WATER SECURITY ISSUES AFFECTING MIGRATION AND CONFLICT IN THE MIDDLE EAST

THESIS

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Abstract

Iran is facing a daunting reality regarding the future of their water resources which may result in conflict and migration within the country with the potential to affect the Middle East and North African region and beyond. The country has failed to address critical preservation, risk mitigation, infrastructural, and political efforts to accommodate their rising population due to economic expansion. Water resources are dependent on social, political, economic, and environmental variables related to conflict and migration. Given the recent examples of water security issues in Syria resulting in migration and conflict, this thesis investigates the total available water per capita as a driver for the potential collapse of Iran's water resources. Portions of two key world system dynamics models were combined to identify interrelated variables leading to migration and conflict. It was found through multiple simulations that decreasing water per capita levels leads to increases in aggregated migration and death rates for this particular investigation. Further experimentation with other interrelated variables such as civil liberties, level of government, and GDP per capita may highlight other drivers and allow extension of this model to other countries of interest.

Acknowledgments

Our sacrifices are a reflection of our responsibilities—I whole heartedly appreciate and am indebted to the innumerable sacrifices my children and wife have endured so that I could educate myself to better serve my country. I appreciate the time sacrificed by my colleagues, with whom I have served, listening to me when I doubted my own abilities. And to my sage advisor, who never ceased to impress upon me the numerous perspectives of life's most important lessons no matter the time of day, I am thankful for his generous latitude for finding my own way.

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WATER SECURITY ISSUES AFFECTING MIGRATION AND CONFLICT IN THE MIDDLE EAST

I. Introduction

Recent conflicts and migrations around the globe have drawn the attention of military strategists and leaders who are interested in which environments are particularly vulnerable to impact stability, especially when conflict is imminent. Conflict and migration are complex issues which become even more convoluted when combined. Military forces conducting offensive, defensive, sustainment, and humanitarian operations must understand how to adapt to these issues within a given operational environment.

There are a number of varying degrees of interdependency between water security, migration, and conflict within a region, country, or population. These causes can vary in intensity, frequency, and influence each other resulting in complex interdependencies. They are linked through social, economic, political, and environmental aspects within a community, country, and region. Within these aspects, there are both exclusive and common variables at play, weighing on the potential outcomes.

Major events involving water security, conflict, and migration have recently occurred in countries such as Sudan, Yemen, Iraq, and Syria. For example, Syria suffered from an extensive drought from 2006-2010 that negatively affected their agricultural sector, forcing an internal migration from rural to urban areas as farmers and pastoralists sought employment and social opportunities. As resources became more overexploited, tensions in cities such as Aleppo and Damascus inevitably rose, resulting in protests and ultimately violence as the oppressive Assad-backed regime stepped in to the unrest. Civil war ensued, millions became internally displaced or left the country altogether to flee conflict and enjoy opportunities in a safer environment.

The fragility of Syria is not unique to the region of the Middle East and North Africa (MENA). Most of the countries suffer from some level of resource scarcity, especially water, mostly due to rising populations, arid conditions, and waning preservation efforts in the form of sustainability, services, and risk mitigation [1]. The Islamic Republic of Iran (Iran) is of particular interest due to a rapidly expanding population that has more than doubled in the last 40 years. This growth is coupled with the consumption of water at an unprecedented rate due to a lack of more modern and sustainable resource, risk, and service management. Iran's water resources are being overexploited as their agricultural sector continues over abstraction of fossil aquifers and transboundary surface waters even after investing millions in dam infrastructure to meet self-imposed food self-sufficiency directives [2].

Iran recently has experienced violent protests due to rising costs and reduced government subsidies in the wake of lifting trade sanctions. Iran experienced a huge economic growth as inflation rates soared and the government supported subsidies on key commodities such as fuel under President Ahmadinejad in preparation for sanctions being lifted. As President Rouhani ushered in new impositions on Iranians to reduce government spending, a backlash by the people has ensued due to waning subsidies, lack of employment opportunities, and dwindling resources. This example generalizes a link between water security and conflict as a simple introduction to the complexities they share.

The purpose of this research is to identify potential triggers signaling the collapse of Iran's water resources and possible subsequent incidences of conflict and migration. Extensive research on the subjects of water security, conflict, and migration are necessary to systematically qualify and quantify variables linking these subjects through social, political, economic, and environmental lenses. Applying these variables towards a simulation model provides a framework for the investigation of future incidences in Iran and other countries of interest.

Background of the Problem

The United States Special Operations Command, SOCOM, has expressed an interest in understanding and analyzing the burgeoning issue of water security and its potential interdependency with migration and conflict. Water security has become more prevalent in recent decades as populations grow, pollution spreads, and populations engage in conflict over resources. Special Forces units operate in environments where resources are often scarce, typically before the sustainment offered by large scale campaigns and operations is established. Sustainment operations enable a force to continue operations without significant lack of proper supplies and materials. Operating in an environment without sustainment or sufficient supplies to source in the host nation limits the reach and capabilities of any force. While the former point is interesting, the purpose of this thesis focuses on identifying the potential sensitivity of the scarcity and triggers of these issues so as to enable forces operating in austere environments suffering from migration, water security, and/or conflict.

Islamic Republic of Iran

This research focuses on the water security of the Islamic Republic of Iran (Iran) along with potential affects due to migration and conflict. Other aspects of Iran will be included in order to reinforce an understanding of these topics as it relates to the research, but not so much as to obscure the overall intent.

Iran possesses several water sources from key geographical features allowing one of the highest usages of water for agricultural purposes (see Figure 1). Iran covers 1.75 M km^2 and is bordered by, Afghanistan and Pakistan to the east, the Gulf of Oman, the Strait of Hormuz and the Persian Gulf to the south, Iraq and Turkey to the west, and Armenia, Azerbaijan, the Caspian Sea and Turkmenistan to the north. The majority of land is desert and mountains, some of which rise above 2000 m. The large Central Plateau covers more than half of the country, includes a salt swamp, and is located between several mountain chains. Nearly 30 percent of the land is cultivable, of which approximately 40 percent is utilized annually. Iran is a semi-arid to arid country with extreme temperature fluctuations ($55^{o}C$ to $-30^{o}C$) and a rainfall average of 275 mm with the majority of precipitation arriving in the winter months [3].

(Source: UN FAO AQUASTAT)

Figure 1: Major Iranian Water Features

Iran is a country of 80.2 million people with nearly three-quarters of them residing in urban areas, contrasting the fact that 92 percent of the country's water is for agricultural use versus nearly seven percent for municipal use and just over one percent for industrial usage. Population growth is the starting point for water issues in Iran; its population more than doubled since the Revolution in 1979. The capital city of Tehran contains over 18 percent of the population. As the spatial distribution of population grows more toward the cities, water resources must move as well. As Iran continues toward the stated goal of food self-sufficiency, water is overexploited from both renewable and nonrenewable resources in an effort to grow an increasing amount of food.

Other issues plague Iran's precious water resources while the country struggles towards becoming a global economic power. The country relies on 60 percent of its water from sustainable or renewable sources with more than 55 percent originating from groundwater versus surface water. In addition, small fraction of water is sourced through desalinization. Water tariffs are very low and subsidies high in Iran. Up until recently, fuel prices were affordable for nearly all residents, allowing inefficient pumping and over-abstraction of groundwater. Iran built hundreds of small and large dams in an effort to combat population spatial distribution as well as support the agricultural efforts, but many of these dam systems are now unused due to inadequate flow and a plethora of environmental issues.

Iran has a rich history of water management. The Persians developed the qanat millennia ago in order to transport water under the surface towards irrigation reservoirs, which many are still maintained and used today. Iran continues using technology and has invested in modern inter-basin water transfer (IWT) projects to connect water rich areas near the mountain watersheds and Caspian Sea towards urban areas, although not without controversy. These efforts are largely done to offset insufficient water resources, but also as mitigation for environmental issues such as droughts and floods. Other environmental issues include potential climate change affects, wastewater mismanagement, desalinization affects, and a lack of conservancy awareness on behalf of the population and government.

Iran's government has failed to properly manage water resources, infrastructure, and risk mitigating efforts for the increasing demands of a growing population. In the next chapter, several of these issues will be further explored and compared with other countries who shared similar water resource failures and subsequently endured migration and/or conflict events. Many of these issues are not unlike the situation in the U.S. southwest, where the Colorado River has been overexploited for decades by huge aqueducts diverting water towards Californian cities. The Colorado now fails to run its natural course to the Gulf of California in Mexico.

Statement of the Problem

Currently, no regional dynamic water security models exist that incorporate migration and conflict. Several global models exist that have predicted available water resources [4]–[6]. Other local models forecast water security, but lack interactions of migration and conflict [7]–[9]. Extensive research has been conducted on water security—causes, effects, predicted outcomes, policy reforms, and resource securitization to name a few [10]–[12]. Additionally, U.S. water provision and management efforts have varied domestically and with foreign states which is evident from large infrastructure nation building project conducted in Iraq and Afghanistan since 2003 [13, p. 30].

The majority of human migratory models include the ‘push-pull’ or gravity theory, where origin-nation factors are ‘pushing’ individuals away and host-nation factors are ‘pulling’ individuals towards their borders. These models allow researchers to explain the migratory structure based on a population’s reaction towards origin and host nations events to include an understanding of the consequences of such migration. Fussel *et al.* used micro-level demographics in the form of surveys and to analyze and model environmental aspects of human migration [14]. Greenwood investigated migration drivers for U.S. citizens between 1965 and 1983 using microdata and time-series data based on familial and economic variables [15]. Edwards posits that most research and models miss accounting for critical social drivers of migration, linking individual decisions with the larger factors affecting their communities [16]. While these researchers created fairly accurate migratory models, they noted their results were limited to specific instances in time given the available data such that further research on an expanded scale would require additional variables.

The causes of conflict are entrenched in social, political, economic, cultural and environmental factors, much like migration. Research often highlights inequalities within classes or groups that alienate them based on education, employment, ethnicity, religion, clan, and resources. Extensive research has been conducted on the fundamental causes of conflict, with particular attention to the horizontal inequalities existing between groups within a country or state [17], [18] that required further review for our purpose. Due to the inherent nature of warfighting, analyzing causes of conflict for the sponsor has less priority than migration and water security and therefore will be cursory within this research.

Purpose of the Study

Water security can negatively influence a number of operational capabilities, including operational reach, sustainment, and flexibility. Acknowledging water security causes in an operational environment enables the Department of Defense, DoD, to anticipate and include its effects into mission planning, preparation, and execution. Determining a baseline (minimum) number of contributing factors allows other military research to more accurately model these interactions in the future. The U.S. military is interested in the overall stability of global partners, especially those whose resources are scarce and may be of interest for contingency planning. Finally, U.S. efforts to help stabilize or reinforce the infrastructure of these developing countries sends powerful signals of responsibility and strength to burgeoning and competing superpowers [13].

Significance of the Study

There are a number of potential water scarce environments DoD may conduct operations in during the coming years. By anticipating potential water security interdependencies of operational and mission variables, DoD may increase readiness and reduce the negative influence on operational capabilities. They may also be more informed about evolving patterns in other regions of the globe while forecasting planning efforts in migration prone regions. This topic also clearly impacts the concepts for human aspects in military operations.

Significance to Leadership

Presenting a model capable of simulating the interaction of water security, migration, and conflict permits follow on research for expanded models with more factors. Expanded models will be more accurate in predicting the effects of additional influencers within an operational environment.

Nature of the Study

The research and methodologies applied in this thesis are computationally based analyses focused in the operational sciences. For the purpose of simulating water security, migration and conflict, the primary modeling technique utilized is system dynamics (SD). System dynamics offers a holistic approach, incorporating as many system elements as possible, with the time available to conduct this research. Statistical and linear regression techniques are applied to various continuous data sources in order to determine interdependencies between elements and create equations to describe flows within the system dynamic model [19]. Scenarios are generated to support a design of experiments in order to exercise the limits of available data sources.

Research Questions and Hypotheses

Using past and current hydrology and demographic data, this study models water security and its effects on migration and conflict by identifying indicators related to the stated problem. The state of critical water insecurity, rate of migration, and type of conflict will be further defined. Available narrative and analysis sources support Iran's lack of water security. Within this thesis, these sources are explored for corroborating data in order to support our modeling and analyses. Prior to addressing the analyses, significant exploration and explanation water security encompassing management, sustainment, policy, delivery, economy, environment, and population will also be explored in order to address several questions.

1. What are the possible drivers of failing water security and can they be categorized within social, economic, political, and environmental areas?
2. Do available water resource data sufficiently quantify a particular country's water security?
3. Does the amount of per capita renewable water resources available serve as a trigger for potential migration and/or conflict within a country?

These questions are addressed throughout this thesis in order to meet the hypothesis that water security fails due to a decrease of per capita renewable water resources available below 800 m^3/yr. This value is selected on the occurrence of internal displacement of personnel in Syria prior to the protests in 2011, the proceeding civil war, and mass migration and refugee flow from the country.

Definition of Terms

A number of key terms are used throughout the research. Water scarcity is the lack of sufficient water supply to meet the immediate demands of water users or consumers. Water security is the availability and access of sufficient quantities of a safe quality in order to sustain livelihoods without negatively affecting the environment in order to promote development. Migration is the movement of a person or persons from one location to another. People that migrate are called migrants and can be categorized as internally displaced persons or refugees. Internally displaced persons are migrants who are without a permanent residence within their legal country of citizenship. Refugees are migrants who have been forcibly removed from their residences and either cannot return or fearful for their life if they were to return. Refugees can be internally displaced within their country or have left the country. Conflict is the disagreement between two or more entities. These entities can include, for example, political parties, extremist groups, neighboring ethnicities, or combatants. More detailed definitions are presented in the literature review of this thesis.

Study Scope

Causes of migration and conflict are numerous and their interdependencies convoluted. Water security was selected as a hypothesized cause by this research's sponsoring party. The topic of water scarcity is included with the parent issue, water security. Simulating water security requires a scientific model, which for this research is defined using a system dynamics methodology.

Study Limitations

There are many factors causing migration, conflict, and water security individually, in addition to an interdependent whole. This research focuses on observable data and narrative to combine the extensive research conducted from various disciplines. Much of the narrative on water security typically included references to climate change including precipitation, temperature, and weather patterns. Associated correlations between climate change and its potential causes are not explored in this study.

Summary

This research includes significant and important insights into modeling and simulating water security to identify potential effects on migration and conflict using operational science methodologies. The literature review presents a background on the topics of water security, migration, conflict, and system dynamics. The models and analysis presented in this thesis build on many previous works involving global water models. While world water models may showcase scarcity across the globe, a more regionalized or localized model is required to simulate water security in support of DoD strategies and operational planning efforts in various operational environments.

Water, migration, and conflict data exist for many industrialized nations. Many of the potential operational environments that the DoD is interested in lack sufficient data required to perform extensive classical simulation. The methodologies within chapter three model and simulate the interdependencies of the variables and elements with available open source data. Following the testing and experimentation, analyses are performed and results presented in chapter four. Finally, the conclusions of the research are presented in chapter five along with offerings for follow on research.

II. Literature Review

Overview

This chapter presents an overview sources pertinent to water security, migration, and conflict, as well as methodologies by which these topics can be modeled. This research is dependent on representing the topics accurately to present a robust model for simulation. The relationships between the topics are well documented by various experts in a wide range of scientific fields including hydrology, climatology, sociology, and political science. The available research has stressed, and continues to stress, the importance and critical requirement to address water security, conflict, and migration; yet a methodology to model the interaction is absent. Additionally, contributing factors to the problem both underlap and overlap further convoluting the modeling and simulation process. Each topic is examined individually to build a cumulative knowledge of the problem and how it applies in the country of Iran. Issues, subjects, and data pertinent to Syria and Iran will be included to support and reinforce the subsequent modeling and simulation in later chapters.

Water Security

Water security was defined by Grey, Sadoff, and Claudia [20, p. 546] as the availability of an acceptable quantity and quality of water for health, livelihoods, ecosystems and production, coupled with an acceptable level of water-related risks to people, environments, and economies. The United Nations (UN) presents an expanded definition by stating that water security is

> the capacity of a population to safeguard sustainable access to adequate quantities of acceptable quality water for sustaining livelihoods, human well-being, and

> socio-economic development, for ensuring protection against water-borne pollution and water-related disasters, and for preserving ecosystems in a climate of peace and political stability [21, p. 1].

The UN pointed out in their World Water Development report that water security is the "availability of a reliable and secure access to water over time." [12, p. 379]. This mention of time is an important characteristic when assessing water scarcity and water security.

Defining water scarcity is necessary when considering water security. Simply stated, water scarcity occurs when water supply does not meet water demand. The UN reports individuals begin experiencing water stress when the annual supply is less than 1,700 m^3, water scarcity below 1,000 m^3, and absolute scarcity below 500 m^3 per person [12, p. 124]. As an example, recent water shortages in South Africa have restricted Cape Town residents to absolute scarcity at 6.6 gallons per day (9.12 m^3/year), which equates to 0.97% of their total renewable water resources per capita per year [22]. Progressing towards a more contextual definition in a seminal work regarding environmental scarcity linked to violent conflicts, Homer-Dixon [23] defined the term "environmental scarcity" as subjective and not immune to policy or economy. From his perspective, environmental scarcity is the result of unequal resource access due to the combination of a decrease in quality and quantity of renewable resources along with population growth.

Water scarcity has been assessed in several ways based primarily on supply and demand. However, water scarcity assessments have typically accounted for water quantity, not necessarily water quality. Zeng, Liu, and Savenije stated that three known water scarcity assessments (Falkenmark index, Criticality ratio, and IWMI indicator) fail to account for water quality and a fourth assessment, water poverty index, is complicated to calculate or explain [24]. Their research applied a new water scarcity index since water use, pollution, and excessive withdrawal impacts affects not only water quantity, but water quality. Nevertheless, the state of water quality and scarcity requires an understanding of water resources, and in particular, the country of interest, Iran.

Water Resources

Iran relies very little on external water resources and is therefore dependent upon precipitation to recharge groundwater aquifers and replenish flow to the watershed. Watersheds naturally transport water to lakes, rivers, oceans, and aquifers while man-made aqueducts channel water to or from rivers and reservoirs, usually formed by a dam. As mentioned in the introduction, the majority of the water in Iran is sourced internally from surface water, which is comprised of water flowing over or stored on or above the ground level. Surface water includes transboundary rivers originate in other countries, but may transit through to a downstream country, or may cease within before reaching another body of water.

Water for use and consumption originates from the natural water cycle, which includes the watershed, and from deep underground in fossil aquifers. Fossil aquifers are formed over thousands of years as water seeps through the Earth’s crust layers into sealed caverns. Fossil aquifers are considered non-renewable water resources due to the time required to fill them. These aquifers are typically quite deep, some down to 2,000 m below the surface, and often require a great deal of specialized technology and energy to extract. For this reason, most countries have focused their attention towards renewable water resources as non-renewable water resources cannot be certain to hold sufficient quantities or quality for use and consumption.

Renewable Water Resources

Water resources are quantified through physical measurements and qualitatively assessed through various social, economic, political, and environmental aspects. Quantitatively, water resources are determined through the stocks and flows of total renewable water resources [25], which are further defined by internal and external or *IRWR* and *ERWR*, for brevity. A nation's internal resources, consists of both surface and groundwater available from the land, are calculated based on surface runoff, groundwater recharge, groundwater drainage, and seepage. These quantities are modelled [26] as:

$$IRWR = R + I - \underbrace{(Q_{out} - Q_{in})} \tag{1}$$

where R is the surface runoff, the total volume of the long-term average annual flow of surface water generated by direct runoff from endogenous precipitation, I is the groundwater recharge, generated from precipitation within the country, Q_{out} is the groundwater drainage into rivers (typically, base flow of rivers), and Q_{in} is the seepage from rivers into aquifers. The bracketed portion of equation (1) is the overlap representing the shared quantity of ground and surface water (since both are measured separately and therefore by subtracting the overlap accounts for the total quantity).

Evaporation is also considered in the total estimated *IRWR*, especially in arid lands where surface runoff is prevalent and therefore is accounted for by separate measurements [26]. Several arid countries can have evaporation rates near 50 percent of the total estimated *IRWR*, which significantly reduces the total renewable water resources (TRWR). Countries with water stored in large surface areas can lose up to 100 percent of their IRWR, although “loss” is categorized by whether the water contributes to biomass production [25]. Evaporation is accounted for in the data used throughout this research.

Quantifying external renewable water resources, or *ERWR*, accounts for more variables than *IRWR* since there are social and political aspects (treaties) to consider. *ERWR* is estimated using:

$$ERWR_{Total} = SW_{in}^{1} + SW_{in}^{2} + SW_{PR} + SW_{PL} - SW_{out}^{*} + GW_{in} \tag{2}$$

where SW_{in}^{1} is the volume of surface water entering the country, which is not submitted to treaties, SW_{in}^{2} is the volume of surface water entering the country which is secured through treaties, SW_{PR} is the accounted flow of border rivers, SW_{PL} is the accounted part of shared lakes, SW_{out}^{*} is the volume of surface water leaving the country which is reserved by treaties for downstream countries, and GW_{in} is the groundwater entering the country. This study is focused on *IRWR*, particularly groundwater, considering Iran has limited *ERWR* and surface water can be visually monitored whereas exact groundwater storage and capacities are less known.

Water Security Issues

The state of water security within a country and its relation to migration and conflict requires social, economic, political, and environmental perspectives. The World Bank’s *World Development Report 2011 on Conflict, Security, and Development* defined state fragility as periods when states or institutions lack the capacity, accountability, or legitimacy to mediate relations between citizen groups and between citizens and the state, making them vulnerable to violence [27, p. 85]. They stress the importance of governments and associated institutions such as nongovernment organizations (NGO) in determining the risks associated with fragility so as to acknowledge and avoid potential paths to conflict. It is pertinent to recognize the dynamic nature of fragility in regards to water security.

Fragility is linked to a number of other security issues such as social, political, health, personal, food, energy, and environmental [28]. These issues are dependent—when water insecurity is present, a state of fragility usually follows as one or more insecurities prevail. Failures are not mutually exclusive within the securities. Fragility, conflict, and violence can be the cause of these failures, and these failures can exacerbate fragility, conflict, and violence [28]. Homer-Dixon hypothesized the interaction of securities with sources of fragility including environmental, social, economic, population growth, and resource distribution may interact to cause conflict [23]. He described several examples in countries where conflict was and was not present based on that country's ability to adapt, but stresses more research is required.

Conflicts of any kind are rarely, if ever, attributable to single causes. As such, any analysis or efforts at reducing the risks of conflict must consider a multitude of complex relationships and contributing factors, including water [29]. Gleick stated that populations have been warring over water resources for more than 4500 years, beginning in Mesopotamia and most recently between Turkey, Iraq, and Syria [30]. Femia and Werrell acknowledged a number of underlying causes of the Syrian civil war that erupted in 2011, including a number of social, economic, environmental, and climatic changes [31]. From 2006 to 2010, Syrians experienced a drought causing water shortages in more than 60 percent of the arable cultivated land. The lead to crop and livestock failures, ultimately resulting in millions without their livelihoods and driven to migration. Civil unrest began in March of 2011 in Syria, rapidly escalating into full conflict as it was exploited by internal and external factors. This conflict is ongoing.

Research and discussion pertaining to water scarcity and security generally mention climate change. King pointed out in an article examining water stress and violence that climate change in Syria caused third and fourth order effects on populations, including food security issues, which includes water scarcity [32]. Gleick explained the effects of climate change ranging from geopolitical relations to food and water scarcity with several prominent sources [29]. Syria is particularly prone to the effects from climate change considering recent droughts in the early 2000's along with poor water usage, governmental cooperation, and continued violent conflict. Conversely, a study performed in Iran using 79 climatological reporting station over 36 years resulted in a lack of evidence supporting climate change [33]. The study determined there were no appreciable increases in temperature or decreases in precipitation, but the authors did conclude that some may be inclined to consider climate change as a cause of water scarcity due to a decrease in precipitation during drought years [33, p. 8].

Researchers have found a lack of water security can be related to conflict, but there are many complex interdependencies between causes that have not been studied. Peter Gleick, president of the Pacific Institute, maintains a chronological list containing all known water-related conflicts dating back to 3000 BC [30]. He states that while there are binned reasons for each conflict, the study and analysis of water-related conflict is not a "clean, precise field of study" [30]. Others posit that many experts seek a direct linkage between water scarcity (which includes natural variability), migration (and refugee flows), and conflict [34]. Jägerskog and Swain argued "that it is important not to draw hasty conclusions in terms of causal linkages in this respect" [34, p. 4]. Fluctuating factors such as climate change, seasonal resource variability, disease outbreaks, lapses in basic services (infrastructure), and socio-economic statuses cannot be isolated along with water security as root causes.

Recent Examples and Potential Causes

The outcomes discussed in the previous section were held to be clearly the result of inadequate water securities, or simply water insecurities, and a combination of other factors. In the most recent World Bank publication on water security assessments of the MENA region, researchers explored water security fundamentals including resource sustainability and efficiency management, reliability and affordability of services, and risk management of potential water-related events [1, p. xxix]. All countries in the MENA region endure significant water scarcity. However, they have adopted strategies in attempts to compensate for their failure to support the aforementioned fundamentals in some form or another. The failure of the Syrian government to support water security fundamentals serves as a comparison for a potentially similar outcome in Iran.

Syria

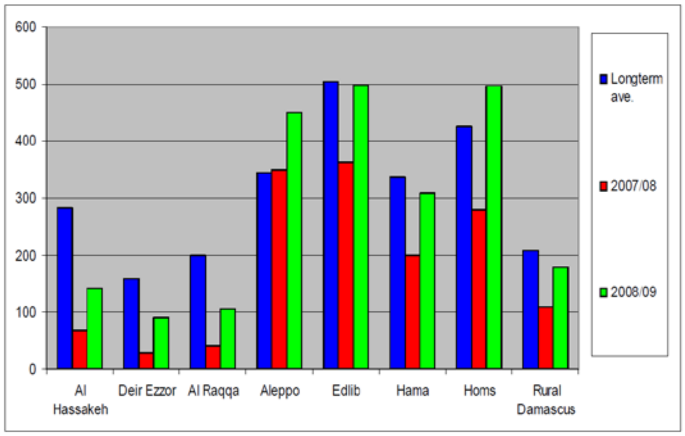
As previously noted, drought has been a frequently cited cause of the conflict and subsequent internal displacement and migration within Syria since 2011. It is prudent to mention that droughts occurred more than 50 percent of the time in the last 50 years within Syria. But isolating drought as a primary driver of such events excludes many social, economic, and political aspects that must be investigated. Natural resource mismanagement occurred over long periods of time in Syria resulting in increases in poverty, corruption, rural-urban divide, and unemployment along with decreases in state subsidies, agricultural and livestock production, and food exports [35, p. 521]. Several researchers believe Basher al-Assad is to blame for the conflict in Syria since al-Assad aimed to increase Syria's world market appeal to the World Trade Organization by converting the centrally planned market economy to a social market economy by cutting subsidies to reduce the growing budget deficit [35], [36].

Culturally and politically, water is a sensitive topic in Syria since the government focused on increasing water supply with little regard for available renewable water resources. Government water management is divided: a hopeful modernization effort driven by construction and irrigation and unrealistic goalsetting by corrupt, ineffective policy makers aimed to exploit all resources [35]. Water data is unequally collected and assessed by a number of resource managing ministries and agencies within the country causing differences in estimates and degrading efficacy. Furthermore, corruption is fueled by rivalries between agencies, poorly paid senior leadership, and the practice of nepotism and clientism [35], [36].

The 2009 reduction in fuel subsidies in Syria was a way to control the over-abstraction of groundwater occurring since the 1960's. Farmers depleted groundwater resources by running diesel pumps with subsidized, inexpensive fuel in order to increase productivity to meet rising demands. The immediate effect of cutting fuel subsidies shocked the agricultural workers. Without sufficient fuel, farmers either chose to use limited funds on fuel to irrigate their crops and then were unable to transport them to market, or abandon their land altogether [35]. As agricultural yields decreased without subsidized fuel and fertilizer, Syria began losing their position in the global economy as the government blamed the outcome on drought.

The rapid rise of groundwater wells to support government-encouraged large-scale irrigation for water intense crops like cotton largely occurring from the 1970s to the late 1990s depleted several aquifer levels from 6 to 100 m. Slowly realizing the reality of this huge over-abstraction of groundwater, the government unsuccessfully attempted to impose licensing restriction on all illegal wells in 2005 [37]. Aquifers in the Hassakeh governate in the northeast of Syria dried up causing migration and the Barada River in Damascus that once fed lush gardens is now all but a trickle [38]. As of 2010, over 30 percent of Syria's population was experiencing high or extremely high groundwater stress, above the MENA average of 23 percent [1]. Syria's over-abstraction of groundwater compromises between 20 to 50 percent of environmental flow requirements, undoubtedly due to a high (>90%) agricultural irrigation demand [1]. Syria's once plentiful water resources were subjected to exploitation by a growing population, over-abstraction, and an economically motivated and corrupt governance first unknowingly and subsequently with disregard to a devastatingly environmental and humanitarian crisis, which ultimately led to war.

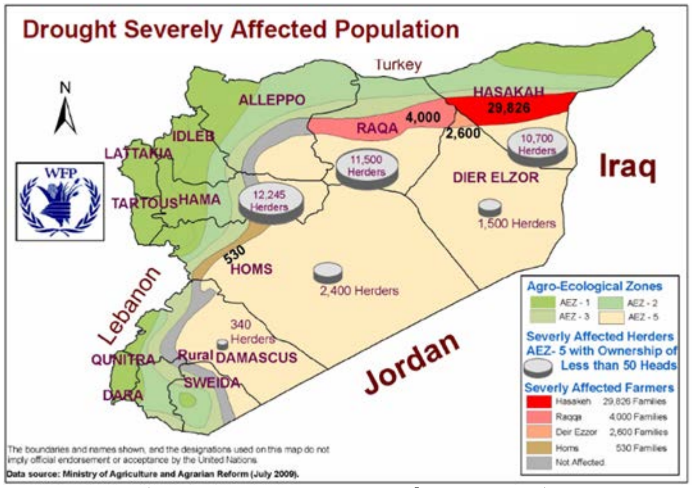
Coupled with the mismanagement occurring in Syria, drought still played a major roll, especially during the 2008 growing season. Wheat production dropped 47% from 2007's season, coinciding with the driest winter in the same year and causing a loss of green water availability for agricultural use (Green water availability is reliant on precipitation to replenish soil and higher amounts usually lower blue water consumption [39]). The drought affected the majority of the agricultural community as precipitation levels fell to 15-30 percent of annual averages [11].



(Source: USDA)

Figure 2: Syrian Provincial Rainfall

Syria heavily relies on external surface water (72.36 percent) and over twice the dependency of Iran on overall surface to groundwater (12.63 km^3 to 6.174 km^3). Syria's overall water consumption of total available renewable water resources rose from 19 percent in 1977 to 99 percent as of 2007 [3]. Their total internal freshwater (surface and groundwater) withdrawals have risen from 46.8 percent in 1977 to 235 percent in 2007. Farming populations in the northeast province of Hassakeh were most affected beginning in 2006 and into the 2007-2008 planting season, resulting in the internal displacement of 36,000 families [40].



(Source: UN Syria Drought Response)

Figure 3: Drought Affected Syrian Families as of 2009

Initially, impacts were estimated at 1.3 million people affected including 803,000 farmers and pastoralists (80 percent losing livelihoods subsiding on 50 percent of daily caloric intake) [40]. According to Mohamad Alloush, director of the environment department at the State Planning Commission (SPC), the drought forced 250,000-300,000 families (at least 1.25-1.5 million people) to leave their villages and concentrate in the suburbs of Damascus and other cities like Aleppo and Daa'ra [41]. Fortunately, wheat production rebounded, but continued its pre-drought decline throughout the duration of the conflict.

Many other contributing issues stemming from water security affected Syrians. Water supply service in Syria declined by 70 percent between 2011 and 2013 due to conflict as dissident groups and militaries fought to control supply [42]. Decline in water supply usually is accompanied by a decline in water quality. Water-borne diseases in poor quality water cause increases in diarrhea related deaths, especially in children. In Syria, these deaths accounted for 14.4 percent of all deaths of children under five years of age, far higher than other MENA countries. Poor sanitation and hygiene become life threatening issues for refugees and internally displaced persons (IDPs) as conflict and migration continued. Other issues influenced by the status of water security in Syria include migration and conflict, which are addressed in separate sections further in this study.

Water Resource Metrics

A drastic loss of available water resources in a short period of time can certainly be portrayed as a primary effect of drought, especially when other less commonly understood causes are absent. Kumma *et al.* presented a methodology for water scarcity and stress trajectories based on per capita consumption in m^3/yr [39]. They state water scarcity is population driven; the available resources insufficiently satisfy an increasing large population. Water stress is a demand driven influence based on the amount used, regardless of the population. Kummu *et al.* define per capita use as equations (3) and (4), which are equivalent.

$$\frac{water\ use}{population} = \frac{water\ use}{water\ availability} * \frac{water\ availability}{population} \tag{3}$$

$$per\ capita\ consumption = stress * shortage \tag{4}$$

Within their study, Kummu *et al.* defined water scarcity and stress levels based on long-term decadal scale availability, consumption, and population data for the world (Table 1).

Table 1: Shortage and Stress Thresholds

Threshold	Shortage (m^3/capita/year)	Stress (Percentage of Water Consumed)
Moderate	1700	20
High	1000	40

(Source: Kumma *et al.*)

Regionally MENA, representing 17 percent of the global population, faces both water scarcity and stress. Syria's land area is a 'stress first' archetype defined by Kummu *et al.* (Table 2) as a result of demand driven per capita water use given the amount of water available prior to a water shortage. Iran is defined by the 'stress and shortage at same time' archetype, indicating per capita consumption occurred along with exceeding the stress point (>20%). The authors define the water scarcity trajectories based on the Falkenmark water scarcity matrix that combines stress and shortage values along per capita consumption iso-lines in order to highlight the drivers (Figure 4 and Figure 5). Since Syria falls into a 'stress first' archetype based on Table 2, the authors posit that demand is typically prioritized before supply, resulting in increased per capita consumption.

Table 2: Trajectory Types

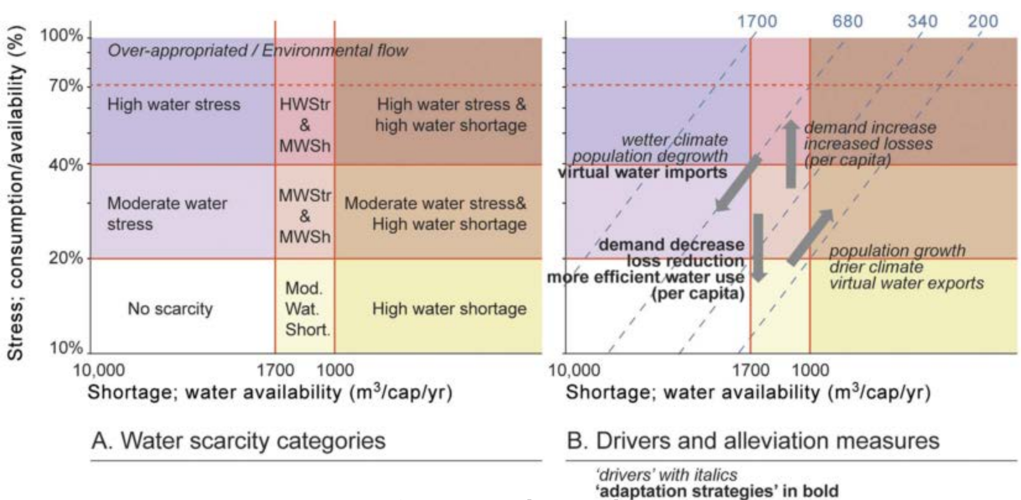
Type of trajectory*	Description
A. Archetype	
No scarcity yet	Per capita available water >1700 m^3 cap^{-1} yr^{-1} and stress <0.2 always, corresponds to FPU trajectories confined to bottom-left of Falkenmark matrix
Shortage alone	Per capita available water <1700 m^3 cap^{-1} yr^{-1} for some decades and stress <0.2 always, corresponds to FPU trajectories confined to bottom of Falkenmark matrix
Stress alone	Stress >0.2 for some decades, but per capita available water <1700 m^3 cap^{-1} yr^{-1} always, corresponds to FPU trajectories confined to left of Falkenmark matrix
Shortage first	Per capita available water >1700 is reached before stress >0.2, includes FPUs that have reached top-right of Falkenmark matrix, and generally where per capita consumption is low (<340 m^3 cap^{-1} yr^{-1})
Stress first	Stress >0.2 is reached before per capita available water >1700 m^3 cap^{-1} yr^{-1}, includes FPUs that have reached top-right of Falkenmark matrix, and generally where per capita consumption is high (>340 m^3 cap^{-1} yr^{-1})
Stress and shortage at same time	Stress >0.2 and per capita available water >1700 m^3 cap^{-1} yr^{-1} both reached in the same decade. Includes FPUs that have reached top-right of Falkenmark matrix and where per capita consumption is either close to 340 m^3 cap^{-1} yr^{-1}, highly variable or the FPU has always been subject to water scarcity within the data period studied
B. Shape of trajectory$^+$	
Increasing scarcity	Both stress and shortage increase every decade
Increasing shortage	Shortage increases every decade, stress may vary
Increasing stress	Stress increases every decade, shortage may vary
Decreased stress	(Max stress – stress in 2005)/(max stress – min stress) > 0.2 Final stress is less than 20% of its maximum
Stress ceiling	$\lvert Stress_d$- Stress in 2005$\rvert$<0.04 for some 1915 ≤ d ≤ 1995 and $\lvert Stress_d$- Stress in 2005$\rvert$<0.06 from some 1915 ≤ d ≤ 1995 onward i.e. stress becomes close to its final value, and stays close to its final value from some decades, but in both cases not from the start, and not just before the end
Constant per capita demand	Linear fit to stress=m.(1/shortage)+c has R^2>0.95

(Source: Kumma *et al.*)

Using (3), (4) and referenced values, calculations indicate Syria was experiencing water scarcity and stress leading up to the civil war and subsequent migration (Table 3). This thesis utilizes these calculated figures in scenarios modeling Syrian and Iranian water balance.

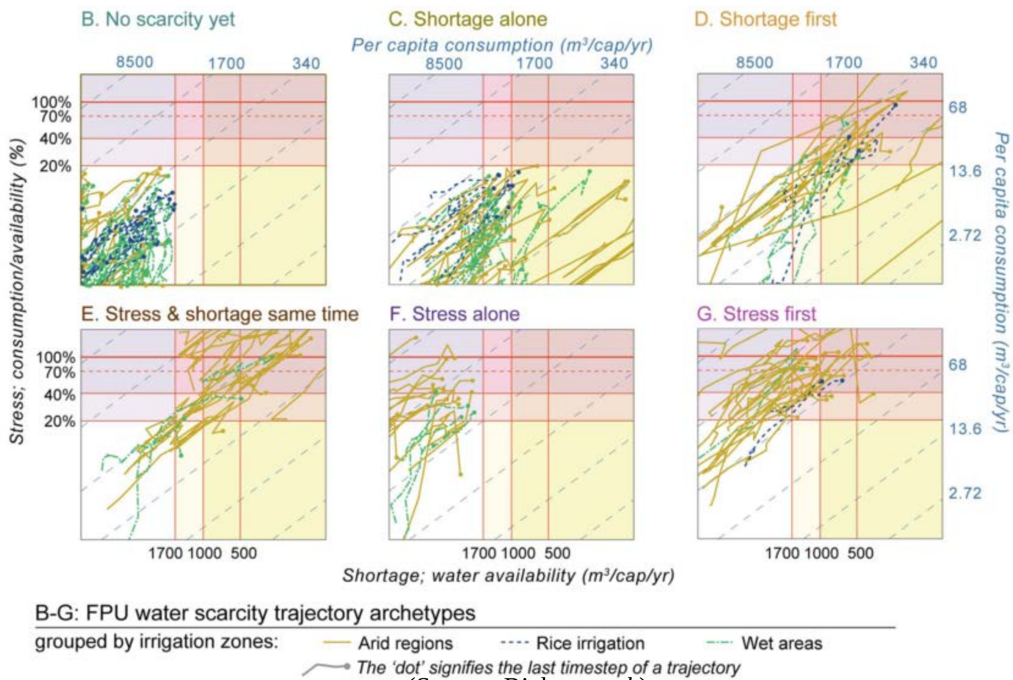
Table 3: Estimated Stress, Shortage, and Consumption

Country	Reference	Population	Water Availability (m^3/year)	Water Use (m^3/year)	Stress	Shortage	Per Capita Consumption, (m^3/capita/year)
Iran	Tehran Times, 2018	8.02E+07	8.80E+10	9.70E+10	1.1023	1097.2569	1209.4763
	FAO, AQUASTAT	7.91E+07 (2015)	1.37E+11 (2014)	9.33E+10 (2004)	0.6810	1731.9848	1179.5196
Syria	GTZ, 2007	1.77E+07	1.56E+10	1.92E+10	1.2308	881.3559	1084.7458
	FAO, AQUASTAT	1.85E+07 (2015)	1.68E+10 (2014)	1.68E+10 (2005)	0.9976	908.1081	905.9459



(Source: Richey *et al.*)

Figure 4: Falkenmark Water Scarcity Matrix

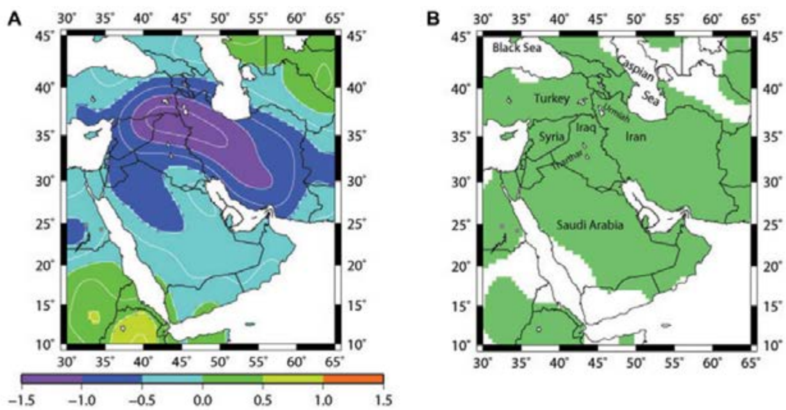


(Source: Richey *et al.*)

Figure 5: Water Scarcity Trajectories

Research into measuring available groundwater has included satellite technology rather than pure terrestrial means. Using NASA's Gravity Recovery and Climate Experiment (GRACE) data, Richey *et al.* measured the groundwater depletion rates of major world aquifers in 2015, but none of which are within Syrian borders [43]. Voss *et al.* analyzed groundwater availability using a combination of GRACE data and remote sensors in the Tigris and Euphrates River basins and western Iran from 2003 to 2009 and found disturbing rates of groundwater storage [44]. These data support the trend of declining groundwater storage levels in an area encompassing portions of Turkey, Syria, Iraq, Georgia, Azerbaijan, Armenia, and western Iran along with Lake Daryace, Lake Van, Lake Tharthar, the Asad Reservoir, and the Qadisiyah Reservoir.

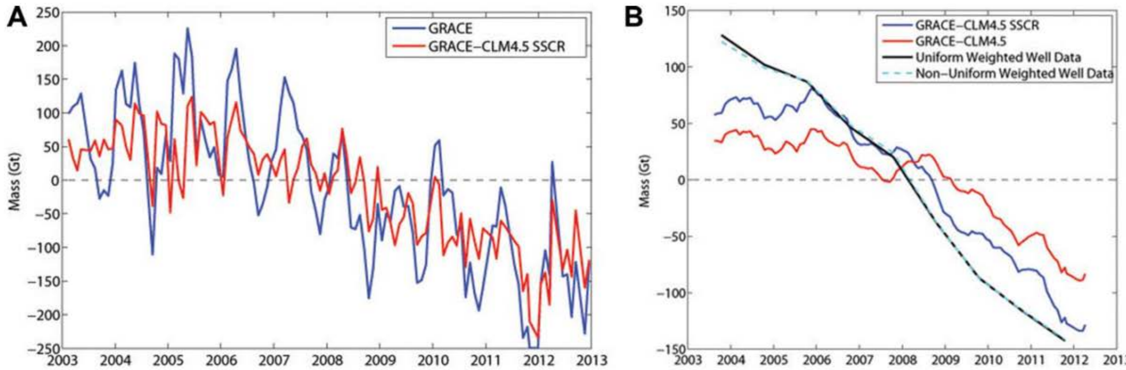
With no major deep aquifer below Syria or Iran, the studies by Kummu *et al.* and Voss *et al.* highlight aggregated global and regional quantities and consumption, respectively. Joodaki *et al.* utilized higher resolution GRACE data along with 562 active well observations sourced from the Iran Water Resources Management Company in order to determine monthly averages of total groundwater storage in Iran [45]. Their total groundwater storage estimates account for naturally occurring and anthropogenic components across most of the Middle East region and a portion of North Africa (Figure 6).



(Source: Joodaki *et al.*)

Figure 6: GRACE Data Coverage

Groundwater storage estimates were isolated by subtracting soil moisture, snow, canopy storage, and river storage changes along with Caspian Sea and large lake contributions. Joodaki *et al.* scaled each country estimate and applied a parametric test at a 95 percent confidence interval before comparing GRACE coefficients with Iranian observed well data. The authors caveat that increases in monthly storage data may be anthropogenic considering that broad-scale irrigation is typically practiced, and that a portion of the increases could be due to recharge from runoff and seepage [45]. Regardless of monthly groundwater storage increases, significant decreases in total groundwater storage were observed from both GRACE coefficients and well data (Figure 7).



(Source: Joodaki *et al.*)

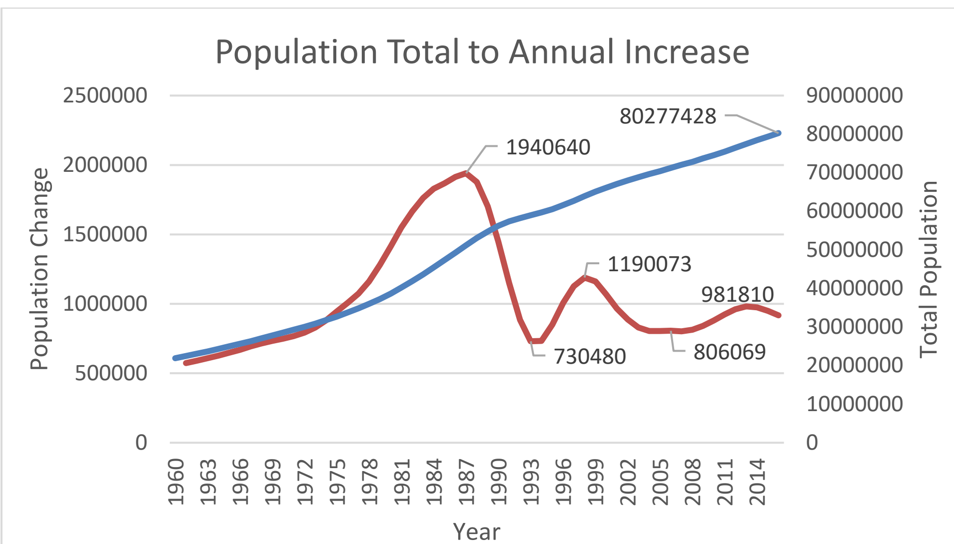
Figure 7: Groundwater Storage Estimates

Overestimated well data may have resulted in the larger (black line) loss versus GRACE coefficient estimates, but the authors state GRACE data did include an area extending past the Iranian border due to a sensitivity kernel.

Iranian Issues

Madani published a paper in Iranian Studies in 2016 outlining many of the drought-related issues affecting Iran [2]. Population growth, pollution, agricultural self-sufficiency, fuel and water subsidies, and unbalanced infrastructure have influenced water security in Iran, but mismanagement and unsustainable usage are the major factors in shortages. Even though Iran's water history includes the Persian development of qanats, 2,500-year-old underground aqueducts channeling groundwater to reservoirs for agricultural irrigation still widely used in the region, economic growth, urban expansion, and competition with the world trade market is unsustainably depleting water resources. Additionally, land subsidence, deteriorating water quality, desertification, eutrophication, and erosion are problems plaguing a country once famous for its sustainable water practices [2].

As Iran's population rate of change decreases from its height during the Revolution, the government anticipates a 1.3 percent increase to balance age distribution. Current population in Iran is 80.2 million with a rate of change +1.14 percent (for 2016) [46]. As shown in Figure 8, annual increase of population indicates a stabilizing trend as the variance between high and low amplitudes decreases. Madani's research stated the urban population growth runs counter to the water resource locations, stressing existing infrastructure within cities. Nearly all of the urban and three-quarters of the rural population has access to clean water, but most consume more than twice the global average at 250 liters per person, per day, which equates to $250\ l * 365\ days = 91250\ l/year$ or $91.25\ m^3/year$. This quantity represents the municipal portion of the total water resources per capita in Table 3.



(Source: World Bank)

Figure 8: Iranian Population Trends

Since 92.18 percent of water in Iran is used for agricultural purposes, municipal and industrial use is divided into 6.645 percent and 1.179 percent, respectively, which puts the urban daily estimate in a sensible range given the variance in years.

Iran relies on oil for the majority of its GDP, although it is determined to be food self-sufficient as are many other MENA countries due to their vulnerability to food shortages from limited water, large populations, and political instability [2]. Virtual water imports are a contentious topic in Iran [47], but self-sufficiency goals challenge remaining water resources, infrastructure, and services. Water is still quite inexpensive in Iran, as are gasoline, diesel, cooking gas, and electricity because Iran is an oil-based economy. Efforts to cut subsidies across several five-year plans to reduce a $100 billion program were meant to stabilize consumption and privatize services such as transportation. Cuts in subsidies created backlash from the population, causing policy makers to provide cash handouts to nearly everyone as an offset. Instead of boosting the economy by convincing rural workers to seek more lucrative employment in urban centers, rural populations remained in the country side and lived off of the government handouts [48].

Dams offered much promise for water sustainability in Iran. At one point after the Revolution Iran was the third largest dam builder in the world. Despite several hundred dams built and hundreds more planned, many sit empty as watersheds and river flows dried up due to over abstraction from irrigation and other uses. Over the decades many environmental issues resulted from dams, including human displacement, sedimentation, eutrophication, biodiversity damage, and downstream development, caused further issues for governing water and energy ministries and agencies.

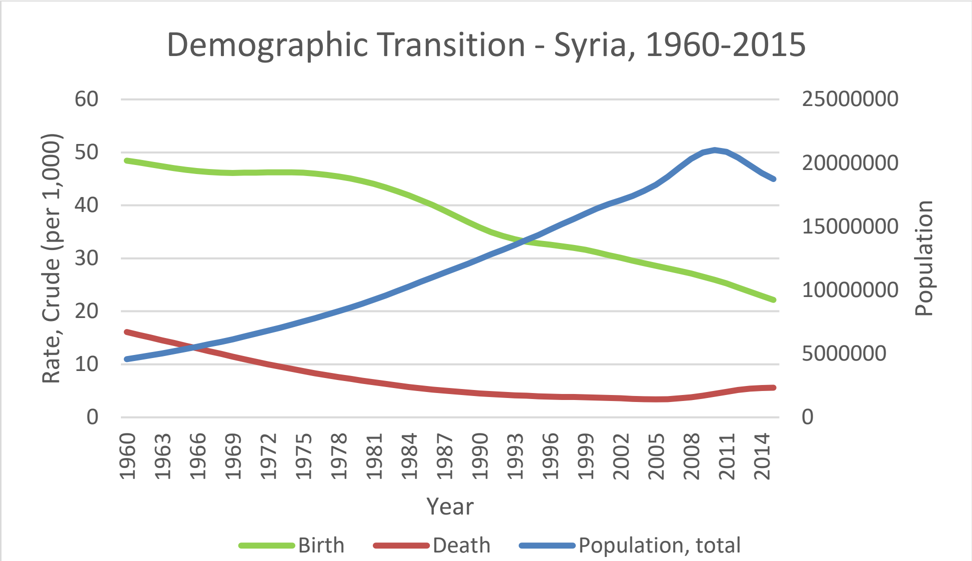
The number of wells increased in the 1960s as fuel subsidies decreased fuel prices in favor of increased production and development [1], [2]. As more wells were drilled to meet agricultural demands, groundwater storage levels decreased and fuel consumption rose to draw water from lower levels. The Iranian government unsuccessfully attempted to curtail illegal well drilling, as the Syrian government attempted to do, by requiring permits for all wells. Since water management in Iran is unable to detect and monitor wells, the effort was changed to smart water meters, with limited success [49]. Nevertheless, the need to control a water source is paramount in a country where droughts are common and floods can be devastating.

Interbasin water transfers are another infrastructure investment the government has supported in order to supply urban areas such as Tehran and Zayandeh-Rud located towards the center of Iran where resources are scarce. The process desalinates water from renewable water sources such as the Persian Gulf and Sea of Oman and pump the water through an underground pipeline to offset dwindling urban resources. These projects are expensive, on the order of hundreds of millions to billions of US dollars, along with having high energy requirements. Experts question the value of such endeavors suggesting other sustainability, service and risk-mitigating efforts for water resources [50].

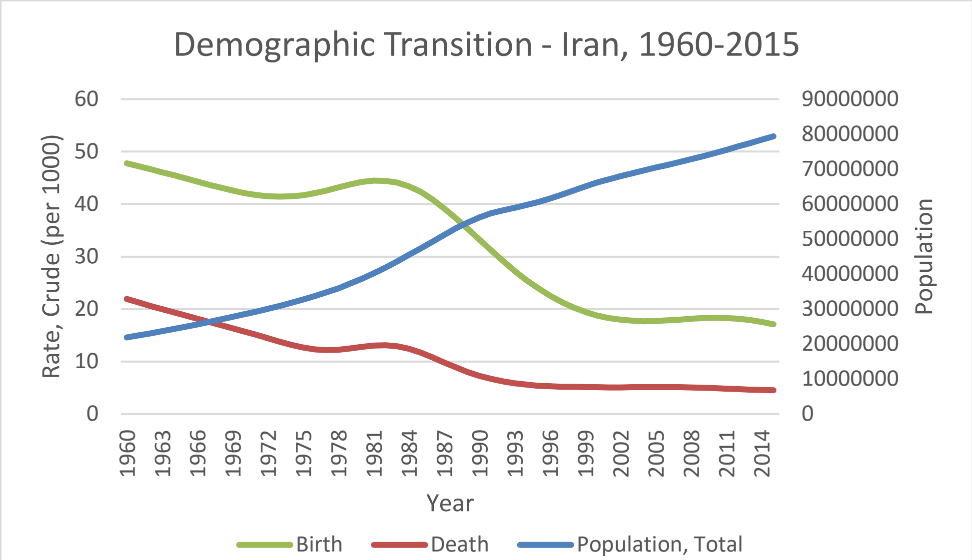
Similar to Syria, Iran's water governance structure is mismanaged due to insufficient support from political powers. President Ahmadinejad converted the water management jurisdiction from watershed-based boundaries to provincial-based causing infighting over trans-provincial water resources. Corruption is also a problem affecting the long-term goals necessary to prevent environmental crises thus allowing irreversible damage to mount [2]. The population had little environmental awareness until recently when water levels in Lake Urmia dropped due to irrigation, upstream storage from dam and diversions, and droughts [2], [47], [51]. Public media reports regarding environmental issues and events have improved as a result. Other water-related issues are noteworthy. These include wastewater management, network losses (leakage rate), pollution from nitrates and phosphates (agriculturally sourced), and water-borne diseases.

Comparison

There are many similarities concerning water resources in Syria and Iran, but there are differences between the countries themselves. Syria is a lower economic status than Iran, mostly due to Iran's higher GDP [10]. This lower class led to fewer investments in Syria. The difference in demographic transition graphs for Iran and Syria describe the population trend and act as a potential predictor of total population [52], [53]. In Figure 9, birth and death rates in Syria are converging such that the population is experiencing a reduction, whereas birth and death rates of change in Iran are moving in the same direction. Syria's birth rate (22.158 births per 1000) is currently falling as death rate increases (5.589 deaths per 1000), due in part to the ongoing civil war. These rate variations are an indication of a slowly decreasing or potentially slowly increasing total population. However, the birth and death rates prior to the beginning of the civil war in 2009 were trending at a similar rate 27.139 and 3.798, respectively. The population of Iran is over three times that of Syria, but the birth and death rates have remained more synchronized following the Revolution, which may be indicative of other socio-economic factors.



(Source: World Bank)



(Source: World Bank)

Figure 9: Syrian and Iranian Demographic Transition Graphs

The recent civil war and mass migration have left many services unfilled, setting behind on any future developments, maintenance, and repairs of the infrastructure. Iran has a much larger population than Syria (80.2 million to 18.3 million) and landmass (636,400 mi² to 71,498 mi²) requiring more infrastructure and governance. Focusing on the water security leads this study towards water availability and consumption by a growing population. Using the example of Syria's water security failures as a potential outcome for Iran's current course highlights the importance of investigating models linking Syria's outcomes onto Iran.

Models

The available research has and continues to stress the importance and critical requirement to address water security, yet a methodology to model its interaction with influencers is absent. Many researchers understand that water security involves monitoring more than surface, ground, and transboundary water sources [23], [29], [34]. Currently, scientific models of linkages between water securities, migration, and conflict are unavailable. Hydrological models of the world such as WaterGAP provide the UN and other international assessors do exist with freshwater flow and storages statistics. The Food and Agriculture Organization (FAO) of the UN maintains AQUASTAT, a collection of analyzed water resource, use, and agricultural management data for all countries [3]. The World Bank has an extensive database of fragility and conflict meta- and micro-data for numerous countries [54]. The aforementioned resources possess potentially applicable models for water security analysis, particularly Simonovic's *WorldWater* model and Zarghami's *Tabriz Systems Dynamics* model [4], [51].

Migration

The International Organization of Migration (IOM), the UN migration agency, defined migration as

> The movement of a person or a group of persons, either across an international border, or within a State. It is a population movement, encompassing any kind of movement of people, whatever its length, composition and causes; it includes

migration of refugees, displaced persons, economic migrants, and persons moving for other purposes, including family reunification [55].

The number of migrants in 2017, including refugees and internally displaced persons, topped 258 million, or three percent of the world's population [56]. According to the World Bank's 2016 Migration and Remittance Report, migrant numbers have risen in recent years due to job opportunities, labor shortages resulting from falling birth rates, internal conflict and war, natural disasters, climate change, and improved access to information through phone and the Internet [46].

While there are many apparent causes of migration, there are also a variety of theories postulating its drivers. Beginning with Ernst Georg Ravenstein's seminal work in the 1880's, migration theories progressed throughout the 20th century through works by Greenwood, Graves, and Lee. As a demographer, Lee provided a framework to describe migration volume, streams and counter streams, along with the characteristics of migrants [57]. He simply stated that migrants permanently or non-permanently move from one location to another. Those moves are characterized by attractiveness measured in 'pluses and 'minuses' at the origin and destination separated by varying degrees of intervening obstacles. These moves occur on more broadly defined 'push-pull' networks between two or more locations, including transit locations between an origin and a destination. Migrants consider both rational and irrational reasons for moving from an unattractive origin to a perceived more attractive destination.

The resulting volume of migrants causes streams and counter streams to and from the destination and origin, respectively. Positive and negative characteristics influence migration; migrants with higher intelligence or more education typically make rational and positive decisions based on their assessment of pluses at the destination. Positively inclined migrants can maneuver through and overcome the intervening obstacles in the migration process. The opposite is true for those migrants negatively associated with the minuses in the origin. Lee provided a similar conclusion by stating that incorporating personal characteristics of migrants in the form of micro-data may be influential towards advancing empirical research in migration including dynamic models of migratory behavior using time-series data [57, p. 541].

While micro-data is unavailable for one of the more major and recent migrations caused by water scarcity in Syria, exploring the larger drivers is necessary. Syria experienced a significant drought from 2004-2011 that resulted in the unemployment and eventual migration of 1.5 million people from rural agriculture populations into the urban areas. Although Syrians endured a civil war with a government capable of supplying 50 percent of them access to clean water, the infrastructure and supply were being weaponized by Islamic State (IS) terrorists in attempts to incentivize recruitment and control. Other catalysts fired the migration and reinforced the subsequent civil war. Water scarcity forced farmers and herders from their homes in the country side into the cities and urban areas looking for better livelihoods and resources. But the cities were already taxed beyond capacity in terms of water, which placed demands on the government to deliver increased water supply and other resources. Keep in mind that Syria’s population had experienced major growth—from 3 million in 1950 to 22 million in 2012. The reformed government failed to provide additional water supply, which preceded violent uprisings against the government. The primary demand of those leading many uprisings was not for reform but for water [58, p. 14].

Edwards offered a more in-depth analysis of migrant behavior in attempts to model the complexities of forced migration, particularly the reasoning behind why micro and macro level inputs, along with push-pull and migratory networks insufficiently explain the subject [16]. With extensive support for his analysis, he stated there are two primary types of migrants: those who move for economic reasons and those who are forced to migrate due to other reasons. Other studies have emulated these results [59]–[61] . Typically, forced migration is said to be the result of some crisis or combination of crises whereas voluntary migration is by choice and is therefore rationalized by the decision maker. Edwards focused on what is lost to many migration and refugee flow studies; the choices of those migrants within the migration framework. While there is merit to the push-pull methodology as it links the micro (individual) and macro (structural inputs) level causes, studies and research largely omit the meso (social) level that Edwards investigated [16].

Refugees experiencing forced migration are subject to social drivers unlike those in voluntary or economic migrants. Drivers are usually apparent or reported by voluntary migrants in a push-pull model whereas the drivers in a forced migration are far more obscure. Refugees are driven by complexities and variances in their environment, especially those social networks that determine migratory networks that must be acknowledged before becoming a crisis. Edwards pointed out that the UNHCR identifies potential signs of migration that include ethnic, racial, social, or religious tensions, human rights violations, opposing political movements, faulty relationships with neighboring countries, demographics, environmental issues, economic instability, drug trafficking and historical evidence within their contingency planning guidelines for their field staff [16, p. 22].

Over time, studies have accumulated on the drivers of different forms of migration. Violence, especially armed conflict sponsored by government militaries causes displacement (IDPs) and refugee outflow [59], [60]. States not protecting the human rights of their population cause more refugees [62]. Poverty stricken populations as a result of economic depravation increase displacement as well [60], [63]. These drivers have been postulated in studies of early warning models of potential humanitarian disasters resulting in migration [64]. Migratory causes are extensive but nevertheless include a population’s dependency on resources, and when water becomes scarce, people will relocate. Water security and water scarcity are both integrated into migration in many direct and indirect aspects. Data sets originating from experiments, observations over time, and modeled simulations vary in terms of density and fidelity. These facts support the primary issue of water scarcity in this study.

Conflict

There are a range of definitions for conflict applicable to the topic at hand. From a civilian perspective, Maurer defined conflict as a “disagreement resulting from incompatible demands between or among two or more parties [65, p. 1].” NATO defined the term as a

> political-military situation between peace and war, distinguished from peace by the introduction of organized political violence and from war by its reliance on political methods. It shares many of the goals and characteristics of war, including the destruction of governments and the control of territory [66].

Interestingly, the US Department of Defense official dictionary [67] had no definition for conflict, but offered supporting terminology of a similar context. They defined the term engagement as “a tactical conflict, usually between opposing lower echelons maneuver forces [67].” The DoD officially defines conflict prevention as a

> peace operation employing complementary diplomatic, civil, and, when necessary, military means, to monitor and identify the cause of conflict, and take timely action to prevent the occurrence, escalation, or resumption of hostilities [67].”

References to conflict within DoD joint publications usually accompanied the term “armed” or “continuum.” Conflict continuum is a “measure of military instrument of national power applied between the states of peace and war [68, p. 119].” The definitions vary based on political, organizational, and individual involvement along with the level and intensity of violence occurring. With respect to this research, the more important aspect of conflict are the causes.

Stewart [17] presented cultural and economic drivers to wars and conflict that include ethnic, religious, economic, and social causes. The author briefly described four interrelated economic hypotheses supported by evidence from analyses of countries exhibiting conflict or war. Economics plays a fundamental rather than supplementary role in each hypothesis. In the first, the author states groups may exhibit cultural or religious differences, but conflict is not realized until political or economic power is imbalanced [17]. The second hypothesis states that personal gain is realized during war and conflict when largely uneducated young men become attracted to more lucrative opportunities, regardless of the morality, when socially accepted employment options are minimal or nonexistent. In the third hypothesis, when the unwritten socially acceptable balance between a population and the government fails, it is typically due to the populations lack of faith in the government’s commitment to provide basic needs. Finally, when the environment ceases to sustain the population, such as a water scarcity, the population suffers. A particular resource scarcity may be caused by a lack of governance or policy in management, sustainability, disaster preparedness and response, and infrastructure.

The hypotheses presented by Stewart are supported by evidence in the form of analyses and studies across numerous populations. Group inequality occurs within a population in the form of horizontal inequalities, which when they become widespread and persist, can cause a range of conflict from protests to rebellions. When groups are unable or unwilling to consider peaceful negotiations, especially if their government has failed to address inequalities, conflict can occur. Horizontal inequalities occur when groups, not individuals, share common identities but differ in social, economic, political, and cultural statuses and is largely measured in terms of income or consumption [18]. One study supports the theory that personal gain in the form of greed outweighs grievance between a populace and their governments although the methodologies of the study are contentious [69].

Other evidence regarding econometrics and environments indicated significant variances. These variances existed when per capita incomes, life expectancy, and economic growth figures were analyzed when determining vertical separation and conflict. Countries vulnerable to conflict typically do not receive support from outside funding, especially when their governments are failing. In terms of environments, particularly resources, there are disparities between scarcity and abundance. Scarcity tends to cause conflict from the populace given inadequate resources whereas abundance is fortuitous to groups willing and able to seize control. As mentioned, these hypotheses are not mutually exclusive, and result in horizontal inequalities driving conflict such as those listed in Table 4. Causes of conflict presented by Stewart [17] require further investigation of horizontal inequalities in countries where populations are suffering from imbalanced governments and unfair policies that favor particular groups, empower corruption, devalue education, and misuse resources.

Table 4: Horizontal Inequality (HI) Examples

Categories of differentiation	Selected examples
Political participation	
Participation in government	Fiji, Burundi, Bosnia and Herzogovinia, Uganda, Sri Lanka
Membership of army and police	Fiji, Northern Ireland, Burundi, Kosova
Economic power	
Assets:	
Land	Fiji, Cambodia, El Salvador, Haiti
Privately owned capital	Malaysia, South Africa, Burundi
Government infrastructure	Chiapas, Mexico, Burundi
Aid	Afghanistan, Sudan, Rwanda
Natural resources	Liberia, Sierra Leone
Employment and incomes:	
Incomes	Malaysia, South Africa, Fiji, Chiapas
Government employment	Sri Lanka, Fiji
Private employment	Fiji, Uganda, Malaysia
Elite employment	South Africa, Fiji, Northern Ireland
Unemployment	South Africa, Northern Ireland
Social access and situation	
Education	Rwanda, Burundi, Haiti, South Africa, Northern Uganda, Kosova
Health services	Burundi, Northern Uganda, Chiapas
Safe drinking water	Uganda, Chiapas
Housing	Northern Ireland
Poverty	Chiapas, Uganda, South Africa

(Source: Stewart)

One of the primary underlying drivers to the majority of conflict is a propensity for conflict within a country's history. Østby's empirical and spatial analysis across Sub-Saharan African countries, for 1986–2003, reveals a significant rise in the probability of conflict in countries with severe economic and social HIs [70]. Specifically, these HIs include low educational levels along with high levels of intra-regional socioeconomic inequalities influence higher levels of conflict [70]. Østby cites that abundant natural resources cause conflict due to deprivation levels. Other statistical research supporting this relationship includes relative deprivation and conflict in Sub-Saharan African countries in the 1960s [71], [72]. Data from 1946–2005 for the world indicates that countries exhibiting political exclusion of populations experience more violence [73].

Countries with high value natural resources are potentially susceptible to conflict, especially when the level of scarcity changes drastically [18]. Across groups of people, unbalanced quantities or access create opportunities for powerful groups to control a perceived inferior group. While Stewart cites oil and diamonds as valuable natural resource, water has the potential to incite significant HIs if an abundant water resource falls under the control of a corrupt or violent group. Governments have the ability to enact policy limiting resource infrastructure to poorer or impoverished populations in efforts to reform or force them to migrate.

O'Brien presented a fuzzy algorithm application approach to forecasting conflict using social, economic, and political variables such as GDP per capita, number of civil liberties, and ratio of young-to-old [74]. His results indicated an 80 percent success of predicting conflict from data used to categorically rank conflicts. O'Brien recommended a collaborative social science experiment where a repository of interdisciplinary efforts could be submitted, recorded, incorporated, and analyzed [75]. This large-scale project aimed to aggregate social, economic, political, cultural, and military drivers of conflict based on the extensive studies and research of past and present in order to increase the collective knowledge for future conflict research.

There are significantly more studies and research about conflict than water security and migration. The key aspect of the reviewed literature is that water as a natural resource with the potential to influence conflict. People intuitively seek out water as a necessity for life, and in water scarce and insecure countries many often migrate to do so. Yet as the literature has suggested, engaging in conflict over water resources may be a choice motivated by one or several known or unknown contributing drivers. As with migration, exploring the causes of conflict is necessary towards understanding the potential influence water resources can exercise.

System Dynamics

System dynamics is a methodology applicable to modeling factors of a convoluted system of interdependent factors such as the one presented in this thesis. Jay Forrester developed system dynamics following his work with management at General Electric and with radar systems for the US Navy. He blended the complexities of social systems with physical systems at the recently established School of Management at the Massachusetts Institute of Technology, MIT [76]. Forrester describes systems as "a grouping of parts that operate together for a common purpose" [77]. The DoD operates in a hierarchical manner with information and knowledge controlled by classification and necessity. Relatedly, Forrester informs that "without an organizing structure, knowledge is a mere collection of observations, practices and conflicting incidents" [77]. To arrive at solutions for strategic and operational planning efforts, systems that define the intricacies and relationships within the operational environment are necessary.

System dynamics, stated simply, attempts to model the interdependent elements within a system in order to understand its behavior over time [4], [5], [78]. That behavior is characterized by the complexity of the system's elements, and the accuracy of the behavior is dependent on proper system modeling. A system dynamics model is comprised of causal loops identifying the feedback of interactions between elements of a system. These causal loops are typically converted to ‘stocks’ and ‘flows’. Stocks represent an element with a capacity that can change over time whereas a flow is the rate at which a stock can change. Stock and flow diagrams display the interactions between elements in the system so information can be traced throughout. Linear and/or continuous equations in time are applied to the system flows before initializing the system with appropriate stock levels based on expert input, previous research, or analyses [79].

The dynamic nature of an operational environment demands the analysis and planning to which the DoD currently subscribes in addition to a number of system dynamics methods introduced over the last fifty years. An operational environment is a complex system to model. Forrester progressed his work in system dynamics by publishing a provocative urban model highlighting the negative effects of inner city housing projects [76], [80]. He continued his non-corporate work on the WORLD models after an invitation to the Club of Rome led to development of a world socioeconomic model [81].

Forrester continued refining and applying system dynamics methodologies to the US economy and education while other researchers developed models for other applications. These included energy and in particular, gas, coal, oil, and electricity utilities [76]. More pertinent to the research supporting this thesis, system dynamics has been applied to hydrology and water scarcity issues in particular regions of the world. Elshorbagy described methodologies for teaching watershed hydrology, which is a natural renewable water source where precipitation and snow melt is collected and channeled on or in the ground towards an outlet [5, p. 1203]. The watershed models created by Elshorbagy are one application of system dynamics applicable to this research. Other than watersheds, system dynamics models approximating world parameters have notable applicability. Kojiri, Hori, Nakatsuka, and Chong assessed future water scarcity on population growth for each continent using six societal sectors [6]. These sectors included population (birth, maturation and death), agriculture (land development, land fertility, food production); capital (industrial and service outputs), nonrenewable resources (resources use and extraction), persistent pollution (pollution emission and assimilation) and water (water quality and water quantity) interacting with migration, trade of food, nonrenewable resources and industrial outputs, and foreign investments of services [6].

Simonovic produced a similar model, WorldWater, using the existing World3 model. The World3 model is dynamic versus many other water resource models (Table 5) whose applicability to world development Simonovic felt was limited [4, p. 250].

Table 5: Water Models

Available Water Models
Policy Dialogue Model (PODIUM)
International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT)
POLESTAR
Water Evaluation and Planning System (WEAP)
Water Global Assessment and Prognosis (WATERGAP)
Tool to Assess Regional and Global Environment and health Targets for Sustainability (TARGETS)

(Source: Simonovic)

Simonovic concludes that developing regional models of the WorldWater model would be far more effective in understanding dynamic regional water issues rather than attempting to convey water issues from a global standpoint. In a working paper on the topic of global water by Gassert, Landis, Luck, Reig, and Shiao, hydrological information is presented through a composite index approach [82]. Gassert *et al.* attempted to enable decision makers with water related risk indicators across the world, but cautioned this type of methodology was not advised for site or regional applications. These are important aspects for the research in this thesis since determining the affect water scarcity has on a local rather than global population towards migration or conflict is far more specific.

System dynamics is an ideal methodology to be applied to a dynamic environment with a multitude of potentially applicable dependent and independent variables. This overview of literature concerning system dynamics and pertinent research enables this study to model select water security variables with the intent of investigating the influence on migration and conflict.

Model Validation

Generally, modelers understand that their models are an abstraction of the truth, but that their perspective ultimately fails to address the truth entirely. The usefulness of a model is largely dependent on the modeler's ability to convey the practicality in its purpose whether that is to highlight previously accepted assumptions, challenge preconceived notions, or solicit input from varying disciplines. Forrester defined validation as

> a process of establishing confidence in the soundness and usefulness of a model…beginning as the model builder accumulates confidence that a model behaves plausibly and generates problem symptoms or modes of behavior seen in the real system [83, p. 210].

Sterman recited the fundamental definitions of verification and validation as examples of the fact that it is impossible to truly prove a model's worth since it is wrong [79, p. 846]. Zagonel consolidated validation and verification processes for both Forrester and Senge, and Sterman into five components each with ranked tests that avoid a "check-list" structure such that is commensurate with the modeling effort itself (Table 6).

Table 6: Five Components of Modeling Practice

Loosely constrained ←→ highly constrained

System's mapping	Quantitative modeling	Hypothesis-testing	Uncertainty analysis	Forecasting and optimization
Qualitative and inductive; involves drawing influence diagrams, CLDs, S&F diagrams, or any form of mapping or organization of the elements forming a system; attempts to get at the key causal interrelationships; focused upon identification of inter-organizational linkages and inter-dependencies	Quantitative and descriptive; involves formulation and simulation; largely system-focused; emphasizes S&F dynamics and the effects of delays; requires specification of the decision rules governing interrelationships; focused on representing and tracking consequences; sometimes rich in detail complexity	Quantitative and deductive; requires stating a hypothesis that explains dynamic behavior from the causal structure of the system; largely problem focused; emphasizes feedback-rich dynamics, learning, and exploration of the effect of changes in system structure; focused upon understanding and insight	Quantitative and exploratory; requires examining behavioral and quantitative sensitivity; emphasizes testing the robustness of the results produced from both quantitative modeling and hypothesis testing; focused upon uncertainty and risk, and identification of points of leverage for intervening in the system	Quantitative and predictive; within the range of the parameter space specified in the model, attempts to shed light on future behavioral patterns and the cross-sectional quantitative values of variables of interest, or to suggest optimal or robust solutions that maximize or "satisfice" particular utility functions

(Source: Zagonel)

Considering this study, our validation and verification efforts begin with mapping the topics of interest: water security, migration, and conflict. The narrative described within this chapter has led us towards a qualitative relationship between the variables to be investigated in our model. These social and environmental parameters include population (birth rate, death rate, and migration rate) and water balance (total internal and external renewable water resources, current per capita water consumption, water demand, and estimated change in migration rate). This study performs quantitative modeling using Vensim ® DSS [84], which permits stock and flow diagram formulation and simulation.

Our study proposes four questions for investigation:

1. What are the possible drivers of failing water security and can they be categorized within social, economic, political, and environmental areas?
2. Do available water resource data sufficiently quantify a particular country's water security?
3. Does the amount of available renewable water resources per capita serve as a trigger for potential migration and/or conflict within a country?

The third question is supported by the modeling and simulation efforts in Vensim while the remaining questions are based on qualitative deduction. The dynamics between parameters in the model is investigated over time through simulation. The simulations are varied by exercising the limits of particular parameters in order to determine their sensitivity. Finally simulation enables prediction across the model parameters in order to demonstrate behavior. Within the next chapter of this study, the validation processes are specifically defined.

Summary

The literature on relationships between water security, migration, and conflict humbly spans decades. While system dynamics has the most recent genesis in the mid-20th century by Forrester, migration research has its roots within the 19th century by the early work of Ravenstein. Even more incredible is that water security has been directly and indirectly strategized for several millennia by powers who have risen and fallen. The literature reviewed in this chapter supports the preceding investigation of drivers of water security and migration.

III. Methodology

Chapter Overview

This chapter describes the model building process, including the course of action required to define the causal relationships between water security and migration. Data required to parameterize the stock and flow system dynamic model is identified. Several verification and validation processes are executed in order to ensure sufficient accuracy for the simulation. A design of experiments is created and implemented to identify the extent of the drivers (parameters). Several scenarios are executed in Chapter 4 to investigate the overall influence of the drivers in Iran.

Model Purpose

As previously discussed, there are several narratives claiming that interdependent social, economic, political, and environmental factors drive water scarcity, migration, and conflict. The model defined in this chapter focuses on the total per capita renewable water resource availability, and the migration rate of change to address the following questions:

1. What are the possible drivers of failing water security and can they be categorized within social, economic, political, and environmental areas?
2. Do available water resource data sufficiently quantify Iran's water security?
3. Does the amount of per capita renewable water resources available serve as a trigger for potential migration and/or conflict within Iran?

The first question is rhetorical, since we have identified total per capita renewable water resource consumption and availability (TRWR-C and TRWR-A, respectively), and the migration rate of change as potential drivers. It is important to investigate the relationship between TRWR-A and migration, since they are separate observations with various data sources. Finally, investigating TRWR-A may or may not indicate a difference between actual or perceived influence, or whether it is a direct or indirect driver of migration.

Data Requirements

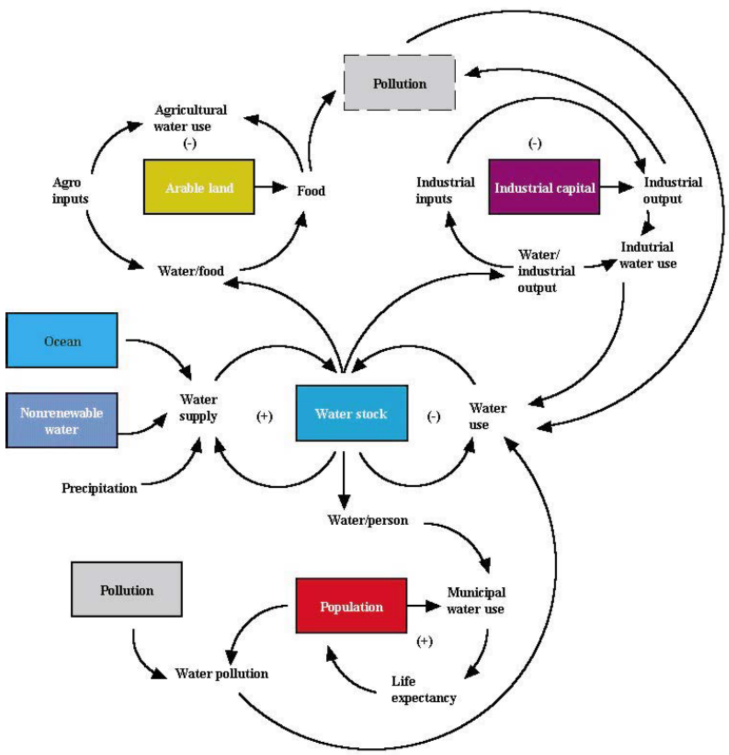
Many data sources were reviewed for possible application as social, economic, political, and environmental drivers. Those database sources considered for inclusion included: The UN Food and Agriculture Organization's (FAO) AQUASTAT website [3], World Development Indicators from the World Bank DataBank website [85], the US Census Bureau, International Division [86], and the UN High Commissioner for Refugees [87]. Several other water resource data sources referencing AQUASTAT data were excluded due to lack of value added from the aforementioned data sources.

It is noteworthy that the aggregated AQUASTAT data utilized for this study, particularly the TRWR-A is based on long-term averages of known internal and external sources. The AQUASTAT database was aggregated by country, rather than by region. All TRWR-A observations occurred every five years beginning in 1962 and ending in 2014. Consequently, if the observation data was unchanged throughout the range, those calculated data utilized the long-term average. This fact is problematic since other sources cite different annual water resource observations from regional municipal, industrial, or agricultural sources. However, no available regional sources possessed time-series data covering the period AQUASTAT offered. The World Development Indicators database offered on the World Bank DataBank website contained several observation series from the AQUASTAT database. The World Bank database was queried by country along with 1,574 estimated ‘indicators’ relevant to global, national, and regional development [85]. The input parameters and model variables and corresponding data sources are listed in Table 7. Migration and death figures are not delineated by cause and are assumed to encompass all causes including water scarcity and conflict-related deaths.

There were other studies regarding drivers and causes water scarcity and insecurity available that were also considered as data sources. As previously mentioned, GRACE and observed Iranian well level data analyzed by Joodaki *et al.* resulted in significant decreases in groundwater storage due to both climate and anthropogenic influence [44], [45]. Rainfall, drought, and agricultural studies offered total renewable water resource data as well [33], [88], [89]. Observations direct from Iranian water resource managers was publicly available, but access restricted offered the best potential water resource and consumption data [45]. News outlets offered sparse estimated annual water resource levels and consumption rates from independent and government sources [41], [50], [90], [91]. The reputation of the UN and the vast number of citations for other water scarcity and security researchers solidified the decision to utilize AQUASTAT estimates in this thesis. The case for migration rates and data was taken in the same regard. More independent researchers, aid organizations, and governments referenced the UN Refugee database than any other source. Of course, as better data sources become available, they can be utilized.

Model Construction

The causal model and stock and flow diagram developed for this study is an adaptation Simonovic's *WorldWater* (Figure 10) model along with s-shaped limits to growth feedback systems found in several texts [77], [79], [81], [92]. The primary focus is population, since total renewable water resources per capita (TRWR-P) is the quotient of TRWR-A and population. The causal loop diagram in Figure 11 denotes this focus. Population has a positive influence on consumption, which has a negative influence on water resources.



(Source: Simonovic, 2002 p. 256)

Figure 10: WorldWater Model

Since water resources are the limit to growth in this model, they negatively influence population as they decrease, thus positively influencing migration (emigration).

Migration is typically denoted as net migration, which is the net change of migration from both emigration and immigration. We are concerned with emigration due to the historically observed examples of populations migrating towards abundant resources or away from areas lacking resources.

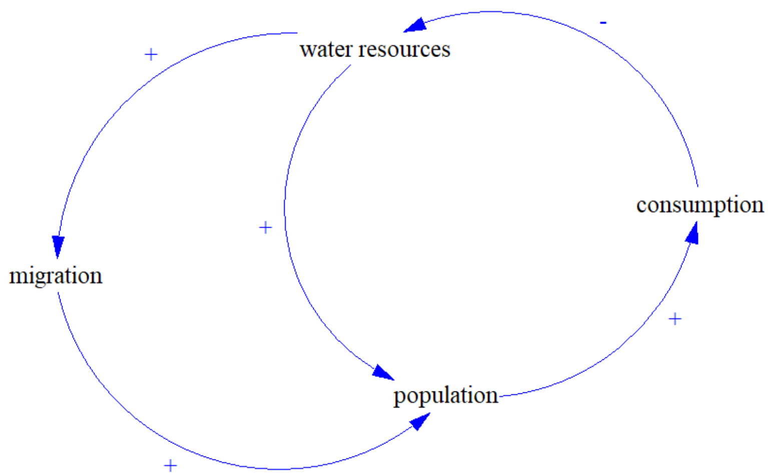


Figure 11: Causal Loop Diagram of Model

There are many parameters and variables influencing population. The parameters and variables used in this study's model are described in Table 7. The exogenous parameters we utilized in the model include average lifetime (years), birth, death, and net migration rates (approximated as number per 1000 people), and the initial population. Specific to modeling limits to growth models, a carrying capacity is introduced to balance the reinforcing growth loop from births through migration and deaths. The carrying capacity is defined as the quotient of TRWR-A divided by the TRWR-P (above 95 percent consumed, TRWR-C/TRWR-A) giving a population (persons).

We hypothesize migration and death rates of change increase as TRWR-P decreases. These rates of change are modeled through both UN FAO AQUASTAT and

US Census Bureau migration and birth rate data beginning from the point in time (years) when TRWR-C is 95 percent or greater than TRWR-A. In the case of Syria, TRWR-C was over 95 percent of TRWR-A in the year 2001 according to UN FAO AQUASTAT estimates [3]. Migration and death rates are modeled and parameterized as lookup tables with percentages of normalized population (population divided by carrying capacity) as input and the gross migration and death rates as outputs. Lookup table outputs are input as a multiplier of the normal migration and death rates, respectively. Migration and death rates are integrated over time along with the population as feedback. Since the effects of TRWR-P are not instantaneous on a population, migration and death rates have exponential smoothing factors with corresponding delays (years). Delays are varied depending on the model's response (population level, in persons). The UN World Population Prospects 2017 projected that 40 per cent of Syrian refugees return in 2020-2025, 30 per cent in 2025-2030 and 10 per cent in 2030-2035 [93].

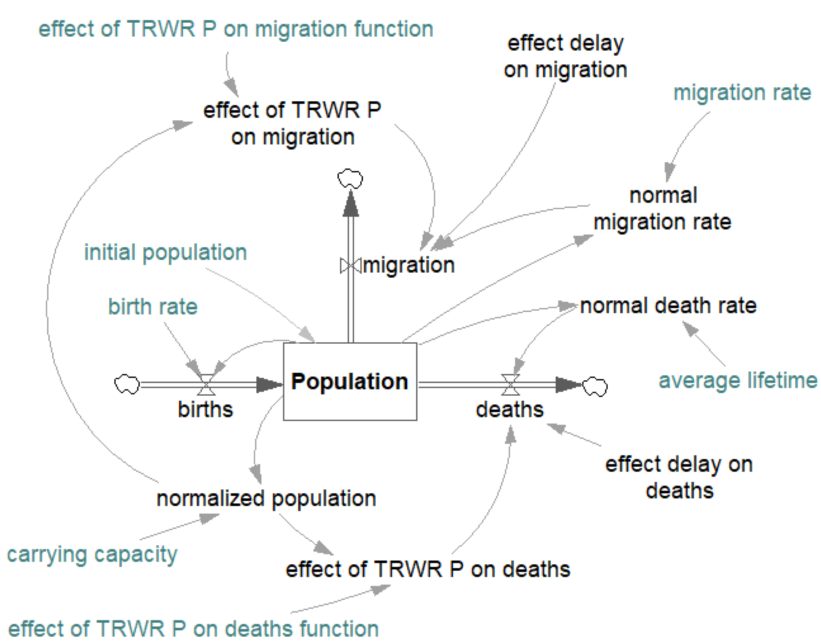


Figure 12: Model

Table 7: Model Parameters and Variables

Parameter / Variable	Description	Data Source	Input / Model
Population	Number of persons given births, deaths, and emigrants over time (*persons*)	WDI, US Census	Model
Initial Population	Number of persons at simulation start time (*year*)	WDI, US Census	Input
Carrying Capacity	Quotient of TRWR-A and TRWR-P (at 95% consumption of TRWR-A) (*persons)*	AQUASTAT	Input
Normalized Population	Fraction of Population and Carrying Capacity (*percent*)	-	Input
Births	Quantity of births *(person)*	-	Model
Birth Rate	Fraction of births occurring per 1000 persons per year *(fraction / year)*	WDI, US Census	Input
Average Lifetime	Life expectancy at birth (*years*)	WDI, US Census	Input
Deaths	Quantity of deaths *(person)*	-	Model
Normal Death Rate	Fraction of deaths occurring per 1000 persons per year *(fraction / year)*	WDI, US Census	Input
Effect of TRWR-P on Deaths	Product of Effect of TRWR-P on Deaths Function and Normalized Population (*Dimensionless*)	-	Model
Effect Delay on Deaths	Parameter of exponential delay (*years*)	WDI, US Census	Model
Effect of TRWR-P on Deaths Function	Table of inputs of Normalized Population corresponding to crude deaths (*Dimensionless*)	WDI, US Census	Input
Migration	Product of Normal migration rate and Effect of TRWR-P on migration	WDI, US Census	Model
Normal Migration Rate	Product of Emigrants and Population (*persons*)	WDI, US Census	Model
Effect of TRWR-P on Migration	Product of Effect of TRWR-P on Migration Function and Normalized Population (*Dimensionless*)	-	Model
Effect Delay on Migration	Parameter of exponential delay (*years*)	WDI, US Census	Input
Effect of TRWR-P on Migration Function	Table of inputs of Normalized Population corresponding to crude migration (*Dimensionless*)	WDI, US Census	Input
Emigration Rate	Fraction of emigrants per 1000 persons per year *(fraction / year)*	WDI, US Census	Input

Training Model Initialization

The model is initialized using Syria data as the training set in order to determine performance, verify, and validate the model for the test set (Iran). All initialization data is sourced from US Census Bureau, UN FAO AQUASTAT. Simulation time begins in the year 2001 and ends in 2025, with recorded Syrian population, migration, births, and deaths from 2001 to present, and forecasted data from 2018 to 2025. Initialization values are defined in Table 8.

Table 8: Syria Model Initialization Values

Parameter	Description	Starting Value (Year)
Initial Population	Number of persons at simulation start time (*year*)	16.93 million (2001)
Carrying Capacity	Quotient of TRWR-A and TRWR-P: (16.8 billion cu. meters / 825 cu. Meters)	20.63 million
Birth Rate	Fraction of births occurring per 1000 persons per year *(fraction / year)*	30 (2001)
Average Lifetime	Life expectancy at birth (*years*)	72
Normal Death Rate	Fraction of deaths occurring per 1000 persons per year *(fraction / year)*	4
Effect Delay on Deaths	Parameter of exponential delay (*years*)	2.7
Effect of TRWR-P on Deaths Function	Table of inputs of Normalized Population corresponding to crude deaths (*Dimensionless*)	(1,0), (1.01,47), (1.02,147), (1.03,114), (1.04,20), (1.05,1)
Emigration Rate	Fraction of emigrants per 1000 persons per year *(fraction / year)*	0.1
Effect Delay on Migration	Parameter of exponential delay (*years*)	2.1
Effect of TRWR-P on Migration Function	Table of inputs of Normalized Population corresponding to crude migration (*Dimensionless*)	(1,0), (1.01,1.15), (1.02,1.3), (1.03,1.45), (1.04,1.6), (1.05,1.75)

Model Verification

Recognizing that system dynamics models behave differently than discrete event simulation, Sterman stated that both model verification and validation of a system dynamics model are impossible based on existing traditional definitions of the terms [79, p. 846]. This statement is meant to enable thorough and robust model building rather than dissuade modelers from even attempting to produce a realistic perspective. The purpose of the model in this study is to investigate the applicability of TRWR-P as a driver of migration and/or conflict within a country. Model verification is implemented by inputting Syrian migration, birth, death, and TRWR-P data and comparing the model's output to Syrian population over the same time period. The model is validated using several of Forrester and Senge's validation tests adapted and redefined by Zagonel [83], [94].

The US Census Bureau provided Syrian migration rate using UN High Commissioner for Refugees (UNHCR) data from 2001 through 2013 and estimated data through 2025 (Figure 13). The simulation begins at 2001 since net migration prior to that year had a mean of -1.05 (1981-2000), which implies an approximately steady state rate. 2001 is also the period of time when TRWR-C rose above 95 percent of TRWR-A. Including migration data from 2001 to 2005 prior to the beginning of the drought in 2004 enables simulation and visualization of a steady state migration preceding the significant decrease through 2013.

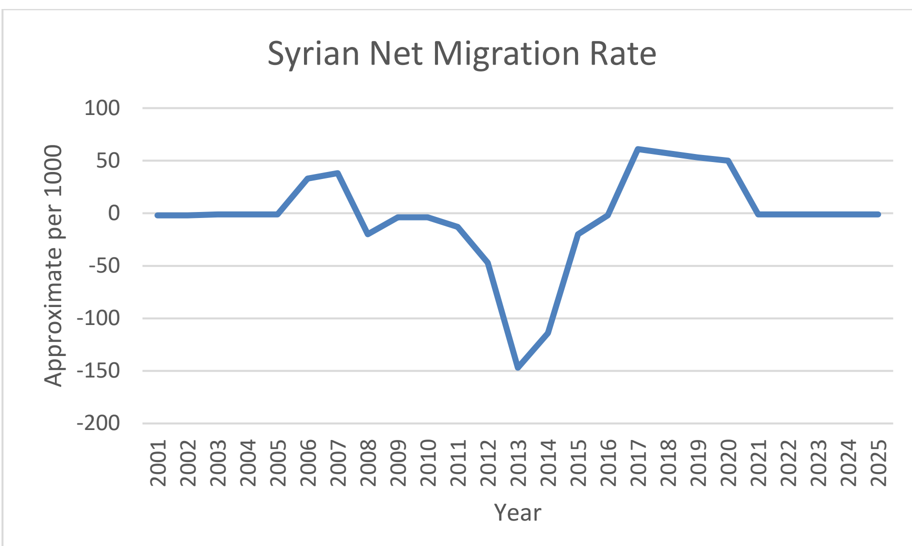
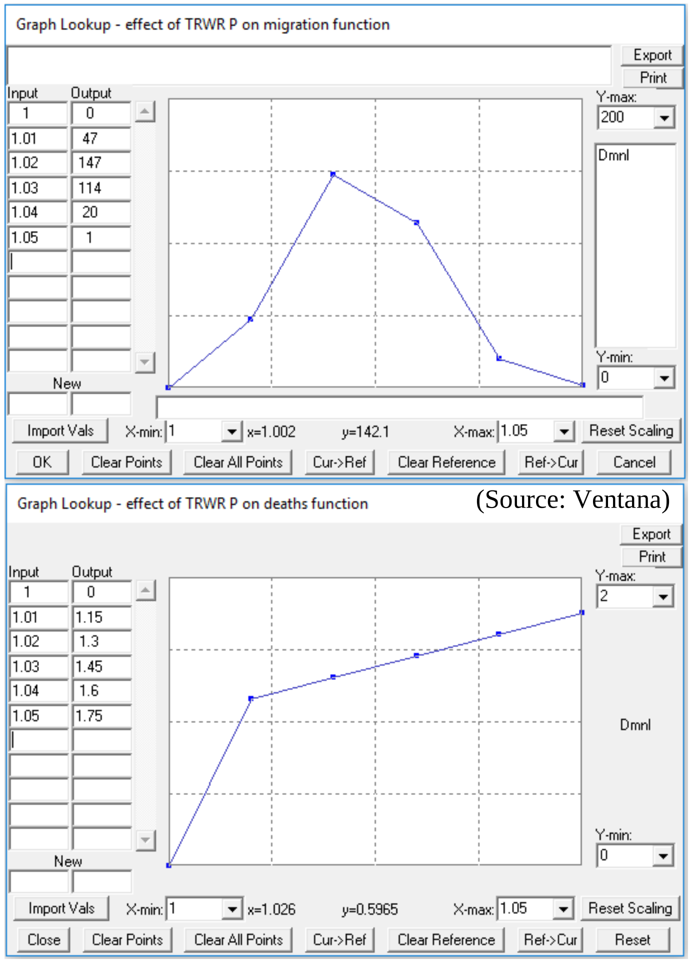


Figure 13: US Census Bureau Migration Data for Syria

Using estimated migration data following 2013 enables the simulation of a stabilizing population following the significant migration. Immigration rates occurring from 2005-2007 are omitted in the simulation due to the fact that sources defining the cause were unavailable. The migration rates were included as outputs of the lookup function Effect of TRWR-P on Migration Function with the Normalized Population values as inputs. The window of migration rates are reduced from 2006-2013 to 2012-2015 to prevent the effect on exponential delay in the migration rate and influencing the population level. The Effect of TRWR-P on Deaths Function is established with a simpler ramp function in order to replicate the change in death rates from 4 to 7 per 1000 from 2011-2012. Death rates provided by the World Bank sourced from UN World Population Prospects were estimated to the nearest thousandth, and were used in the Effect of TRWR-P on Deaths Function along with the Normalized Population values as inputs.



(Source: Ventana)

Figure 14: Effects of TRWR-P on Migration and Deaths Functions

Using standard least squares regression, the simulated model fit the actual population data (2001-2016) with a $R^2 = 0.94$ with a $R^2_{adj} = 0.93$ indicating 94 percent of the variability in the strength is accounted for by the model (Figure 15, Figure 16). Adding the additional estimated data (2017-2025) from the US Census Bureau to the model results in a $R^2 = 0.42$ with a $R^2_{adj} = 0.40$ (Figure 17, Figure 18). The addition of the estimated US Census Bureau data (2017-2025) reduced the strength of the model according to standard least squares regression. However, the model displays a strong variability for actual Syrian population data providing a starting point from which to predict population changes based on net migration, birth, and death rates. In addition, while the $R^2 = 0.42$ would not be considered high for engineering data, it is respectable for behavioral data.

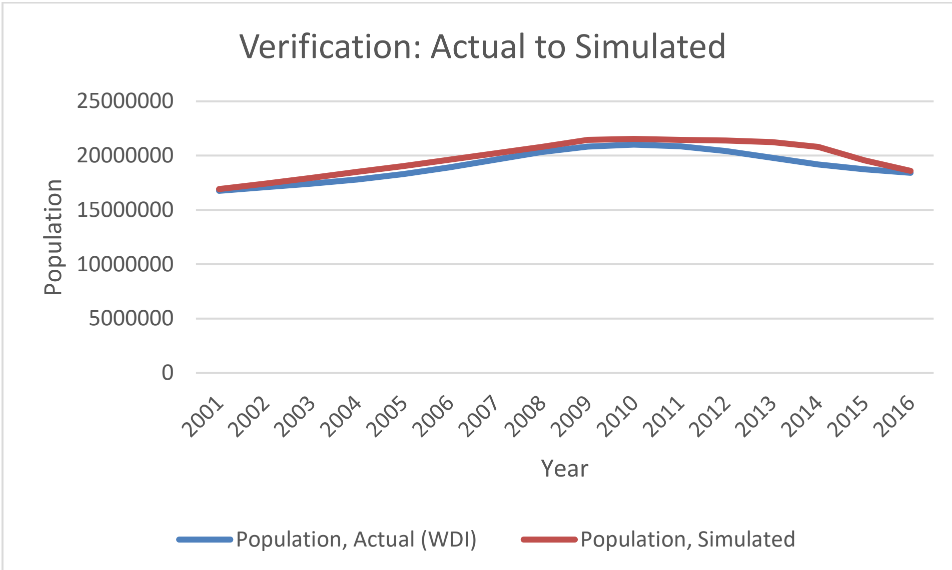


Figure 15: Model Verification of Population

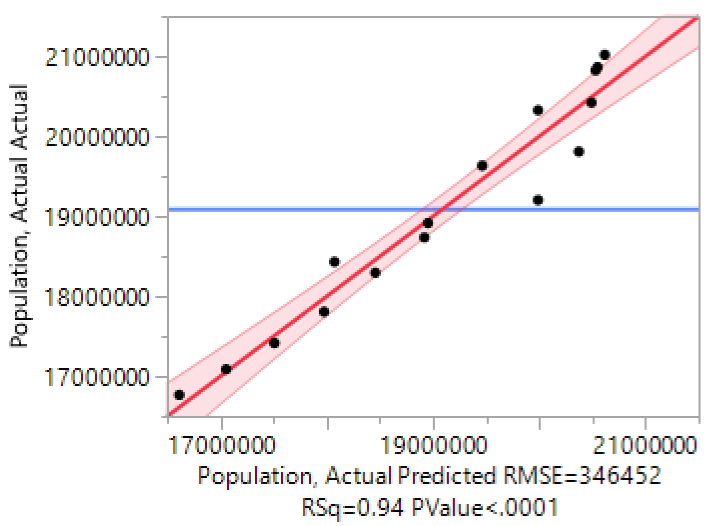


Figure 16: Predicted Fit of Simulated to Actual Population Data

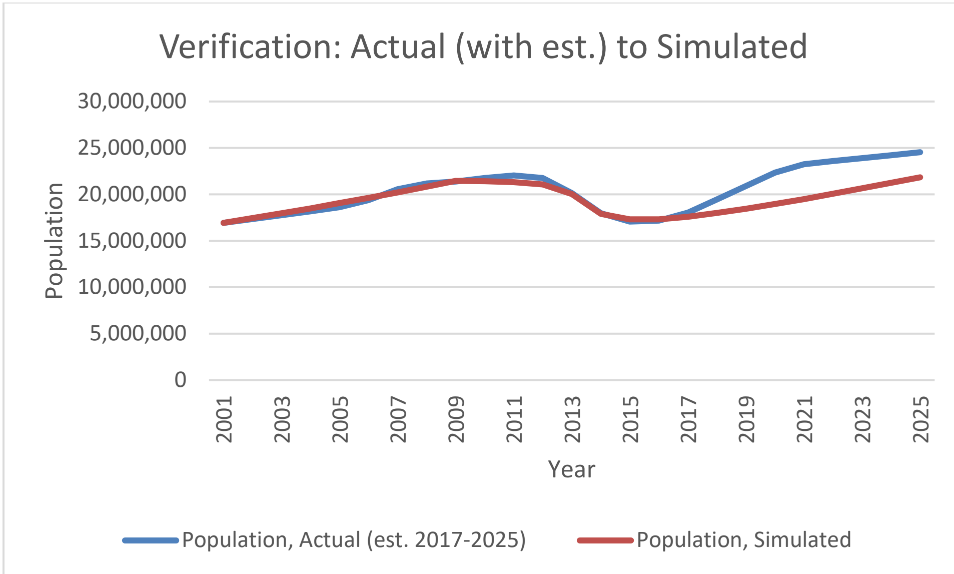


Figure 17: Model Verification of Population (with est. data)

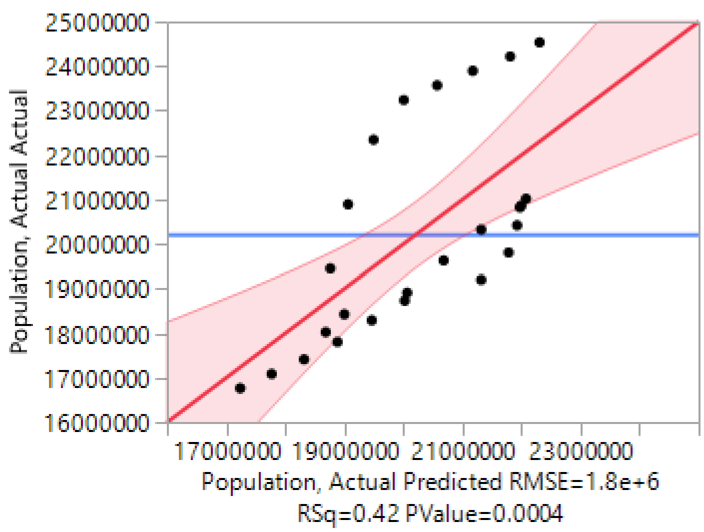


Figure 18: Predicted Fit of Simulated to Actual Population Data (with est. data)

Model Validation

Five tests adapted by Zagonel's reorganization of Forrester and Senge's validation tests provided in Appendix A are performed [83], [94]. The tests cover three of the five components including quantitative, hypothesis, and uncertainty. These tests are selected due to their ‘basic’ categorization within the five component organization and their applicability on the simplistic design of the model.

The first test determines physical conservation—does the model adhere to real-world conditions in Syria? The model outputs population levels by simulating actual rate data retrieved from credible sources (UN, World Bank) with methodologies commensurate with accepted population definitions [10], [12], [87]. The second test determines the dimensional consistency within the model—are all parameters, variables, levels, and rates realistic for Syria? All dimensions are appropriately and accurately applied within the model. The dimensionless parameters in the model are fractions of known dimensions and do not inappropriately dimension other parameters or variables. The third test determines the qualitative behavior—does the model simulate the real-world response? The model demonstrates expected behavior determined by the availability of actual population data. However, the model does not respond in an expected manner with estimated data, particularly US Census Bureau population from 2017-2025. The lack of actual census data, variability of water security and conflict in the modeled country (Syria), and unknown outcome of current events in the modeled country limit modeling accuracy for future time periods.

The fourth test determines whether TRWR-P is endogenous—does limiting the population drive migration based on TRWR-P levels? Normalizing the population in order to affect the migration and death rates is accurately represented by the simulated response and verified through standard least squares regression. The fifth test determines the model sensitivity—do values change significantly when parameters are varied over plausible ranges? Dimensionless parameters represent observed rates of change and therefore are not included in this test. The model appears sensitive to migration, birth, and death rates. The five tests offer validity to the model in this study based on the complexity, application, and available parameters.

Model Demonstration

The proposed model and parameters appear to realistically represent what occurred in Syria adding credibility to the overall framework. The model is exercised through a demonstration in order to determine if the observed differences in the factors are due to changes only and if the observed differences are statistically significant [95]. The factors in the demonstration include levels of the Effect Delay on Migration, Effect Delay on Deaths parameters, and Carrying Capacity (correlated to TRWR-P). The treatment levels are defined in Table 9.

Table 9: Treatment Levels

Factor	Level
Effect Delay on Migration	1-10 years
Effect Delay on Deaths	1-10 years
Carrying Capacity	72.20 – 91.10 million

As of 2007, the Iranian population was 72,203,000 people, with a TRWR-A of 137 billion cubic meters (TRWR-P of 1910 m^3/person/year), and a consumption of 68.1 percent (TRWR-C of 1301 m^3/person/year). The consumption rate of change increased an average of 3.76 percent from 1997 to 2007. A level of 95 percent consumption of TRWR-A is reached in the year 2047 by extrapolating the consumption rate of change. The population in the year 2047 is estimated to be 85,694,055 by extrapolating the 2014 population using the proposed 1.3 percent annual growth rate. In the year 2047, Iranian

TRWR-P is an estimated 1582 m^3/person/year. Simulation of the model with Iranian data begins in the year 2007, since this marks the last available observed consumption of TRWR-A data. The Effect of TRWR-P on Deaths Function and Effect of TRWR-P on Migration Function are maintained from the Syrian model and Effect Delays on Migration and Deaths are initialized at 1 year. The range of delay is selected based on assumed ranges of response time to both water scarcity and conflict as well as the limitations of the exponential delay function within the software. Delay values below 1 resulted in oscillation of all variables, thus a lower bound of 1 was established. Model initialization values for Iran are located in Table 11. The model is also simulated at optimal Effect Delay on Migration and Effect Delay on Deaths for Syria with Carrying Capacity at 86.6 million people. Finally, the model is optimized using Vensim software. Simulation occurs over the 2007-2032 time period in order to maintain the same time period as the Syrian simulation, but adjusted to the right in order to capture the most recent TRWR-C value (2007). Simulation scenarios are listed in Table 10.

Model Tuning

The model is "optimized" using the Vensim Optimizer function by weighting the specified factor as the highest priority and tuning the remaining model parameters (factors) in Table 9. Tuning in the Vensim software maximizes the prioritized factor across the simulation period. The payoff value for tuning is population and migration; maximizing these factors across the period of simulation minimizes the balancing and reinforcing feedback endogenous to the model.

Summary

In this chapter, we developed a population simulation model using Syrian parameters and variables. The data required to simulate the model were identified, interpolated, and extrapolated only when necessary to satisfy simulation periods over estimated population responses. Using actual and estimated Syrian data, we verified the simulation model using standard regression techniques. The simulation model was validated through several known tests in an effort to most accurately represent population growth. A demonstration was designed to test the effects of various treatments on specific factors through four scenarios. Finally the scenarios were executed as a method to determine if the Iranian population (response) will follow the Syrian population given the same effects on migration and death functions and delays.

Table 10: Simulation Scenarios.

Scenario	Effect Delay on Migration	Effect Delay on Deaths	Carrying Capacity
Baseline	1	1	86.6 million
Syria	2.1	2.7	86.6 million
Vensim Opt. Population	?	?	?
Vensim Opt. Migration	?	?	?

Table 11: Iranian Initialization Values

Parameter	Description	Starting Value (Year)
Initial Population	Number of persons at simulation start time (*year*)	72.20 million (2007)
Carrying Capacity	Quotient of TRWR-A and TRWR-P: (137 billion cu. meters / 1582 cu. Meters)	86.60 million (est. 2047)
Birth Rate	Fraction of births occurring per 1000 persons per year *(fraction / year)*	18
Average Lifetime	Life expectancy at birth (*years*)	72
Normal Death Rate	Fraction of deaths occurring per 1000 persons per year *(fraction / year)*	5
Effect Delay on Deaths	Parameter of exponential delay (*years*)	1
Effect of TRWR-P on Deaths Function	Table of inputs of Normalized Population corresponding to crude deaths (*Dimensionless*)	(1,0), (1.01,47), (1.02,147), (1.03,114), (1.04,20), (1.05,1)
Emigration Rate	Fraction of emigrants per 1000 persons per year *(fraction / year)*	1
Effect Delay on Migration	Parameter of exponential delay (*years*)	1
Effect of TRWR-P on Migration Function	Table of inputs of Normalized Population corresponding to crude migration (*Dimensionless*)	(1,0), (1.01,1.15), (1.02,1.3), (1.03,1.45), (1.04,1.6), (1.05,1.75)

IV. Analysis and Results

Chapter Overview

The results of the model simulation include outputs for Population, Births, Deaths, and Migration across four scenarios presented in the previous chapter. We used the Vensim sensitivity analysis function to produce sensitivity graphs of each rate and level. The investigative questions is addressed separately based on the results of the simulation, when applicable, and the research conducted for this study.

Results of Simulation Scenarios

Sensitivity Analysis

Sensitivity was performed on Population, Births, Deaths, and Migration variables of the baseline Iran model based on the treatment levels in Table 9. Birth rate established the initial Population (Figure 19) growth increasing from 75 million to 89.4 million people before decreasing as a result of the Effect of TRWR-P on Migration and the Effect of TRWR-P on Deaths. The range of Population growth results from the limits of the Carrying Capacity. The uncertainty of Population increased over time and particularly following the increase in Migration and Deaths. This behavior is validated through the realistic uncertainty occurring after a major event such as a natural disaster or war.

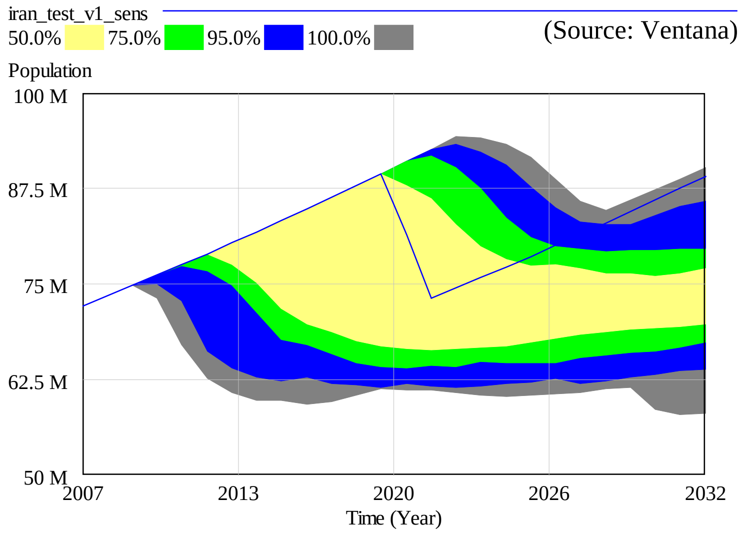


Figure 19: Population Sensitivity Graph – Baseline

Births (Figure 20) and Population shared the same sensitivity since Birth Rate reinforces the Population through feedback. Births followed the same uncertainty as Population because Births was the only reinforcing feedback in the model. Realistically, birth rates do fluctuate in a population experiencing a major event, particularly when health care is limited as a regulator of disease. Birth rates can also be affected by malnourishment if food and water supplies are restricted or contaminated.

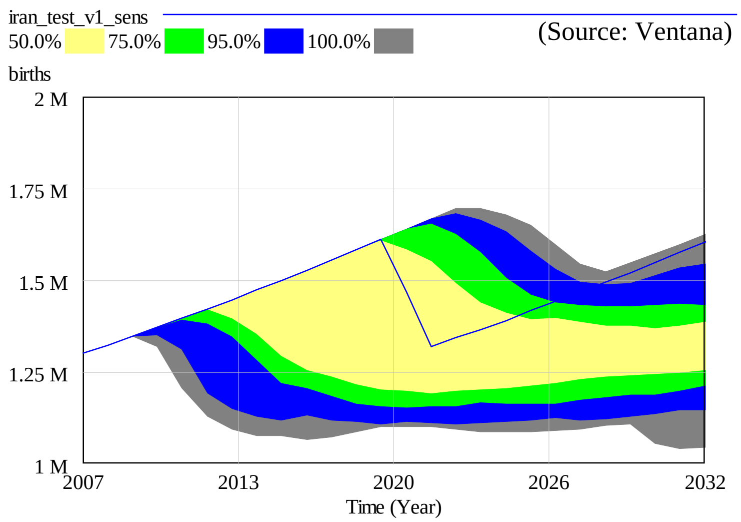


Figure 20: Births Sensitivity Graph – Baseline

The variable Deaths (Figure 21) increased sensitivity as a result of Effect of TRWR-P on Deaths and Effect of TRWR-P on Migration. Lower values (years) of Effect of TRWR-P on Deaths and Effect of TRWR-P on Migration allowed both Effect of TRWR-P on Deaths and Effect of TRWR-P on Migration Functions to maximize the reinforcing effect from Birth Rate on the population. The death rate of a population can vary for several reasons. Deaths are mainly attributed to life expectancy, but conflict and war can increase the death rate for those younger adult age categories, especially males. The uncertainty in Deaths from this simulation indicates significant variability within the 75 to 100 percent range.

The variable Migration (Figure 22) exhibited similar sensitivity as Deaths, although the Migration values were higher due to the order of magnitude increases in the Effect of TRWR-P on Migration Function. The uncertainty of migration rates have been discussed considerably in this study and are largely due to improved livelihoods through increasing economic opportunities. The variability of uncertainty for Migration between 75 and 100 percent appears lower than the variability in the same range for Deaths. However, the variability of Migration is clearly increased between 95 and 100 percent uncertainty compared to Deaths. The cause of increased variability in this particular range is unknown.

The sensitivity of this model was determined largely through the parameters Effects Delay on Migration (and Deaths) that either shortened or lengthened the model's response to the Effects of TRWR-P on Migration (and Deaths) Function. The length of each delay was essential to simulating the actual migration and death rates in the Syria and Iran model.

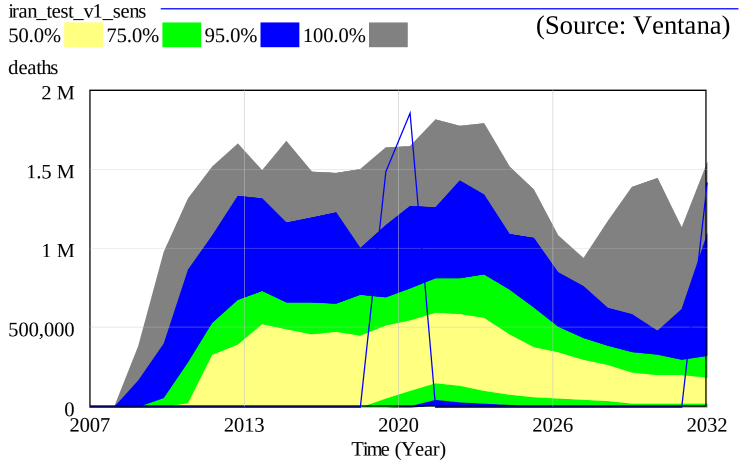


Figure 21: Deaths Sensitivity – Baseline

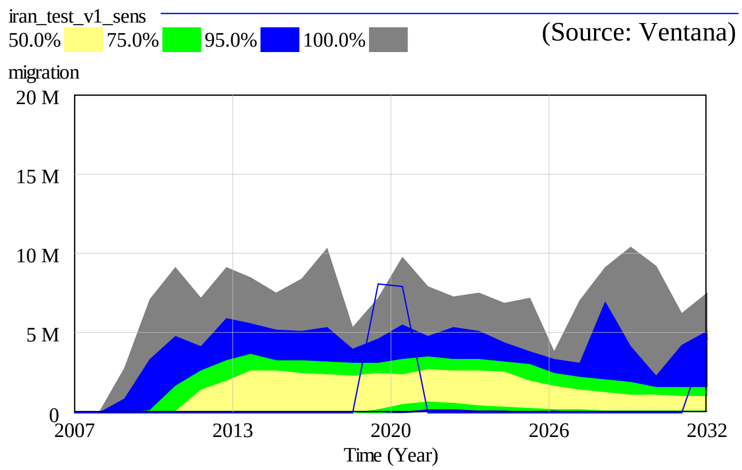


Figure 22: Migration – Baseline

Simulation Results

The results from simulating each of the four scenarios are shown in Figure 23, Figure 24, Figure 25, and Figure 26. The tuned factors for Vensim simulations are presented in Table 12. The baseline output (Figure 23) indicates a migration of 3.8

million and 0.5 million deaths from 2018 to 2019. Migration and deaths follow the Effect of TRWR-P on Migration and Deaths Functions with no delay. This outcome follows the delay of 1 year, as input, but does not adhere to the refugee return rate forecasted by the UN. The increase of Migration and Deaths at year 2031 indicate the Population level triggered the Effect of TRWR-P on Migration and Deaths Functions. This behavior may be desirable if the migration and death rates were to respond within a year of some underlying cause. However, the widely accepted S-shaped growth (or decay) curve is not evident, and therefore this population response is unrealistic.

Table 12: Vensim Simulation Outcome – Factors

Scenario	Effect Delay on Migration	Effect Delay on Deaths	Carrying Capacity
Vensim Opt. Population	1.87	10	86.6 million
Vensim Opt. Migration	1	10	86.95 million

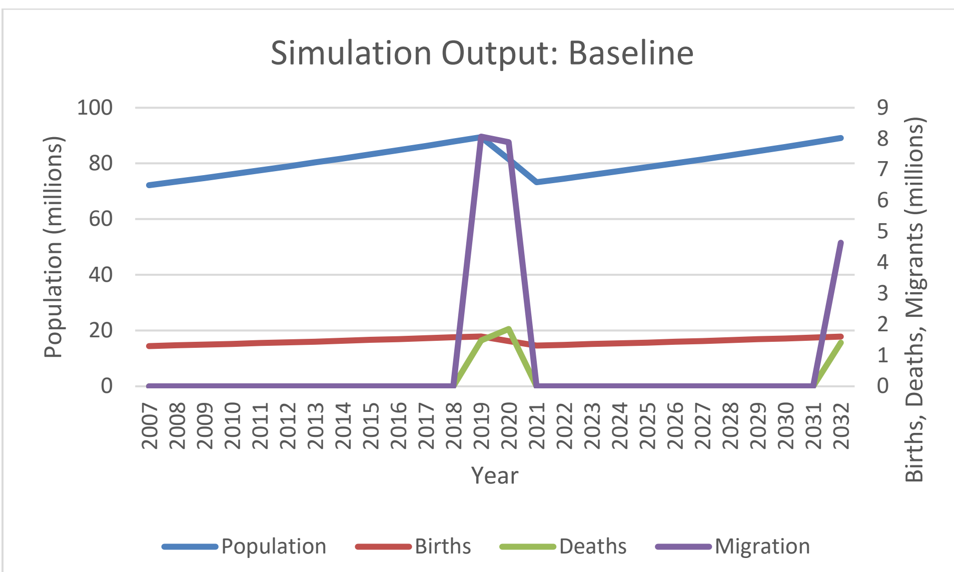


Figure 23: Simulation Output – Baseline

The simulation output using the Effect on Migration and Deaths Delays (2.1 and 2.7 years, respectively) from the Syria validation model (Figure 24) resulted in a more realistic response according to the UN World Population Prospect 2017 refugee return rates. Again Carrying Capacity was set to 86.6 million, the estimated population of Iran when 95 percent of TRWR-A was consumed (in the year 2047). This study cannot assume the model's exponential delay for Migration and Deaths include refugee returns considering available refugee return rates recorded by UNHCR sites include only those returnees who seek UN assistance as they return to their country of origin [87]. As previously mentioned, Migration and Deaths are all inclusive; separate subcategories for water and conflict related migrants and deaths were not modeled.

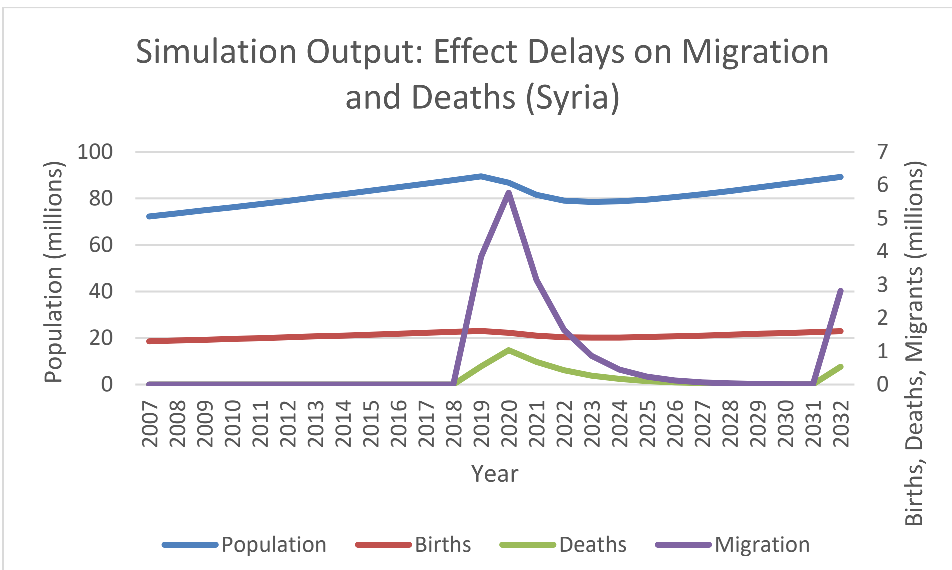


Figure 24: Simulation Output – Syria Optimal

The simulation output using Vensim Optimization function (Figure 25) performed similarly to the model using the Syria validation model in terms of Migration and

Population levels. Since the software optimized Population, the Effect Delay on Migration (and Death) parameters were optimized. The software set Effect Delay on Migration to 1.87 years and Effect Delay on Deaths to 10 years. The Effect Delay on Deaths caused deaths to be distributed over a 10-year period, which is plausible given victimization from long-term conflict and/or contraction of water-borne viruses, but unlikely at such a constant rate. The uncertainty of Deaths shown in the sensitivity analysis in Figure 21 indicate there would be more variability in the number of deaths.

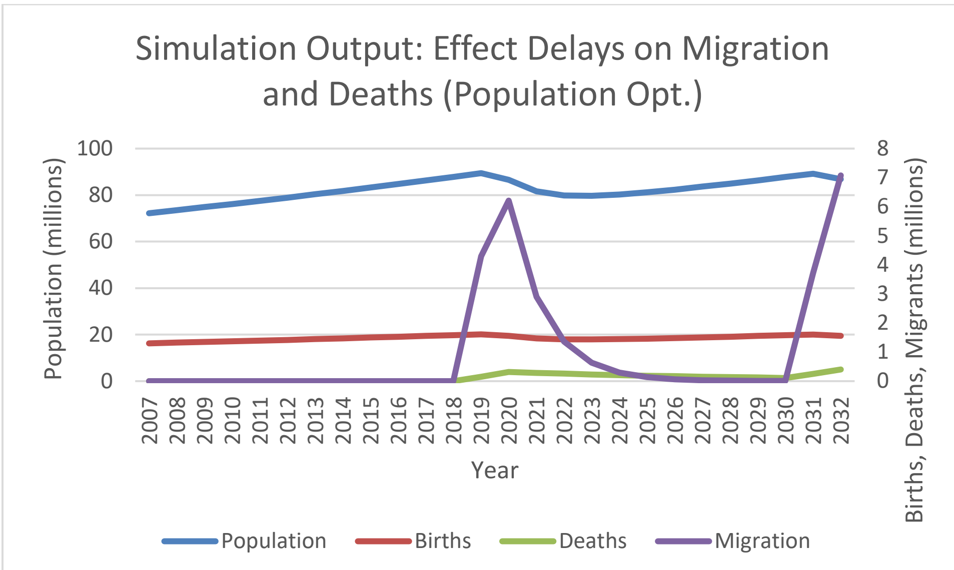


Figure 25: Simulation Output – Population Opt.

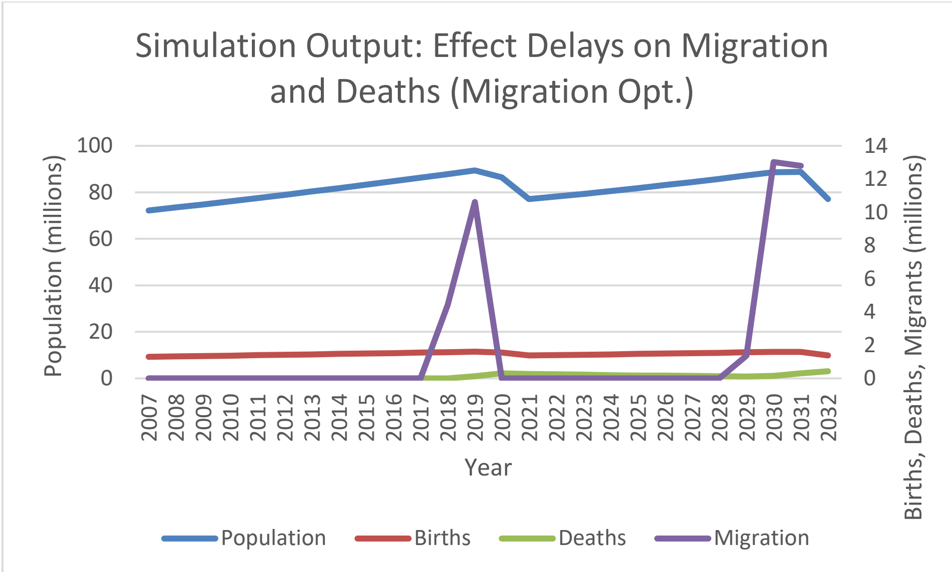


Figure 26: Simulation Output – Migration Opt.

The simulation output using Vensim Optimization function (Figure 26) maximized Migration over time that resulted in a different Population response. Migration increased at a lower rate than for the Syrian Optimal or Population Opt. simulations, but resulted in a higher peak Migration. The software tuned the Effect Delay on Migration to one year, the Effect Delay on Deaths to 10 years, and the Carrying Capacity to 86.95 million persons. As mentioned previously with the Syrian Optimal simulation, the Effect Delay on Deaths set to 10 years is plausible, but unlikely.

Additionally, retaining the same carrying capacity over the simulation period resulted in "activating" the Effect of TRWR-P on Migration and Deaths Functions more than once. This translates to water resources remaining constant over time, which may or may not be accurate. Allowing this simulation behavior in the model, however, may identify other endogenous issues if migration and death rates were disaggregated or parameterized.

Investigative Questions Answered

The following were the questions posed at the beginning of this study in order to investigate the interdependencies between water security, migration, and conflict:

1. What are the possible drivers of failing water security and can they be categorized within social, economic, political, and environmental areas?
2. Do available water resource data sufficiently quantify Iran's water security?
3. Does the amount of per capita renewable water resources available (TRWR-P) serve as a trigger for potential migration and/or conflict within Iran?

Question 1: Possible Drivers

This question was largely investigated through the literature review. Specific examples of social, economic, political, and environmental drivers in Syria and Iran were showcased. Socially, water has been a generally abundant resource to populations in the MENA region, and the people have a long history of controlling water resources through millennia-old technologies such as the qanat. This abundance has permitted cultures to endure long drought periods as well as devastating floods. However, as populations increase due to advanced technologies, improved hygiene and sanitation, and state health care, natural recharge rates decline resulting in increased demand on fuel. People, especially rural dwellers, have less resources to maintain their existing lifestyle and over time are led to make decisions to move.

Economically, populations are increasingly adapting to urban lifestyles as more people move towards cities. Increases in urban populations stress employment opportunities, infrastructure, and basic services for existing and transient people. As resources become stressed, the economy is stressed to keep pace with migrants and internally displaced people. Politically, a government can exacerbate these stressors by applying untimely and inappropriate measures such as reducing or ending subsidies for essential services and resources such as fuel, fertilizer, or water. Frustrated, dissident groups may rise in power over limited resources in efforts to denounce government responses. Horizontal inequalities such as employment, education, land ownership, and basic services existing within groups may lead to protests, infighting, corruption, or conflict. Finally, the environment may suffer. Governments, especially those of low to middle class economies, which fail to manage or control resources may resort to more drastic solutions such as over abstraction of renewable groundwater, exploitation of fossil aquifers, and over damming to increase surface waters. Such solutions lead to biodiversity depletion through loss of green water, pollution of existing water sources, and eutrophication.

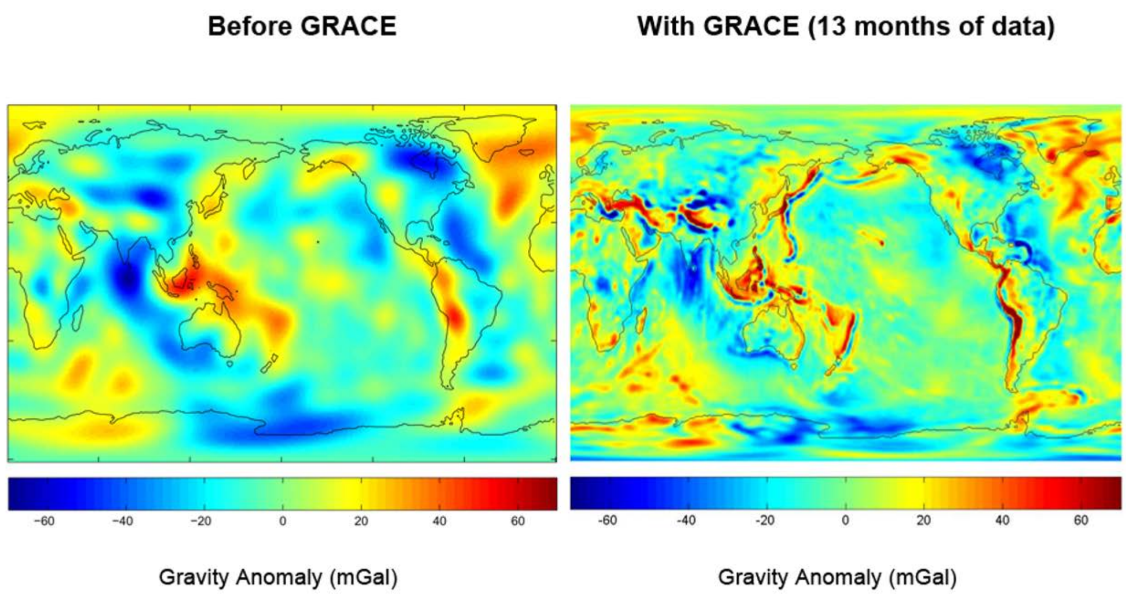
The sustainable goals set by the World Bank focus on governments' accountability for water resource management, preparation for water-related risks, and capability of water delivery services. These goals are echoed through the numerous narratives, studies, and news articles supporting this study. Corrupt governments that mismanage resources due to a lack of expertise and observed data have been proven to fail to protect their populaces during droughts and floods. Similarly, those same governments struggle to maintain sufficient and quality water supplies via reliable infrastructure.

Question 2: Available Water Resource Data

Many MENA countries such as Saudi Arabia, Jordan, Israel, Qatar, and U.A.E. understand and have improved their water security. The increase use of desalination, inter-basin water transfers, and groundwater monitoring are commonplace in such countries, which inherently enable the government to provide water through proper management. Regardless, countries such as Iran and especially Syria are experiencing the effects of water insecurity due to mismanagement and unsustainable practices. Water data have historically been estimated through measurement of surface flows, groundwater tables, precipitation, as well as all the watershed and water cycle variables provided. Many of these estimates are based on long-term averages of previous measurements of which the dates are unknown [3], [82].

The available water data used in this study included those long-term average data. Calculating the percentage of TRWR-A based on consumption was performed with four data points. All water data used was sourced from the UN's AQUASTAT website, which was referenced by nearly all water research, except for those researchers fortunate to have direct measurement capability or access to the source. Denser data foster increased dependence and relevance for models than do sparse data. Iran possesses and offers regional water data for public use and research [96] and has been accessed and referenced by researchers [45]. The World Resource Institute leaned heavily on UN AQUASTAT data for their Aqueduct Global Maps 2.1 project to determine water risk indicators [82].

Research on water storage and usage is increasingly being conducted using data obtained through satellite observation as technologies become more accurate and precise. The GRACE project has continued to provide increasing levels of both accuracy and precision in order to deliver enhanced resolution groundwater storage products for analysis (Figure 27). Improvements such as this are encouraging to researchers attempting to realistically model and predict and track natural seasonal variances and anthropogenic effects.



Source: https://phys.org/news

Figure 27: Increase in GRACE Resolution

The data used in this study, particularly TRWR-A and TRWR-P fail to address Iran's water security with a measurable degree of certainty. Modeling the water security in Syria required several key assumptions. The long-term average TRWR-A has not been affected by known reductions in rainfall quantities. Rainfall directly affects *IRWR* as precipitation is absorbed into the ground, infiltrating the alluvial flows, seeping into other water sources, evaporating into the atmosphere, or running off into waterways. The value of TRWR-A includes groundwater abstraction, which is typically measured through well water withdrawals. Governments may or may not track every well, and attempts to license wells so as to monitor withdrawal rates are not reliable. Surface water flow in a country such as Iran which has a large quantity of dams for hydroelectric power generation and irrigation for agricultural purposes may or may not be affected, especially if transboundary surface flows upstream are dammed as well.

Question 3: TRWR-P as a Potential Trigger

The total renewable water resources per capita available is a quotient of TRWR-A and the current population. As previously mentioned, TRWR-A is a long-term average. Population is an aggregated total of all TRWR users: agricultural, industrial, and municipal. UN AQUASTAT divides TRWR-A between agriculture, industrial, and municipal usages based on available observations, government or otherwise, and modelled estimations. UN AQUASTAT data is labeled with a variety of dates—many older than a decade. The infrequency of data updates is cause for concern when relying on this TRWR-P data as a potential trigger for migration and/or conflict.

TRWR-P could be a potential indicator if a well-defined lower bound were identified and accepted for an entire population or if TRWR-P were disaggregated to state or local users. The UN-defined range of water scarcity addresses populations with less than 1000 m^3 per person annually (and absolute scarcity at 500 m^3 per person annually) is without explanation. There is correlation with this definition and the estimated 825 m^3 per person annually Syrians experienced in 2007 during a multi-year drought preceding civil war and mass migration. However, the proximity in time to the outbreak of conflict and migration in conjunction with the aggregated TRWR-P fail to support causation. Furthermore, agricultural, industrial, and municipal withdrawal and consumption data would be necessary to increase the validity of TRWR-P considering variance between agricultural users in rural farming areas and urban dwellers.

V. Conclusions and Recommendations

The purpose of this study was to investigate the interdependencies of water security, migration, and conflict through research and a system dynamics modeling methodology in order to inform military planners and strategists about their influences on future military operations. The research addressed three investigative questions primarily concerning water security as a way to begin modeling interdependent variables.

The research conducted was informative; it incorporated several dynamic global issues previously studied separately, or in pairs, but not as an entirety. One of the key aspects of water security are the sustainability goals established by the World Bank. Those include resource sustainability and efficiency management, reliability and affordability of services, and risk management of potential water-related events. Governments working towards these goals are currently reducing their probabilities of experiencing water insecurity and subsequent migration and/or conflict.

Modeling the effects due to the total renewable water resources per capita improved our understanding of the problem's complexity. The uncertainty determined through sensitivity analysis identified unanticipated endogenous behavior that appeared to be directly related to the delay of migration and death rates. The population decrease from the actual migration and death rates increasing over time highlights the potential response. Finally, the decay of migration and death rates over time indicates a realistic human response as conditions improve.

Further work would enhance the research and modeling efforts presented in this study. Potentially data-rich sources direct from government sites in Iran or high resolution satellite observations from projects such as GRACE may offer extensive adaptations. Improving the underrepresented conflict topic in the model using Political Instability Task Force (PITF) data may increase realism by disaggregating migration and death rates. Specific modeling of horizontal inequalities including civil liberties, level of democracy, GDP per capita, availability of primary education, and employment rates along with these specific water data overlaid with geospatial data could localize water security and help forecast future migration and conflict.

Appendix A: System Dynamics Validation Tests (Source: Zagonel)

System's Mapping

1. Face validity (structural assessment through deductive process) – Q: Is the model structure consistent with relevant descriptive knowledge of the system?

2. Validity of decision rules (structural focus) – Q: Do the decision rules capture the behavior of the actors in the system?

Quantitative Modeling

3. Physical conservation – Q: Does the model conform to basic physical laws such as conservation laws?

4. Dimensional consistency – Q: Is each equation dimensionally consistent without the use of parameters having no real world meaning?

5. Integration error – Q: Are the results sensitive to the choice of time step or numerical integration method?

6. Extreme conditions tests (equations focus) – Q: Does each equation make sense even when its inputs take on extreme conditions?

7. Parameter assessment – Q: Do all parameters have real world counterparts? Are they consistent with relevant descriptive and numerical knowledge of the system?

8. Basic-behaviors reproduction – Q: Does the model generate the various modes of behavior observed in the system?

9. Endogenous behavior-reproduction tests – Q: Does the model pass behavioral reproduction tests without the aid of exogenous inputs driving the model in predetermined ways?

10. Boundary adequacy tests (modes of behavior) – Q: Does the behavior of the model change significantly when boundary assumptions are relaxed?

11. Qualitative problem-behavior test – Q: Does the model qualitatively reproduce the behavior(s) of interest in the system?

12. Boundary adequacy test (problem endogeneity) – Q: Are the important concepts for addressing the problem endogenous to the model?

13. Validity of decision rules (policy focus) – Q: Do the decision rules capture the behaviors of the actors in the system? (policy focus)

14. Assessment of surprise behaviors – Inspection for unusual, novel, unexpected or surprise behaviors. Q: Does the model generate previously unobserved or unrecognized behavior? Does the model successfully anticipate the response of the system to novel conditions?

15. Behavior sensitivity analysis – Q: Do the modes of behavior generated by the model change significantly when assumptions about parameters, boundary, and aggregation are varied over the plausible range of uncertainty?

16. Extreme conditions tests (model behaviors focus) – Q: Does the model respond plausibly when subjected to extreme policies, shocks, and parameters?

17. Behavior anomaly tests (changed assumptions tests) – Q: Do anomalous behaviors result when assumptions of the model are changed or deleted?

18. Family member (generalizability) – Ability to generalize. Q: Can the model generate the behavior observed in other instances of the same system?

Uncertainty Analysis

19. Quantitative sensitivity analysis – Q: Do the numerical values change significantly when assumptions about parameters, boundary, and aggregation are varied over the plausible range of uncertainty?

20. Policy sensitivity analysis – Q: Do the policy implications change significantly when assumptions about parameters are varied over the plausible range of uncertainty? Is the level of aggregation appropriate?

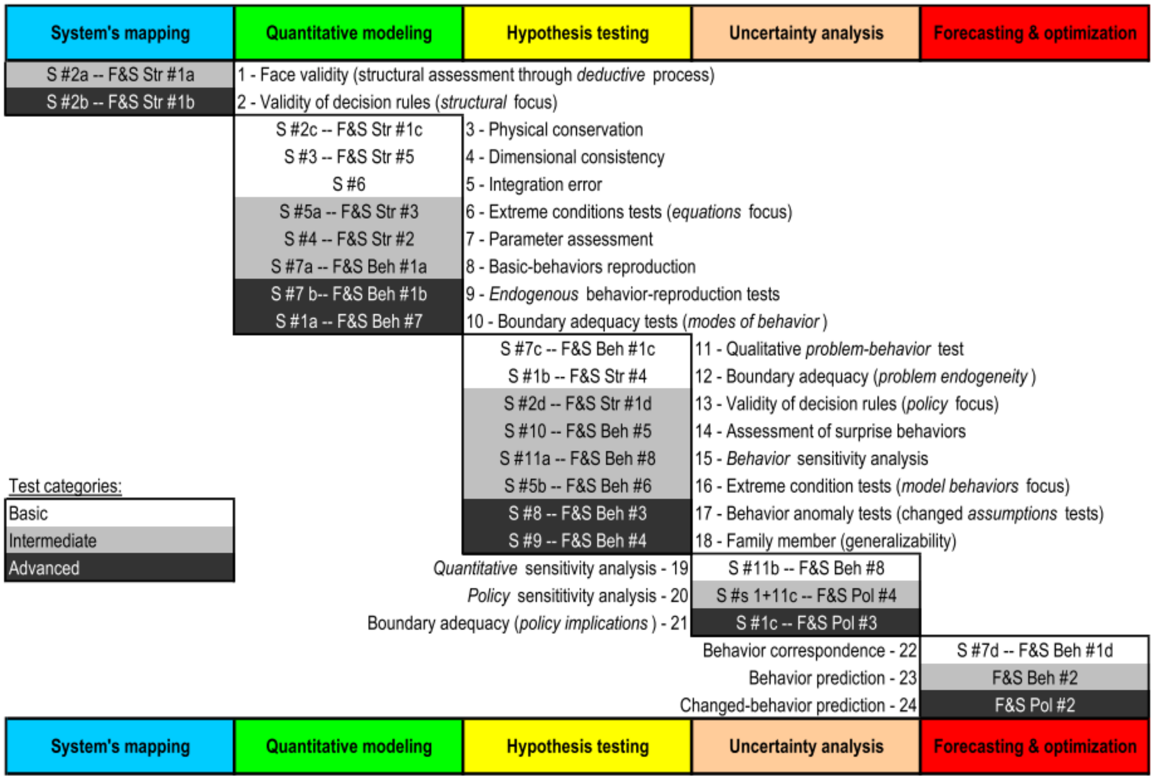
21. Boundary adequacy tests (policy implications) – Q: Do the policy recommendations change when the model boundary is extended?

Forecasting And Optimization

22. Behavior correspondence – Q: Does the model quantitatively reproduce the behavior(s) of interest in the system?

23. Behavior prediction – Pattern prediction, event prediction, shifting-mode prediction 24. Changed-behavior prediction (prior to worry about number forecast; behavioral forecast)

Appendix B: System Dynamics Test Components Chart



S - Sterman (2000); F&S - Forrester and Senge (1980); Str - Structure; Beh - Behavior; Pol - Policy implications (Source: Zagonel)

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14. ABSTRACT
Iran is facing a daunting reality regarding the future of their water resources which may result in conflict and migration within the country with the potential to affect the Middle East and North African region and beyond. The country has failed to address critical preservation, risk mitigation, infrastructural, and political efforts to accommodate their rising population due to economic expansion. Water resources are dependent on social, political, economic, and environmental variables related to conflict and migration. Given the recent examples of water security issues in Syria resulting in migration and conflict, this thesis investigates the total available water per capita as a driver for the potential collapse of Iran's water resources. Portions of two key world system dynamics models were combined to identify interrelated variables leading to migration and conflict. It was found through multiple simulations that decreasing water per capita levels leads to increases in aggregated migration and death rates for this particular investigation. Further experimentation with other interrelated variables such as civil liberties, level of government, and GDP per capita may highlight other drivers and allow extension of this model to other countries of interest.

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