 Absolute Temperature Change}}-1)$

Region 2 Early Century Percent Change in Rainfall = IF THEN ELSE (Time <2040, RANDOM NORMAL (-29.4655,92.7039,20.0027,27.2061,1),0)

Region 2 Mid Century Percent Change in Rainfall = IF THEN ELSE (Region 2 Early Century Percent Change in Rainfall+Region 2 Late Century Percent Change in Rainfall=0, RANDOM NORMAL (-27.6254,165.421,25.7794,42.2176,1),0)

Region 2 Late Century Percent Change in Rainfall = IF THEN ELSE (Time >=2070, RANDOM NORMAL (-43.0666,283.378,38.5919,69.4741,1),0)

Region 2 Percent Rainfall Change = (Climate Change Toggle Button*((Region 2 Early Century Percent Change in Rainfall+Region 2 Mid Century Percent Change in Rainfall+Region 2 Late Century Percent Change in Rainfall)*0.01))

Percent Change in Nile River Flow as a Percent of Precipitation Change = IF THEN ELSE (Time>=1994,((-0.0004*(Region 2 Percent Rainfall Change^3))+0.0098*(Region 2 Percent Rainfall Change^2))+3.5578*Region 2 Percent Rainfall Change) + 0.7986) * 0.01,0) * Climate Change Toggle Button

Region 1:

Region 1 Temp Change Early Century = IF THEN ELSE (Time <2040, RANDOM NORMAL (0.615538,2.15678,1.33971,0.336522,1),0)

Region 1 Temp Change Mid Century = IF THEN ELSE (Region 1 Temp Change Early Century+Region 1 Temp Change Late Century=0, RANDOM NORMAL (0.989572,4.19612,2.55795,0.682266,1),0)

Region 1 Temp Change Late Century = IF THEN ELSE (Time >=2070, RANDOM NORMAL (1.15478,6.5809,3.75401,1.38667,1),0)

Region 1 Absolute Temperature Change = Climate Change Toggle Button*(Region 1 Temp Change Early Century+Region 1 Temp Change Mid Century +Region 1 Temp Change Late Century)

Region 1 Percent Change in Nile River Flow as a Result of Absolute Change in Temperature = -((1.0375^Region 1 Absolute Temperature Change)-1)

Region 1 Early Century Percent Change in Rainfall = IF THEN ELSE (Time <2040, RANDOM NORMAL (-15.0666,34.0816,0.76817,9.46445,1),0)

Region 1 Mid Century Percent Change in Rainfall = IF THEN ELSE (Region 1 Early Century Percent Change in Rainfall+Region 1 Late Century Percent Change in Rainfall=0, RANDOM NORMAL (-30.1275,42.4958,-5.4842,13.4465,1),0)

Region 1 Late Century Percent Change in Rainfall = IF THEN ELSE (Time >=2070, RANDOM NORMAL (-51.3757,19.871,-10.1646,16.4891,1),0)

Region 1 Percent Rainfall Change = (Climate Change Toggle Button*((Region 1 Early Century Percent Change in Rainfall+Region 1 Late Century Percent Change in Rainfall+Region 1 Mid Century Percent Change in Rainfall)))

Percent Change in Nile River Flow as a Percent of Precipitation Change = IF THEN ELSE (Time>=1994,((-0.0003*(Region 1 Percent Rainfall Change^3))+0.0085*(Region 1 Percent Rainfall Change^2))+2.902*Region 1 Percent Rainfall Change) +0.9994) *0.01,0) * Climate Change Toggle Button