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Abstract

The Integrated Human Futures Project provides a set of analytical and quantitative modeling and simulation tools that help explore the links among human social, economic, and ecological conditions, human resilience, conflict, and peace, and allows users to simulate tradeoffs and consequences associated with different future development and mitigation scenarios.

In the current study, we integrate five distinct modeling platforms to simulate the potential risk of social unrest in Egypt resulting from the Grand Ethiopian Renaissance Dam (GERD) on the Blue Nile in Ethiopia. The five platforms simulate hydrology, agriculture, economy, human ecology, and human psychology/behavior, and show how impacts derived from development initiatives in one sector (e.g.,

hydrology) might ripple through to affect other sectors and how development and security concerns may be triggered across the region. This approach evaluates potential consequences, intended and unintended, associated with strategic policy actions that span the development-security nexus at the national, regional, and international levels. Model results are not intended to provide explicit predictions, but rather to provide system-level insight for policy makers into the dynamics among these interacting sectors, and to demonstrate an approach to evaluating short- and long-term policy trade-offs across different policy domains and stakeholders.

The GERD project is critical to government-planned development efforts in Ethiopia but is expected to reduce downstream freshwater availability in the Nile Basin, fueling fears of negative social and economic impacts that could threaten stability and security in Egypt. We tested these hypotheses and came to the following preliminary conclusions. First, the GERD will have an important short-term impact on water availability, food production, and hydropower production in Egypt, depending on the short-term reservoir fill rate. Second, the GERD will have a very small impact on water availability in the Nile Basin over the longer term. Depending on the GERD fill rate, short-term (e.g., within its first 5 years of operation) annual losses in Egyptian food production may peak briefly at 25 percent. Long-term (e.g., 15 to 30 year) cumulative losses in Egypt's food production may be less than 3 percent regardless of the fill rate, with the GERD having essentially no impact on projected annual food production in Egypt about 25 years after opening. For the quick fill rates, the short-term losses may be sufficient to create an important decrease in overall household health among the general population, which, along with other economic stressors and different strategies employed by the government, could lead to social unrest.

Third, and perhaps most importantly, our modeling suggests that the GERD's effect on Egypt's food and water resources is small when compared to the effect of projected Egyptian population and economic growth (and the concomitant increase in water consumption). The latter dominating factors are exacerbated in the modeling by natural climate variability and may be further exacerbated by climate change. Our modeling suggests that these growth dynamics combine to create long-term water scarcity in Egypt, regardless of the Ethiopian project. All else being equal, filling strategies that employ slow fill rates for the GERD (e.g., 8 to 13 years) may mitigate the risks in future scenarios for Egypt somewhat, but no policy or action regarding the GERD is likely to significantly alleviate the projected water scarcity in Egypt's Nile Basin. However, general beliefs among the Egyptian populace regarding the GERD as a major contributing factor for scarcities in Egypt could make Ethiopia a scapegoat for Egyptian grievances—contributing to social unrest in Egypt and generating undesirable (and unnecessary) tension between these two countries. Such tension could threaten the constructive relationships between Egypt and Ethiopia that are vital to maintaining stability and security within and between their respective regional spheres of influence, Middle East and North Africa, and the Horn of Africa.

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INTRODUCTION

Regional security and stability are driven by complex dynamics that involve the human demand for and availability of natural resources, the state of economic development, governmental policies and their effect on local norms, and the population's perception of and satisfaction with those policies. Identifying the dynamic factors that increase the risk of political instability and violent civil conflict can inform policies that limit conflict and preserve future security and stability. Growing global dependencies, increasing threats of global terrorism and nuclear proliferation, and belligerence of foreign powers combined with the global reach of U.S. security commitments provide a firm national security relevance for the development of scientific models that consider conditions that lead to conflict. The goal is to advance understanding of complex causal mechanisms of conflict while offering policy makers better tools for exploring options to prevent or manage conflict.

The Integrated Human Futures (IHF) Project is a step towards that goal by allowing hypotheses regarding those dynamics to be explicitly formulated, tested, and evaluated. The IHF platform permits researchers and policy makers to conduct in-depth sensitivity studies within environmental, economic, and social sectors, while conducting integrated studies across sectors to examine interdependencies between variables. This approach, motivated by and configured for the GERD, is expected to be widely applicable.

We first review theoretical connections between conflict and resource allocation to illustrate the generality of the problem and the uncertain state of current understanding. We next review previous modeling projects directed towards forecasting the consequences of alternative resource use policies. We then introduce the component models that comprise the IHF platform. Finally, we describe the environmental, economic, and political stresses associated with GERD construction, and the results of the component models as applied to that problem.

Resources and Conflict

At the country level, the highest risk of conflict and instability is generally agreed to be strongly and positively correlated to prevalent poverty, economic contraction, weak government institutions and infrastructures (especially in anocracies or partial democracies), heavy reliance of the export sector on primary commodities, political upheaval, and a recent history of armed conflict.[1] Intrastate conflicts and political instability are postulated to arise when local demands for resources exceed supply or one form of resource use pressures other uses. While a large number of individual case studies – mostly involving agriculture, animal grazing, or forest utilization – can be cited, research based on large-N statistical studies have not shown a generalizable correlation between the risk of armed civil conflict and natural resource scarcity.[2] This can be attributed to the large number of counterexamples that exist, and the conflating interactions between natural resource scarcity and poverty, low economic development, and weak governing institutions that often co-exist. The literature highlights the need to conduct more research on local level factors (such as resiliency), equitable distribution of scarce resources (a governance issue), and the role of state actors in escalating internal conflict over scarce resources.[3,4]

The relationship between natural resources and conflict is contested in the literature, whether considering resource abundance or scarcity.[5] Methodology problems have impeded analysis of causal mechanisms between conflict, instability, and resource scarcity. Country-level analysis of civil conflict and resource scarcity is particularly problematic.[6] Many such conflicts are initiated by local, geographically constrained factors that may not have been captured in conflict datasets.[7] Conflicts not contained within national borders may involve cross-border effects of poor governance, conflict spillover, and competition for control of resources.[8] Even so, the United Nations (UN) Environment Programme has assessed that 40 percent of intrastate conflicts in the past 60 years have links to natural resources, such as fertile land and water.[9] While causal mechanisms are difficult to identify, policy makers must consider the potential for aggravating tensions and conflicts when addressing more widely recognized conflict drivers, such as economic contraction and poverty. This must be set in the context of development efforts in an environment of global population rise, increased demand for resources, and potential consequences of climate change.

Policy interventions involving development of natural resources to alleviate risk of conflict and political instability are attractive for expanding people's choices, broadening their opportunities, and increasing human security.[10] However, these same interventions may induce changes that exacerbate existing political and societal grievances (perceived or real), increase competition for power and scarce resources, and create new struggles and sources of conflict, such as corruption or dissatisfaction with distribution of benefits from development. Indeed, the US Agency for International Development requires that a country level risk assessment be performed before embarking on new development programs.[11] The potential for an international upstream-downstream conflict over water between Egypt and Ethiopia has been frequently cited in the literature as an example of how tensions created by development initiatives within one country could generate broader regional security concerns. It is worth noting that negotiation between these two countries over Nile River water resources appears to be moving in the direction of cooperation rather than conflict.

Demonstration Case Study: Egypt, Ethiopia, and the GERD

Our demonstration case study examines the potential risk of social unrest in Egypt resulting from resource scarcity generated by downstream impacts of Ethiopia's GERD development project. This case study is chosen as a salient example of the interrelationship between security and development issues and potential impacts on regional stability. The issues of resource scarcity addressed by the IHF are two-fold: understanding the connections between variables that drive conflict and instability due to resource scarcity and understanding the impacts of policy interventions to ameliorate and/or manage potential conflict due to resource scarcity.

Background

Egypt's identity is intricately tied to the Nile, and the country has long enjoyed significant bargaining power over Nile resources.[12] The Nile River has three primary tributaries: the White Nile, which originates in Lake Victoria in Uganda, and the Blue Nile and Atbara River, both of which rise in the Ethiopian Highlands (Figure 1). The White and Blue Niles merge to form the Nile River near Khartoum, Sudan.[13] Beginning in 1929 with the Nile Water Agreement between Egypt and the United Kingdom, Egypt has been in the center of conflict over Nile water allocation.[14] Most historic cooperative agreements over Nile water allocation have not included all Nile riparian countries. The 1959 treaty between Egypt and Sudan that allocated 75 percent of Nile flow to Egypt (55.5 km^3) and 25 percent to Sudan (29 km^3) is an example.[15] However, the establishment of the Nile Basin Initiative in 1999 did include all 10 riparian countries.[16]

Our analysis of the relationship between national security, political stability, and resource scarcity in Egypt is informed by the history of agricultural production and the complex relationship between food subsidies, water use, rioting, and political treaties.

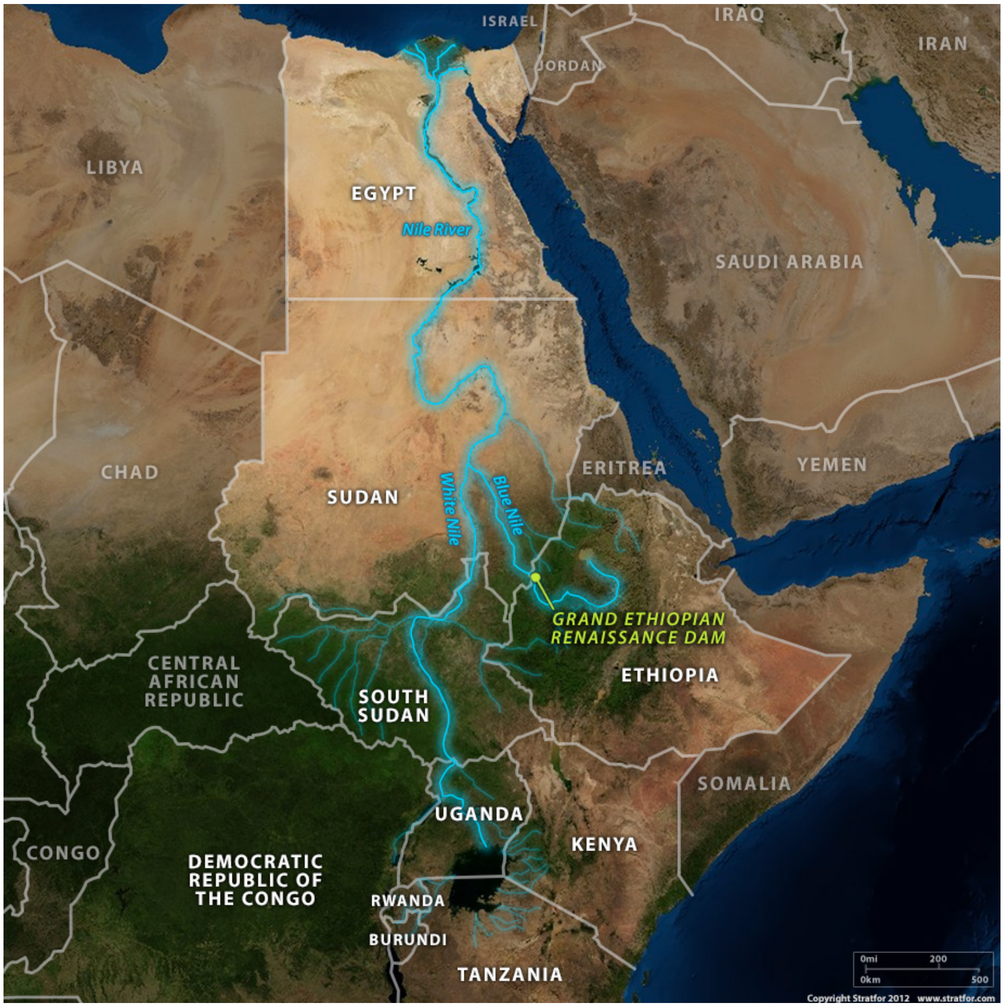

Figure 1. The Nile River

Source: "The Geopolitical Impact of the Nile," Stratfor Global Intelligence, 2012. Photo is republished with permission of Stratfor. https://www.stratfor.com/video/geopolitical-impact-nile.

Food in Egypt has been heavily subsidized since riots in 1977 occurred over issues of food prices and general equity. With more than half of Egypt's population living below the poverty line, these food subsidies are critical to well-being.[17] Baladi bread, baladi wheat flour, sugar, and cooking oil are currently subsidized for all income levels while sugar and cooking oil are subsidized for those with ration cards.[18] Egypt imports 45 to 55 percent of wheat needs, which means the country is vulnerable to price increases and fluctuations.[19] Historically, when Egyptian food subsidies have not kept up with surges in international food prices, rioting, demonstrations, and civil conflict have resulted, followed by deterioration of democratic institutions.[20]

Egypt's large urban population (43 percent) provides an environment for groups to assemble quickly and impact a large percentage of the population. Sources of social and political tensions in the country include the Muslim Brotherhood, militants in the Sinai Peninsula, general crime, and the flow of weapons and people from Libya, Gaza, and other borders.[21] The Muslim Brotherhood, in spite of being officially declared a terrorist organization in 2013 and enduring periodic censorship by the government, has enjoyed popular support as a civic organization and primary provider of social services in Egypt for almost a century.[22]

The Gross Domestic Product (GDP) growth rate in Egypt increased rapidly from 2002 to 2007, fueled by aggressive pursuit of economic reforms to attract foreign direct investment by the government. However, a combination of poor economic and social conditions led to a significant decline in GDP between 2007 and 2008, and an even more dramatic decline between 2009 and 2011, creating additional risk of conflict and instability. As of 2013, Egypt's per capita GDP ranked 144th in the world and GDP growth ranked 150th.

In contrast to Egypt, Ethiopia's population is largely agricultural, with less than 20 percent living in urban areas, and has one of the lowest per capita annual incomes in the world (US$1200). In recent years, however, Ethiopia has achieved one of the highest GDP growth rates in the world, reaching seven percent annually under a state-led economic transformation plan. This plan is fueled in large part by infrastructure investments to attract and support foreign investments in commercial agriculture and manufacturing.[23] Ethiopia views the GERD, currently under construction and due for completion in 2017, as critical to meeting future development targets and supporting increased domestic needs of a large youth population (64 percent under the age of 24).

The Problem

The GERD will store 63 billion cubic meters of water in its reservoir (which, by some accounting methods is roughly equal to a full year's flow from the Blue Nile) and produce 6,000 MW of hydroelectric power for Ethiopia.[24] The dam construction project has raised fears among Egyptians that their freshwater supply will be impaired and that agricultural production, food availability, and overall wellbeing of the population may be affected. In some circles, as seen in various public media reports, military action against Ethiopia has been considered. The GERD project arose during a time of political turmoil for Egypt, and with Chinese firms supporting Ethiopia's attempts to utilize hydropower, dam construction has become a geopolitically contentious issue.[25] Nile flow into Egypt may be significantly impacted as some estimates cite a reduction in function at the High Dam and Aswan Dam.[26] Recent attempts by President el-Sisi of Egypt to attend a summit at the African Union and meet with Prime Minister Desalegn of Ethiopia are underscored by the long rivalry between the two countries over Nile water allocation.[27]

The Modeling Approach

The potential social, cultural, and political impacts of GERD construction and alternative policies for its use make a compelling test case for using the IHF integrated modeling framework to map possible policy consequences, intended and unintended. The modeling approach is being developed to be scalable and applicable to a wide range of localized, regional, national, and international security and stability topics around the world. Case studies are essential for shaping and assessing the approach. Model results are not intended to provide explicit predictions, but rather to provide insight for policy makers into the dynamics among interacting and interdependent systems.

Although models exist for simulating systems-level impacts of critical infrastructure policies on aspects of human security, not many integrate multiple sectors and systems to leverage the unique capabilities of each.[28] The IHF framework represents the key theoretical findings on social and economic drivers of conflict and instability across five modeling platforms while testing hypotheses and causal mechanisms for some of the contested environmental and social variables. The five distinct modeling platforms simulate hydrology, agriculture/food, economy, human ecology, and human psychology/behavior, and show how impacts in one sector might ripple through the others. This approach provides a scalable, context-specific platform for exploring many complex and inter-related issues at the heart of the security-politics-development nexus while remaining transparent and simple enough to produce testable results.

Assessing Effects of the GERD on Egypt with IHF

The five IHF modeling platform capabilities are well-matched to simulate potential risks resulting from the GERD. The World Water and Agriculture Model (WWAM)[29] allows exploration of the relationship between GERD filling policies and the water, hydropower, and food sectors. The Infrastructure Resilience Assessment model identifies policy options for fostering agricultural resiliency in Egypt given significant water shortfalls expected during and after the construction of the GERD and the filling of its reservoir. The Exchange modeling platform is designed to study the dynamics of complex systems composed of specialized consumers and producers of resources, which interact through resource exchange.[30] Together, these three platforms represent various economic and natural resource processes proposed in the literature and discussed above for explaining risk of conflict and instability and potential impact on human security.

The Human Resilience Index (HRI) model provides a coarse measure of a country's human ecological condition and incorporates economic and demographic variables consistent with the conflict literature for assessing risk of instability and violence. Finally, Behavior Influence Assessment (BIA) is a generalized, theory-based, dynamic systems modeling capability intended to better assess the effects of events, actions, and counter-actions within and among groups of people within a country or countries.[31] The BIA has been configured to incorporate dynamic political, economic, and social drivers of conflict and instability into the IHF. Table 1 presents the five modeling platforms and their general characteristics.

Table 1. General modeling characteristics of the five platforms used in the Integrated Human Futures Project

Modeling Platform	Capability	Inputs	Outputs
World Water and Agriculture Model (WWAM)	Provide water, hydropower, and food sector balances as a function of filling policies for the GERD	Climate projections; basin parameters; crop parameters; population; GDP initial world prices; elasticities between commodities	Water supply to municipal, industrial, livestock, and irrigation;[a] food supply for 17 commodities; food prices

Modeling Platform	Capability	Inputs	Outputs
Infrastructure Resilience Assessment	Provide resilience measures to evaluate a variety of policies with respect to the impacts of the GERD in Egypt	WWAM outputs	Evaluation of cost/benefit of certain policies regarding the GERD
Exchange (Economics and Agriculture)	Model the flow of resources, goods, and labor	Nominal resource flows between sectors, and between Egypt and other countries	Changes in flows and final consumption resulting from imposed changes in resource availability
Human Resilience Index (HRI)	Characterizes a country or region based on indicators of human ecological condition	Population growth rate, population density, median age, per capita water, food and arable land, infant and child mortality, and lifespan	Historic and projected future values of the HRI, given available data
Behavioral Influence Assessment (BIA)	Simulates group and individual behavior based on the interplay between groups as well as external influences	Development of cognitive structure for important and/or cohesive groups	Fraction of individuals within groups, or strength of choice by a single individual, for a particular decision from a list of possible decisions

[a]In WWAM, supply and demand are not perfectly matched.

In the current IHF implementation, inputs and outputs of one model are coordinated externally and exogenously with the other models. Additionally, each model shares insights with the others, so they all address a coordinated scenario. In subsequent work, the models will be coupled to allow for direct treatment of dynamic feedback that may occur between the different systems.

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WORLD WATER AND AGRICULTURE MODEL

Overview

The WWAM is a global-scale model for water flow between regions, water storage, and food production in regions and countries around the world.[32] A conceptual model of the WWAM is shown in Figure 2. We used the WWAM to evaluate water storage in Egypt's Lake Nasser above the Aswan Dam and changes to agricultural production in Egypt resulting from hydrological impacts associated with the implementation of the GERD in Ethiopia.

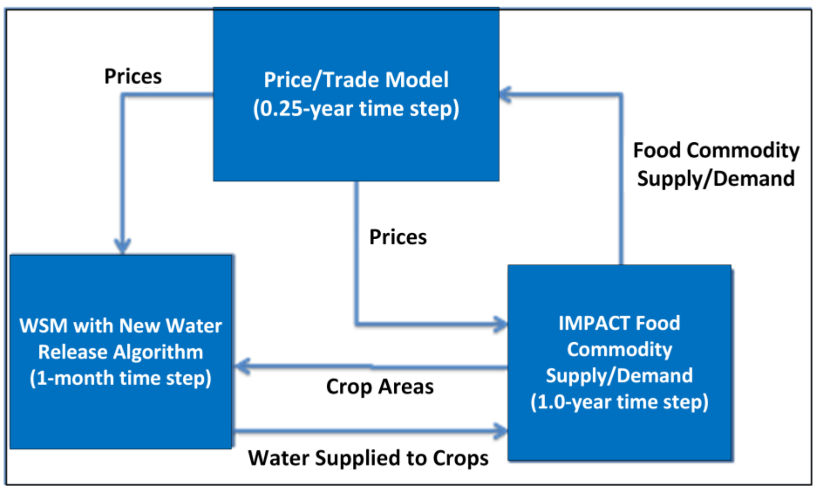

Figure 2. Conceptual model for the WWAM

Modeling Scenarios

The WWAM evaluated the impact of GERD filling scenarios encompassing 16 fill rates ranging from 0 to 50 percent of annual withdrawals from the Blue Nile under five future regional climate scenarios. Evaporation from the GERD reservoir and from Lake Nasser was evaluated monthly based on regional long-term potential evapotranspiration multiplied by the surface area for each modeled reservoir. The climate scenarios provide changes in precipitation and runoff in the upper Blue Nile basin above the GERD, and include a base case with no temperature or precipitation changes (drawn from long-term average data from 1912 to 1997), and other scenarios drawn from the Intergovernmental Panel on Climate Change (IPCC) and the Coupled Model Intercomparison Project Phase 5 (CMIP5).[33] Changes in runoff from the long term average include 23.5%, 0%, 9.85%, and 23.2%, all drawn from CMIP5.[34] These scenarios do not represent extreme bounds of possibility but provide enough variability to consider whether conclusions about GERD filling scenarios are robust.

Modeling Details

For this study, a percentage of the stream flow of the Blue Nile is withheld in the GERD reservoir after the GERD is completed starting in January, 2018, even if Egypt's annual water allotment of 55.5 km^3, stipulated by the 1959 Nile Waters Agreement between Egypt and Sudan, is not met. In addition to these withdrawals, Ethiopia is permitted to hold back additional water if downstream demands have been satisfied. The WWAM uses Cobb-Douglas–type functions to assess crop areas and yields to calculate water demand.[35] The crop area fluctuates with water availability and is reduced if a water shortage occurs. The resulting crop area and water received are then used to calculate a yield per area. These results are then input into a system dynamics price algorithm that approximates market clearing but allows supply and demand mismatches.[36] WWAM currently simulates 17 food commodities that include beef, pork, sheep, poultry, eggs, milk, rice, sugar, wheat, corn, other grains, soybeans, potatoes, sweet potatoes and yams, cassava and other roots and tubers, meals, and oils.

Model results are strongly influenced by population and GDP projections, which interact to determine the demand functions for food products. Population and GDP data come from a composite of projected UN population growth rates and historical World Bank data from 1960 to 2100.[37] Post-2014 time-series data are sourced from the IPCC 2007 Fourth Assessment Report and developed with further processing.[38] The resulting population and GDP time series from 2000 to 2060 are provided in Figure 3.

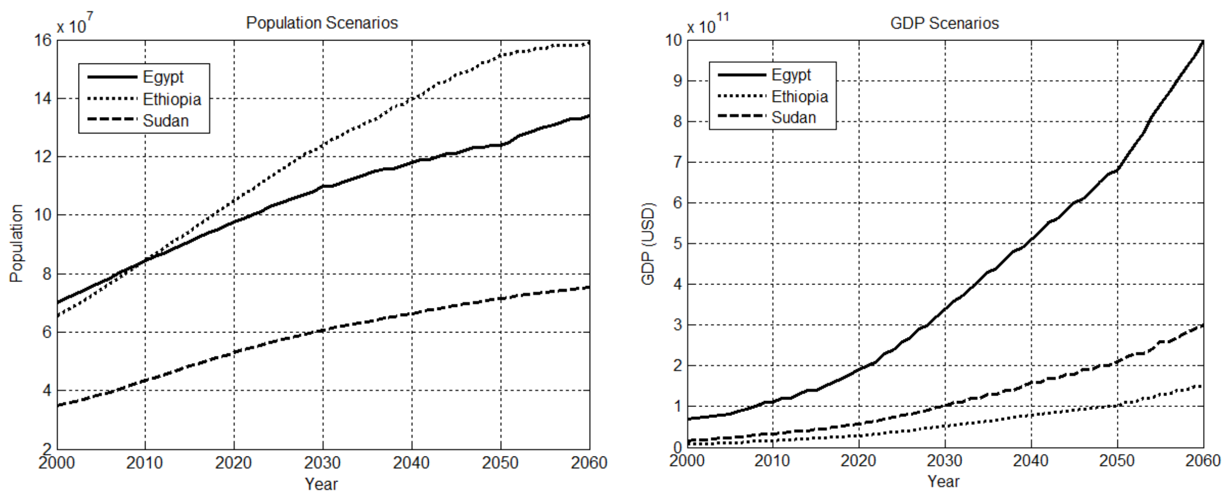

Figure 3. Population and GDP scenarios used by WWAM analysis

Results

Simulation results suggest that Egyptian water supply cannot keep up with demand in the decades to come. As a result, Egyptian water storage reaches Lake Nasser's dead storage (i.e., water below the dam outlets and accessible only by pumping) between the middle of 2019 and the end of 2026 as seen in Figure 4. This depletion of reserves for Egypt occurs regardless of whether the GERD is filled. Even so, the GERD causes reservoir depletion to occur one to five years earlier than it would have otherwise. Afterwards, Egypt's shortage is sporadically alleviated by wet seasons and the role of the GERD is no longer significant. The projected water shortage makes a significant impact on Egyptian food production. Gross food production drops by as much as 25 percent for the worst-case climate scenario as seen in Figure 5 (2020 to 2023). Fill rate for the GERD does not decrease this loss but slower fill rates delay when it occurs by one to two years. The overall loss of food production in Egypt to 2050 has no significant correlation with the GERD fill rate.

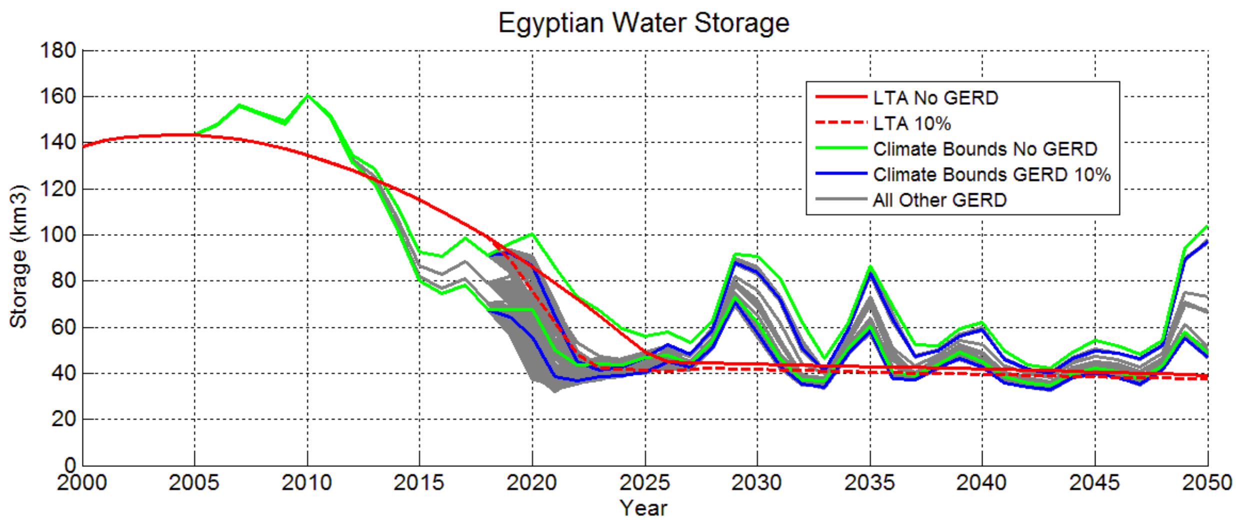

Figure 4. WWAM projected Egyptian water storage

Note: LTA signifies long-term average

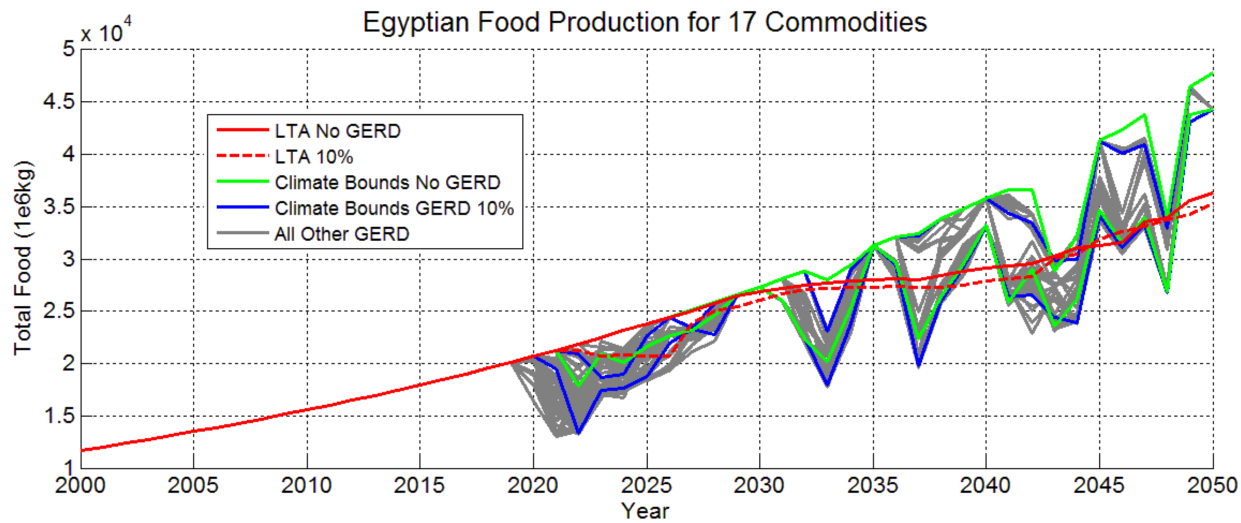

Figure 5. WWAM projected Egyptian food production

Climate variability significantly influences the way to fill the GERD that best optimizes between Ethiopia's need to fill the dam and Egypt's need for water. In the climate scenarios used, filling the GERD coincides with a dry spell, yet the timing of wet and dry spells is highly uncertain. A scenario with the same amount of water and a wet season during the filling of the GERD would cause Egyptian losses due to the GERD to be minimal. The model results therefore support a cooperative strategy to slowly fill the GERD during dry periods and withhold larger amounts of water during wet periods to minimize Egyptian losses during filling. The benefits of considerable increases in hydropower will result as seen in Figure 6. This ensures eventual filling of the GERD while minimizing impacts on downstream flows.

As presented, these results are useful, yet they warrant a more detailed political, social, and economic analysis using the other modeling platforms in the IHF framework that address the interplay of consequences to the timing of losses of water and food production and increases in hydropower production.

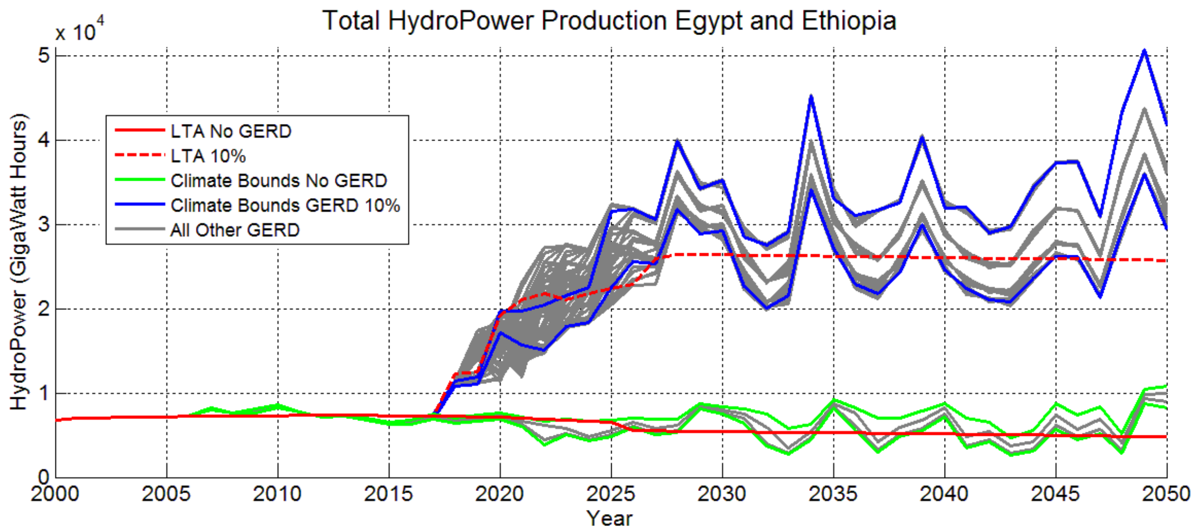

Figure 6. WWAM projected hydropower production in Egypt and Ethiopia

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32 See endnote 29 on page 12.

33 J. V. Sutcliffe and Y. P. Parks, "The Hydrology of the Nile, IAHS Special Publication No. 5. (Oxfordshire, UK: IAHS Press, 1999); "The GRDC," *Global Runoff Data Center,* German Federal Institute of Hydrology (BfG), 2014, http://www.bafg.de/GRDC/EN/01_GRDC/12_plcy/data_policy_node.html;jsessionid=9D6245570E488F693BA2CCB51E27FE50.live2052.; Taylor et al., An Overview of CMIP5." Long term average data were drawn from Sutcliffe and Parks and the Global Runoff Data Center. Scenarios from IPCC and CMIP5 include the Representative Concentration Pathway 8.5, representing a high-emissions future.

34 M. E. Elshamy et al., "Impacts of Climate Change on Blue Nile Flows using Bias-Corrected GCM Scenarios" *Hydrology and Earth System Sciences* (2009) 13:551-565; V. Aich et al., "Comparing Impacts of Climate Change on Streamflow in Four Large African River Basins." *Hydrology and Earth Systems Sciences* (2014) 18:1305-1321.

35 C. W. Cobb and P. H. Douglas, "A Theory of Production," *American Economic Review* (1928) 18 no. 1, Supplement: 139–165. http://www.jstor.org/stable/1811556.

36 This means that price is set and that supply and demand are then calculated. Price drops if supply exceeds demand and rises if demand exceeds supply. Surpluses are kept but have a shelf life that depends on the commodity. On the other hand, a market clearing assumption recalculates the price at each time step until supply equals demand so that surpluses do not occur.

37 United Nations, Department of Economic and Social Affairs, *World Population Prospects: The 2010 Revision, Volume I: Comprehensive Tables,* (New York: United Nations, 2011), http://esa.un.org/wpp/Documentation/pdf/WPP2010_Volume-I_Comprehensive-Tables.pdf; World Bank, "Population Data," (2014), http://data.worldbank.org/indicator/SP.POP.TOTL, Accessed September 23, 2014.

38 IPCC, Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (Geneva, Switzerland: IPCC 2007), http://www.ipcc.ch/pdf/assessment-report/ar4/syr/ar4_syr_full_report.pdf. For the years following 2014, the time series were developed with further processing by the Center for International Earth Science Information Network at Columbia University to make GDP consistent with population.

INFRASTRUCTURE RESILIENCE ASSESSMENT MODEL

Overview

One of the core objectives of this effort is to aid in understanding the system resilience in Egypt's water-agriculture-food system. For most of Egypt's history the Nile has served as a key strategic resource enabling food production in an area that would otherwise be barren. However, population growth has driven Egypt to increasingly diversify its food source. In 2011 Egypt imported approximately 45 percent of all of its grains.[39]

Egypt's precarious situation is as follows:

- Egypt faces a growing population, deepening Egypt's trade balance deficit
- Global food price shocks create a desire to produce more food within Egypt
- Subsistence farmers make up a significant portion of Egypt's population—3 million tonnes, or about 23 percent of wheat consumption, is grown, processed, and consumed rurally[40]
- The GERD, at the same time, threatens to decrease water flow to Egypt

Given this situation, this portion of the study seeks to coarsely answer the following research question: What options exist for Egypt to improve its water-agriculture-food resilience?

To account for these issues we consider the whole of Egypt's water-agriculture-food production system as illustrated in Figure 7.

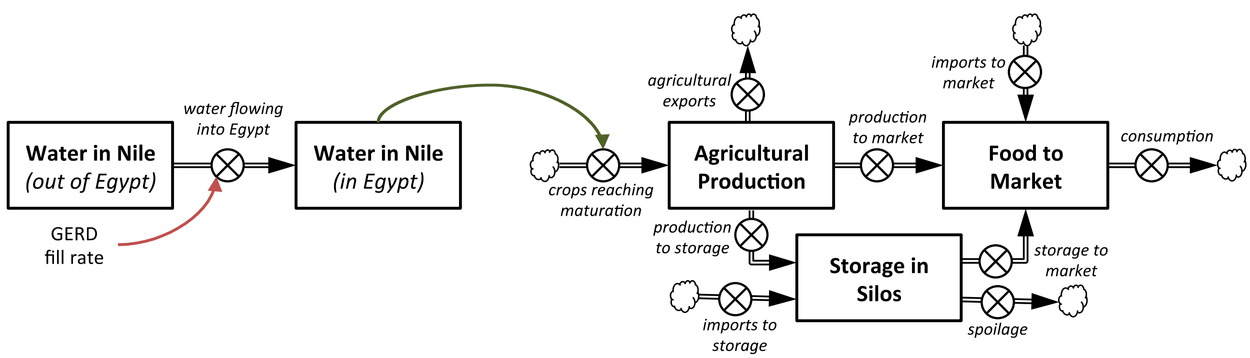


Figure 7. Overview of scope for water-agriculture-food resilience

Note: Water from the Nile is divided between the flow outside of Egypt and the flow into Egypt. The flow of water into Egypt affects the amount available for agriculture and therefore influences Egyptian agricultural production. Once harvested, agricultural outputs can be exported, put into storage, or be sent directly to market (with some potential intervening process). Egypt also stores imported agricultural products (when products are low in price). The majority of stored grains in Egypt tend to be used in the domestic market, but, due to the size of storage, is subject to considerable spoilage.

Qualitative Resilience Assessment

Sandia's methodology defines infrastructure resilience in the following way:

> Given the occurrence of a particular, disruptive event (or set of events), the resilience of a system to that event (or events) is the ability to reduce efficiently both the magnitude and duration of the deviation from targeted system performance levels.[41]

Qualitatively, the ability to cope with disruptions like the GERD are derived from the system's ability to adapt, withstand, and recover (e.g., extract groundwater, produce drought tolerant crops, import crops to make up the losses in water) from the disruption. These qualitative interventions are useful to understand from a policy perspective; however, their effects are difficult to measure and compare.

A review of the relevant literature has led us to a three-class resilience policy architecture for Egypt, as shown in Table 2. Water resilience policies are meant to increase the ability of Egypt to maintain its supply of water. Agriculture resilience policies seek to reduce the impact to agricultural production given a reduction in water supply. Finally, food resilience policies are designed to increase the nutritional content of the foods produced by Egypt as well as to maintain an adequate food supply for Egypt's population.

Table 2. Qualitative resilience policy architecture for Egypt's water, agriculture, and food sectors

Water Resilience Policy	Agriculture Resilience Policy	Food Resilience Policy
• Increase supply of water o Diversion projects o Water transfer projects o Groundwater o Desalination o Greater reuse o Decrease upstream diversions • Reduce evaporation losses	• Implement water-efficient agriculture practices • Reduce use of heavy water use crops • Plant drought tolerant strains • Centralize food production planning and policy • Reduce waste at silos • Provide insurance/credit for farmers • Maintain stocks of agricultural products • Decrease water demand for non-agricultural uses	• Increase food import capacity • Reduce spoilage • Grow nutrition rich food • Increase food storage capacity and food reserves • Reduce exports

A list of qualitative resilience methods can help the decision-maker know the options but will not provide understanding of which policies will yield more resilient outcomes. A quantitative measure of resilience will provide a consistent way to evaluate policy interventions, explore trade-offs, and enable policy optimization. Therefore, we define how resilience is measured with a set of equations.

Knowing the total impact of a given disruption (in this case the supply of water to Egypt) is essential to any risk or resilience assessment. In the Sandia Integrated Resilience Assessment Methodology, this is defined as the *Systemic Impact*. However, the systemic impact is rarely the end of the cost of the impact—often there is a response to a given disruption. In our case, this could range from greater imports to decreasing non-food agricultural outputs. The cost associated with these responses is termed the *Total Recovery Effort*. The sum of Systemic Impact and Total Recovery Effort yields a total *Resilience Cost* for any given disruption.

One additional facet must be considered. While recovery efforts are used to reactively resolve issues and shortages, it is possible to preemptively invest in preparedness to reduce the effects of a disruption (such as the GERD) by reducing the Systemic Impacts and therefore Total Recovery Effort. These pre-emptive actions are referred to as *Resilience Enhancing Investments* (REI).

REIs help reduce the Systemic Impact as well as reduce the cost of recovery efforts.[42] In the case of Egypt, these REIs could include storing foods to make up for any losses from the GERD, increasing the water efficiency of farmland, etc. REIs reduce the costs associated with the Systemic Impact and Total Recovery Effort, but require investment (imposing costs) prior to a disruption (Fig. 8).

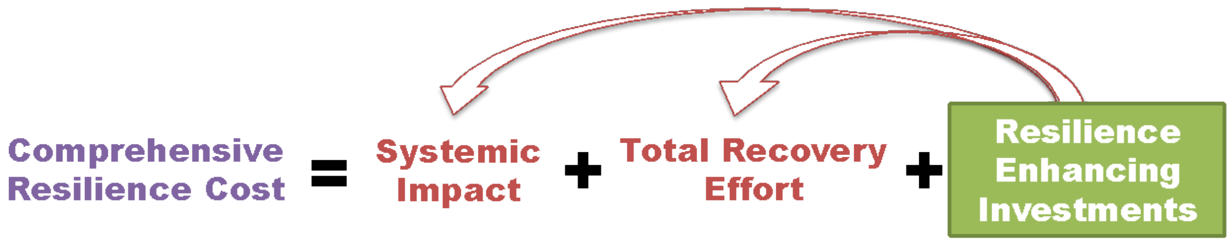


Figure 8. Comprehensive Resilience Costs

Note: Comprehensive Resilience Cost (CRC) is one of the core equations in measuring infrastructure resilience. In this equation, Resilience Enhancing Investments can decrease Systemic Impacts and Total Recovery Effort, but also increase the CRC. Quantifying the resilience tradeoff is key to understanding which policies will minimize the CRC given the Systemic Impacts and cost of recovery.

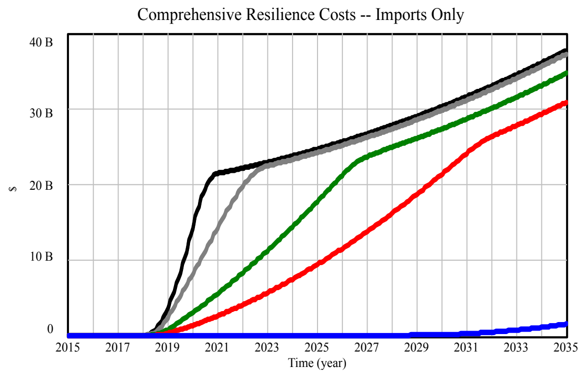
Modeling Scenarios

Using resilience equations, outputs from WWAM, and data from the Food and Agriculture Organization we (1) developed a non-linear differential equations model to represent the agricultural system, (2) ran a preliminary quantitative resilience assessment on Egyptian water-agriculture-food sector resilience, and (3) tested several water-agriculture-food resilience policies (e.g., ground water drilling, more efficient agricultural lands, and food imports—the policies for which we had the most data).

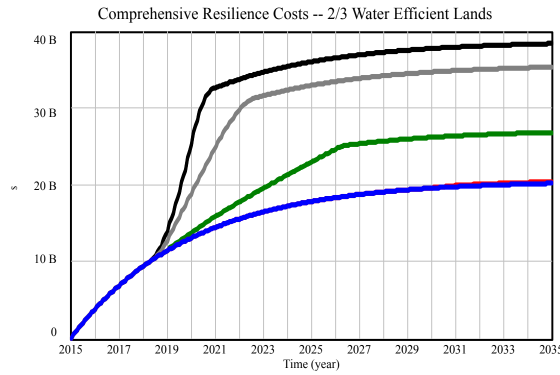
We ran the developed model and respective policies using average climate runs from WWAM. We imported WWAM hydrological results for a baseline scenario (no GERD) and four GERD fill rates (5%, 10%, 25%, and 50%). We then observed the CRC subject to different resilience policies.

Results

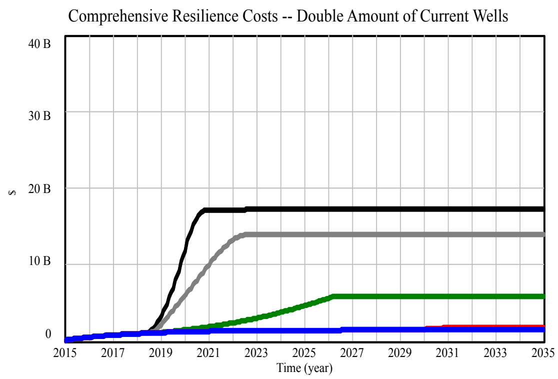
Given this set of policies, preliminary results show that ground water extraction provides a good short-term option for dealing with the shortage from the GERD. However, this option proves to be unsustainable in the long-term. More efficient agricultural land is a more expensive option and takes longer to implement as it involves training farmers on water and input use. However, this policy is much more sustainable in the long-term. Increasing food imports is more expensive than drilling but cheaper than developing more efficient farm practices. Although importing food will always be important to Egypt, increasing imports does not create a long-term pay-off for the country (Figure 9).



(a) Increasing food imports to make up for shortfalls



(b) Increasing water efficiency of farming by 20% for approximately 2/3 of Egypt's lands



(c) Doubling well capacity in Egypt (costs do not include operation of wells)

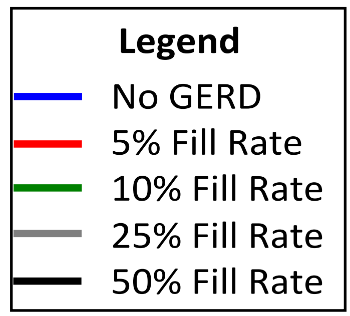


Figure 9. Cumulative Comprehensive Resilience Costs from resilience analysis of three policies

Note: In these preliminary results, increasing food imports (a) to make up for the short fall is not a sustainable policy even after the GERD has been filled due to the decrease in the Nile's long-term water flow. Increasing water efficiency of a majority of Egypt's farmlands (b) can have an impact, however, this policy requires a significant long-term investment. Doubling the number of wells in Egypt (c) provides the least expensive option, however this option is not sustainable in the long term. A mix of policies is required, and additional cost factors and funding sources need to be considered. Additional resilience policies should also be considered.

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[42] Mark Turnquist and Eric Vugrin, "Design for Resilience in Infrastructure DIstribution Networks," *Environment Systems and Decisions* (2013) Vol. 33: 104-120, doi: 10.1007/s10669-012-9428-z.

[43] Beyeler et al., *A General Model of Resource Production.*

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[46] United Nations, Department of Economic and Social Affairs, Population Division, World Population Prospects:

2010 Revision (2010), http://esa.un.org/unpd/wpp/index.htm), accessed Sep. 4, 2012.
[47] R. Cincotta, "Half a Chance: Youth Bulges and Transitions to Liberal Democracy," Environmental Change and Security Program Report, Issue 13 (Washington, DC: Woodrow Wilson Center, 2008-2009), http://www.wilsoncenter.org/publication/half-chance-youth-bulges-and-transitions-to-liberal-democracy.
[48] United Nations, Department of Economic and Social Affairs, Population Division, World Population Prospects: 2010 Revision (2010), http://esa.un.org/unpd/wpp/index.htm), accessed Sep. 4, 2012.
[49] D. T. Rowland, "Demographic Methods and Concepts," (Oxford University Press, Oxford, England: 2003), 92
[50] Passell et al., *Human Ecology, Resilience, and Security.* A widely accepted minimum level of freshwater availability at which water scarcity is presumed to have negative impacts on human health is 1700 cubic meters/person/year. Increases in availability above that level increase population growth rate but only up to a maximum value (5*1700=8500), at which population growth levels off. At availability levels below that minimum threshold, population growth rate declines.
[51] Forrester, J. W., *World Dynamics,* (Wright-Allen Press: Cambridge, MA, 1971).
[52] Passell et al., *Human Ecology, Resilience, and Security.*
[53] Ibid.
[54] Ibid.
[55] S. Abed-Kotob, "The Accommodationists Speak: Goals and Strategies of the Muslim Brotherhood of Egypt," *International Journal of Middle East Studies* 27 (1995): 321-339, doi:10.1017/S0020743800062115; C. Wickham, "The Muslim Brotherhood After Mubarak," *Foreign Affairs* (February 3, 2011), http://www.foreignaffairs.com/articles/67348/carrie-rosefsky-wickham/the-muslim-brotherhood-after-mubarak.
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EXCHANGE MODEL

Overview

The Exchange Model is a general-purpose model of networks of resource consumers and producers configured to help understand the possible responses of the Egyptian economy to curtailed Nile flow.[43] Many of these sectors also trade resources in international markets. When applied to economic systems, the model emphasizes the material dependencies that both enable and constrain the networks' behavior and evolution. The configuration represents a number of interdependent sectors of the Egyptian economy that consume and produce distinct resources. The government is a market participant by levying taxes, consuming labor, and providing subsidies for sensitive commodities. A dynamic model of the Egyptian economy that includes interactions among sectors and international markets allows us to measure the possible consequences of a disruption, such as a reduction in Nile river flow, in terms that are salient to decision-makers of employment, government spending, and key commodity prices. The model helps identify delayed or distant reactions that may be otherwise hard to foresee. By studying the system's reaction to other kinds of shocks, the model also helps define priorities for policy design for the most effective use of political capital.

In its current configuration, reductions on water availability include the range of results from the WWAM. Many of the time series produced by the Exchange Model, such as employment, household health, and commodity prices, are input to influence decision-making in the BIA representation of political and social dynamics. Some decisions that emerge from this process, such as levels of taxes and subsidies, are important parameters in the economic model.

Figure 10 illustrates the associations and dependencies among economic sectors. Flows of labor and energy resources, used as inputs in all but the sectors that produce them, have been omitted for clarity. Each sector can be represented by a single entity or by several entities with differing parameters. Individual entities embody a process for converting input resources into output resources. They interact with their environment to obtain needed inputs and to make their outputs available to consuming entities.

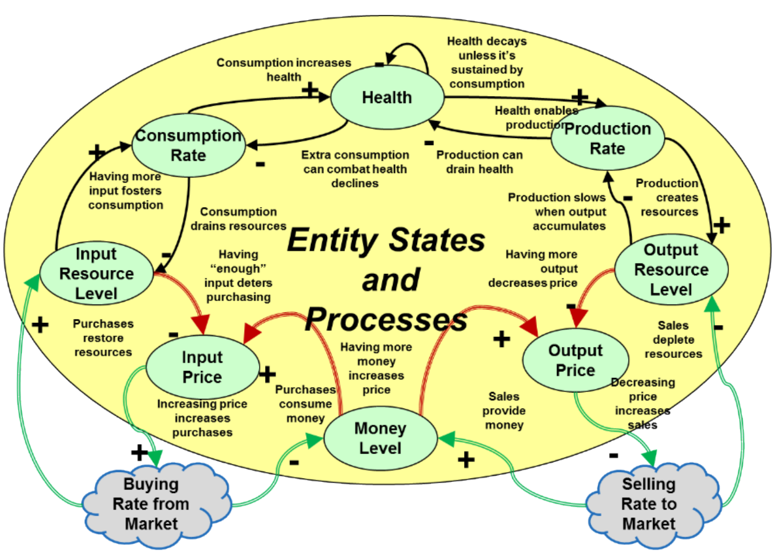

Figure 10. Causal loop diagram of the states and processes defining Exchange model entities

The processes of resource management, production, and interaction are coupled through a chain of feedback relationships as shown in Figure 11.

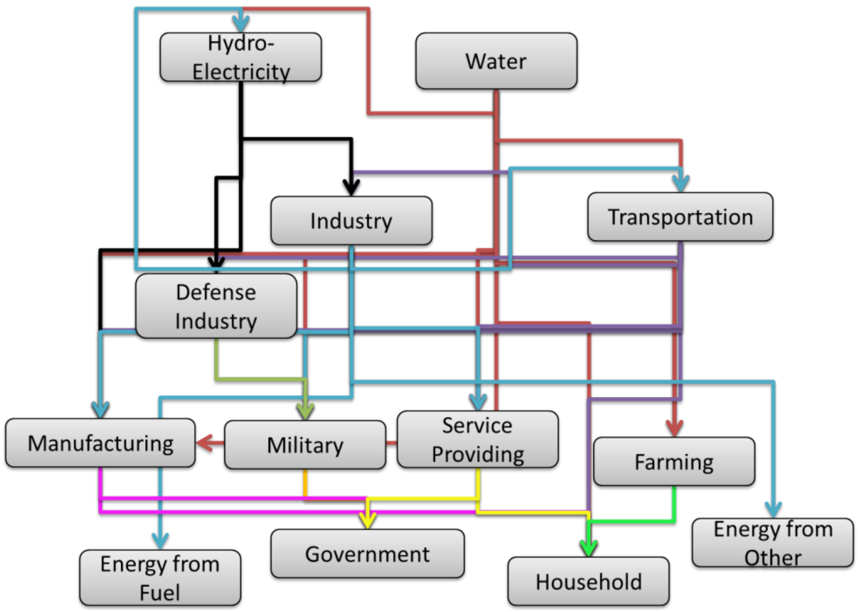

Figure 11. Sectors and resource flows within a nation

The model of Egypt and how it is impacted by the GERD's operation is a variant of the models of nation-states that have been analyzed for impacts of energy policy.[44] The system consists of a collection of nation entities, each composed of a group of productive sectors. The Exchange Model was configured to represent two compound entities: Egypt and the rest of the world. Each compound entity comprises a set of economic sector entities configured to represent the Egyptian economy and its interaction through markets with the rest of the world. Table 3 describes the sectors used in this model and the resources consumed and produced by each sector.

Table 3. Description of sector resources produced and consumed

Sector	Produced Resources	Consumed Resources
Household	Labor	Food, goods, services, energy, fuel, security
Manufacturing	Goods	Labor, energy, security
Farming	Food	Labor, energy, fuel, security
Services (health care, retail, etc.)	Services	Labor, energy, security
Oil production	Oil	Labor, energy, security
Fuel production	Fuel	Labor, energy, oil, security
Natural gas production	Gas	Labor, energy, security
Hydropower	Energy (10%)	Labor, security
Energy production	Energy (90%)	Labor, oil, gas, security
Government	Security	Labor, fuel, energy, goods

Each resource has a domestic market that connects producers and consumers within Egypt. In addition to these domestic markets, some resources (energy, food, goods, oil, fuel, and gas) are traded on international markets that connect Egypt with the rest of the world.

Modeling Scenarios

We ran 10 simulations to examine how a reduction in the Nile River flow would impact the Egyptian economy. Each simulation represented a 12-year time span in which the GERD filling began in year 5, filled for 5 years, and ended in year 10. The reduction in water availability to agriculture is not expected to be proportional to the drop in reservoir storage due, for example, to seasonal variation in demand and supply and uncertain allocation policy. We include a range of shortfalls in flow to the agricultural sector meant to bound possible responses across the filling scenarios. Based on our research and data collection we included some basic features of Egypt's economy in the simulations: (1) Egypt subsidizes 40 percent of the price of domestic food available to its population; (2) unemployment in Egypt is 12 percent; (3) Egypt is a net exporter of electrical power; and (4) the labor utilization by sector is 24 percent industry, 29 percent agriculture, and 47 percent services.[45]

Results

Figure 12 shows the change in farming water utilization over time as a function of the reduction in Nile River flows. Scenarios where Nile reductions are greater than 30 percent show a significant reduction to the farming sector's ability to use water from the Nile. This nonlinearity is a result of feedbacks in the modeling simulation. For example, as Nile reductions occur more land is fallowed and more laborers are laid off. At a 30 percent Nile reduction, the feedbacks from these dynamics result in an agricultural system that is impaired and cannot function normally. In this case, these dynamics result in reduced domestic food supply and higher food prices.

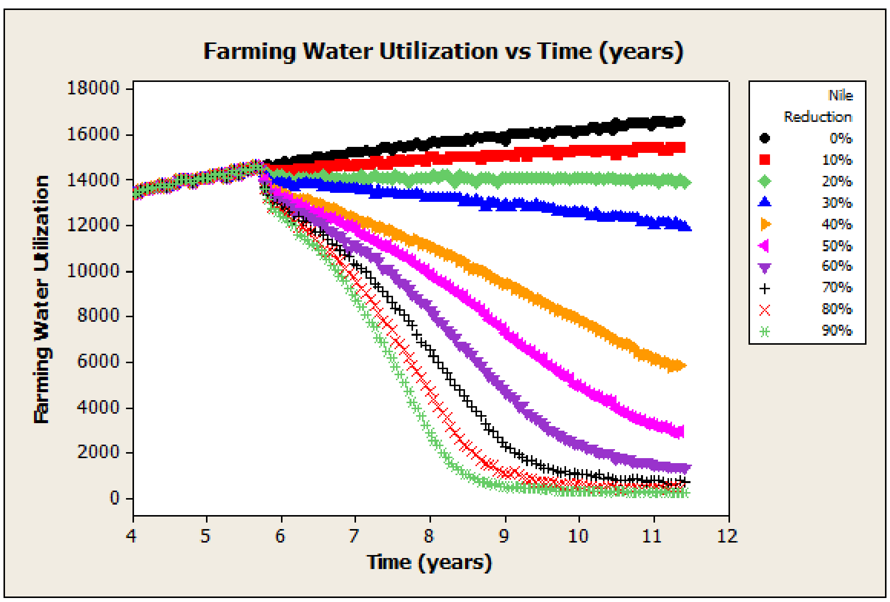

Figure 12. Nile water utilization by Egyptian farming sector for Nile reduction scenarios

Figure 13 shows the amount of food stored by households over time for each degree of change in Nile River reduction. The amount of food stored by households is indicative of the availability and price of food. Households try to maintain a few days' worth of consumption in inventory. When food becomes more scarce or expensive, household consumption rate and inventory level both decline. The fall in inventory is approximately proportional to the reduction in consumption. At Nile reduction scenarios of 40 percent and greater, households are able to maintain only 50 percent of their normal storage levels, and consumption.

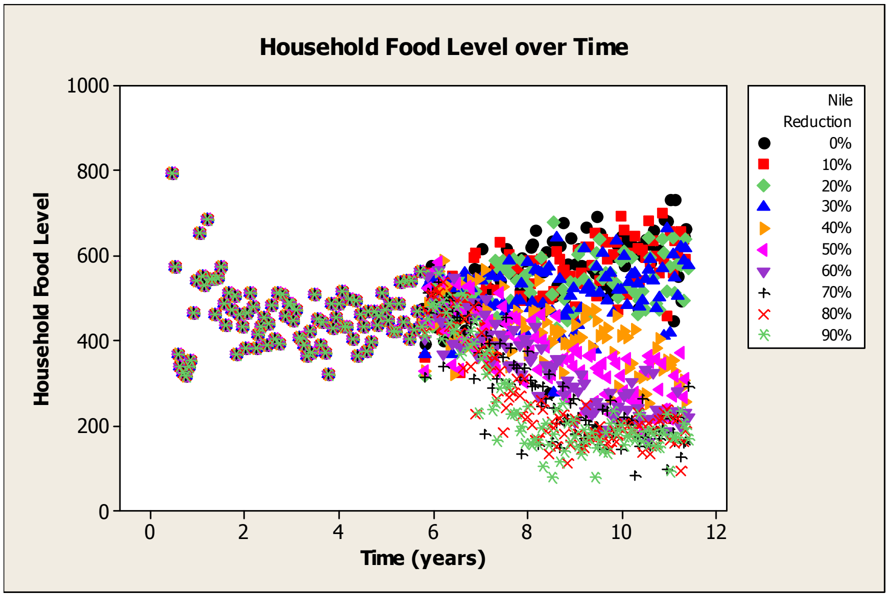

Figure 13. Household food levels over time for Nile flow reduction scenarios

The health variable represents the household entity's ability to obtain all of its desired inputs and to produce labor. A reduction in the availability of key inputs because of resource scarcity or price increases will reduce health over time. In our model, the nominal value for household health is 1.0. The average, pre-disruption, value for Egyptian household health is around 0.7. This lower value is consistent with the underutilization of the labor force (unemployment), inefficiencies in the Egyptian economy, and a high incidence of poverty. Figure 14 shows the trends in household health for different degrees of Nile reduction. Reductions below 30 percent produce small deflections, while reductions of 70 percent and above produce rapid and persisting declines.

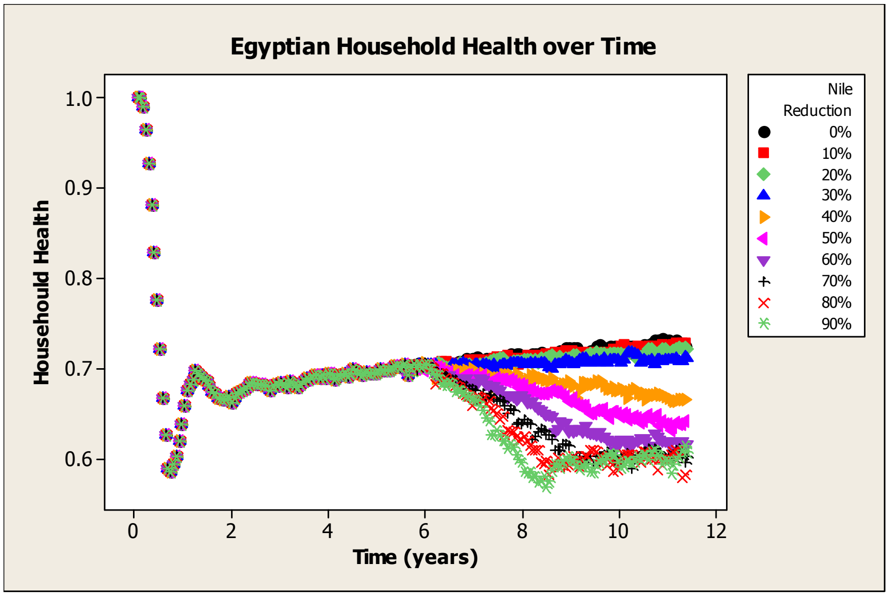

Figure 14. Household health over time for Nile flow reduction scenarios

For the key dependent variables, we performed a sensitivity analysis on parameters whose values were uncertain. Sensitivity analysis is the study of how variability in a mathematical model's output can be apportioned to the variability in the model parameters. The sensitivity analysis showed the most important parameter was *food price subsidies*, meaning that any change in food price subsidies will cause a comparatively large change in household health. The second most significant parameter was *farming utilization of Nile,* which determines how much of an impact a reduction in Nile flow has on food production. The analysis suggests that changes in food subsidies combined with a reduction in domestic food production in Egypt would have a large negative effect on the population. Conversely, an increase in subsidies may offset the effects of reduced food production.

HUMAN RESILIENCE INDEX

Overview

The HRI value is a coarse measure of a country's human ecological condition. Our work tests the hypothesis that human ecological conditions can be directly linked to a country's security, stability, and resilience, that is, its ability to rebound from shocks such as droughts, famines, internal rebellions, and wars. The HRI is calculated using data for nine indicators show in Figure 15.

The HRI assumes that shocks, such as hurricanes, floods, droughts, refugee migrations, economic failures, or ethnic clashes degrade human systems. In a human system with strong resilience, shocks can be absorbed and the system can return relatively quickly toward an average value. In a human system with poor resilience, shocks may cause wide oscillations in system behavior that lead to even more extreme conditions, which in turn may lead to severe forms of instability, violence, or conflict. The HRI focuses on the risk of various forms of instability, violence, or conflict associated with poor human ecological conditions, but not with economic, political, or social conditions.

<u>Indicators</u>

Population growth rate
Caloric intake per capita
Renewable freshwater per capita
Arable land per capita
Median age
Population density
Population health
- Lifespan
- Infant Mortality
- Child Mortality

Figure 15. HRI indicators

Data for HRI calculations come from the UN World Population Prospects and the UN Environment Programme Environmental Data Explorer.[46] The overall availability of data in the original study was an important constraint in the selection of the indicators and sub-indicators.

We experimented with numerous sets of indicators before settling on the one described in Figure 15, which we concluded is parsimonious yet covers some of the most important indicators of the human ecological condition. Population growth rate and density capture population dynamics. Median age helps describe the age structure of the population as a whole, which has been shown to contribute to different measures of stability.[47] Per capita values for caloric intake, renewable freshwater, and arable land capture important resource limitations on the human population. Population health, made up of lifespan, infant mortality and child mortality, provides a snapshot of human health.

Future Projections

Historic calculations, ranging in this study from 1961 to 2008, are static measures of the human ecological condition and human resilience during that time period derived from existing data. Future projections use a mix of UN data projections, our own calculations, and dynamic relationships between several indicator values and population growth. Data on projected population growth rate come from UN World Population Prospects.[48] We calculate median ages using methods described in Rowland.[49] Changes to population growth rate, as projected in the UN data, affect population density and per capita values for caloric intake and freshwater availability, which in turn affect population growth rate dynamically as described below.

The modeled projections show that dynamic relationships exist between various indicators associated with population growth. Increases in caloric intake over the global average increase population growth rate, and decreases in caloric intake below the global average decrease population growth rate, both occurring after a five year time lag. Similarly, increases in freshwater availability increase population growth, and decreases in freshwater availability decrease population growth, both after a five year time lag.[50] Increases in population density reduce population growth with a two year time lag. Insight for the development of these dynamic relationships came from the World Model. More information about these dynamic relationships, including their graphical functions, can be found in Passell et al.[51] See Appendix A for more info on HRI calculation. Methods for calculating future projections for the HRI are experimental and preliminary.

Modeling Scenarios

In this work, the HRI is applied to 12 countries in the Middle East and North Africa (MENA): Syria, Lebanon, Israel, Jordan, Iran, Iraq, Yemen, Morocco, Algeria, Tunisia, Libya, and Egypt. The work uses UN data from 1961 to 2008 for the indicators given in Figure 15. The HRI ranks countries according to their human ecological condition, which is proposed as a measure of resilience to physical, ecological, social, or economic shocks. Earlier HRI calculations evaluated historic data from 154 countries for the historical period of 1961 to 2008, and then projected values from 2009 to 2030 using both non-dynamic and dynamic modeling methods.[52] The current effort models the 12 MENA countries over the same time frames, but for future projections applies a dynamic modeling method described in greater detail below.

Results

Overall HRI results for the historic and future projection calculations for the 12 MENA countries are shown in Figure 16. Various noteworthy patterns emerge. Egypt's HRI in 1961 is the lowest of the 12 but climbs steadily, and in 2008 has the fourth highest HRI value. This implies a very steady improvement in the human ecological condition in Egypt over that time. Other countries also show considerable increases over that time period, but almost all reach peak values as early as the 1970s to 1990s and then begin a decline. The steady increase in its HRI value suggests increasing resilience in Egypt, although the political and social turmoil in that country since 2008 suggests the opposite. Passell et al. postulate that any sudden change in HRI values may be as destabilizing in a country as a steady decline. It is possible that the sudden price shocks associated with food and energy in 2008 coming after such a long period of improvement led to the unrest that occurred in Egypt. Passell et al. also suggest that under some circumstances, turmoil around the world may be linked more closely to social, political, economic, or religious issues than to human ecological conditions.[53] In those cases, as shown in Egypt in the current analysis, human ecological condition may not be a good indicator of potential conflict.

Egypt is also one of the few countries that shows a relatively stable HRI value in the future projection. This projection is a manifestation of conditions leading up to 2008 in combination with UN population and child welfare projections and the dynamic relationships between population growth, population density, caloric intake, and freshwater availability, as described above. Future projections are unaffected by the events in Egypt since 2008, since data after 2008 were not used in this analysis.

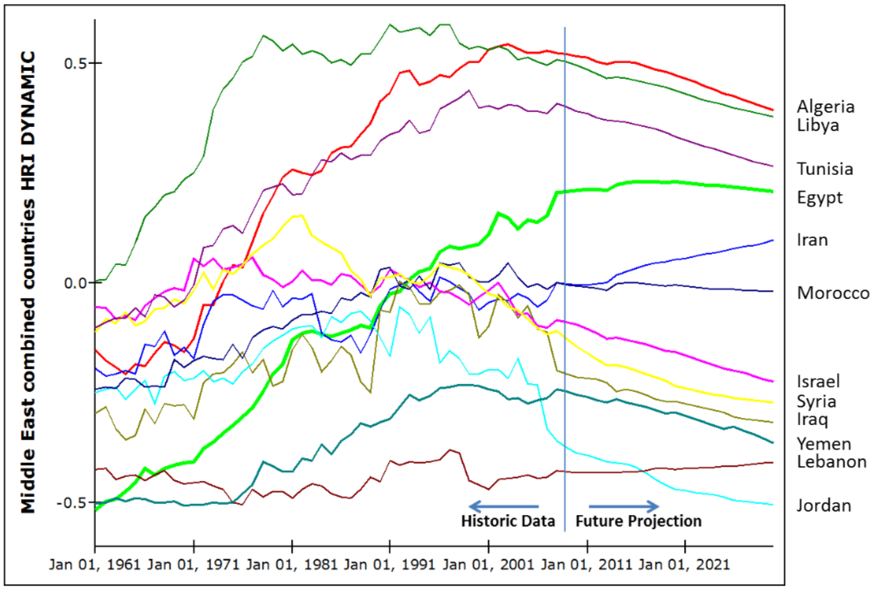

Figure 16. Historic and future projected HRI values for Egypt and the MENA countries
Note: Future projections are not derived from actual data.

Figure 17 shows the values over time for the primary indicators in the overall HRI. From the 1960s to the 1980s, the increasing HRI value tracks very closely with increasing caloric intake, although values for all indicators are rising. In the 1980s, the value for caloric intake levels off, but the value for population health begins increasing rapidly. Increases in the overall HRI value from the late 1980s to 2008 track closely with increasing population health. Overall, the indicators suggest ever-increasing human ecological conditions up until 2008, and then stable conditions during the future projection. More analysis is required to better understand how HRI values correspond to historic events, and how indicators interact dynamically in future projections.

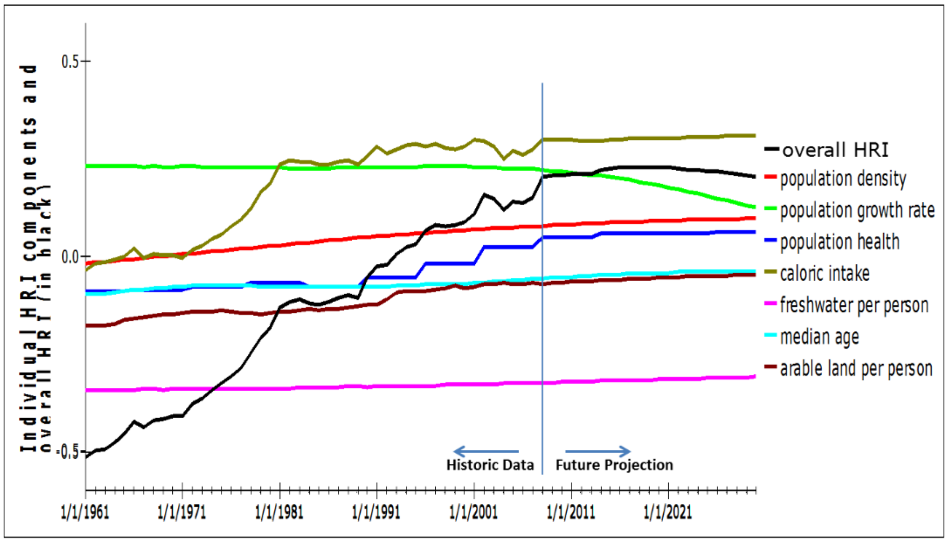

Figure 17. Values over time for the overall HRI and for the primary indicators in the HRI
Note: Future projections are not derived from actual data.

The HRI and associated modeling provides quantitative assessment of the increasing threat of risk associated with human population growth, resource consumption, and resource scarcity. It provides a modeling environment in which users can experiment with different future scenarios including shocks to human ecological systems (drought, famine, etc.) and the effects of potential mitigation strategies. Overall, the HRI is a useful framework for considering the sources of instability, conflict, and peace in and among nations. The HRI can also project historic data into the future to provide some insight into what future conditions might be, but much greater work is required to improve the ability of the model to make future projections.

In some cases the HRI may be a leading indicator, meaning that declines in HRI may be describing conditions that lead to unrest. In other cases the HRI may be a lagging indicator, meaning that unrest creates conditions that result in a declining HRI. Also, we presume that there are feedbacks between human ecological conditions and unrest or conflict. Declining human ecological conditions can lead to conflict and conflict can lead to declining conditions, resulting in a downward spiral. Further research is required to better understand these dynamics.

Any importance that might reside in this work is not in the ability to rank countries with the poorest human ecological conditions or to rank their risk of conflict, but in the development of a model that sufficiently captures dynamics associated with human ecological conditions, resilience, and security and which provides insight to decision makers and policy makers. Work on validation of the modeling approach is described in Passell et al. and suggests that it can be useful for analysis of those dynamics.[54]

One value of the effort lies in the use of the model by policy analysis or policy making institutions for better evaluating the sources, interdependencies, and trajectories of regional instability and insecurity. Real-time analysis could help policy makers anticipate dangerous oscillations as they are developing, and allow more time and opportunity for response and mitigation. This kind of real-time analysis would require more real-time data availability on indicators and/or different sets of indicators.

BEHAVIOR INFLUENCE ASSESSMENT MODEL

Overview

The BIA set of modeling tools is a theory-based, dynamic systems modeling capability intended to better assess the effects of events, actions, and counter-actions within and among groups of people within a country or countries. Specifically, the BIA is designed to quantifiably address the social, political, military, and economic dynamics between individuals, groups, and countries, as well as unanticipated, higher-order consequences of events or actions. Included in this assessment are considerations of the dynamics that drive stability and instability. BIA is the result of 10 years of internal cognitive modeling and simulation research and development, and 15 to 20 years in systems modeling and simulation research and development. Appendix A presents more information about the BIA's origin.

Behavior Influence Assessment Structural Assumptions

We developed a Causal Loop Diagram (CLD) (Figure 18) that describes hypotheses and assumptions about the causal influences between potential actions and conditions related to how the GERD may impact unrest within Egypt. This CLD was informed by previous analyses that Sandia has performed on unrest, as well as open source research, discussion with subject matter experts, and feedback from the Atlantic Council. Causal relationships are represented as arrows. Some feedback loops are marked by their overall tendency to dampen (−) or reinforce (+) behavior through time. See Appendix A for a more detailed description of Figure 18.

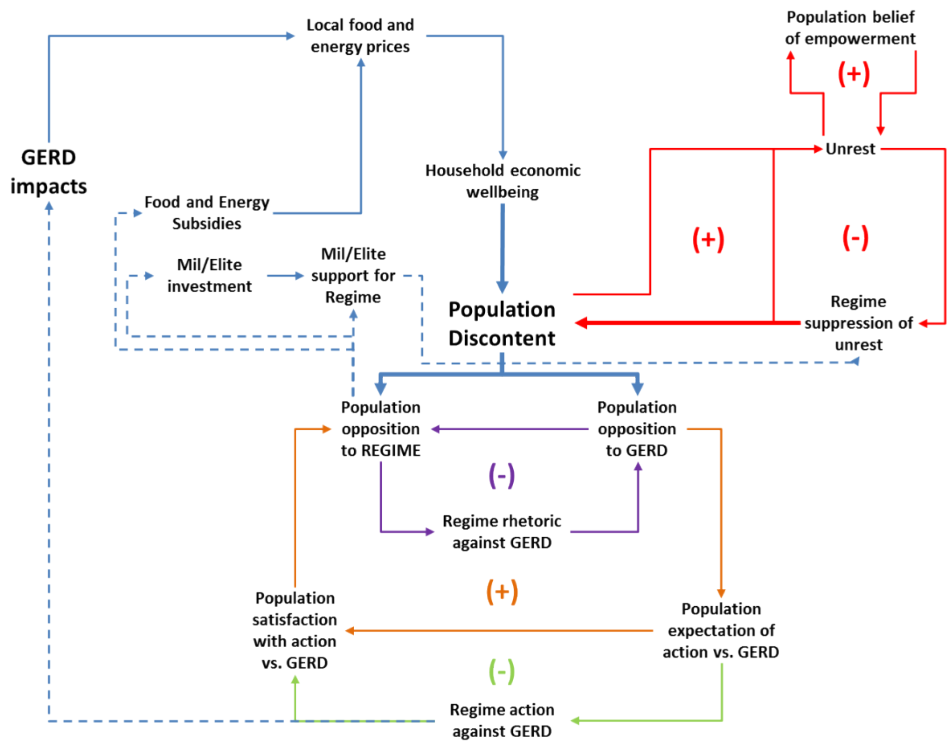

Figure 18. Causal Loop Diagram of key hypothesized relationships associated with unrest in Egypt

The BIA approach was applied to lend insight to the following questions:

1. How might unrest within Egypt progress and toward whom would it be directed given different assumptions about the impact of the GERD?
2. How do different Egyptian economic policies and factors, such as the use of food and energy subsidies, military spending, and external food or energy price shocks affect the population's response to the GERD?
3. How do Egyptian non-economic policies, such as suppression of unrest and the spread of outside agendas influence how the population will respond to impacts from the GERD?

Entities and Decisions

BIA models are composed of socio-political entities within society. The following informative yet compact set of cognitive entities was the focus of this set of questions about Egypt:

The Regime: Assumed to be composed of a set of former military/elite individuals, the Regime is primarily interested in improving the economy of Egypt, decreasing the perception of instability by internal and external parties, and maintaining power.

The Military Elite: Represents the business owners and executives as well as the high-ranking officials within the Egyptian military. The Military Elite is motivated to keep their positions of wealth and power.

The Islamists: Represents the minority within Egypt that is motivated to increase the role of Islam within the Egyptian government, and includes those who will pursue this goal through peaceful as well as violent means. While the Muslim Brotherhood has made headlines in Egypt, the Islamists in this model represent a much broader set of motivators and opinions, including a strong inclination toward greater and more open democracy within Egypt.[55]

The General Population: Includes, in essence, everyone else. Both the general population and the Islamists are financially poor by Western standards.[56] Beliefs within this group include a high sense of pride that Egypt remains the leader of the Arab world. Motivations stem from distrust of corrupt regimes and of colonial influencers (from Alexander the Great to British colonization), balanced with a buildup of fatigue from recent instability and economic hardship.

Decisions of certain entities define the strength of relationships in the diagram. The BIA model includes all relationships in Figure 18 as well as many others—such as communication within and between entities. By determining the relationships between the entities, a list of potential behaviors, motivations for these behaviors, and cues that would activate these motivations was generated. This set of potential behaviors, motivations, and cues and their relationship to one another is the core cognitive input that defines a BIA model's structure.

Modeling Scenarios

The cognitive entities and behavioral assumptions described herein were instantiated in a BIA model that was driven by multiple scenarios, including GERD impacts to agricultural and energy production defined by WWAM and Exchange. These inputs and assumptions were tested against assumptions about how the Egyptian Regime will respond to the economic impacts and their social implications, and furthermore, the effectiveness of those responses.

Core to the BIA model is the role of population discontent. We modeled:

1. Physical effects of the GERD and how it will influence peoples' experience of satisfaction of the government and their lives
2. Behavioral manifestations including how the population may or will become unsatisfied with the GERD and how this dissatisfaction could influence the regime to take action against the GERD
3. Internal stability dynamics of Egypt leading to the potential of unrest and regime actions to calm the unrest

Primarily, we tested how unrest might evolve if the Regime were to increase food subsidies to maintain public support, while blaming the GERD for economic hardship including their own budgetary imbalances. Furthermore, we tested whether the Regime would pursue diplomatic action against Ethiopia and whether this action would be effective.

Results

For conciseness, only the results of how the effectiveness of diplomacy between the Egyptian Regime and Ethiopia affects the population's propensity for unrest are presented here. Results of other scenarios are available from the authors. For the purpose of illustration, this scenario uses an extreme impact to food prices drawn from WWAM and Exchange: a 10 percent increase in food cost to Egypt for 7 years. Naturally, smaller disruptions result in smaller levels of unrest. Figure 19 describes how a small change in diplomacy effectiveness can result in drastically different unrest behavior. The left side of Figure 19 shows the food prices before and after subsidy (*Market Price* and *Local Price*, respectively), with and without effective diplomacy. The effect of the GERD is seen most clearly in the pre-subsidy food price from month 12 to month 96 of the simulation. Effective diplomacy is able to cut the overall impact on food prices in half by month 72 of the simulation. We made no assumption as to the mechanism behind this impact, only that when diplomacy is effective, the impact of the GERD on food prices is lessened. Food subsidies are based on a dynamic decision variable by the Regime and are subtracted from the *Market Price* to calculate the *Local Price*.

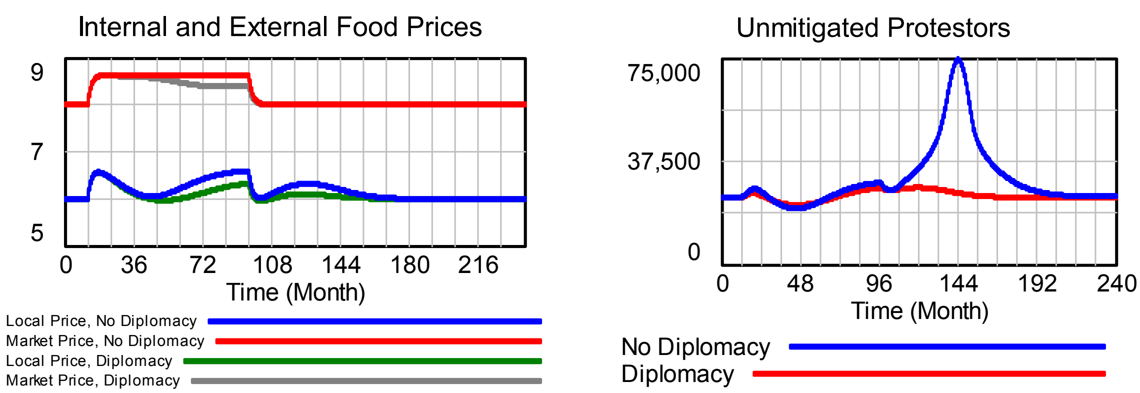

Figure 19. Diplomacy effectiveness and impact on food prices and unrest behavior

Referencing Figure 19 (and dynamics that occur intrinsically in the model), the food subsidy decision by the Regime is partially dependent on the population's opposition to the Regime (both the Islamist and the General Population opposition). It is also dependent on the Regime's ability to fund the subsidies. In both the effective and ineffective diplomacy scenarios, food subsidies begin to increase after the GERD effects are realized. However, about halfway through the GERD's impact period, the food subsidies decrease; effectively increasing the price Egyptians are paying for food. This is partially because the Regime is having trouble paying for the subsidy, and partially because the Regime has been successful up to this point in placing blame on the GERD for the economic hardship (not shown) experienced by Islamists and the General Population. Meanwhile at this point in the simulation, the Regime is defunding programs that benefit the Military/Elite to remain fiscally sound (also not shown). Therefore, while the effectiveness of diplomacy has a simple effect on food prices, it has a more complex effect on how the Military/Elite, the General Population, and the Islamists view the Regime.

In the ineffective diplomacy scenario, the combination of economic stressors on the Regime leading to a larger defunding of Military/Elite programs creates a tipping point situation for unrest as shown on the right graph in Figure 19. Notably, the conditions for unrest happen *after* the GERD has finished filling. These conditions are related to (1) the choice by the Regime to defund Military/Elite programs so that they can pay for food subsidies, which leads to a lack of support from the Military/Elite, (2) higher population opposition to the Regime due to higher overall food prices and higher potential for protests, and (3) the end of the GERD fill period, meaning the Regime can no longer effectively place blame on the GERD for economic hardship. The combination of higher opposition to the Regime by the Islamists and General Population with the Military/Elite's decreased support for suppression leads to the strengthening of the positive feedback loop known as the suppression loop in Figure 18 This highlights how a host of dynamic, human decision-related factors can reveal an unrest tipping point, primarily when the Regime cannot effectively mitigate the impacts of the GERD.

CONCLUSIONS

World Water Assessment Model

The WWAM results suggest that filling the GERD reservoir can have an important short term impact on water supply and food production in Egypt, depending on the fill rate and the precipitation patterns in the region during the filling period. Food production could be reduced by about 25% in a worst-case climate scenario. The model suggests that slower filling rates can reduce that impact, and also that overall food production averaged out to 2050 has no significant correlation with the GERD.

However, the model also suggests that Egyptian population growth and economic growth – along with the corresponding increase in per capita water consumption that goes with economic growth – will likely have a much more important and long-term impact on the Egyptian water supply. The model suggests that Lake Nasser would be drained to the level of the dead pool sometime between 2025 and 2030 if the GERD was never finished, and that the GERD might accelerate that process by five years or so. Continued modeling with higher resolution models and better data will be required to provide higher resolution results.

Infrastructure Resilience Assessment Model

There are effective policies that can be investigated to reduce Egypt's short-term and long-term dependence on the Nile. These policies should be assessed for their ability to improve Egypt's economic development while increasing Egypt's ability to withstand shocks like the GERD. Our assessment showed that of the three policy options tested, investment in drilling groundwater wells and improving agricultural practices were the most promising. Of the two, drilling wells represents a non-sustainable policy as Egypt's aquifers do not recharge. Improving water use practice (as is currently being funded by the World Bank) is more expensive in the short term but can pay dividends in the long term. However, to have any large impact a significant set of the farmlands in Egypt would have to use more efficient water practices (requiring greater investment).

We also reviewed and categorized a variety of resilience policies that we did not quantitatively test. Further modeling of these policies can enable the international community assess which policies have a robust effect on Egypt's ability to withstand, adapt, and recover from water availability shocks.

Last, it may be worthwhile for Egypt to consider greater industrialization and central planning of its agricultural sector. This could significantly increase yields and enable the application of labor towards other economic activities that generate trade for Egypt.

Exchange Model

The aggregate condition of households in Egypt, as measured by the household health variable, is to some extent buffered against small reductions on water availability to the agricultural sector. For the parameters we considered here, a reduction of up to 30% deflected the trends in household health and food availability towards lower values over time, but did not produce a sharp reduction in health or food availability. Beyond this point, the reinforcing feedbacks linking household conditions to labor availability, and labor to production in other sectors, produce a sharp and rapid decline in conditions. The provisional state of the model does not warrant confidence about the specific reduction fraction required to tip the system from gradual attenuation to rapid decline, however the potential for this this phenomenon should concentrate attention on making sure that food remains available and affordable for a range of possible filling and climate scenarios.

Human Resilience Index Model

The HRI shows that the human ecological condition in Egypt began among the lowest in the region in the early 1960s but climbed steadily into the early years of the new millennium. This steady rise in conditions suggests that the human ecological condition may not be a good predictor of the collapse and conflict that has occurred in the Egypt over much of the last decade, but that other social, political, or religious factors may be important. One hypothesis associated with this work in general is that a steady improvement in conditions suddenly interrupted by some set of events could contribute to collapse and conflict. It is possible that a sudden increase in food prices in the years following 2008 may have destabilized what was otherwise a resilient system. More data and modeling will be required to test that.

Behavior Influence Assessment Model

This work is meant to be a dynamic hypothesis of the relationships that affect unrest in Egypt between the most important groups during the period in which the GERD is refilling. We simulated many other scenarios that were not published in this manuscript. Insights from this work include:

- Unrest, combined with suppression of unrest and an emboldened population exhibits tipping point behavior.
- It is common to find the highest potential for unrest well after the GERD's impacts are over. This counter-intuitive finding is largely due to the long delays in the system. Structurally, unrest is buffered by the Regime's ability to decrease the economic hardship of the population, and also by its ability to spread propaganda against the GERD.
- Propaganda against the GERD and food/energy subsidies only delay unrest. The best way to prevent unrest is to prevent or mitigate the GERD's impacts. Effective diplomacy is one strategy that was tested and found to prevent extreme unrest.
- External shocks to food prices – not related to the GERD –would have a significant effect on popular support for the Regime. A price shock occurring before the GERD filling period has potential to be more disruptive than a price shock after this period.
- Maintaining the support of the Military/Elite matters, but can be effectively relied upon by the Regime as a buffer while it concentrates on satisfying the population. If diplomacy with Ethiopia is ineffective at decreasing GERD impacts, then military support becomes more important later in the period of effects.
- The short, intense filling period is more sensitive to assumptions about diplomacy than the longer filling period.

These insights provide a forum for discussion of the detailed relationships responsible for unrest within Egypt–and ultimately could help to explore the policy space of options to lower the potential for future unrest. Conflict between Egypt and Ethiopia is also important, and should be explored in future versions of this model. Additionally, the economic relationships in this model are approximate, and the use of a more robust economic model should be explored. Finally, confidence-building exercises should be performed with this model. Namely, the model should be tested against historic behavior, with a separate calibration and validation period. The 2011 Arab Spring uprising might be an ideal time series for this effort. An exploration of the most uncertain variables could then be performed, and sensitivity analysis could drive future exploration.

Unrest within Egypt does not appear to be unique to Islamists versus the General Population in response to food prices and behaviors of the Regime in response to the GERD. Both groups have the potential to protest the failure of the Regime to mitigate impacts.

Effective diplomacy with Ethiopia is one mitigation strategy that could prevent the complex host of factors that lead to unrest escalation.

Strong potential exists for the unrest to occur years after impacts of the GERD have stopped.

The strength of Military/Elite support is a major factor in whether the suppression loop becomes active and drives unrest escalation. If the Regime must defund Military/Elite programs, thereby losing some of their support, they are more likely to respond brutally to unrest, which further angers the public and leads to more unrest.

Overall Conclusions

Social, political, economic, and ecological dynamics in countries and regions make up complex systems that shape the course of history. Reductionist approaches to model each of the sectors independently are useful, but fall short of describing the behavior of the integrated systems. The Integrated Human Futures Modeling described in this report is a preliminary effort to integrate across various modeling platforms to better understand the complex dynamics that interact across sectors.

In this work, modeling platforms remained independent of each other in terms of construction and operation, although output from one became input for another. Actual integration of the models might be an improvement, but would also represent considerable expense and difficulty. Better complementarity between the models may be a propitious middle path. Further work is required.

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Appendix A. Modelling Technical Discussions

A.1 Human Resilience Index

The Human Resilience Index (HRI) is calculated using equation (1). I_i is the indicator value, $\bar{I}_i$ is the average indicator value across all countries for any given year, and $\bar{\bar{I}}_i$ is the standard deviation of the indicator values for all the countries for that year.

$$HRI = \sum_i w_i \frac{I_i - \bar{I}_i}{\bar{\bar{I}}_i} \quad (1)$$

This "standardizes" indicator values and puts them all in roughly the same numeric range. (This also makes the HRI a relativistic measure, meaning that the value of any indicator in any country is related to the values in all the other countries. Work to develop the HRI as an absolute measure is underway.) w_i is a weighting factor. In the current analysis all indicators are equally weighted at 1, although the sign ($+$ or $-$) varies. Indicators that are judged to improve the human ecological condition (caloric intake, renewable fresh water, arable land, median age, and lifespan) have a positive sign, and those judged to impair the human ecological condition (population growth rate, population density, and infant and child mortality) have a negative sign. The sum (Σ) of all the standardized indicator values provides the HRI value for the country in a given year. More detail on the calculation and testing of the HRI is shown in *Appendix A* in Passell et al.

A.2 Behavior Influence Assessment Model

The foundation of the Behavior Influence Assessment (BIA) system is a synthesis of a set of data-supported, psychological, social (psychosocial), and socioeconomic theories of decision-making and behavior. The BIA integrates cognitive, social, and system dynamics approaches and theories as shown below.

- Theory of Planned Behavior (Ajzen 1991)
- Expectancy Value (Fishbein and Ajzen 1975)
- Elaboration Likelihood (Petty and Cacioppo 1986)
- Cognitive Dissonance (Festinger 1957)
- Social Learning (Bandura 1977)
- Bounded Rationality (Simon 1991)
- Qualitative Choice (McFadden 1973)
- Imperfect Information (Stiglitz 1976)
- Risk Asymmetry (Kahneman 1979)
- Cointegration (Granger and Engle 1987)

The BIA model consists of cognitive entities that make decisions through time from sets of user-defined potential decisions. The decision-making process that is based on the theories above is shown in Figure A.1 at a framework theory level. Cues on the left side of the diagram come from measurable events in the model, such as world events, the actions of other entities, or the entity's own previous actions. Based on the entity's beliefs and attitudes, these cues become perceptions. Perceptions change motivations dependent on several psychosocial controls, such as perceived social norms and behavioral controls. For example, police presence at every city block would be a perceived behavior control against street riots. If a motivation becomes active and receives the correct set of cues, the entity develops an intention to act on that motivation. Finally, dependent on the entity's effect (positive or negative) the intention can be manifest in one or more behaviors. Generally, a stronger effect associated with the intention expands the range of the ultimate behavior.

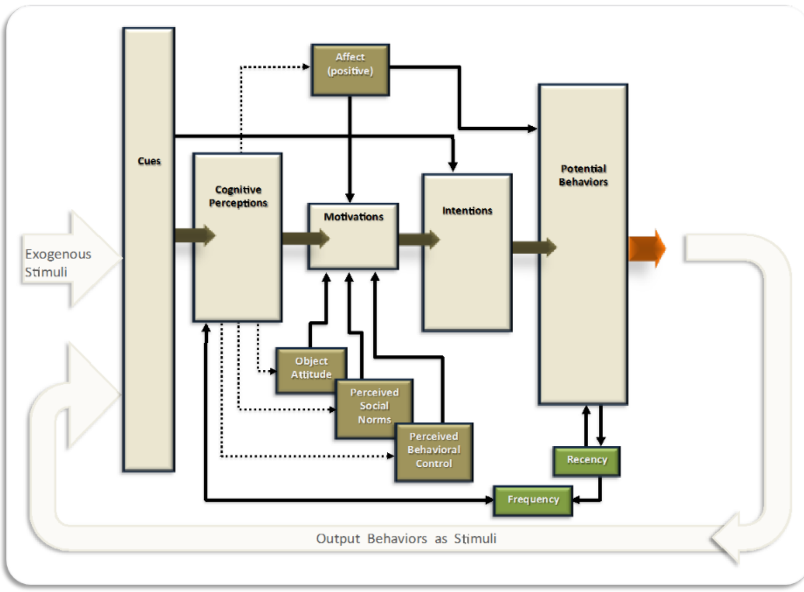

Figure A.1. BIA decision making process

Model information is refined by using specific knowledge of an individual's likely behaviors—from subject matter expert guidance, opinion polls, field reports, and social media. BIA computationally represents the mindset of specific individuals and groups, encompassing beliefs, motivations, affective states, intentions, and potential behaviors. The actions of one modeled individual or group can affect the mindset and actions of others, including the society in which they are situated. This provides a theoretically consistent, data-driven, analytical capability appropriate for assessing responses to events.

A.2.1 Entities and Decisions

The entities selected for the Egyptian modeling scenarios were determined after multiple lessons learned from sharing the Causal Loop Diagram (CLD) in Figure A.2 with subject matter experts. These entities can be thought of as existing within the causal structure of Figure A.2.

A.2.2 Causal Loop Diagram

The CLD in Figure A.2 provided an early discussion catalyst for collective hypotheses about how unrest can exhibit tipping point behavior, highly dependent on the strategies that a regime might employ before population discontent grows to unmanageable levels. This CLD is not a computational model in itself, but a visual representation of hypotheses about the causal relationships important for modeling unrest within Egypt. The CLD does not give all information about implementation of the relationships;

for instance, some variables are linearly related while others have non-linear cause-and-effect relationships. Some variables are split among multiple groups within the population of Egypt.

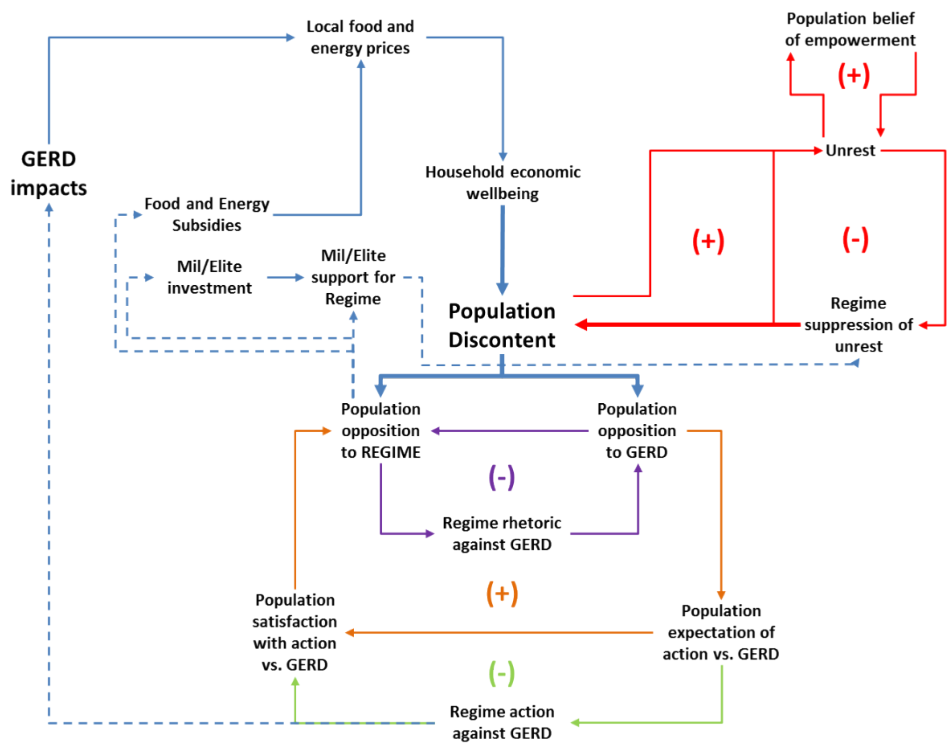

Figure A.2. Causal loop diagram of key hypothesized relationships associated with unrest in Egypt

Figure A.2 contains multiple feedback loops affecting how population discontent can lead to unrest and opposition toward the current regime. Of particular note are the positive and negative loops toward the right of the diagram. The positive loop most closely situated to population discontent is referred to as the suppression loop, in which the government's decision to suppress unrest directly leads to more population dissatisfaction and more unrest. This loop is dependent on the mechanisms used in suppression, as well as the reaction of the population to these methods.[1] Even if the suppression is successful at first, the second positive loop in the upper right-hand corner can lead to long-term escalation of unrest, as the population begins to feel empowered if their protests are making a difference in their condition or sociopolitical standing.[2] The suppression loop affects how successful governments will be at quelling unrest in the short term, while the empowerment loop determines the amount of time a regime has to fix the underlying conditions that lead to unrest.

Another key feedback mechanism expressed in Figure A.2 describes the Regime's ability to control the military, and the influence of this power on the government's ability to suppress unrest. If the Regime runs into financial difficulty and is forced to decide between removal of food/energy subsidies and defunding of programs that benefit the Military/Elite, this model assumes they will choose to defund the Military/Elite. This defunding causes the slow erosion of the Military/Elite's support for the Regime, which could ultimately lead to the Regime being ineffective at suppressing unrest. There is an empirically supported bidirectional causal relationship between military spending and economic growth in Egypt, which suggests that as military spending is increased, economic growth and investment in the general population decreases.[3] However, Egypt remains a military-dominated country in which military and political elite are intricately woven together in a system of reciprocity that may indicate a desire on the part of politicians to appease military officers and vice versa, particularly when unrest threatens one or both systems.[4]

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[1] J. C. Davies, "Toward a Theory of Revolution," *American Sociological Review* 27, no. 1 (1962): 5-19. http://www.jstor.org/stable/2089714; S. I. Bhuiyan, "Social media and its effectiveness in the political reform movement in Egypt," *Middle East Media Educator* 1, no. 1 (2011): 14-20.

[2] Davies, "Toward a Theory."

[3] S. Abu-Bader and A. Abu-Qarn, "Government Expenditures, Military Spending and Economic Growth: Causality Evidence from Egypt, Israel and Syria," Journal of Policy Modeling 25 (2003): 567-583.

[4] S. A. Cook, *Ruling but not Governing; the Military and Political Development in Egypt, Algeria, and Turkey* (Baltimore: John Hopkins University Press, 2007).

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