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Dynamics of Migration: Population Growth, Food Security, and Water Resource Management in the Nile River Basin

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Author Note: The authors are First Class cadets within the Department of Systems Engineering at the United States Military Academy enrolled in a culminating capstone course advised by Dr. Bruce Keith. Designed to test and put into practice what the cadets have learned over the tenure at the Academy, the capstone focuses on system dynamics modeling.

Abstract: The purpose of our research is to apply a system dynamics approach to the interactive relationships between water resources, food production, population, and migration in the Nile River Basin region. In order to conduct our study we relied on the World Bank Database in order to provide a historical reference mode that acts as a base case for our study and further analysis. We created a model, which builds upon two previously validated models, within the modeling platform, Vensim. Our model results currently produce an overshoot and collapse behavior of the population within the Nile River Basin. This study will contribute to the field of System Dynamics because we address a dynamic and complex problem that affects many underdeveloped regions. Our simulation model will be helpful in diagnosing the potential impacts of a water crisis that is applicable for both humanitarian and security reasons.

Keywords: System Dynamics, Migration, Climate Change, Nile River Basin Region, Overshoot and Collapse

1. Introduction

The continent of Africa has a population of approximately 1.25 billion inhabitants with a projected annual growth rate of 2.5% (Worldometers, 2017). Currently, 70% of the population within Africa relies on subsistence farming, an occupation that depends on consistent climate patterns (Mamadou, 2016). As climate patterns place restraints on the current water supply, extreme water disparity issues are a major concern (Falkenmark, 1992). The Human Development Index, a holistic picture of a country's respective development, places sub-Saharan countries of Africa towards the lower end of the spectrum, implying that these nations lack the infrastructure and resources to adequately prepare for the climate change effects on precipitation (Falkenmark, 1992). Thus, the advances in infrastructure and education regarding water disparity must continue at a rate faster than the inevitable changes in precipitation patterns. Our study seeks to apply System Dynamics in order to raise awareness of the severity of a changing climate in a region of finite resources.

2. Problem Articulation

2.1 Purpose

The purpose of our study is to explain the effect of changes in water resources, food production, and population changes on human displacement in the Nile River Basin**.** In an attempt to find the most sensitive sector of analysis, we hope to provide insight into the ballooning issue of climate change and human displacement throughout the region. Our variables of study are water availability, population, migration, and food availability. These are the driving stocks within our model that we will apply using Ethiopia as our case study. We hope to create a model that is widely applicable and versatile across any region that has the potential to face a water crisis.

2.2 Sectors of Analysis

Given the desert climate of Africa and reliance on subsistence farming, water's essential role in Africa is the irrigation of crops. However, some of the regions with the largest supply of water "irrigate only about 6 percent of their collective cropland" (Swendsen, 2009). There is data that shows "developing countries, particularly those in Africa, are likely to be especially vulnerable to climate change as recurrent floods and droughts continue to bring misery to millions" (Bellerby, 2010). The lack of irrigation, coupled with the desert climate and increasing volatility of rain cycles, creates an environment that is not conducive to the production of crops, and ultimately the sustainment of human life.

Given the variability in precipitation patterns, and that "the Nile Basin is one of the most water-limited basins in the world," (Mohamed, 2010) it is difficult to pinpoint when Africa will experience extreme water disparity issues. As the climate continues to change and creates unpredictable precipitation cycles, the amount of available and usable water will decrease. In a region suffering from a lack of available water, additional constraints on access to available water will only compound the magnitude of the problem.

Africa is far from reaching a stable population and continues to grow exponentially, a behavior that places further strain on available resources. Predictions estimate an increase in population from 3.1 to 5.7 billion by the end of the century (Gerland, 2014). An extreme population growth that supersedes the environmental and societal ability to sustain the current population will cause many to either die or migrate out of the region. This compounds the issue because those who have the means to exit sub-Saharan Africa are more likely to have greater cognitive skill and social capital, therefore further degrading the system and its ability to recover from the exponential growth.

In an event of temperature and precipitation shifts, it is likely that the arability of the land will decrease (Turner, 2016). Intuitively, food demand will increase with population driving the need to utilize more land, stressing the existing arable land, causing crop yield to go up and fill food shortages, but not without straining the earth and increasing demand for water. Since water and land both have a finite supply this will eventually reach a capacity constraint.

2.3 Time Horizon

We understand that the model will not be accurate in extrapolating long term behavior. However, we can assume that contextual factors used in our current model will be the same as in the future.

2.4 Reference Mode and Description

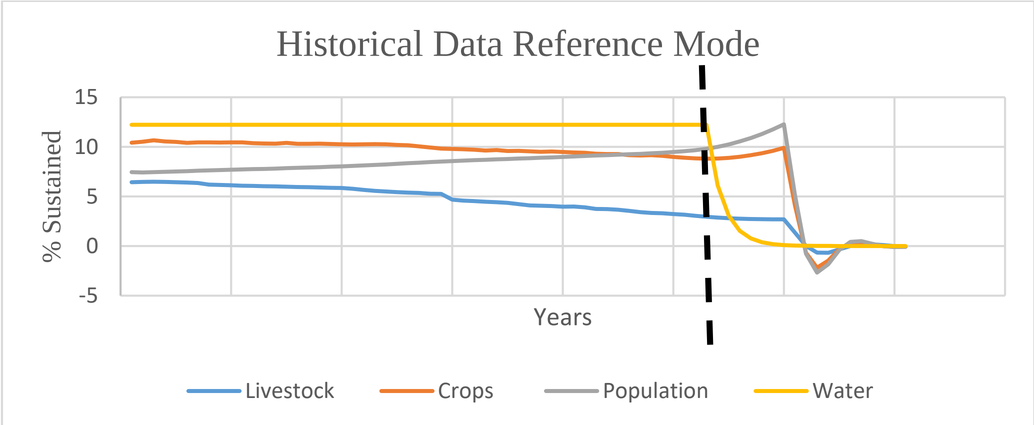

Figure 1: Historical Reference Mode

This reference mode is a visual depiction of the historical behavior of Ethiopia using data compiled from the World Bank Database. This reference mode will function as a base case in which we will compare the results of our simulation output. This historical data will assist us in the validation of our model as well as understanding the basic behaviors of our stock variables that we seek to model.

3. Formulation of Dynamic Hypothesis

3.1 Dynamic Hypothesis

Migration in the Nile River Basin is a function of three stocks: population, food, and water resources. We expect that the volatility of rain cycles within the region will continue and subsequently spur a migration through a series of causal relationships and reinforcing and balancing feedback mechanisms. While climate change alone cannot lead to migration, we rely on the assumption that the interactions between our variables of focus will lead to second and third order effects that will subsequently lead to the inability to sustain life effectively in an area and thus induce migratory patterns that are larger than throughout history.

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As the availability of food, water, and jobs decrease, it is assumed that the population affected will attempt to move to find a new place to sustain their lifestyles. The severity of the migration is dependent on the existing infrastructure and preventative measures in place by the country in question. The more preparations taken to alleviate the effects of climate change, the less individuals who will find themselves displaced in the immediate time horizon.

By using the fundamentals of system dynamics, we are able to model the feedback structures of the system and account for the exogenous variables outside the scope of our system in order to model the collapsing behavior of our problem.

3.2 Causal Loop Diagram

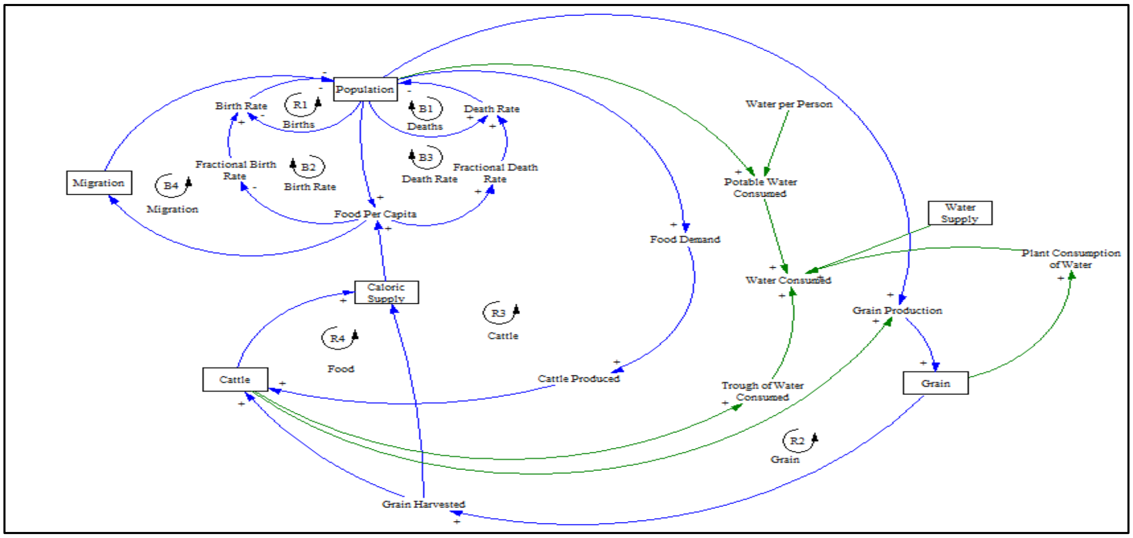

Figure 2: Causal Loop Diagram

As displayed by the population loop consisting of sub loops R1 and B1-3, the dominant behavior shown by this relationship is overshoot and collapse. The initial growth of the population (overshoot) is due to the fractional birth rate being greater than the fractional death rate. This explains why the reinforcing loop is so dominant in describing the consistent growth of the population. However, as shown by our final reference mode, the population subsequently collapses. This is due to the balancing loops throughout the rest of the model.

As overall temperatures increases, the oscillation and volatility of climate patterns and precipitation also increases. This oscillation is induced by an increased delay in rain cycles that ultimately lead to longer periods of drought and longer periods of rainfall. In an area where the primary driver of economics is agriculture, the effects of sustained drought and flooding can be severe. As the water supply, comprised of ground water and surface water either decreases or increases, the current food supply produced in a particular region will be forced to either adapt or be replaced by a less susceptible crop. This will increase or decrease the water consumption and water per capita.

With an overall higher demand for food and a lower capacity of arable land, the rate of soil degradation will be accelerated by the over farming of what land is still available. This will lead to an overall change in the dynamics of the population. A population will be forced to learn new skills in harvesting new crops, and the international and domestic markets will adjust, or fail to adjust to a new supply of crops. As shown in the reinforcing loops "Grain" and "Cattle," both loops are dependent on the available water supply and demand from the population. As water is readily available, the grain and cattle supply will grow and the population demand will grow as more nutritive properties are added to the existing diet. However, if the inverse occurs because a population depletes the existing water supply, the supply of grain and cattle will also decrease-leading to a subsequent decline in availability and overall food supply. This explains the behavior of overshoot and collapse that we expect to see with the cattle and grain variables. As the water supply is sustained, crops and cattle will overshoot the capacity and then ultimately crash.

Initially our model experiences the overshoot behavior due to the dominance of the "fractional birth rate." However, as the system reaches its carrying capacity, dominance shifts to the "fractional death rate" causing a collapse in the behavior of our model. As the population is unable to be sustained by the available resources, the amount of deaths will increase and thus, we will see a collapse in the population. This degraded situation will lead to an anticipated migration of people out of the suffering region.

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We anticipate that the migration behavior out of the region will be exponential. This migration behavior has long term implication because as more people depart, there will be less people available to address the problem in the future. Therefore, this migration leads to a decrease in the overall population leading to the balancing behavior of population as shown in the "Migration" loop.

4. Simulation Model

4.1 Method

4.1.1 Platform and Formulation

Vensim allows for our team to model the dynamic relationship of our variables: water, food, population, and migration. The foundation of our model was the previously validated Nile River Basin Streamflow Model and the Sahel model. The Sahel model incorporated similar types of feedback loops that related population growth with cattle supply. The biggest alteration from this model was incorporating human water consumption. We used the Nile River Basin Streamflow Model to account for rainfall patterns within the region. In our completed model, we also factored in grain as a part of the human diet. Considering these three contributors to population sustainment, grain, cattle, and water, we created adequacy ratios. These ratios define the effect caused by discrepancies between supply and demand of the population. These effects manifest into two outflows from the population stock, which are immigration and death.

4.1.2 Initial Assumptions and Conditions

For the purpose of the model, we made necessary assumptions to aide in our model development. We assumed that water is used by cattle, people, grain, and runoff. Additionally, we assumed the amount of water consumed by cattle, people, and acreage of farm land per year. Assumptions were made regarding the daily caloric diet of people, the calories available per cow, and the slaughter rate, all of which were constants within the model. Other general assumptions regarding grain was that grain will oscillate due to weather patterns as well as the ability of grain to grow without a population present. Another key assumption in our model is the lookup function dealing with levels of malnutrition. We assume that it takes a parabolic ark shape, with the lower levels of adequacy causing more people to die than go malnourished with the mid-levels of inadequacy causing more people to go malnourished than die, and an adequate supply resulting in less people going malnourished.

4.2 Sensitivity Analysis

In order to conduct our sensitivity analysis we varied certain exogenous variable by a percentage of their original value and then overlay the data and compare it to a base case. For example, the exogenous variables we have chosen to analyze is the percentage of diet comprised of livestock. From this analysis, we have determined that the greater reliance of the population on cattle for nutrition, the longer the population will remain stable. According to our model, this will prolong the life expectancy of the population and draw out the collapse. When the population experiences this increase, the subsequent collapse occurs more rapidly. Our future sensitivity analysis will follow the same procedures.

Table 1: Sensitivity Analysis

Year	35	36	37	38	39	40	41	42	43	44	45	46	47	48
Diet 50% Livestock	386700	493000	628600	801500	455100	258500	146800	83360	47340	26880	15270	8670	4923	2796
Slope		*106300*	*135600*	*172900*	*-346400*	*-196600*	*-111700*	*-63440*	*-36020*	*-20460*	*-11610*	*-6600*	*-3747*	*-2127*
Diet 75% Livestock	386700	493000	628600	801500	1022000	1303000	1661000	943400	535700	304200	172800	98120	55720	31640
Slope		*106300*	*135600*	*172900*	*220500*	*281000*	*358000*	*-717600*	*-407700*	*-231500*	*-131400*	*-74680*	*-42400*	*-24080*
Diet 100% Livestock	386700	493000	628600	801500	1022000	1303000	1661000	2118000	2535000	2886000	3182000	3432000	3642000	3820000
Slope		*106300*	*135600*	*172900*	*220500*	*281000*	*358000*	*457000*	*417000*	*351000*	*296000*	*250000*	*210000*	*178000*

4.4 Results

The model predicts the overshoot and collapse displayed by our reference mode and future predictions graph. The graph shows that water and its structure are drive the behavior of this model. Since grain growth is heavily reliant on an ample supply of water, it grows more with more available water. Cattle is reliant on both grain and water supply, so the simultaneous increase of both results in an increase in the quantity of livestock. Finally, the increase in all three stocks: water, cattle, and

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grain, lead to a new level of population growth. When this growth begins to outpace the carrying capacity of water people begin to die, become malnourished, or migrate. This is depicted by the rapid population decline of Figure 5. Figure 5 shows a scenario in which majority of the population decides to emigrate from their home country. As resources become scarce, large quantities of people begin to leave rather than stay and die due to malnutrition. This is depicted by the spike in emigration around year 36. Though our model results match the behavior of our reference mode, the results are not complete. From a numerical perspective, the values predicted by our model are much smaller in scale and with varying relationships to each other. Also one of the most prominent issues is the immediate collapse of population. This result is due to a simultaneous collapse of the resource pool that makes the severity of the collapse dramatic. Additionally, in some of the outputs we see values returning to positive from a negative state which is a flaw in our model.

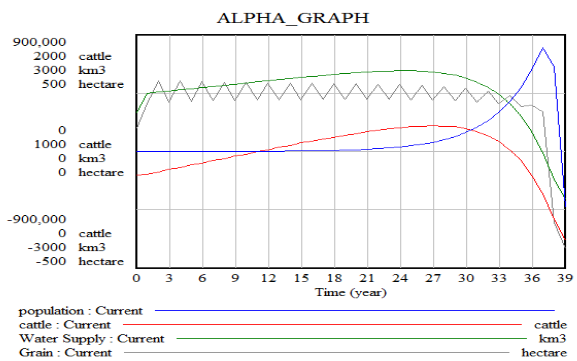

Figure 3: Model Output showing Overshoot and Collapse

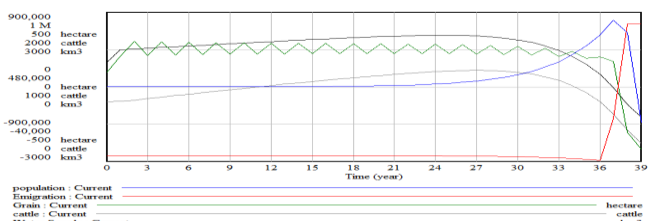

Figure 4: Model Output displaying Migration Prediction

4.5 Discussion and Conclusion

Migration in the Nile River Basin is a function of three stocks population food and water resources. Our model is able to simulate the behavior of the relationship between the variables and produce outputs that are reflective of historical data. While our model produces behavior that is similar to that of historical data, we still have a few disparities between what our model produces and what historical data has reflected. One difference is that oscillation of the grain stock. Currently we are working through adjusting our model to create a smooth function as opposed to an oscillation. This is occurring due to an incongruence between our primary variables: population and water.

Our next step is to further critique the model, structure our data more intuitively, and analyzing and address the effects of changing variable inputs. Once the model is further solidified we will enhance the effects of climate change on the inputs. This will focus on the effects of climate change on rainfall and temperature change on crop growth. We anticipate the climate change will enhance the collapse depicted by the current Vensim model by subtracting from the already limited water supply. We hope to have a model that is robustly applicable and able to be transferred to a vast number of regions. Therefore, our solidification of the model and data organization is imperative to meet this goal.

With our sensitivity analysis, we hope to determine which exogenous variables are the most sensitive to the model. Identifying these variables will be key to determining our policy measures and recommendations for the best course of actions these volatile regions should focus on. We anticipate that a cattle based diet will cause a more severe crash, and thus, we urge regulation of meat consumption as well as awareness and education on water as a finite resource.

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